Is It Worth It? The Economics of Reusable Space Transportation
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Richard Webb
KAR Enterprises

Abstract

Over the past several decades billions of dollars have been invested by governments and private companies in the pursuit of lower cost access to space through earth-to-orbit (ETO) space transportation systems. Much of that investment has been focused on the development and operation of various forms of reusable transportation systems. From the Space Shuttle to current efforts by private commercial companies, the overarching belief of those making such investments has been that reusing system elements will be cheaper than utilizing expendable systems that involve throwing away costly engines, avionics, and other hardware with each flight. However, the view that reusable systems are ultimately a "better" approach to providing ETO transportation is not held universally by major stakeholders within the space transportation industry. While the technical feasibility of at least some degree of reusability has been demonstrated, there continues to be a sometimes lively debate over the merits and drawbacks of reusable versus expendable systems from an economic perspective. In summary, is it worth it?

Based on our many years of direct involvement with the business aspects of several expendable and reusable transportation systems, it appears to us that much of the discussion surrounding reusability is hindered by a failure to clearly define and understand the financial and other metrics by which the financial "goodness" of a reusable or expandable approach is measured. As stakeholders, the different users and suppliers of space transportation have a varied set of criteria for determining the relative economic viability of alternative strategies, including reusability. Many different metrics have been used to measure the affordability of space transportation, such as dollars per payload pound (kilogram) to orbit, cost per flight, life cycle cost, net present value/internal rate of return, and many others. This paper will examine the key considerations that influence stakeholders as they make space transportation investment decisions, including primary metrics by which various stakeholders measure financial goodness and other factors that significantly shape decisions to invest in reusable or expendable systems. It must be noted at the outset that reusable systems take many forms and perform different transportation functions including, but not limited to, ETO payload delivery. *The discussion in this paper is limited to the economics of ETO transportation systems*.

Introduction

Investment decisions regarding the "best" approach to providing space transportation services are shaped by several considerations. The aerospace industry has been pursuing reusable systems at some level for over 50 years. The central thesis, in a nutshell, is essentially that "It's cheaper if you don't throw stuff away with every use, especially expensive stuff like rocket engines and avionics." That thesis, however, is not universally accepted. Numerous notable aerospace executives and experts have publicly expressed a range of opinions regarding the economic viability of reusable versus expendable systems. In addition, the space industry's various public media sources, from printed and on-line news sources such as Space

News and Aviation Week and Space Technology, to on-line discussion websites such as Nasaspaceflight.com and Reddit.com, to public discussion forums such as the recent American Institute of Aeronautics and Astronautics forum on propulsion titled "Launch Vehicle Reusability: Holy Grail, Chasing Our Tail, or Somewhere in Between?", are rife with opinions regarding the efficacy of reusable systems. Figure 1 illustrates this with a small selection of differing opinions as stated by recognized stakeholders in the industry.

"Costs of Reusable Launch Vehicles: Should We Pay Up Front to Build in High Reliability or Pay Later to Buy More Vehicles?": demonstrated that there is no scenario in which the economics of reusable launch vehicles makes them preferable in cost to expendable launch vehicles."
Dr. Stephen Book, PARAMETRIC WORLD, Winter 2012

"If one can figure out how to effectively reuse rockets just like airplanes, the cost of access to space will be reduced by as much as a factor of a hundred. A fully reusable vehicle has never been done before. That really is the fundamental breakthrough needed to revolutionize access to space."
--Elon Musk, SpaceX.com, 3/31/2013

The payoff of a reusable rocket is only possible if the launcher is flown many times, and market outlooks in the commercial sector and with European institutional missions do not add up to tip the scales in favor of reuse (he said).
--Stephen Israel, Chairman an CEO, Arianespace, Spaceflight Now.com, 1/11/2016

Commercial space exploration can advance at the fast pace of Internet commerce only if the cost is reduced through advances in reusable rockets.
Jeff Bezos, Amazon CEO, bloomberg.com, 4/12/2016

Figure 1. Opinions differ regarding the efficacy of reusable space transportation systems

Even a cursory look at the various media sources leads to the conclusion that after 50 years there is still no consensus regarding the economic viability of reusable space systems.

While it is not within the scope of this paper to offer a comprehensive history of the pursuit of reusable systems, a short summary of where the industry has been is important to understanding alternative future paths that might be taken. To date well over $10B has been invested in various reusable systems ranging from small startups that never "got off the ground" to multi-billion dollar programs that were ultimately cancelled during development prior to producing flight hardware, to operational reusable systems. Figure 2 summarizes some of the largest past U.S. Government-funded reusable systems, including ETO delivery systems as well as other systems not designed to provide ETO services.

Program	Approx. Invest (TY$)
X20 Dynasoar	~ $400M
Project START	~ $1B
Space Shuttle	~12B
X30 National Aerospace Plane (NASP)	$3 - $5B
Delta Clipper Flight Experiment	$50M
X33 Advanced Technology Demonstrator	$1B
X34 Technology Testbed Demonstrator	$219M
X37 Advanced Technology Flight Demonstrator	$301M

Source: National Space Transportation Policy Issues for the Future, Hogan and Villhard, WR-105-OSTP, October 2003

Figure 2. Summary of past key U.S. Government-funded reusable space transportation systems

Early pioneers such as Kraft Ehricke, Phil Bono, and Eugen Sanger put forward some of the earliest reusable concepts. Maxwell (Max) Hunter was an influential early proponent of Single-Stage-To-Orbit (SSTO) reusable systems with his X-Rocket design. Most notable of the reusable systems to date is, of course, the Space Shuttle which flew 135 flights from 1981 through 2011. The Shuttle, a partially reusable system, has been cited in much of the discussion regarding reusable systems as both a good and bad example of the economic potential of reusable systems. We will discuss the applicability and lessons to be taken from the Shuttle experience in greater depth later in this paper.

More recently privately-funded companies, most notably Space X, Blue Origin, and Virgin Galatic have invested heavily in reusable systems. As of the writing of this paper Space X has made eleven attempts to recover their first stage booster with six successes, all after the booster successfully performed its part in delivering payloads to orbit. Blue Origin has successfully launched and recovered their New Shepard sub-orbital vehicle to an altitude of 100km. A joint venture between Scaled Composites and Paul Allen (Mojave Aerospace Ventures - a group that is now essentially controlled by Virgin Galactic) successfully launched their manned suborbital Spaceship One to 100km three times while winning the Ansari X prize in 2004. The Defense Advanced Research Projects Agency (DARPA) has received proposals from industry in response to their Request for Proposal for a reusable first stage called XS-1. The RFP calls for design, fabrication, and flight test of a demonstrator vehicle that will lead to an operational system. The flight tests will include 10 flights in 10 days of the booster and will culminate with a flight that (with an expendable upper stage) will insert a payload into low earth orbit. DARPA intends to invest $140M in the project while calling on industry to provide additional investment. While the debate continues, development of reusable systems continues apace.

