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RESPONSIVE LAUNCH VEHICLE COST MODEL*

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Abstract

This paper presents a launch vehicle cost model designed specifically to estimate the additional economic cost of two related system properties that have substantial military utility — responsiveness and surge capability. In addition, the model can be used to compare alternative methods for achieving these objectives, such as reusable, partially reusable, or fully expendable vehicles.

In general, we estimate that making small space systems responsive, i.e., being able to launch with a few hours or days of demand, will add less than 5% to the total system cost per launch. Surge capability is somewhat more expensive, increasing the total cost per launch from 5% to 35%. Having a robust surge capability and the ability to do it again quickly is the most expensive option and will likely increase the cost per launch by 30% to 80%.

For all of the options considered, the cost per launch decreases with increasing number of launches per year. In addition, the percentage increase for responsiveness decreases with increasing launch rate as the impact of maintaining vehicles in inventory decreases. In all of the cases considered, expendable vehicles are lower cost than reusable vehicles for all launch rates considered, i.e., 5 launches per year to 100 per year.

1. Introduction

The Microcosm Responsive Launch Cost Model (RLCM) is an extension of work previously done by Microcosm to create an economic model of the cost per launch and cost per pound for both expendable and reusable launch vehicles [Wertz, 2000A]. The model was designed to facilitate comparison between the two approaches and each cost element is discussed in terms of the impact of reusing or discarding vehicles or components. This prior work has now been extended to explicitly model the economic cost of responsiveness and surge capability for both reusable and expendable systems.

Specific numerical examples are provided, and sensitivities are computed for the major independent parameters, which allows us to draw broad conclusions about the probable cost of responsiveness and the relative cost between reusable and expendable responsive launch systems. 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, scenarios, or technologies. Finally, the model is used to determine the broad economic consequences of responsiveness and the conditions under which reusable or expendable vehicles will be more or less expensive. This methodology can also be applied to determining under what economic conditions portions of a launch vehicle should be reused or expended.

Note that the RLCM is concerned only with direct economic cost and not the value of responsiveness, typically called "opportunity cost." Thus, having a responsive system provides opportunities not otherwise available, such as preventing a war, repairing a damaged spacecraft, or making a scientific observation that would otherwise be lost. This is discussed in broad terms, but is not taken into account in the launch cost model.

It is often assumed that reusable launch vehicles will dramatically reduce launch costs because the vehicle isn't "thrown away" 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.

Basic cost data for most existing and planned launch systems is given by Isakowitz [1998]. 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 [2000B], Koelle

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[1998], and Hammond [1999]. Specific comparisons of single-stage to orbit and two-stage to orbit launch costs are provided by Koelle [1996, 1998].

2. The Microcosm Reusable vs. Expendable Launch Cost Model (RvsELCM)

The Microcosm Reusable vs. Expendable Launch Cost Model, RvsELCM, is intended to be used for both expendable and reusable launch vehicles and is not biased toward either [Wertz, 2000A]. 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. The paper assumes specific values or ranges for each of the input parameters in order to parameterize launch costs for both expendable and reusable vehicles. The model is then used to estimate 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 of the prior work was 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, RvsELCM models the total launch cost as the sum of six individual components:

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

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 in the paper, with the formulas for computing them based on various input parameters and a brief description of the basis for the range of parameters used.

The sample mission examined in the RvsELCM paper was for a 5,000 kg (11,000 lb) payload to LEO, amortized over 15 years, at 15% per annum and 87.5% learning curve in fixed year dollars. To provide a range of data, low cost and moderate cost expendables and resusables were analyzed to give the summary results shown in Fig. 1. Costs were broken down by individual cost element and both the sensitivities and numerical partial derivatives were computed to determine both the robustness and broad applicability of the model.

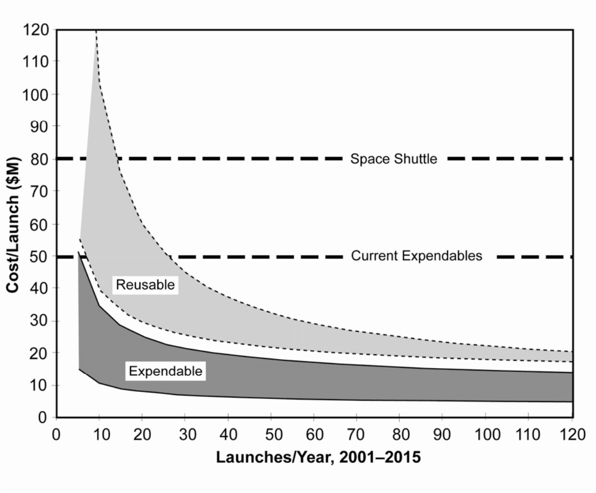

Fig 1. Cost per Launch vs. Average Launch Rate (2001 to 2015) for Launch of 5,000 kg to LEO. The expected launch rate for a very successful new vehicle is 10 to 15 launches per year over this period with only 2 to 4 launches per year for the first several years. (Plot and analytic basis from Wertz [2000A].)

