IAF Congress, Rio de Janeiro, Brazil Oct. 2–6, 2000
Symposium IAA.1: Economics and Commercialization of Space Activities
Session 1AA.1.1: Launch Vehicle Cost Engineering and Economic Competitiveness

ECONOMIC MODEL OF REUSABLE VS. EXPENDABLE LAUNCH VEHICLES

James R. Wertz, Microcosm
401 Coral Circle, El Segundo, CA 90245
E-mail: jwertz@smad.com

ABSTRACT

It is generally assumed by the community that reusable launch vehicles will dramatically reduce launch costs because you don't "throw away the vehicle" every time it is used. However, this is usually taken as an element of faith, without any substantive analysis to support the conclusion. The example of the Space Shuttle, originally sold to Congress on the basis of dramatically cutting launch costs, suggests that this conclusion might not be accurate under realistic conditions of development and operations.

This paper presents an economic model of the cost per launch and cost per pound of both expendable and reusable launch vehicles. The model is presented so as to facilitate comparison between the two approaches and each cost element is discussed in terms of the impact of reusability or discard of vehicles or components. Specific numerical examples are provided. However, the model is given in a fully analytic form as well so that others can work with values of their choosing or explore alternative solutions. Finally, the model is used to determine the broad economic conditions under which reusable or expendable vehicles will be more or less expensive. This is also applied to determining under what economic conditions portions of a launch vehicle should be reused or expended.

1. BACKGROUND

There is an unrelenting worldwide demand to reduce space mission cost. This demand applies to all types of missions—scientific, military, and commercial—and all facets of the missions, including nonrecurring development, manufacture, launch, and operations. There is also general agreement with at least some analytic basis that a large portion of the problem is due to high launch costs. (See, for example, Wertz [1996], London [1996], or Hammond [1999]). While launch costs may not be the largest cost element for a given program, they effectively prevent dramatic cost reductions in most other program elements [Wertz 1996, Hammond 1999].

Unfortunately, as illustrated in Fig. 1, launch costs have remained essentially unchanged and dramatically high for over thirty years. Isakowitz [1998] and Apgar, et al. [1999] provide a summary of current launch costs for various worldwide launch vehicles. The reasons for the high costs are discussed at length by London [1994, 1996]. At least ten organizations worldwide have active programs to significantly reduce launch costs. However, there are dramatic differences in their approach. Perhaps the only characteristic that they share is that none have to date been able to significantly reduce the launch costs shown in Fig. 1.

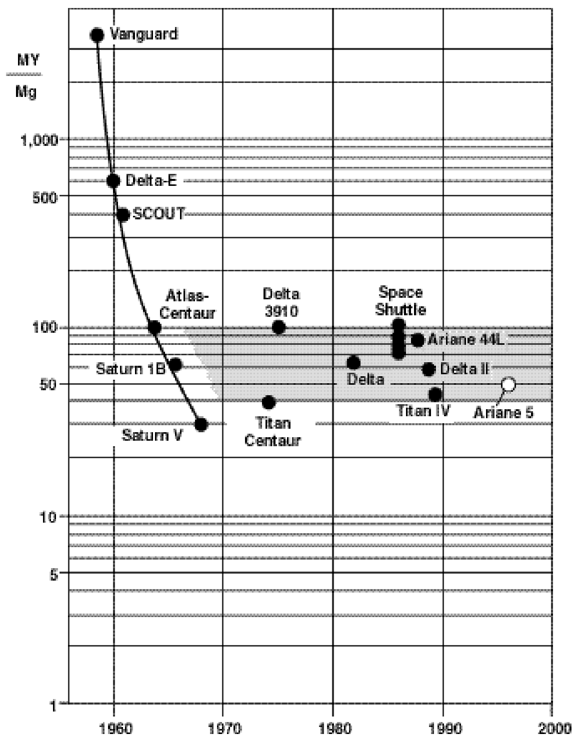

Fig. 1. Historical Trends in Space Launch Cost. Costs are in man-year (MY) per megagram (mg). Data is from Koelle [1991].

There is also a widely held belief that the solution to the problem of high launch costs is a fully reusable launch vehicle, RLV. (See, for example, X-Prize [1999] or Stine [1996]). Historically, the only reusable launch vehicle has been the American Space Shuttle. Unfortunately for comparison purposes, this is also a manned vehicle which makes comparing the cost with unmanned vehicles of comparable size more difficult. Nonetheless, the Shuttle was originally sold to Congress on the basis of dramatically reducing cost [London, 1994]. The Shuttle has been exceptionally successful technically and has the highest overall reliability of any launch vehicle. Nonetheless, it has not driven down launch cost and is approximately 60% more expensive than typical, unmanned, expendable launch vehicles [London, 1996].

The purpose of this paper is to create an economic model of launch vehicle costs that allows a direct comparison between the cost of expendable and reusable vehicles. We will then make a range of assumptions about the various cost elements and use this both to draw broad conclusions and to provide the reader with the basis for testing those conclusions against their own data and assumptions.

2. THE MICROCOSM REUSABLE VS. EXPENDABLE LAUNCH VEHICLE COST MODEL

Koelle [1998] provides a comparison of alternative launch vehicle cost models. Koelle's most recent TRANSCOST model [1991] is perhaps the most widely used. Other models and approaches to modeling launch costs are discussed, for example, by Wertz [2000], Koelle [1998], and Hammond [1999]. Specific comparisons of single-stage to orbit and two-stage to orbit launch costs are provided by Koelle [1996, 1998].

Here we would like to provide a cost model that can be used for both expendable and reusable launch vehicles and which is not biased toward either. The model itself is purely analytic, such that users can put in their own assumptions, data, or projections about specific cost elements, or undertake more extensive trades on alternative approaches or market conditions. We will then assume specific values or ranges for each of the input parameters in order to parameterize launch costs for both expendable and reusable vehicles. We would like to determine the broad set of conditions under which expendable vehicles are likely to be lower cost, reusable vehicles are likely to be lower cost, or the two approaches will be broadly competitive. A specific objective here is to clearly separate the economic model from the conclusions based on using it, so that others can use the model to draw their own conclusions based on their data and assumptions.

Specifically, we model the total launch cost as the sum of six individual components:

$$C_{launch} = C_{development} + C_{vehicle} + C_{flightops} + C_{recovery} + C_{refurb} + C_{insurance} \quad (1)$$

where

C_{launch} ≡ Total cost of launch in FY00 dollars (i.e., excluding inflation)

$C_{development}$ ≡ Amortization of nonrecurring development cost

$C_{vehicle}$ ≡ Reusable: Amortization of vehicle production cost
Expendable: Recurring production cost (Theoretical First Unit cost reduced by learning curve)

$C_{flightops}$ ≡ Total cost of flight operations per flight

$C_{recovery}$ ≡ Recurring cost of recovery (reusable only)

C_{refurb} ≡ Refurbishment cost (reusable only)

$C_{insurance}$ ≡ Cost of launch insurance

Each of these individual cost elements is discussed below.