Based on our experience on the commercial Atlas, Shuttle, X33/Venture Star, and other systems we have found that an answer to the basic question regarding reusable space transportation system "Is it worth it?" is very dependent on considerations that can be categorized in six essential areas:

- **Who Cares?**
    - The stakeholders, that is the users and suppliers of space transportation, and what they care about.
- **Why Are You Doing This?**
    - Investors' motivations for investing in reusable space transportation systems.
- **If You Build It They Will Come…**
    - The demand for space transportation.
- **A Matter of Degree**
    - The different approaches to and types of reusable transportation systems.
- **How Many?**
    - Sizing the reusable transportation fleet in terms of number of systems in service.
- **Size Matters**
    - The importance of the size of the system in considering the reusable/expendable decision.

The balance of this paper will consider some of the key factors in each of these areas that weigh significantly on decisions to invest in reusable (or expendable) ETO transportation systems.

Who Cares?

The primary stakeholders in the space transportation industry include users and suppliers of space transportation. The users of space transportation systems are varied and disparate. Summarized in Figure 3, users range from civil governments engaged in science and exploration missions, to military organizations utilizing space for, among other things, communications and intelligence gathering, to commercial companies making use of space for such things as communications and remote sensing. A recent addition to the user community has been the developer/operators of very small satellites termed (depending on their size) cubesats, nanosats, and small sats which have been used for small science experiments, remote sensing, and other uses.

DEMAND	STAKEHOLDERS	PRIMARY USES
Civil Government	NASA, ESA, NOAA, etc.	earth sciences, astrophysics, planetary exploration, manned exploration, ISS
Military Government	US Department of Defense, Foreign Governments	communications, intelligence, treaty verification
Commercial - Geosynchronous Orbit (GSO)	Communications & broadcast companies	communications and direct broadcast satellites
Commercial - Low Earth Orbit (LEO)	Mobile communications & remote sensing companies	communications constellations, remote earth sensing
Commercial - Other (LEO)	New/current commercial companies; cube/nano sats; small sats	remote sensing, telecom, broadband internet

Adapted from: ACHIEVING RESPONSIVE ACCESS TO SPACE--MARKET, MONEY, MECHANICS, AND MANAGEMENT LESSONS FROM X-33, Meade, Lane, Webb, 1st Responsive Space Conference, April 1–3, 2003

Figure 3. Summary of key stakeholders/users of ETO space transportation systems

For users of space transportation, transportation to space is a means, not an end. Typically the value of the payload or payloads in terms of their actual cost and/or value in generating (for instance) revenue, scientific return, or intelligence information, are much greater than the price of the launch service to place them in orbit. Among the attributes users value most are low price, high schedule availability, and high reliability. However users often differ in the priority and importance placed on these attributes. Commercial satellites generally value low price although, particularly for higher value satellites such as geosynchronous communications satellites, launch system reliability and schedule availability can be important. Military intelligence users typically value high reliability over other attributes given the high dollar value and importance placed on the satellites and the information they provide. They are willing to pay premium prices for launch systems they consider to have higher reliability. Recent military interest in so-called "sortie" missions such as Prompt Global Strike emphasizes availability. Depending on the cost and nature of the mission, civil governments prioritize price, although reliability and availability can also be of significant importance.

An overarching consideration of all users of space transportation is the payload capability of the launch system. The greater the launch system's payload capability the higher the price. Accordingly users will

generally choose the system that most closely matches their payload launch weight while meeting their other most valued attributes. This leads to an important consideration. Many of those engaging in discussion regarding the economics of reusable space transportation assume the cost (actually price) per payload mass unit (e.g. price per kilogram (pound)) to the user is their most important metric. We have found that to not necessarily be true. While price per unit mass is useful for comparing the price efficiency of different systems, *ultimately users pay a price per flight, not a price per kilogram*. This has become particularly apparent to the set of users whose payloads fit in the Delta II launch system class. With the retirement of the Delta II there are no systems in the current stable of available vehicles that closely match the Delta II's performance, forcing users to the higher capability vehicle class such as Falcon 9, Atlas V, or Ariane V. As a result users are paying higher prices while not utilizing the full payload capability of the launch system. A possible exception are the cubesat-class users who, by the nature of their missions, have begun to utilize the services of a launch broker to load several satellites on one launch as secondary payloads launched at lower prices for each satellite.

Under the direction of NASA Marshall Space Flight Center's Engineering Cost Office, the Victory Solutions Marshall Integrated Program Support Services (MIPSS) team is developing the Project Cost Estimating Capability (PCEC), a set of parametric cost models for modeling robotic spacecraft and manned and unmanned crew and space transportation systems. As part of the PCEC model, we have developed a Launch Services ROM Estimator to provide a Rough Order of Magnitude (ROM) estimate of the launch services cost for robotic spacecraft. The estimator considers launch mass and destination (orbit altitude and inclination) to provide the estimate as shown in Figure 4. The estimator is based on historical launch prices for NASA and other satellites. There are price breakpoints as satellite mass increases to the point that, for instance a Minotaur or Pegasus vehicle can no longer launch the satellite, necessitating the purchase of an Atlas or Falcon.

	Destination:					
Mass (kg):	GEO	Planetary	Polar	Lunar	LEO	Helio
< 3,000	$ 120					
> 3,000	$ 140					
< 1,000		$ 80				
1,000 to 2,000		$ 110				
> 2,000		$ 175				
< 1,000			$ 55			
1,000 to 2,000			$ 85			
> 2,000			$ 130			
< 500				$ 85	40	
> 500				$ 160	80	
All						$ 100

Figure 4. NASA PCEC Launch Services ROM Estimator (M15$)

The graph on the left side of Figure 5 plots the database from which the price points shown in Figure 4 are taken. Dividing the Y-axis prices by the X-axis launch weights provides the corresponding price per kilogram in the graph on the right. While there are many variables that factor into each individual data point that are not shown on the graph, most particularly destination, at a top level it can be seen that as

expected launch prices increase with increasing launch mass and the corresponding price per kilogram decreases as launch mass increases.