Three fundamental conclusions came about as a result of the RvsELCM analysis:

1. Economics, rather than philosophy, should be the major driver in how new launch vehicles are designed and built.
2. 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 even lower costs in the future.
3. It is unlikely that reusable vehicles can be as economical as expendable vehicles for launch rates less than about 100 times the current rate.

I believe the first conclusion above should be the major driver in all new launch vehicle design and development. The purpose of the current work is to extend the prior model to smaller payloads (on the order of 400 kg to LEO) and, more specifically, to extend the model to include vehicles with a specific requirement of being responsive. We would like to determine whether conclusions (2) and (3) remain valid and to obtain an estimate of the cost of responsiveness as an additional system requirement.

3. The Microcosm Responsive Launch Cost Model (RLCM)

The objective of the Microcosm Responsive Launch Cost Model (RLCM) is to maintain as much of the structure of the RvsELCM as possible, while expanding the model to explicitly include elements which are required to create a responsive launch system. This "model upgrade" involves adjusting some of the basic formulas, adding one term to the model, adding one component to the operations term, and adjusting some of the baseline input parameters.

3.1 Launch Vehicle Inventory Model

In the traditional process, launch vehicles are effectively built for each individual mission and must be ordered months or years in advance. In a responsive launch system, vehicles must be built to inventory and are then taken out of inventory to be used as needed. Building a vehicle in advance implies that we must spend money at the time the vehicle is built and not recover that money until the vehicle is actually used at some later time. How long a particular vehicle will sit in inventory depends on many factors, but, fortunately, doesn't matter for the purpose of cost modeling. We assume there is a requirement to maintain a specific number of vehicles in inventory. (As discussed in Section 4, how many vehicles must be held in inventory is a measure of the level of responsiveness and is one of the basic input parameters.) When a vehicle is used from inventory, it is replaced with another. Therefore, for purposes of the model, we simply assume that the required number of vehicles are continuously in storage.

The need for more vehicles than are actually used has a number of impacts on system cost. There is a higher recurring production cost for the entire fleet, but, because of the learning curve, the cost per vehicle is less. The vehicles maintained in storage result in a new term in our RLCM called "Cost of Inventory," which represents the cost of building these vehicles before they are needed. (The cost of maintaining them will be taken as a part of flight operations cost.) How the vehicle cost and cost of inventory are handled differs between expendable and reusable vehicles.

The cost of inventory for expendable vehicles is the most straightforward. First, because of the size of the production run, the production cost per vehicle is reduced, based on the same learning curve as the traditional model. Second, the new term in the cost model, the Cost of Inventory per launch, $C_{inventory}$, is computed as:

$$C_{inventory} = C_{vehicle} N_{inventory} I_{inventory} / L_{year} \quad (2)$$

where $C_{vehicle}$ is the average production cost per vehicle, $N_{inventory}$ is the number of vehicles required to be in inventory, $I_{inventory}$ is the annual interest rate for the vehicles in inventory, and L_{year} is the number of launches per year. In the baseline cost model, the annual interest rate for amortization was assumed to be 15%, corresponding to the interest associated with modest business risk. This value is also assumed for manufacture of the production vehicles in the responsive launch model. However, the assembled and tested vehicle put into storage is simply a capital asset, which can be bought or sold just as a truck or building would be. This asset in inventory is likely to carry a lower rate of interest and, therefore, is given a different interest rate in the model. For the examples below, we have chosen 10% interest on the inventory.

Inventory is more complex for the reusable vehicle because it is already the case that vehicles will be stored and used over an extended period. However, the need to launch multiple payloads rapidly may lead to a need for more vehicles than might otherwise be necessary. There are two possibilities for reusables:

- **Case 1.** Vehicles can be launched, recovered, refurbished, and prepared for relaunch in time to meet the system responsiveness requirements.
- **Case 2.** A sufficient number of vehicles must be made available such that the responsiveness requirement is met by launching a different vehicle for each responsive payload launched in a short period. All of these vehicles are then recovered and reused on a schedule that allows low-cost operations and refurbishment.