2.1 Nonrecurring Development Cost

In the launch cost model, $C_{Development}$ is the amortization amount per launch of the nonrecurring development cost. The same standard amortization model is used for both reusable and expendable vehicles. The model spreads the development cost uniformly over the total number of launches in the same fashion that a commercial loan spreads the amount of the loan over an equal number of fixed payments.

The amortization model assumes a fixed amount, $C_{totalNR}$ to be paid off in N equal payments at an annual interest rate, *i*. Consequently,

$$C_{development} = C_{totalNR} [i / (1 - (1 + i) - N)] / L_{yr} \quad (2)$$

where L_{yr} is the number of launches per year, the total cost = N × Annual Payment = $C_{development}$ × Total Number of Launches, and the total interest expense = Total Cost – $C_{totalNR}$.

We will use the same nominal numerical values for all amortized elements, assuming amortization over a 15-year period at an interest of 15% per year. This interest rate is low for a project such as launch vehicle development with significant financial risk.

In general, the nonrecurring development cost will be less for expendable vehicles then for reusables since there are fewer items to develop and the development is less demanding. This means that the amortization of the nonrecurring development cost will generally be significantly higher for reusable vehicles then for expendables.

In most cost models, inflation is not an issue and results are presented in constant-year dollars. In this case, the inherently higher nonrecurring cost for expendable vehicles implies that inflation can play a significant economic role in that the large nonrecurring development cost can be paid off with cheaper out-year dollars. Consequently, the amortization model is adjusted for inflation as described in the appendix.

2.2 Nonrecurring Production Cost

$C_{vehicle}$ in the economic model is the recurring production cost for the launch vehicle, once the development has been completed. Here the cost model is different for reusable and expendable vehicles. For the expendable, $C_{vehicle}$ is the recurring production cost for the launch vehicle itself. This is modeled as a classic learning curve. (See, for example, Apgar, et al. [1999]) which uses the cost of a Theoretical First Unit (TFU) reduced by the learning curve factor. The Theoretical First Unit is the production cost of a single vehicle if only one was to be built. Generally, each successive vehicle will be less expensive. The learning curve takes into account not only an improved understanding of how to build the vehicle (i.e., learning), but also economies of scales such as buying parts cheaper in larger quantities and the ability to make specialized tooling and set up production lines when larger quantities are produced.

Using a standard learning curve, the total production cost for *N* units with a fixed learning curve, *S*, is:

$$\text{Total production cost} = \text{TFU} \times \text{L} \quad (3)$$

$$\text{L} \equiv \text{N}^{\text{B}} \quad (4)$$

$$\text{B} \equiv 1 - [\log (100\% / \text{S}) / \log 2] \quad (5)$$

where *S* is called the *learning curve percentage* and is typically chosen as 95% for less then 10 units, 90% for 10 to 50 units, and 85% for 50 or more units [Apgar, et al. 1999]. Ordinarily, considerably more then 50 launch vehicles would be constructed over a 15-year period. However, to be more conservative, we will assume an 87.5% learning curve for all of the elements. This can also be thought of as a somewhat lower percentage learning curve plus a small amount to account for inflation. (Sensitivity to the learning curve factor and other inputs are discussed in Sec. 6.2.)

Two principal learning curve characteristics are of interest in the cost model. The first, $C_{vehicle}$, is the average cost per vehicle over the period of time being modeled. This is given by

$$C_{vehicle} = \text{Average cost} = \text{Total production cost} / \text{N} \quad (6)$$

Also of interest is the cost of the Nth unit given by:

$$\text{Nth unit cost} = \text{TFU} \times (\text{N}^{\text{B}} - (\text{N-1})^{\text{B}}) \approx \text{TFU} \times \text{B} \times \text{N}^{\text{B}}/\text{N} = \text{B} \times \text{average cost} \quad (7)$$

For reusable vehicles, the cost model is more complex. Here we assume that the entire fleet of vehicles is built at one time and then amortized over the life of the vehicles, which we will assume to be 15 years. Consequently, we model the total production cost of the reusable fleet as being a theoretical first unit cost for a reusable vehicle, reduced by the same learning curve used for the expendables for subsequent vehicles. This gives us a total production cost for the fleet of vehicles which is then amortized over the number of launches in the vehicle lifetime, assumed to be 15 years.

The economic model for the recurring production cost implies that the expendable cost will drop as more units are produced, whereas the reusable amortization cost is fixed over the planned life of the fleet. Inflation and cost of money therefore have a somewhat different impact on reusable and expendable vehicles. In the reusable vehicles, most of the money is spent up-front and, therefore, we are sensitive to interest rates. On the other hand, high inflation is valuable for reusable vehicles, in that the initial loan can be paid back with lower-cost dollars in future years. The expendable vehicle represents a lower up-front cost with the cost of the individual vehicles being spread out over time. Consequently, interest rates and inflation rates have less of an impact on expendables, although they are still important.

2.3 Flight Operations

$C_{flight\ ops}$ in the cost model represents the total cost of flight operations per flight. This covers on-pad test and checkout, payload mating, consumables, flight operations, and a negotiated portion of facilities cost. The typical cost range for consumables ranges from approximately $ 0.06/lb for liquid oxygen to $ 5/lb for solid rocket propellant. Consumables are not modeled separately, but are taken as a component of the flight operations cost.

$C_{flight\ ops}$ is modeled as a theoretical first unit cost reduced by a learning curve for both expendables and reusables. In general, flight operations are expected to be more expensive for reusable vehicles due to added launch complexity. The vehicle itself is more complex and goes through more operations in that it must be recovered and returned and all of these systems must be checked prior to launch. Therefore, with comparable amounts of development, we would expect that the operations cost would be less for an expendable vehicle. For expendables, the flight operations cost is typically $0.5 million to $1.0 million per mission after the procedures have been fully established. It is much more difficult to estimate the flight operations for reusable vehicles since the only example available is the Space Shuttle, which is not only reusable but also manned, and the latter characteristic is clearly a major cost driver. Orbiter flight operations cost estimates vary widely, but probably fall in the range of $200 million to $400 million per launch, excluding refurbishment costs. Clearly this is far too expensive for any competitive reusable vehicle in the future. Therefore, the economic model should assume a range of costs for flight operations.

Generally, operations costs are reduced by a higher level of spending in nonrecurring development in order to create a vehicle which does not require repetitive operations. However, most launch vehicle development programs have suffered higher than projected nonrecurring development cost. Consequently, historically high operations costs have come about, in part, in an effort to hold down the initial nonrecurring development cost. (See London [1994].) While most launch vehicle manufacturers would argue that they are developing vehicles which will have a very low operations cost, there is also very little evidence that they are willing to accept additional nonrecurring development expenses to achieve this. Indeed, the marketplace for launch vehicle development has not been strong in terms of the capacity of new vehicle manufacturers to raise money.

It is important to note that in traditional space system cost models "operations and maintenance cost" includes the cost of buying potential replacement vehicles at the end of life of the current fleet. This cost is <u>not</u> included in the current model. This implies that we may need to set aside some money to cover both development and production cost of follow-on units at the end of the useful life for the fleet of either expendable or reusable vehicles.