Consider as an example, a program developing a 500kg payload. The program could expect to pay on the order of $50M for launch services, which corresponds to approximately $100,000 per kilogram. If that payload were to grow to, for instance, 2,000kg the transportation price would increase to approximately $100M while the price per kilogram would drop to $50,000 per kilogram. As a result an additional $50M would be required to launch the satellite. The program budget decrease in price per kilogram is of little consolation for the program manager who has budgeted $50M for transportation services but now faces a bill of $100M to launch their satellite.
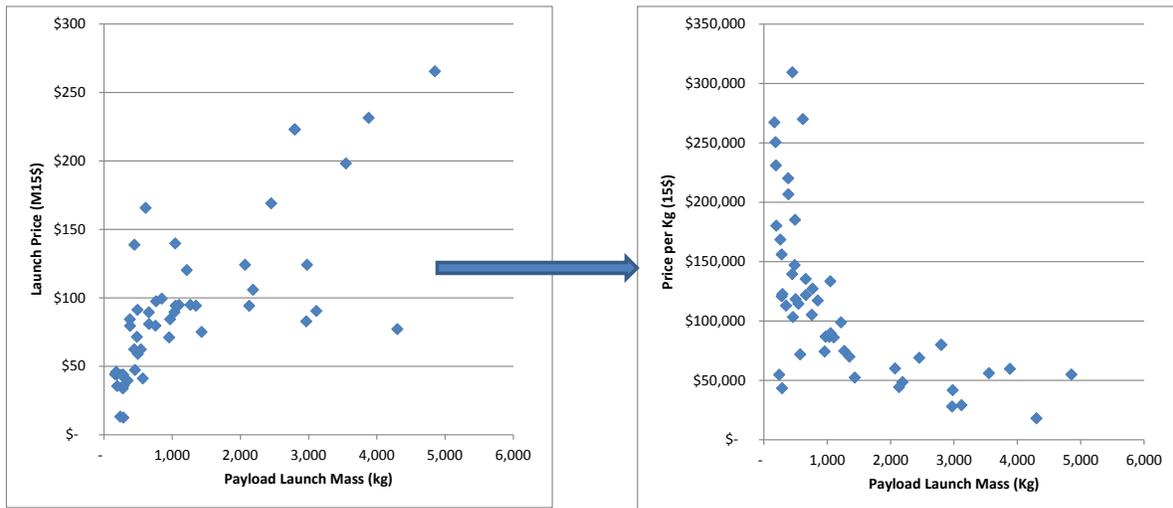

Figure 5. Historical prices per flight and resulting prices per kilogram

While price per launch mass can be an important metric, it is not necessarily the most important to users in determining the most economical transportation system for their set of circumstances.

Suppliers of space transportation are also many and varied. In calendar year 2015 there were 86 ETO launches accomplished by 21 launch systems representing governments and commercial companies from 7 countries (Figure 6). The launch system attributes valued by suppliers can be as varied as they are for users. As discussed in greater depth in the next section, what suppliers value depends in large measure on their motivations for providing ETO transportation. With some exceptions and varying definitions, in summary suppliers are generally interested in making money. As such space transportation is the end, not the means. At the same time suppliers' values are of necessity influenced greatly by the values held by their customers (the users) which, as discussed above, can vary greatly depending upon the market segment being served. The key is for suppliers to incorporate the key attributes valued by their customers in a way that allows them to sell launch services for as much or more money than it costs them to provide the attributes. At the same time it must be noted, however, that strategically motivated suppliers (discussed below) can diverge significantly from the order of attribute prioritization typically seen with most transportation suppliers.

| Vehicle	Country	2015 Flights		Vehicle	Country	2015 Flights
CZ (DF-5)	China	17		Zenit	Russia	1
R-7	Russia/EU	16		GSLV	India	1
Atlas 5	US	9		H-2B	Japan	1
Proton	Russia	8		Delta 2	US	1
Falcon 9	US	7		Dnepr	Russia	1
Ariane 5	EU	6		CZ-6	China	1
PSLV	India	4		CZ-11	China	1
H-2A	Japan	3		Safir 1B	Iran	1
Delta 4	US	2		Soyuz 2-1v	Russia	1
Rokot/Briz KM	Russia/EU	2		Super Strypi	US	1
Vega	EU	2		TOTAL		86

SOURCE: spacelaunchreport.com, Ed Kyle

Figure 6. 2015 ETO launches by launch system and country

The manifestation of decisions to be made regarding how best to meet customer requirements while at the same time making money occurs in two primary circumstances: 1) during the non-recurring investment phase when capital budgeting decisions are being made regarding whether or not to invest in reusable (or expendable) systems and the specific configuration of such; and 2) during recurring production and operations when generating high returns on sales (i.e. profit) by maximizing price while minimizing cost becomes key. The primary metrics many suppliers employ are different depending upon the phase. During the non-recurring phase discounted cash flow (DCF) analysis techniques are often utilized with the primary measures of economic "goodness" being net present value (NPV) and/or internal rate of return (IRR). During the recurring phase profit, generally measured as return on sales (ROS) is the primary measure.

As illustrated in Figure 7, in both phases the suppliers' decision making process becomes a balancing act between the multiple, often competing interests of users and suppliers. As an obvious example, during the recurring phase a user's "cost" is a supplier's "price". Users value low cost while suppliers value high price, setting up a need to balance between the competing values. As another example, during the non-recurring phase investment decisions must be made regarding alternative approaches to meeting customer's values such as high availability and high reliability while minimizing investment. Is it "worth it", for instance, to spend additional money to design subsystems with multiple-string redundancies to increase reliability, or is it "worth it" to design a reusable system that returns to the launch site to increase availability?

For suppliers of space transportation the question of whether or not to invest in a reusable system demands consideration of several factors, the first of which is: why are you doing this?
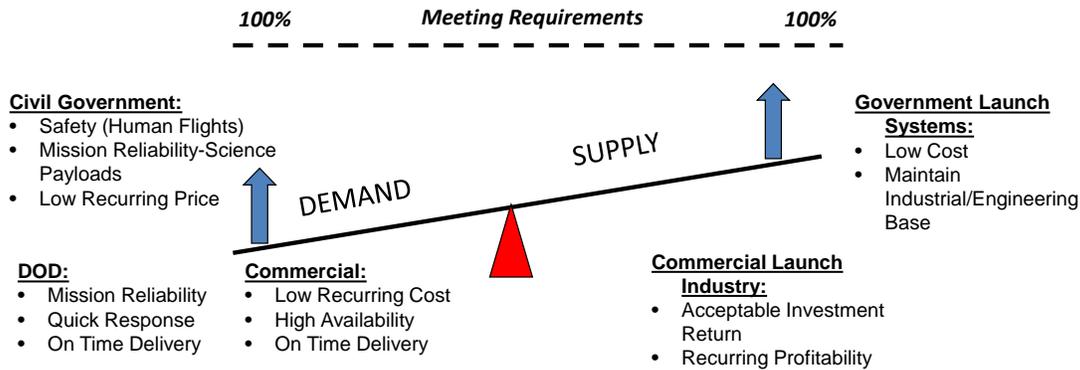
Figure 7. Stakeholders' multiple, sometimes competing interests sets up a balancing act

Why Are You Doing This?

Deciding upon an approach to providing space transportation services depends in large measure on the interplay between several key considerations: what missions/market segments are you supporting; where in space are you attempting to go; and, most importantly, what are your motivations for investing in a reusable system?