The first case could potentially reduce the cost of inventory, but would drive up the development and manufacture costs by putting very severe requirements on system operability. The Space Shuttle experience is of very little use to us here, because it is so far from instant turn-around as to require an entirely different vehicle (or processing paradigm) to be used as a "responsive" launch vehicle.

Consequently, we will look primarily at case (2) in which there are sufficient vehicles available to meet the short term responsiveness requirement. In this case, there are two different drivers for the number of RLVs that must be built. First, we calculate the number of vehicles, N_{RLV}, needed to meet the total launch demand by

$$N_{RLV} = L_{yr} N / L_{RLV} \quad (3)$$

where L_{yr} is the number of launches per year (assumed to be 20 in the examples below, consistent with the DARPA FALCON study), N is the number of years over which the program runs (assumed to be 10, again consistent with the FALCON study), and L_{RLV} is the number of launches per individual RLV. If N_{RLV} is greater than the number of responsive launches required, then the responsiveness is assumed to be met by the normal inventory of RLVs and the cost of inventory is assumed to be 0. For example, if 20 vehicles are needed to meet the overall mission requirement and we need only 10 vehicles in inventory to meet the responsiveness need, then there is no added cost of inventory and that term in the cost model is 0. Of course, this scenario implies either a very large number of launches or a small number of flights per RLV. The production cost of the RLVs is amortized over the total launch base, as in the traditional, non-responsive model.

The more likely circumstance is that the number of required launches to meet the responsiveness requirement, N_{RL}, is larger than the number of RLVs needed to meet the overall mission requirement. In this case, we need to build ($N_{RL} - N_{RLV}$) additional vehicles to satisfy the responsive launch demand. All of the vehicles must be built at the outset to meet the need for responsiveness. However, the costs are treated differently for the two sets. The N_{RLV} vehicles needed to satisfy the mission demand are amortized over their life as described above. The ($N_{RL} - N_{RLV}$) additional vehicles represent a valuable asset which is unused over the life of the program, but which will presumably be used or sold after the program or otherwise used to meet an ongoing need for responsiveness. (In practice, it is likely that all of the vehicles will see some use and all will have some launches remaining at the end of the program. However, this result doesn't matter to the cost model.) These "excess" vehicles, like the expendable ones, are treated as an asset, such that we need to pay only the interest on the money it took to build them. This is charged at the lower "asset interest rate," which we have initially assumed to be 10%.

The Microcosm RLCM is in units of constant year dollars, as are most cost models. However, inflation is more advantageous for RLVs than ELVs because we borrow more money up front to build the RLVs and then pay it back with cheaper, inflated dollars. This effect is taken into account in the RLCM as described in the RvsELCM paper [Wertz, 2000A].

3.2 Adjustments to Operations Cost Element

The dominant added cost for responsive launch systems is likely to be the cost of inventory. However, there will be additional operations costs as well. Among these are:

- Having additional people available to support responsive operations (the "standing army cost")
- Having to do additional work to support responsiveness, such as:
  - Maintenance and testing of the vehicles in inventory
  - Maintaining the launch facility at a high level of readiness
  - Additional practice and training
  - Additional processes and procedures

As described in the next section, most of this added cost will depend on the level of responsiveness required. From a cost modeling perspective, it is sufficient to increase the cost of operations, recovery, and refurbishment to account for the added effort required. The only element added specifically to the cost model is the "standing army cost," which is modeled as a number of additional full time equivalent (FTE) personnel required to support responsiveness and a fully burdened cost per FTE, initially assumed to be $150K/FTE. The number of FTE people is an input variable that is varied among the sample missions.

4. Baseline Inputs — Levels of Responsiveness

The added cost of responsiveness depends, of course, on how responsive the system needs to be. If we are given a reasonable advance warning of the need for launch and are able to launch during normal business hours, the additional cost of being able to launch within hours rather than months, as is now the case, may be very little more than the inventory cost described in Section 3. However, if we are required to launch within a few hours with no advance notice, then we will need a large standing army at the launch complex. It is likely that a realistic responsive launch system will be somewhere between these extremes. To make the problem tractable and get an idea of the range of costs involved, we define 4 scenarios (called Baseline, Commercial, FALCON, and Full Responsiveness) and a Level of Responsiveness (LR), which is defined as the number of vehicles that need to be kept in inventory at any time. Each of these scenarios is discussed below.