2.4 Recovery and Refurbishment

These costs are applicable only to reusable vehicles or vehicle components. $C_{recovery}$ represents the cost of actual recovery plus return to the launch site or wherever the equipment is checked-out and refurbished. This is modeled as a percentage of launch operations cost. The potential cost range here can be extremely large. It will depend strongly on whether the vehicle or component is flown back from space to the launch or recovery site (such as the Orbiter), recovered after landing in the water (Shuttle Solid Rocket Boosters), or on land (Soviet and Russian manned capsules).

The refurbishment cost represents the cost of all inspection, cleaning, maintenance, retest, re-certification and return to the launch site if the vehicle and components are processed elsewhere. This cost is modeled as a percentage of the average launch vehicle production cost ($C_{vehicle}$) increased by a 105% to 115% learning curve over time to account for wear with increasing use. Historical experience in aircraft and virtually all transportation systems has shown that repair and refurbishment costs increase as vehicles age. Thus, we can expect that more components will need to be tested, replaced, or rebuilt as the reusable vehicles become older.

The refurbishment cost includes the replacement cost for components which may be destroyed from time to time; for example, if a Solid Rocket Booster sinks rather than being recovered include the cost if the entire vehicle is destroyed. That is covered by the insurance cost discussed in the next section.

For the Shuttle's Solid Rocket Boosters, the recovery and refurbishment cost is approximately equal to their manufacturing cost [London 1994, 1996]. Consequently, for these components there is very little gain by recovery, refurbishment, and reuse. In contrast, the recovery and refurbishment cost for the Orbiter is much less than its initial manufacturing cost and therefore does provide substantial savings.

2.5 Insurance

$C_{insurance}$ is the cost of launch insurance which we model as a percentage of the launch vehicle cost. We include here only the cost of insuring the launch itself, not other components of the mission. Insurance costs can include the cost of replacement spacecraft plus the "opportunity cost" associated with not having the payload available until some later time. However, these costs depend strongly on both the spacecraft cost and the importance of having the system available on orbit. Consequently, there is no good way to model this in a general-purpose launch cost model for all vehicles, either reusable or expendable. The insurance cost will drop with time as vehicle reliability is proven. Thus, the cost of insurance for the first flight of a vehicle will ordinarily be quite high and will come down significantly if reliability is established by the initial flights.

Typically, government agencies self-insure their launch. That is, they do not buy commercial insurance, but instead replace vehicles and payloads which are lost. Nonetheless, this has the same effect in terms of cost modeling as an insurance cost, except for the profit margin and cost associated with independent insurance.

A typical insurance cost for current launch systems is on the order of 15% of the launch cost. This fluctuates somewhat due to launch vehicle performance over the last few years of a specific vehicle type. Consequently, we will assume that 15% represents an upper limit for launch vehicle insurance cost. Any new vehicle which wishes to be economically competitive will have to establish a reliability and, therefore, an insurance cost equal to or better than the current vehicle fleet. Of course, most vehicles will attempt to provide significantly better reliability performance.

Because of the very high nonrecurring cost of the vehicle itself, a reusable vehicle cannot afford to spend 15% of the vehicle cost for insurance. This would imply that each vehicle be amortized over only seven flights. This, in turn, implies that reusable vehicles must be made significantly more reliable than expendable vehicles in order to be economically viable. This is both an advantage and disadvantage for reusables. They will necessarily be more reliable than current expendables, although not necessarily more reliable than a new generation of expendables. Because they must be made significantly more reliable, the nonrecurring development cost and recurring manufacturing cost can be expected to be significantly higher. The insurance characteristics are applicable irrespective of whether you choose to buy insurance or to self-insure. In either case, a destructive accident requires that a very expensive reusable vehicle be replaced.

3. LAUNCH VEHICLE MARKETPLACE

Generally we will use *launch vehicle demand*, i.e. the projected number of launches per year for a specific new vehicle over the next 15 years as the independent variable in the launch vehicle cost model. Our general assumption is that with a sufficiently large demand, the cost per launch of a reusable vehicle will become less than expendable vehicles. We would like to evaluate numerically what level of business is necessary for this to occur.

The general assumption in most reusable models is that significantly lower cost per launch will create new demand and, therefore, increase the number of launches. However, this process does not occur instantaneously. First, a new vehicle must be created with significantly lower costs. This new vehicle must then establish a reliability history and, finally, some change in demand may occur over time. Consequently, the starting point for all launch vehicle economic models should be the current projected launch forecast.

Current launch forecasts call for 1,500 to 2,000 launches worldwide between 2001 and 2010 [Satellite Finance, 2000]. This represents a moderate increase over the launch vehicle activity that has been maintained since the early 1970's [Wertz, 1996]. Most models indicate that this market is relatively inelastic until after a significant cost reduction takes place. Thus, higher demand will result from lower costs <u>after</u> the lower costs and associated reliability record have been established.

Unfortunately, the total launch vehicle market of 150 to 200 launches per year does not represent the addressable market for any given new launch vehicle. First, launches to orbit are currently available from seven countries: the United States, Russia, France, Japan, China, India, and Israel. In addition, the United States and Russia have multiple launch vehicles and vehicle suppliers. More supply is also being created by an "internationally mixed breed" in which, for example, Russian vehicles are modified and launched in the United States. These multiple sources significantly reduce the potential launch market since government sponsored launches will generally make use of national vehicles, irrespective of cost. This is generally the case, however, only for government programs. Commercial programs in the United States, for example, often launch on foreign vehicles in a true cost competition.

In addition to the large number of nations involved in space launch, the business is also segmented by manned versus unmanned flights and by orbital destination. The principal distinctions in the latter category are launches to low Earth orbit, to geosynchronous orbit, and interplanetary destinations. At the present time, the geosynchronous market represents approximately 40% of current launch vehicles, and is dominated by the European Ariane launcher. However, launch forecasts indicate a larger number of launches to low Earth orbit, particularly with the increase in the number of low Earth orbit communications constellations. However, the Iridium and ICO bankruptcies have impacted this market, and, in the best case, slipped the schedule for most low Earth orbit constellations.

Because of the segmentation of the launch market, the maximum launch rate for a new vehicle is far below the total global launch forecast. Nations are very unlikely to give up using their own launchers, irrespective of cost. The market may grow, but that takes substantial time, which will bring competition from both current and new vehicle manufacturers. Consequently, a realistic market for a new very low cost vehicle is 10% of the total worldwide market, or 30% percent of the addressable market segment available to that vehicle. This implies that a new launch vehicle should expect an initial market on the order of 10 to 15 launches per year. There will probably be significantly less than that for the first few years.

The realities of the marketplace produce a classic supply and demand problem. Launch demand may increase if costs drop dramatically. Nonetheless, the nonrecurring cost of any new vehicle is extremely high, which makes it hard to drop prices by a large amount until a much greater demand occurs. It is very difficult to find a funding organization that is willing to forgo recovering its initial investment in order to create demand for both their own and competing launch vehicles.