Missions – One of the first considerations is what types of missions you are supporting. Reusable systems can be employed to support one, some, or all of a number of different types of missions including:

- Up: Up-mass missions can include ETO orbital insertion (*the focus of this paper*), in-space transportation (e.g. a space "tug" such as the cancelled Orbital Maneuvering Vehicle (OMV)), and sortie missions (e.g. Prompt Global Strike).
- Down: Cargo and manned return missions that require a separate ETO system for reaching orbit such as X37, Dragon, Cygnus, and the Soyuz capsules.

Where – Mission destination in terms of altitude and inclination is an important factor. Destination of the mission can range from sub-orbital (New Shepard and SpaceShip II) to orbital. Orbital missions vary in altitude from low earth orbit (LEO) to geosynchronous (GSO) to escape trajectories (e.g. planetary), and they also vary in inclination from due east to polar to retrograde.

It must be noted that the Space Shuttle was designed for multiple missions. As a partially reusable system it was (of course) a manned transportation system but it was, at the same time, much more. The Shuttle was also an ETO transportation system of satellites to a variety of destinations, an in-space system (e.g. Hubble rescue, Intelsat 603), a non-permanent but nonetheless an orbiting space station (Spacelab), and Shuttle returned cargo including space station and other returns (e.g. Long Duration Exposure Facility (LDEF), Palapa and Westar satellites). As such, it is our observation that *Shuttle is not a good model to be used as an argument either for or against reusabilit*y.

Motivations – Ultimately decisions regarding investments in reusable space transportation systems depend most significantly on investor/supplier stakeholders' motives for making the investment.

Motivations impact directly what you value. We have separated investor motives into two summary categories: Financial and Strategic.

- *Financial*: Those whose decisions are motivated primarily by financial metrics are most typically public companies whose main focus is enhancing shareholder value. Their primary end is to make money. As such their primary metrics for determining "is it worth it?" are based on DCF or similar metrics (e.g. NPV and IRR).

- *Strategic*: Those whose decisions are more motivated by strategic interests are typically private companies such as Space X and Blue Origin who may have other aspirations beyond just making money from their offering of ETO transportation services. Examples of more strategic goals might be, for instance, developing, deploying, and operating a LEO high speed internet constellation requiring deployment and replenishment of multiple thousands of satellites. In that instance a vertically integrated company would own their own means of ETO transportation. A reusable system developed and operated by the same company as the satellite constellation operator could serve to ensure availability of ETO transportation while providing the service at cost. At same time the constellation serves as the all-important "anchor tenant" that ensures a high flight rate and, thus, high utilization of the fixed asset reusable system.

Depending upon motivations, then, the answer to "is it worth it" can be either yes or no and, for each stakeholder the answer can be "right" for their circumstances and motivations. The CEO of United Launch Alliance (ULA) said as much in an on-line Twitter discussion (Figure 8).

Figure 8. Decisions for or against reusable systems depend significantly on stakeholder motivations

Another consideration that differs between those motivated by financial or strategic visions is culture, in particular with regard to risk tolerance, the capacity to accept failures. It is worth noting that during the course of bringing their reusable first stage to full operating status Space X has experienced (to date) 5 failures in 11 attempts. At the same time they have been successful 5 of their last 6 attempts. The DC-X Delta Clipper experienced one loss-of-vehicle failure and was cancelled. Its successor, X-33, suffered a significant ground test failure and was cancelled. Both were funded jointly by U.S. Government and large public aerospace companies. The motivation to continue to pursue a reusable system after contending with failure appears to bear greatly on the decision-making processes of the different stakeholders.

Of somewhat lesser concern, but still worth noting, is altruism as a motivating factor. Some apologists for investment in reusable systems predict potentially important benefits to humankind if reusable

transportation reduces the cost of access to space to such a significant degree that space is opened up to ever more, as yet untapped uses. As a somewhat chicken-egg conundrum, the high cost of space access, the argument goes, limits the use of space such that investments in reusable systems are not currently "worth it", but investments in reusable systems would reduce cost such that they would ultimately move the ball down the field so that, in the end, they will be "worth it", if not to the initial investors, ultimately to humankind. The persuasiveness of the argument is very much an individual subjective valuation. Our only observation is that, persuasive or not, unless it generates more money than it expends, altruism in and of itself is not sustainable without subsidy. Ultimately systems resulting from any decisions made based on altruistic motivations would either have to eventually become self-sustaining or will require subsidization from other sources.

One important ramification of the difference between the metrics utilized by those motivated more by financial interests versus strategic interests are the mechanisms of DCF metrics and their influence on investment decisions. As noted above, DCF metrics of IRR and/or NPV can have a significant, although not necessarily an exclusive, impact on the capital budget decision making process, particularly for those motivated primarily by financial considerations. *By their nature DCF metrics generally work against investments in reusable systems* because of the larger influence of the present value of the upfront investment relative to future earnings. Consequently those stakeholders for whom "worth it" is measured in terms such as NPV/IRR would generally not invest in reusability, while those stakeholders whose motivations are centered more on other strategic considerations might be more inclined to proceed with investment in reusability.

While a detailed description of DCF techniques and metrics is beyond the scope of this paper, to understand the ramifications of DCF metrics on capital budgeting decisions it is important to understand their definitions. The fundamental equation of DCF is $\$/(1+r)^n$ where "$\$$" is the net cash flow (positive or negative) in a given year (or other time period), "r" is the discount factor, and "n" is the number of years from initial investment. The NPV is the cumulative total of discounted positive and negative cash flows for the time period considered. IRR is the present value discount factor at which the cumulative sum of the net cash flows (the NPV) over the given time horizon is $0. IRR is a **quantitative** value, calculated from the estimated cash flow stream. The NPV is the total cash flows discounted by a given discount rate. The discount rate is an input. While there are many elaborate means for calculating an appropriate rate, such as the Capital Asset Pricing Model, ultimately the discount rate, sometimes termed the "hurdle rate", is a **qualitative** value set by the investment decision makers. The hurdle rate is the rate at which the cash flows for the project under consideration are discounted. If the NPV of the discounted cash flows is positive, the project is deemed "worth it", if not, not. At the same time an IRR higher than the hurdle rate is "worth it". The hurdle rate is the rate capital investment alternatives must "hurdle" in order to be selected for investment. Investments are considered relative to their *opportunity cost*, the highest valued alternative use of the investment funds. Typical hurdle rates we have worked with range from 20% to 30% or more.