4. EXPENDABLE VS. REUSABLE VEHICLES

The fundamental differences between expendable and reusable vehicles are summarized in Table 1. Not throwing away hardware saves the cost of reproducing dramatically expensive launch vehicle components. This is, of course, the major cost savings associated with reusable vehicles.

Unfortunately, reusable vehicles are more expensive to develop and to build than expendable vehicles. They are more complex in that there are more components and these components and systems must be designed to be used multiple times. In addition, the reusable hardware is inherently less efficient, and efficiency is a key element of launch vehicle performance. The reusable components must be built stronger to accommodate multiple flights. Recovery systems represent dead weight during launch and launch systems are dead weight during recovery.

Exp = Expendable vehicle *ReU = Reusable vehicle*

Exp	***ReU***	***Factor***	***Discussion***
X	X	Amortization of nonrecurring development cost	Higher for ReU due to larger nonrecurring
X	X	Exp: Recurring production cost ReU: Amortization of production cost	Exp uses learning curve; ReU is more complex and expensive to produce; Amortization rather than recurring production is the major ReU cost savings
	X	Recovery cost	0 for Exp
	X	Refurbishment cost	May be substantial for ReU; 0 for Exp
X	X	Flight operations	ReU has more complex systems; more expensive check-out and recovery
X	X	Vehicle insurance	Depends on both replacement cost and reliability; Exp or ReU could be cheaper

Table 1. Comparison of Expendable vs. Reusable Launch Cost Factors. Exp = Expendable Vehicle; ReU = Reusable Vehicle. For existing vehicles or portions of vehicles, reuse will be more economical if the cost of recovery and refurbishment is less than the production cost of new units reduced by the learning curve.

Consequently, the ratio of payload mass to vehicle gross lift-off weight will be significantly higher (i.e. better) for expendables than reusables. A typical expendable has a payload mass of approximately 2% of the gross lift-off weight. The Space Shuttle, in contrast, has a ratio of only 1.1%. Note, however, this comparison may not be valid because the Space Shuttle is also a manned vehicle, and this too represents increased inefficiency. However, to the extent that this ratio is approximately correct, it implies that a reusable vehicle will be approximately twice the size of an expendable vehicle for the same launch capacity.

In addition to the lack of efficiency, there are other additional costs for reusable vehicles. The reusable vehicle or components must be recovered, refurbished and re-tested or re-certified for flight. In addition, there is little or no learning curve advantage because only a small number of reusable vehicles are built. Finally, the vehicle replacement cost is much higher, which implies the need to make the vehicle much more reliable in order to keep insurance costs from being excessive. Thus, from a technical perspective, we are driven to minimize margins in the reusable vehicle in order to increase the launch efficiency and at the same time we are trying significantly improve reliability in order to drive down the failure rate or, equivalently, the insurance cost. Thus, the reusable vehicle is driven to simultaneously minimize margins and maximize reliability. Not discarding the hardware after each use is, in the end, both a major advantage and disadvantage of reusable vehicles. The reusable approach can amortize costs over a large number of flights, but must pay a high price for doing so.

5. BASELINE INPUTS

All costs in the economic model are in millions of FY00 dollars, assuming inflation at a rate of 3% per year. Most economic models work in constant year dollars and ignore inflation. We have chosen to incorporate inflation in the current model largely because it has a different impact on reusable and expendable vehicles as discussed in Sec. 2.1 and the Appendix. The largest advantage for reusables comes when money is borrowed at a low, fixed rate and inflation is much higher than expected such that it is paid back with cheaper-than-anticipated future dollars.

In order to provide a specific target payload and comparable economic conditions, all of the studies involve a 5,000 kg (11,000 lbs) launch to low Earth orbit. An 87.5% learning curve is assumed for all components where the learning curve is applicable and amortization over 15 years at 15% interest is assumed for nonrecurring development costs and all other items which are amortized.

For both the expendable and reusable launch vehicles we will assume a low cost and moderate cost economic model. (There is very little utility in studying a high cost approach to launch vehicle development.) By “low cost” we mean that the development and vehicles costs are low, which in turn suggests moderate levels of operations, refurbishment and insurance cost. In the “moderate cost” model we assume moderate development and vehicle costs. These higher up-front costs result in lower operations, refurbishment and insurance costs. The baseline cost inputs for low cost and moderate cost models for both expendable and reusable vehicles are in Table 2.

Component	***Low Cost Reusable***	***Mod Cost Reusable***	***Low Cost Expendable***	***Mod Cost Expendable***
Nonrecurring Development	$1000	$6000	$250	$1000
TFU Vehicle Cost	$300	$1000	$15	$50
Flights per Vehicle	100	200	N/A	N/A
TFU for Flight Ops	$5.0	$1.0	$2.0	$1.0
Recovery as % of Ops	20%	10%	N/A	N/A
TFU Refurb. as % of Vehicle	2%	0.5%	N/A	N/A
Refurb. "learning curve"	115%	105%	N/A	N/A
Insurance Rate	1.5%	0.3%	15%	8%

Table 2. Inputs for Reusable vs. Expendable Cost Comparison. All costs in a millions of FY00$, assuming an annual inflation of 3%. All models are based on a 5,000 kg (11,000 lb) payload to LEO, amortization over 15 years at 15% per annum, and 87.5% learning curve in fixed year dollars (equivalent to a steeper learning curve plus inflation).

6. RESULTS AND SENSITIVITY

In order to look at the potential for near and long term cost reduction and to compare reusable versus expendable launch vehicles we have used the model described above and the baseline inputs from Section 5 to construct an economic model over a range of expendable and reusable families. The most sensitive parameter in determining long term cost is the launch rate as discussed in Section 3. Consequently, the first section provides outputs from the model in terms of cost per launch as a function of launch rate. Section 6.2 then discusses the sensitivity of each of these results to all of the input parameters defined in Section 5 in order to determine whether the conclusions reached are strongly or weakly dependant on the specific numerical assumptions. Finally, Section 6.3 discusses how the cost of launch changes with time as the learning curve and inflation take effect and as the amortization of the initial development cost concludes.

6.1 Cost Versus Launch Rate

We use the economic model described above and the input parameters from Section 5 to construct a model of the launch cost for 5000 kg to LEO as a function of the average launch rate for the 15 year period 2001 to 2015. The results are shown in Fig. 2. All of the costs are in millions of FY00 dollars with an assumed inflation of 3%/yr. (As described in the appendix, inflation is important because in constant year dollars, the amortization cost is paid off with cheaper dollars in later years).

Note that the current cost of an expendable vehicle of this size is approximately $50 dollars and the proportional cost of a Shuttle launch is approximately $80 million dollars (See, for example, Apgar, Bearden, and Wong [2000].) Of course, the Shuttle launch is difficult to ascribe a precise cost to because it is not a commercially available commodity and because the cost depends strongly on the launch rate. The figure quoted here is based upon the assigned cost of the Government Accounting Office of $400 million per flight with a payload of approximately 25,000 kg.