Figure 9 provides an admittedly simple example to illustrate the difficulty faced by a reusable transportation system in passing a DCF analysis. There are many variables that feed a DCF analysis of a reusable system. Because a reusable system is, at its core, a fixed asset it needs to be fully utilized to its maximum capacity to realize its full value. For an ETO system utilization is measured primarily by flight

rate. *As a rule of thumb the three most important things a reusable system must do to be "worth it" are fly, fly, and fly.*

The example in the Figure plots the flight rate per year which a reusable system must attain in order to pass hurdle rates of 20% and 30%. The assumed time horizon is 10 years, with 5 years of development followed by 5 years of revenue-generating operations. The assumed ROS (profit margins) are 25% and 15% on an assumed price per flight of $80M for each of the 20% and 30% scenarios. Total investment is assumed to range from $500M to $2B. As can be seen in the Figure, the number of flights required for the investment to be deemed "worth it" ranges from 15 to 18 per year for the most favorable set of assumed circumstances ($500M investment, 20% hurdle rate and 25% ROS) to over 100 flights per year for the least favorable ($2B investment, 30% hurdle rate and 15% ROS). The most flights flown by a single ETO system in 2015 was 17 by the Chinese Long March family of expendable systems and 16 by the Russian family of Soyuz expendable systems (see Figure 6). Accordingly, for a reusable system to be found worthy of investment within even the most favorable assumptions of the example, the system would have to enter the competitive market with a flight rate essentially matching the current market share leaders and an investment at a level historically associated with prototype systems.
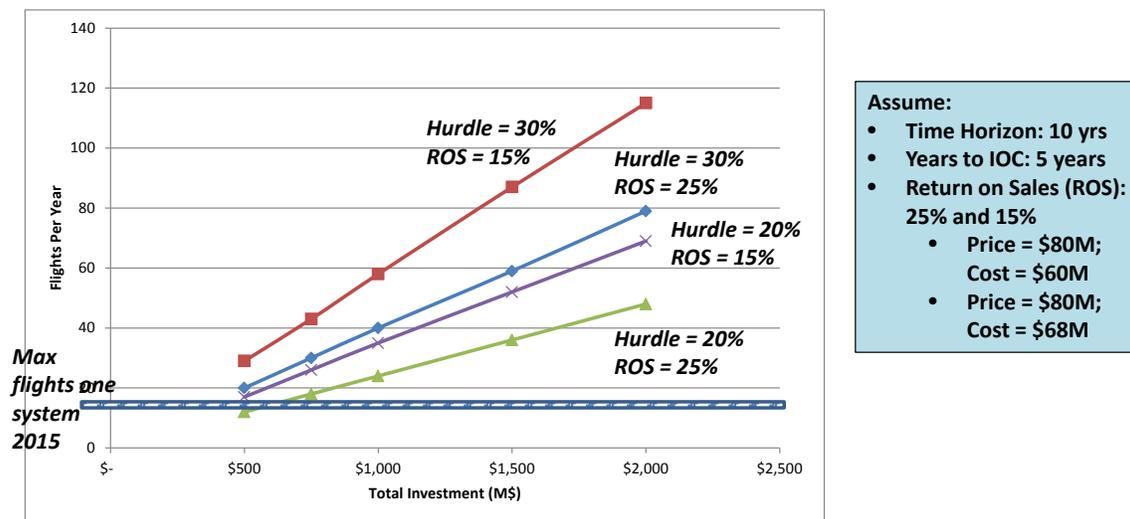

Figure 9. Discounted Cash Flow (DCF) metrics generally work against investment in reusable systems

Certainly one could alter other of the assumptions, such as the total time horizon, the years to Initial Operating Capability (IOC), or any of a host of other variables. Our extensive experience at doing just that has been that there are no combinations of what we have found most decision-makers consider reasonable assumptions that render a DCF analysis favorable to investment in a reusable system, with one recent exception. As noted above, the most important thing a reusable system must do for economic viability is fly. The number of flights flown by the system depends in greatest measure on the demand for space transportation. The recent introduction to the space transportation marketplace of small satellites has been extraordinary. According to one market analysis over 100 micro/nano satellites were launched in 2014 and between 2,000 and 2,750 are projected to be launched through 2020 ("2014 Nano/Microsatellite Market Assessment", Spaceworks Inc.). Other announced plans for large constellations of small LEO satellites (over 1,000 satellites each in some cases) have been made by, most

notably, Boeing, Space X/Fidelity/Google, and OneWeb (Virgin Group/Qualcomm). While still to be realized, the explosive growth of small satellites has the potential to radically change the landscape of the space transportation marketplace and with it the fundamental bases behind the economics of reusable space transportation systems. The next section explores the demand for space transportation and how it shapes the reusable systems discussion.

If You Build It They Will Come

To be "worth it" a reusable system must fly and fly often. How often a transportation system (reusable or expendable) flies is dependent on many factors. The demand for space transportation is arguably the most important of those factors. It is our observation that it is also probably the most debated among both stakeholders and other interested persons. Based on our experience having performed several market studies over the years we have found a few significant "truisms" regarding space transportation demand, consideration of which can be keys in estimating the market for a transportation system.

First, *the demand for space transportation is not monolithic*. Market segmentation is very important. Segmentation by user, type of mission, destination (orbit altitude and inclination), and payload launch mass (weight) plays heavily in making estimates of addressable markets and, ultimately, market capture by the transportation system under consideration. As discussed above, consideration must be made regarding: what the user values (price, reliability, availability), what the user's payload is (satellite, ISS cargo, manned, return, etc.), where the user wants to go (GTO, LEO, planetary, polar, etc.), and how much the payload weighs. The transportation answer for a commercial GSO communications satellite is very different than for a national security spy satellite. To service both market segments could require, for instance, some or all of multiple launch sites (polar versus due east), meeting more stringent reliability requirements, addressing classified payload requirements, and/or prioritization of launch window availabilities.

Secondly, "If you build it they will come" is a tag line from a science fiction movie. As in the movie, acceptance or rejection of the notion is at least somewhat made as an article of faith. As discussed above, different stakeholders with different motivations can be inclined to accept a higher or lesser degree of market risk. In any event, the "if you build it" concept assumes (at least implicitly) that new users and/or a significant expansion of existing users will occur as a result of substantial reductions in the cost of access to space.

One important aspect of assessing the level of market uncertainty is the existence (or not) of a potential anchor tenant. An anchor tenant is a customer whose missions your system has a very high probability of capturing, usually with multiple flights. The commercial Atlas 62-vehicle buy program of the 1990's had the Air Force Defense Satellite Communications (DSCS) and Navy Ultra High Frequency (UHF) satellite constellations as anchor tenants. The VentureStar anchor tenant was to be Space Station missions. Finding an anchor tenant is an important consideration in reducing market uncertainty. Another notion associated with the "if you build" it idea is that a substantial reduction in the price to access space could potentially enable what is sometimes termed a "killer app (application)" that would revolutionize the market for space transportation. Small satellites exhibit some signs of potentially being that application. In any event, the central thesis is that reductions in price per flight will result in a larger demand for space transportation services. This thesis is characterized by what has been termed the "holy grail" of the space

transportation marketplace, the elasticity of demand. One of the most important questions surrounding the reusable/expendable decision is: *What is the price elasticity of demand for the space transportation market segments being served*?