As discussed in Sec. 3, the anticipated launch rate for a new vehicle is on the order of 10 to 15 launches per year. Yet it is likely to start at a significantly lower rate before confidence in the new vehicle is established, and then increase to this level over time as the reliability is proven and initial engineering problems solved. Consequently, the range in Fig. 2 goes from approximately a nominal launch rate over the 15 year period on the left to 10 times the nominal rate on the right. Clearly any launch rate even approaching the right hand side would require a significant increase in the number of payloads launched over the next 10 to 15 years. However, this could occur, if launch costs are significantly reduced.

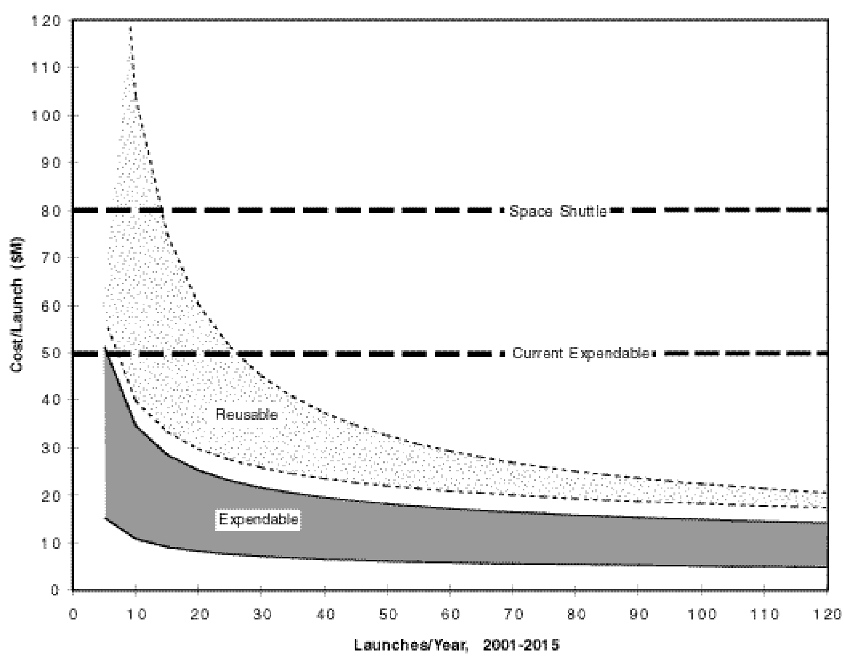

Fig. 2. Cost per Launch vs. Average Launch Rate, 2001 to 2015. Model uses input parameters from Table 2. Note that the expected launch rate for a very successful new vehicle is 10 to 15 launches per year over this period.

	Devel-opment	Vehicle	Flight Ops	Recov-ery	Refurb-ishment	Insur-ance	Total
10 Flights per year = Expected Rate							
Low Cost Expendable	3.40	5.71	0.76			0.86	10.73
Low Cost Reusable	13.61	5.66	1.90	0.38	14.04	4.16	39.77
Mod. Cost Expendable	13.61	19.04	0.38			1.52	34.56
Mod. Cost Reusable	81.66	10.79	0.38	0.04	7.67	3.17	103.72
100 Flights per year							
Low Cost Expendable	0.34	3.67	0.49			0.55	5.05
Low Cost Reusable	1.36	3.64	1.22	0.24	9.01	2.67	18.15
Mod. Cost Expendable	1.36	12.22	0.24			0.98	14.80
Mod. Cost Reusable	8.17	6.92	0.24	0.02	4.92	2.03	22.32
1,000 Flights per year							
Low Cost Expendable	0.03	2.35	0.31			0.35	3.05
Low Cost Reusable	0.14	2.33	0.78	0.16	5.78	1.71	10.91
Mod. Cost Expendable	0.14	7.84	0.16			0.63	8.76
Mod. Cost Reusable	0.82	4.44	0.16	0.02	3.16	1.31	9.90

Table 3. Cost per Launch Broken Down by Cost Element. These are the costs for Fig. 2 broken down by the various components of the cost model. (See also Tables 4 and 5.)

Based on the input parameters and the results shown in Fig. 2, we see that for the expected launch rate the anticipated costs of a new expendable vehicle range from $10 to $35 million per launch versus $50 million for current expendable launches. The reusable costs range from $35 to $90 million per launch relative to the proportional Shuttle cost of approximately $80 million. If the launch rates dramatically increase over the course of time, the curves become relatively flat with the expendable range dropping to $5 to $15 million per launch and the reusables to between $20 and $25 million per launch.

In order to better understand how the costs come about, Table 3 provides a break-down of the total cost by each of the cost elements for 10 flights per year (the anticipated rate), 100 flights per year, and 1000 flights per year. As one would expect, virtually all the constituent costs decline as the launch rate increases. Nonetheless, the amortization of the nonrecurring development cost declines the most for all classes of vehicles and goes from being the dominant cost at 10 flights per year to being a much smaller constituent at 1000 flights per year. Consequently, as the flight rate increases, the dominant cost element shifts from amortization of the initial cost to the other components of vehicle cost, operations, recovery, and refurbishment. Nonetheless, as we see from Fig. 2, although the component costs change in relative importance among themselves, the overall characteristics of reusable versus expendable costs are largely insensitive to the launch rate.

We can draw very general conclusions on reusable versus expendable vehicles from the nature of the learning curve and amortization costs. With the assumed 87.5% learning curve, 100 vehicles cost approximately 40 times the Theoretical First Unit (TFU) cost; the 100th vehicle costs 33% of the TFU cost; and the 1000th costs 21% of the TFU cost. Similarly, at an interest rate of 15% for 15 years, the total cost over the amortization period is 2.7 times the original cost. This provides a broad implication for expendable versus reusable vehicles. Ignoring the recovery and refurbishment cost, a reusable vehicle used for 100 flights will be cheaper then an expendable if it costs approximately 15 times the cost of the expendable (i.e. if the reusable construction cost plus excess development cost is less then 15 times the TFU cost of the expendable). For example, if the development of the expendable vehicle is $100 million and TFU cost is $25 million and if the reusable development plus one vehicle cost is $500 million, the cost of 100 units will be the same, ignoring any recovery and refurbishment costs. This general process of accounting for learning curves on the expendable vehicles and learning curves plus amortization on the reusable vehicles gives us a way of making straightforward comparisons between the relative costs of the two systems.