The elasticity of demand is an often quoted, often misunderstood aspect of economic analysis. In summary, it is calculated as the percentage change in quantity demanded of a good or service given a percentage change in another variable – usually price. While demand elasticity is usually discussed (at least implicitly if not explicitly) as price elasticity, price elasticity is not the only variable which, if changed, could result in an increase/decrease in quantity demanded. A change in launch availability, for instance, could result in increased demand for military sortie-type missions, providing an example of availability elasticity of demand.

In brief, demand can be measured as a curve with quantity demanded on the x-axis and another variable (we will use price throughout this section) on the y-axis. The curve has a downward (negative) slope – the lower the price the higher the quantity demanded. Measurements of elasticity of demand will provide particular characteristics of the demand curve. An inelastic demand curve results if the percentage increase in demand is less than the percentage decrease in price (e.g. <1). The markets for cigarettes, gasoline, and transportation to space of national security assets have all exhibited inelasticity. Elastic demand is characterized by a % increase in demand greater than the % decrease in price (>1). Sports cars, cruise vacations, and (potentially) small sats have or may exhibit elastic demand. Unitary elasticity is the point between elastic and inelastic demand such that the % changes are equal. It is important to note two other aspects of demand elasticity: 1) elasticity is not necessarily constant for the same demand curve, and 2) in the case of elastic demand the marginal revenue to provide one more unit of the product or service is positive, and, conversely, the marginal revenue is negative for inelastic demand. These seemingly esoteric considerations have potentially significant ramifications for demand and supply of space transportation.

Figure 10 illustrates the issue with a simple example. Three different demand curves for space transportation as a function of price are shown in the left graph. The green (top) line is generally more "elastic" while the bottom (blue) line is relatively "inelastic" with the middle (red) line between the two. Each demand curve reaches a point at which they change from being elastic to being inelastic. When the price per flight (y-axis) is multiplied by the number of flights demanded (x-axis) the result is revenue as a function of price and quantity demanded, shown on the graph on the right. Note that at the point where the demand curves switch from being elastic to inelastic (i.e. unitary elasticity) the revenue curve turns downward. The marginal revenue is negative at that point. The total revenue generated by reducing the price to achieve more flights is less than if the price were not reduced.

Figure 10. Depending on elasticity of demand, reductions in cost per flight may not necessarily translate to reductions in price

We have heard it suggested in the discussion surrounding reusability that an "order of magnitude" reduction in cost per flight (or mass) could result in a significant increase in heretofore un-tapped uses of space. The economics suggest that, even if achievable, there may be a point at which reductions in price per flight will not increase quantity demanded sufficiently to support the reductions. The key question is what is the elasticity of demand for space transportation? As suggested previously, demand is not monolithic. Segmenting the market is very important in making decisions regarding investments in reusable systems. One study ("Launch Vehicles: An Economic Perspective", Hertzfeld, Williamson, Peter, Space Policy Institute, George Washington University, September 2005) found that:

> "Demand for heavy lift vehicles will be price inelastic. . . In economic terms, the price elasticity of demand for this class of launchers (small satellites) will be more elastic." (page 25); and "LEO vehicles have a demand elasticity of demand above 1.0 and GTO vehicles have a demand elasticity of demand of 0.5. In other words, our data show that within the price range of today's vehicles, lowering price will not result in increased business for heavier lift, GTO vehicles. For lighter lift LEO vehicles, price decreased may lead to more customers, but not in large numbers." (page 35)

If nothing else, this cursory discussion of demand elasticity illustrates why its characterization has been called the "Holy Grail" for space transportation. It also factors heavily in the next factor impacting decisions regarding reusable transportation system investment: What and how much to attempt to reuse.

A Matter of Degree

The discussion surrounding the efficacy of reusability occasionally suffers from a lack of definition regarding several important terms that, on their face, should be obvious, including "reusability" itself. *Reusability is not monolithic.* Investments in reusable ETO systems have ranged from partially reusable multi-stage systems, including the Shuttle and the current Falcon 9 booster, to SSTO fully reusable systems like X-33/VentureStar. As a rule of thumb, the more energy put into a particular system element (e.g. first stage, second (upper) stage) the faster, higher, and farther down range it goes. As a result it becomes

harder to recover, and thus more expensive to reuse both in terms of investment in more complex subsystems (propulsion, thermal protection, landing/recovery systems, etc.), and recurring cost (downrange landing sites, propellant reserves required for recovery, thermal protection refurbishment, etc.) In determining what to reuse and how, identifying the primary recurring cost contributors factors greatly in decisions regarding whether or not to attempt to reuse them.
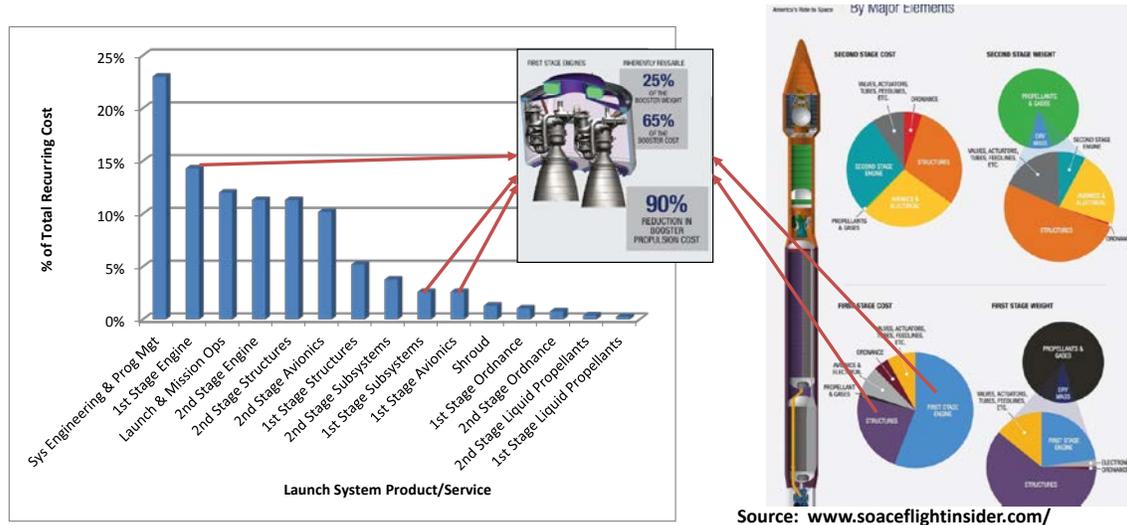

Source: www.soaceflightinsider.com/

Figure 11. Pareto of typical launch system cost contributors illustrates why first stage reuse can be economically attractive.

Figure 11 is a pareto chart of cost contributors for a typical Atlas launch vehicle (an Atlas 401 from the picture; www.spaceflightinsider.com). Using the pie charts provided and based on our experience, we estimated the percentage cost contributions of each stage, launch and mission operations, and other costs to total Atlas cost. We then applied a published, publicly available price for an Atlas 401 launch to the percentages to develop the pareto graph.

The first stage engine is the largest cost contributor that is a candidate for recovery. Most current reusable developments either in process/operation or contemplated (and funded at some level) by major supplier stakeholders are focused on recovering the first stage or portions thereof:

- Space X – Falcon 9: first stage powered vertical return to a barge/down range or land/launch site recovery; reuse first stage engine, avionics, and some or all subsystems (feed system mechanisms, etc.) and primary structures (tanks and adapters).
- United Launch Alliance – Sensible, Modular, Autonomous Return Technology (SMART): modifications to Atlas replacement system (Vulcan) currently in development; recover first stage engine and avionics only; parachute return "snatched" in midair by helicopter.
- Airbus-Safran (Arianespace) – Adeline: recover first stage engines and avionics module only; glideback/propeller driven return to horizontal landing at launch site.

The different stakeholders have made different determinations regarding what are the most economical ways to recover the different elements of the first stage system, but have all (presumably independently) determined that attempts to recover anything beyond the first stage are, at least at present, economically

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a step too far. Blue Origin's New Shepard and Virgin Galactic's SpaceShip II are suborbital and, thus, outside the scope of this discussion.

Once a determination is made to reuse at least some portions of a system a key consideration becomes how many reuses to design for and, by extension, what the appropriate fleet size should be. In essence, the next question is "how many"?

How Many?

By their nature reusable systems are produced in limited quantities. Minimizing production cost is a primary point of reusability. Sizing the fleet correctly upfront is very important for several reasons, primarily because investment in at least a goodly portion of the relatively sizeable cost of reusable elements must be done either prior to commencement of revenue-generating operations or as part of a "booststrapping" effort in parallel with operations of an expendable system. Our experience has shown that one of either design life or turnaround time (TAT) drives the fleet sizing determination. There are several key considerations that factor considerably in the decision.

Choosing between design life and TAT as the driving factor in determining fleet size depends most particularly on what the stakeholder/customers of the market segments being considered most value. A driving motivation for many reusable system development efforts has been to achieve "aircraft-like operations". A prime piece of that focus is to reduce TAT between launches from weeks or months (or even years) to days or hours. The X-33/VentureStar goal was a 7 day TAT. DARPA's XS-1 development and demonstration program calls for 10 launches of a reusable booster within 10 days. There are many potential advantages of fast turnaround, such as enabling of rapid call-up (i.e. "responsive") sortie missions and Prompt Global Strike (PGS) missions. However, our experience has shown that the driving economic factor most important in determining the most cost-effective fleet size is design life.

Figure 12 provides an example of the different breakpoints between design life and TAT in determining fleet size. In the example the design life of the system is 200 flights (for comparison the VentureStar design life goal was 100 flights). This is a simplifying assumption – the design life of the different elements of the system will most likely be different (e.g. a liquid engine will most likely have a different life than avionics, a TPS/leading edge wing, or a cryogenic propellant tank). The TAT is 7 days between flights, assuming 250 workdays per year (i.e. 5/1 shifting). As can be seen in the chart, at no time does TAT by itself drive the fleet sizing determination. It is either driven by design life alone or jointly by design life and TAT.
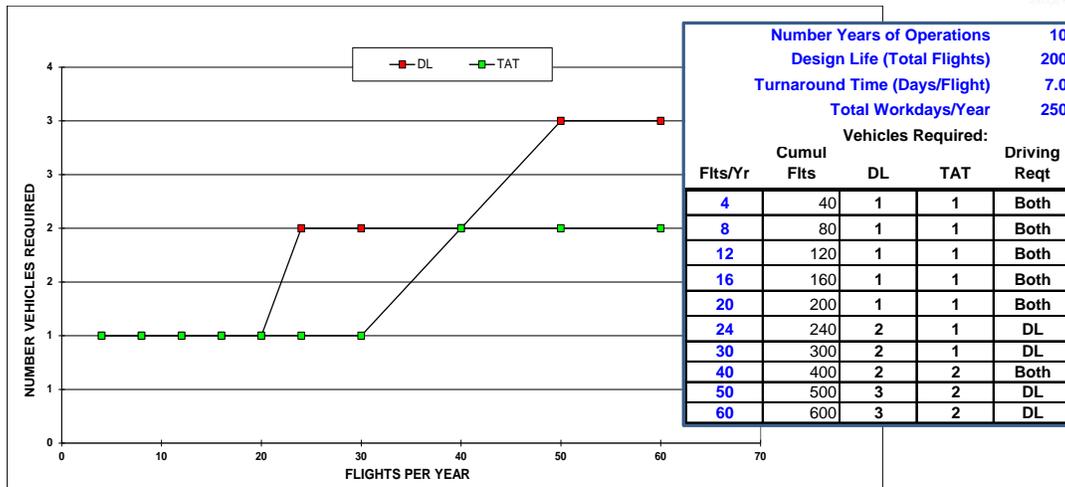
NUMBER VEHICLES REQUIRED — FLIGHTS PER YEAR — DL — TAT

Number Years of Operations	10
Design Life (Total Flights)	200
Turnaround Time (Days/Flight)	7.0
Total Workdays/Year	250

Vehicles Required:

Flts/Yr	Cumul Flts	DL	TAT	Driving Reqt
4	40	1	1	Both
8	80	1	1	Both
12	120	1	1	Both
16	160	1	1	Both
20	200	1	1	Both
24	240	2	1	DL
30	300	2	1	DL
40	400	2	2	Both
50	500	3	2	DL
60	600	3	2	DL

Figure 12. Comparison of design life and turnaround time in determining appropriate fleet size.

At the same time there are several other important factors that bear on fleet sizing analyses.

- Hull insurance: Because the reusable elements are generally high-value fixed assets, it is our experience that stakeholders will expect at least some of the elements that comprise the system will be insured. It should be noted that this is different than the other two types of insurance obtained for most launches. All U.S. launches require third-party liability range insurance. At the option of the customer launch insurance can be purchased to cover the satellite through launch and (typically) one year of orbit operations. On VentureStar we found that obtaining insurance for the asset (the "hull") would be a requirement for investment. Insurance acquired from an underwriter was not feasible due to the perceived risk. As a result, we planned to "self-insure" by fabricating a second vehicle. The number of available vehicles was greater than launch demand required. The net effect was to possess an underutilized fleet relative to achieving 7 day TAT. If hull insurance is required for a contemplated reusable launch system the fleet size will be calculated as one plus however else the fleet size is determined.