6.2 Sensitivity to Driving Parameters

The conclusions reached in Section 6.1 are a result of both the model and, of course, the specific input values used to generate the numerical results. Consequently, it is important to examine the sensitivity of the results of deviations from the baseline cost for the various input parameters. To examine this we varied individually all of the input parameters in the cost model and looked at the outputs for the four cases of low-cost and moderate-cost, expendable and reusable. The results for these variations are compiled in Table 4. The values shown in the table are the total cost per launch for 5000 kg to LEO in millions of FY00 dollars. The baseline costs are shown at the top of the table. Of course, the amount of the change in the total cost will depend on the amount of the change in the input parameter. To eliminate this arbitrariness, we determined the numerical partial derivatives of variations in the input parameters by computing the percent change in the total cost divided by the percent change in the input values. These results are tabulated in Table 5. Here low values indicate an insensitivity to that parameter. Any values greater then 1.0 would indicate a high sensitivity and suggests that the launch vehicle designer should spend additional time and effort to reduce that component of the cost and, consequently, the sensitivity. As we can see from the table, all of the sensitivities are low, indicating at least an approximate balance between the various constituent costs.

In general, the results shown in Tables 4 and 5 indicate a relative insensitivity to small or moderate changes in the numerical input parameters. If one element becomes much cheaper, then other elements become the cost driver. Often, when one parameter goes down, others will go up.

This general balancing of cost increases and decreases can be seen most clearly in looking at the cost vs. the number of flights per vehicle for the low-cost reusable model. One would expect that, in general, increasing the number of flights per vehicle should reduce the amortization cost and, therefore, the overall cost per launch. Generally, this occurs. However, there is a competing effect in that if the total launch rate does not change, then the number of vehicles produced will decrease slightly, as each vehicle is used for more flights. Consequently, the learning curve will proceed somewhat less, and the average cost per vehicle will go up (while the total vehicle cost goes down). This, in turn, increases both the refurbishment and the insurance cost, which, in the case of the low-cost reusable, ends up slightly increasing the total cost per launch.

Component	***Low Cost Reusable***	***Mod Cost Reusable***	***Low Cost Expendable***	***Mod Cost Expendable***
BASELINE COSTS	$39.77	$103.72	$10.73	$34.56
4% inflation (vs. 3%)	$38.44	$97.37	$10.50	$33.62
85% learning curve (vs. 87.5%)	$38.93	$103.90	$9.35	$30.60
Amortized over 18 yrs (vs. 15)	$38.27	$97.14	$10.20	$32.69
12% interest (vs. 15%)	$37.04	$90.64	$10.25	$32.63
15 flights/yr (vs. 10)	$33.26	$74.84	$9.05	$28.45
10% lower NR Development	$38.41	$95.55	$10.39	$33.20
10% lower TFU Vehicle Cost	$37.38	$101.55	$10.08	$32.50
10% more Flights per Vehicle	$39.96	$103.17	N/A	N/A
10% lower TFU for Flight Ops	$39.54	$103.68	$10.66	$34.52
10% lower Recovery cost	$39.73	$103.71	N/A	N/A
10% lower TFU Refurb. cost	$38.36	$102.95	N/A	N/A
110%/103% RLC (vs. 115%/105%)	$36.18	$102.67	N/A	N/A
10% lower Insurance Rate	$39.35	$103.40	$10.65	$34.41

Table 4. Sensitivity Analysis — Effect on Total Cost of Variations in Input Parameters. Baseline costs are in the top row. Baseline input values are shown in parentheses. NR = Nonrecurring. RLC = Refurbishment Learning Curve.

Component	Low Cost Reusable	Mod Cost Reusable	Low Cost Expendable	Mod Cost Expendable
4% inflation (vs. 3%)	–0.10	–0.18	–0.06	–0.08
85% learning curve (vs. 87.5%)	0.11	–0.01	0.64	0.57
Amortized over 18 yrs (vs. 15)	–0.19	–0.32	–0.25	–0.27
12% interest (vs. 15%)	0.34	0.63	0.22	0.28
15 flights/yr (vs. 10)	–0.33	–0.56	–0.31	–0.35
10% lower NR Development	0.34	0.79	0.32	0.39
10% lower TFU Vehicle Cost	0.60	0.21	0.61	0.60
10% more Flights per Vehicle	–0.05	0.05	N/A	N/A
10% lower TFU for Flight Ops	0.06	0.00	0.07	0.01
10% lower Recovery cost	0.01	0.00	N/A	N/A
10% lower TFU Refurb. cost	0.35	0.07	N/A	N/A
110%/103% RLC (vs. 115%/105%)	–0.27	–0.03	N/A	N/A
10% lower Insurance Rate	0.11	0.03	0.07	0.04

Table 5. Numerical Partial Derivatives of Variations in Input Parameters. Value shown is the percent change in total cost divided by the percent change in input values. Low values indicate an insensitivity to that parameter.

From the sensitivity tables we determine that reusable vehicles are most sensitive to the nonrecurring development cost, the TFU cost, interest rate, and flight rate. In contrast, expendables are most sensitive to the learning curve and TFU vehicle cost, and somewhat sensitive to the flight rate and nonrecurring development cost. All of these are consistent with our original expectations that a principal cost driver for a reusable vehicle is the development cost associated with it. The most important characteristic of an expendable vehicle is the degree to which we can drive down the cost by using a learning curve to increase our manufacturing efficiency by developing economies of scale, production techniques, specialized tooling, and other elements used in a high volume business.

In comparing reusable and expendable vehicles, a high unanticipated inflation is advantageous to reusable vehicles because the initial investment will be paid off with cheaper dollars in later years. Conversely, a better (i.e. lower) learning curve favors expendables because they make more use of learning curve elements (i.e. tooling, assembly line production, economies of scale, plus the actual learning process of how to do it better). In general, two basic effects serve to preserve the balance between the relative cost of reusable and expendable vehicles over a very wide range of input parameters. First, there is a broad insensitivity to individual input parameters, as discussed above. Second, changing the basic parameters of flight rate, interest rate, inflation rate, learning curve, or amortization rates effects both the reusable and expendable vehicle. For example, for the moderate cost option there is a significantly higher sensitivity to the flight rate for reusable vehicles than for expendable vehicles. Nonetheless, in going from 10 flights per year to 10,000 flights per year, the expendable vehicle remains somewhat lower-cost then the reusable. Although the differences have become less, the basic conclusions remain over an exceptionally wide range.

The fundamental conclusion of the sensitivity analysis is that our conclusions about expendables versus reusables are relatively insensitive to the specific input parameters. For reusable vehicles to be less expensive then expendables would require a dramatic variation in several of the basic mission parameters.