- Maintain production lines: Balancing system element design life with maintaining production lines is an important factor in design life decisions. Generally the longer the life of the asset the fewer and less frequently the production line is exercised. One of the ramifications is to increase the unit cost of the replacement parts, particularly long-life line replaceable units (LRU's). This can be the case regardless of whether the parts are supplied by a vendor or fabricated in-house. If the parts are supplied by vendors the tendency to end up with de facto sole-source suppliers becomes a potential issue.

- Technology insertion points: A second ramification of balancing system element design life is maintaining points where new technologies can be inserted on the system. The longer the design life the less frequent the opportunity to incorporate a new technology on the system. The qualification cost in particular can make technology insertion unattractive economically.

- Obsolescence: If production lines and technology insertion points are not maintained, ultimately the fleet will most likely face the problem of parts obsolescence. The Shuttle, in particular, found this to be a substantial problem. It became very expensive to maintain inventories of old technology parts, for both flight and ground systems.

- Fleet recapitalization: At some point the fleet elements will begin to reach end-of-life, which requires recapitalization of the fleet through either fabrication and assembly of new elements and/or implementation of a service life extension program. The more expensive the asset the more problematic this can become, especially in the context of an overall business plan using DCF metrics for measuring economic viability.

- Attrition rate: The most significant factor bearing on fleet sizing analyses is the assumed reusable element attrition rate, if any. As shown in Figure 13, using an equation developed by operations research analysts applied to the assumptions defined in the Figure 12 example, a 5% recovery attrition rate reduces the calculated effective life of a system element to 20 flights per year regardless of whether the design life is 100, 200, or 500 flights. The assumed ascent reliability does not have nearly the same effect. The assumed ascent reliability in the Figure 13 example is 100%.
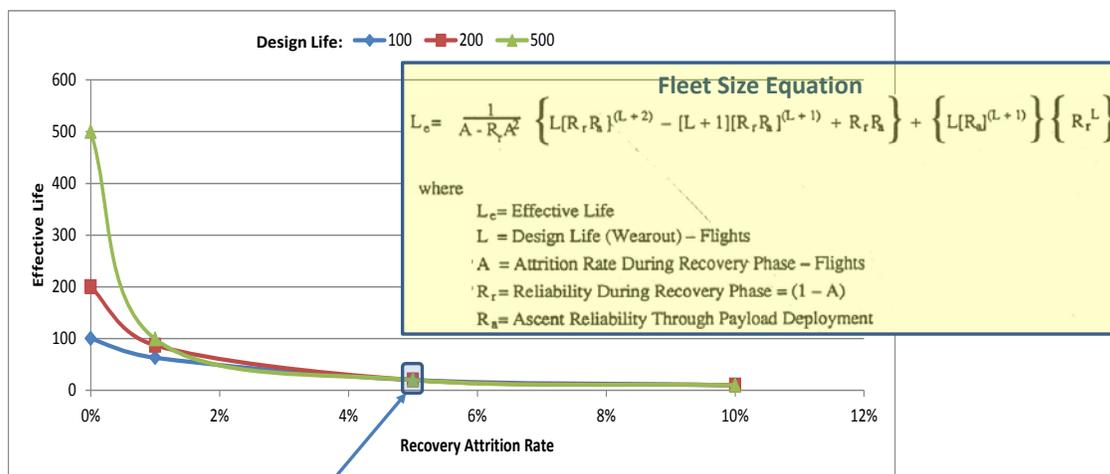

Figure 13 shows the Fleet Size Equation:

$$L_e = \frac{1}{A - R_r A^2} \left\{ L[R_r R_a]^{(L+2)} - [L+1][R_r R_a]^{(L+1)} + R_r R_a \right\} + \left\{ L[R_a]^{(L+1)} \right\} \left\{ R_r^L \right\}$$

where

L_e = Effective Life

L = Design Life (Wearout) – Flights

A = Attrition Rate During Recovery Phase – Flights

R_r = Reliability During Recovery Phase = (1 – A)

R_a = Ascent Reliability Through Payload Deployment

Figure 13. Consideration of attrition plays a significant role in determining economic fleet size.

As noted above, all of these factors figure heavily in determining reusable system economics. The answers resulting from any one consideration bear on the answers to the others. The key is to find the "sweet spot" resulting from a balance between the competing factors. One other key factor in determining reusable system economic practicality, the size of the system, is determined in large measure by answers to the other considerations such as market segments to be served, degree of reusability, etc. The size of the system matters when evaluating reusability.

Size Matters

At a very top level the size of a space transportation system is relatively highly correlated to its non-recurring and recurring cost. Our experience in the parametric estimation of transportation systems is that the slope of a power curve fitting cost to (for instance) Gross Liftoff Weight (GLOW) is an exponent greater than 1.0 for both non-recurring and recurring cost. Generally speaking cost increases at an increasing rate as the overall system grows in size. The consequences are obvious and significant. The bigger the vehicle system the greater the investment required and, as a result the greater the savings required to pass a DCF metric test of economic goodness. The tradeoff is specific to each individual concept and whatever user stakeholder needs the system is trying to satisfy. However it is important to

notice that, as shown in Figure 5, larger systems will typically exhibit lower $/kg at their peak capacity. Given the (potentially significantly) greater investment, this does not necessarily ensure a larger system is more economically attractive, regardless of whether the system is expendable or reusable. However, for a larger reusable system this issue is exacerbated by the increasing complexity of the additional subsystems required for reuse as, for instance:

- Return (landing): size/weight of landing gear and wings/tails for horizontal return; parachutes size and number, and/or size and number of retrorockets and landing legs for vertical return
- Thermal protection: increasing need for more complex thermal protection as a function of vehicle size as maximum speed (e.g. staging mach) increases and/or a system is returning from orbit
- Propellant reserve: for a reusable system utilizing a powered return concept, as the size of the reusable system increases the size of the propellant reserve needed to accomplish the return increases, reducing effective payload capacity

Conclusions

In considering the economics of reusable space transportation systems we have (hopefully) shown in this paper that an effectual examination of the question rests in large measure on a definition and understanding of the key financial and other considerations and metrics by which the financial "goodness" of a reusable or expandable approach is measured. Returning to the original question then, **"is it worth it?"** In our estimation based on the foregoing the answer is: **IT DEPENDS!**

Depending on the motivations of the stakeholders involved, the characteristics of the demand for transportation exhibited in the market segments being served, the degree and type of reusable system elements considered, fleet size determination, and the size of the system necessary to meet stakeholder requirements, a reusable system may or may not be the most economical choice. Ultimately, of course, the decisions rest with the stakeholders themselves. However understanding the factors that shape their decisions provides all of us who share an interest and, thus, have a "stake" in furthering humankind's exploration and development of space helps inform our thoughtful consideration of what will most certainly continue to be a lively and on-going discussion.