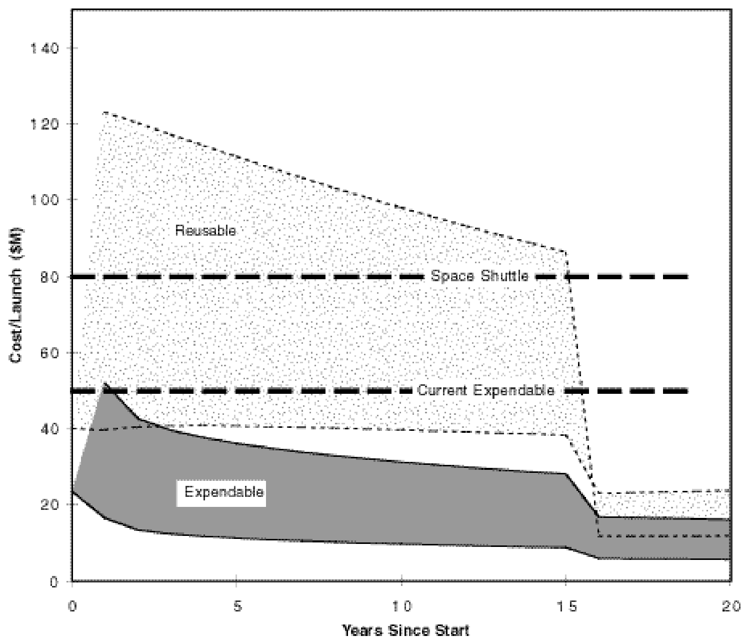

Fig. 3. Expendable vs. Reusable Launch Cost Over Time. Values are in constant FY00$ millions with 3% per year inflation. (See Appendix for numerical method of accounting for inflation and see text for discussion.)

6.3 Time-Phasing of Costs

Thus far we have discussed the average launch costs over a 15 year period. In fact, launch vehicles are sold on a continuing basis, and the capacity to sell them and to influence the market place are dependant not on the long term average costs, but on the costs at any given time. Fig. 3 shows the time-phasing of costs over a 20 year period following the initial introduction of a new expendable or reusable launch vehicle. The general decline in cost over time comes about from two factors; the learning curve allows us to get better at various aspects of the launch problem. In addition, inflation allows us to pay off amortization costs with increasingly cheaper dollars as time goes on because we are operating in constant year dollars and because amortization is nearly always calculated in "then year" dollars (i.e. your car payment does not increase with time to account for inflation). Consequently, the value of these payment in later years will be reduced. This is reflected in the declining cost with time of all of the categories. The very large cliff at Year 15 is when the amortization cost is fully paid off and we are concerned only with the actual flight costs from then on.

Several conclusions can be reached by looking at the general shape of the curves in Fig. 3. As we would expect, the reusable vehicle is impacted significantly more by amortization cost then is the expendable vehicle. This is simply another way of saying that if it didn't cost anything to develop launch vehicles, it would be much easier to justify the development of reusable vehicles. Nonetheless, even with all of the development costs discounted in the period following Year 15, the average cost of the reusables is still higher than that of the expendables. As with virtually any mode of transportation, as the reusable fleet ages, the repair and refurbishment costs increase over time. In the life of virtually any vehicle there comes a time when it is ultimately more cost-effective to replace it then to continue to maintain it. Thus, the fact that we have "paid off our loan" on the original cost of buying both classes of vehicles does not mean that it will necessarily be less expensive to operate the reusable fleet. The model shows that in this case the cost on the two classes of vehicles overlaps to some degree. Thus it may be that the moderate-cost reusable, which was initially extremely expensive, would become cheaper to operate than the moderate-cost expendable. However, the lower-cost expendables remain less expensive then the lower-cost reusables.

Another characteristic of Fig. 3 is the steepness of the drop at Year 15. This steep cost reduction is unrealistic for two reasons. First, we have not accounted in any way for the development of a replacement fleet. There must be some mechanism in the launch cost process to take into account the need to develop another new generation of vehicles as these become obsolete. This requires setting aside

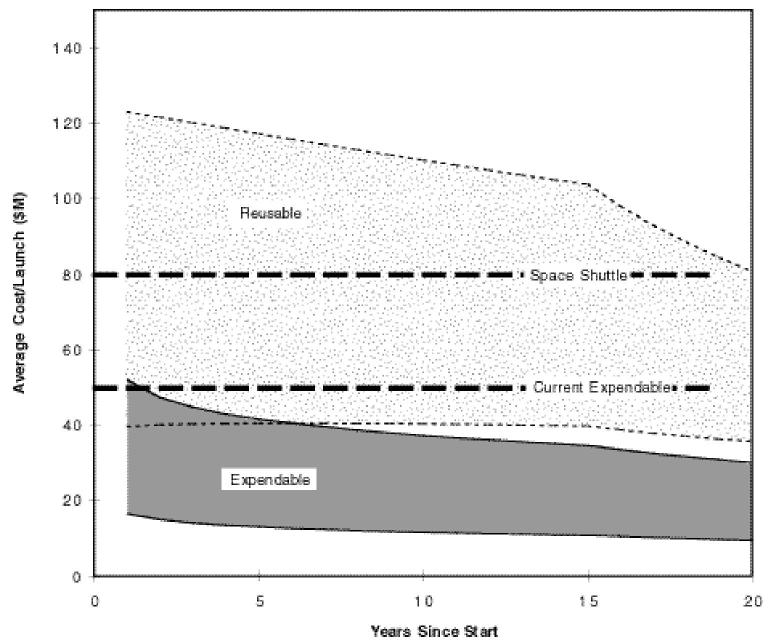

Fig. 4. Expendable vs. Reusable Running Average Launch Cost. This approach provides one method of accounting for the need to develop a new next generation vehicle after 15–20 years and mitigates the steep drop at Year 15 that would create an unmarketable situation for the launch vehicle seller. See text for discussion.

some of the money throughout this period of time, this in turn, is likely to keep the initial costs from dropping as steeply as shown. Second, and perhaps more important, the costs shown in Fig. 3 are virtually unmarketable. Notice specifically the reusable vehicle for which the drop at year 15 is exceptionally steep. In order to sell the original development of the vehicle, we need to emphasize the very dramatic drop once the amortization has been paid off. This implies that the cost vs. time curves will be well known throughout the community. Consider the case of a customer at year 14 being asked to pay $90 million for a launch which a year later will drop to $10 million. In nearly all cases, that customer will either attempt to negotiate a significantly reduced cost or simply wait a year, when the cost has been reduced. This implies that the launch rate in years prior to the end of the amortization curve will fall dramatically and, therefore, there will be insufficient traffic to actually amortize the development.

This issue can be resolved by the process shown in Fig. 4 in which we have used the same data as Fig. 3, but computed a running average launch cost over the 20 year period. In this case, the costs shown are simply the average cost from the initial period to the corresponding time on the chart. This means the initial cost reduction is not so large, and drop off is not so steep. This curve has a much more realistic potential for being marketable and provides a level of funding appropriate to developing the next generation vehicle. Costs continue to drop with time as we hope they would, but do not have a single steep cliff which is unacceptable from a marketing perspective. Consequently, Fig. 4, while not as desirable from the perspective of near-term, low-cost space exploitation, presents what is probably a more realistic model for how launch costs would decline with time.

7. CONCLUSIONS

Generally, expendable launch vehicles will continue to have a significant economic advantage over reusable vehicles until launch rates increase by well over 100 times. (At these large quantities it is probable that the current model or current set of input parameters are no longer valid.) If the modeled costs are achieved, then expendable vehicles have the potential of dropping launch costs by a factor of 5 to 10 in the near term. Also, given that the assumed costs can be achieved, new reusable vehicles should be cheaper then the Space Shuttle, and have a probable lower cost limit approximately equal to current launch costs. They may be able to reduce overall launch costs by a factor of 2 to 3 if the launch rates increase significantly. Amortizing costs over a period longer then 15 years will have only a marginal impact.

The reusable vehicle has a cost advantage primarily in the direct vehicle cost. As often pointed out by reusable proponents, the major advantage of the reusable vehicle is that we don't have to build a new one after every flight. This is, of course, remarkably advantageous. On the other hand, expendable vehicles have a cost factor advantage in nearly all other categories. Specifically:

- Expendable vehicles continue to be cheaper as time goes on.
- Recovery and Refurbishment costs don't exist; operations and insurance are inherently less expensive.
- Because of the vehicle cost, reusable vehicles represent a higher level of risk and must be significantly more reliable while driving the margins to near zero.
- Expendables can incorporate new technology and product upgrades more easily.
- Flight operations are inherently less complex for expendables.

In addition, reusable vehicles suffer significant monetary cost penalties.

- All vehicle costs must be paid out up front, before any income is returned.
- Reusable vehicles are significantly more complex and challenging (and therefore expensive) to develop.
  - — We need to make the very first reusable vehicle work successfully.
  - — We need to drive down the mass fraction, while simultaneously driving up the reliability.
  - — Continuous production of reusable vehicles is unlikely to exist.

The fundamental advantage of reusable launch vehicles is that we don't have to throw them away every time we use them (i.e. we amortize the cost over multiple flights). This is an enormous advantage, and philosophically appealing. The reusable vehicle also has a psychological advantage for the payload in that it must be made more reliable in order to succeed economically. However, the fundamental question is whether amortizing the construction cost over multiple flights is worth the increase in cost in most other categories. The economic models presented here suggest that it does not appear to be worthwhile at launch rates less then about 100 times the current rate.

What can be done to reduce the cost of access to space? A key issue in reducing cost is to avoid the philosophical trap of expendable versus reusable vehicle, and to look for the best economic solution. For existing vehicles, this means that systems or components for which the cost of recovery plus refurbishment is less then the manufacturing cost should be reused. If that isn't the case, new systems should by used. This is no different than with any commercial product or home commodity. If it costs more to take the television in for repair and pay for the repairs than it does to buy a new one, then the solution is to buy a new television when the old one breaks. For new vehicle designs we should reuse systems or components for which the cost of the added amortization plus the recovery and refurbishment cost is less then the manufacturing cost reduced by the learning curve. If that is not the case, they should be expended and new ones built for each flight.

The fundamental conclusions of this work are as follows:

> **Economics, rather than philosophy, should be the major driver in how new launch vehicles are designed and built.**
>
> **A factor of 5 to 10 near term reduction in launch cost appears feasible. That should increase the size of the market, which can then lead to lower costs in the future.**

Greatly increased demand will offer the future opportunity for reusable vehicles to become economically viable.

8. REFERENCES

Apgar, et. al, 1999. "Cost Modeling" (Chap. 20). In J.R. Wertz, and W.J. Larson (eds.), *Space Mission Analysis and Design* (*3rd edition*). Torrance, CA and Dordrecht, The Netherlands: Microcosm Press and Kluwer Academic Publishers.

Hammond, Walter E. 1999. *Space Transportation: A Systems Approach to Analysis and Design*. Reston, VA: AIAA.

Isakowitz, Steven J. 1998. *AIAA International Reference Guide to Space Launch Systems (3rd Edition)*. Washington, DC: AIAA.

Koelle, Dietrich E. 1991. *TRANSCOST, Statistical-Analytical Model for Cost Estimation and Economic Optimization of Space Transportation Systems*. Munich, Germany: MBB Space Communications and Propulsion Systems Division, Deutsche Aerospace.

Koelle, Dietrich E. 1998. “Cost Engineering — The New Paradigm for Space Launch Vehicle Design.” *Journal of Reducing Space Mission Cost*, Vol. 1, No. 1, pp. 73–86. Dordrecht, The Netherlands: Kluwer Academic Publishers.

London, III, John R. 1994. *LEO on the Cheap—Methods for Achieving Drastic Reductions in Space Launch Costs*. Maxwell Air Force Base, AL: Air University Press.

London, III, John R. 1996. “Reducing Launch Cost” (Chap. 4). In J.R. Wertz, and W.J. Larson (eds.), *Reducing Space Mission Cost*. Torrance, CA and Dordrecht, The Netherlands: Microcosm Press and Kluwer Academic Publishers.

Satellite Finance, April 12, 2000. pg. 14.

Stine, Harry G. 1996. *Halfway to Anywhere: Achieving America’s Destiny in Space*. M. Evans and Company, Inc.

Wertz, James R. and Wiley J. Larson (eds.). 1996. *Reducing Space Mission Cost*. Torrance, CA and Dordrecht, The Netherlands: Microcosm Press and Kluwer Academic Publishers.

Wertz, James R. 2000. *Spacecraft Orbit and Design Systems. Vol. 1: Mission Geometry; Orbit and Constellation Design*. Torrance, CA and Dordrecht, The Netherlands: Microcosm Press and Kluwer Academic Publishers.

X-Prize Foundation, http://www.xprize.org, (15 Sept. 2000).

APPENDIX: AMORTIZATION WITH INFLATION

Cost models traditionally use constant year dollars; that is, they ignore the effect of inflation because it applies equally to all of the elements. Unfortunately this is not the case for the reusable versus expendable cost model. Unanticipated high inflation is beneficial to the reusable launch vehicle because it can pay off the high initial cost with lower cost dollars at a later date. For the expendable vehicle, inflation raises (i.e. makes worse) the learning curve and reduces the learning curve benefit. Consequently, in a comparison of expendable versus reusable vehicles, we need to take inflation into account, and therefore, to compute the payment reduction if payments are computed in constant dollars instead of the traditional inflated dollars.

Amortization assumes a constant payment, P_0, over time in real (then-year) dollars of

$$P_0 = Li \, / \, (1 - (1 + i)^{-N}) \qquad (8)$$

where L is amount of the loan, i is the interest rate, and N is the number of payments. For a given constant inflation rate, f, the annual reduction, R, in the value of money is

$$R = 1 \, / \, (1 + f) \qquad (9)$$

Over a period of N years, the average payment, P_{avg}, in constant year dollars, will be reduced to

$$P_{avg} = \mathrm{P}_0 \, (R \, / \, N) \, ((1 - R^N) \, / \, (1 - R)) \qquad (10)$$

This is the fundamental formula needed to take into account inflation for the amortization formula in the launch vehicle model. Other related formulas for amortization with inflation are as follows:

First Payment =	$R \, P_0$
First Principal, F_L =	$R \, (P_0 - iL)$
Annual Growth in Principal, G =	$(1 + i) \, / \, (1 + f)$
Total Payments, T_P =	$R \, P_0 \, ((1 - R^N) \, / \, (1 - R))$
Total Principal, T_L =	$F_L \, ((1 - G^N) \, / \, (1 - G)$
Total Interest, T_i =	$T_P - T_L$