Baseline (LR0). This is the traditional, non-responsive launch scenario. To provide traceability, we matched the launch cost model parameters as nearly as possible with those of the RvsELCM previously studied. The only variations were to allow the RLCM to fit the launch model defined by the AF/DARPA Phase I FALCON study [DARPA. 2003]. The prior model had assumed a 5,000 kg (11,000 lb) payload to LEO, amortized over 15 years with a nominal launch rate of 10 flights/year. To be consistent with the DARPA study, values have been changed to a 400 kg (1,000 lb) payload to LEO, amortized over 10 years, with a nominal launch rate of 20 flights/year. In both cases, the number of launches per year was taken as the independent variable in the studies. As we will see in Sec. 5, adjusting the baseline to accommodate the DARPA parameters has no effect on the prior conclusions.

Commercial (LR3). This scenario is intended to meet the needs of commercial or government customers for launch on demand, without an explicit surge capability. We assume that there is some warning of a potential need for launch and that much of the launch services can be handled by the normal launch crew that is either at the launch site, or brought in as needed from elsewhere. Three vehicles are maintained in inventory, such that if one is called up for a responsive launch, and there is a launch failure, then a back-up payload can still be launched with a reserve vehicle still available to meet additional demand. The vehicle development and production costs are the same as for the baseline case, and the additional operations costs are very low (a standing army of 3 to 6 FTE for the expendable and 5 to 10 for the reusable). The standing army will be larger for the reusable because people will be required to support recovery, both during the flight and on the ground.

FALCON (LR16). This scenario is intended specifically to model the DARPA FALCON launch scenario requiring the launch of 16 payloads in a 24 hour period. Thus, there is a minimum inventory of 16 vehicles. However, we assume that the vehicle costs remain the same as for the traditional vehicle and that the standing army and operations requirements, while greater than the baseline, are still based on some advance warning and extensive use of an existing operations crew. Thus, the upper end of the theoretical first unit (TFU) cost of flight operations approximately doubles, and the standing army is increased to 5 to 10 FTE for the expendable and 10 to 20 for the reusable.

Full Responsiveness (LR32). This scenario is intended to meet a "strong" responsiveness requirement, in which there may be minimal advance warning and, following a 16 launch surge, a second surge of 16 launches in 24 hours may be required before the system has been able to recover. (Alternatively, we can think of having to launch a 16 vehicle surge following a hostile strike on the primary launch site, such that the 16 vehicles must come from a back-up site.) This is a very demanding scenario with cost increases in virtually all areas. The inventory has gone to 32 vehicles, and the standing army to 20 to 50 FTE for the expendable and 40 to 100 for the reusable. In addition, the TFU vehicle cost has been increased by about 20% to account for more stringent readiness requirements. This case is particularly hard to model in that a strongly requirements-driven system may increase the cost many-fold. Thus, at the top end, costs could go up several times to account for requirements that we have not considered.

All of the models have a number of basic parameters in common. All assume 400 kg to LEO, amortized over a 10 year period, with 15% interest on the amortized cost and 10% interest on the inventory (as discussed in Sec. 3). All models also assume $150K per FTE person, 3%/year inflation, and a learning curve of 87.5%. The values of the input parameters which change with various models are given in Table 1.

Scenario	*Units*	LR0	LR0	LR3	LR3	LR16	LR16	LR32	LR32
Low/Moderate Cost		Low	Mod	Low	Mod	Low	Mod	Low	Mod
Required inventory	#	0	0	3	3	16	16	32	32
New Expendable Vehicles									
Non-recurring cost	FY04$M	50	200	50	200	50	200	50	200
TFU Vehicle Cost	FY04$M	7.5	10	7.5	10	7.5	10	8.5	12
TFU for Flight Ops	FY04$M	0.5	0.6	0.5	0.60	0.5	1	1.5	2
Standing army FTEs	FTE	0	0	3	6	5	10	20	50
Insurance rate	%/flight	15%	8%	15%	8%	15%	8%	12%	6%
New Reusable Vehicles									
Flights/reusable veh	#	50	100	50	100	50	100	50	100
Non-recurring develop	FY04$M	500	1500	500	1500	500	1500	500	1500
TFU vehicle cost	FY04$M	50	100	50	100	50	100	60	120
TFU for Flight Ops	FY04$M	1.5	1.00	1.5	1.00	1.5	2	3	3
Standing army FTEs	FTE	0	0	5	10	10	20	40	100
Recovery as % of Ops.	%	50%	20%	50%	25%	50%	30%	60%	50%
Refurbish % of construc	%	2%	1%	2%	1%	2%	1%	3%	1%
Refurb. learning curve	%	115%	105%	115%	105%	115%	105%	115%	105%
Insurance rates	%/flight	2%	0%	2%	0%	2%	0%	1%	0%

Table 1. Input Parameters for the Responsive Launch Cost Model. See text for those parameters which remain fixed for all of the scenarios.

5. Results and Sensitivity

As described in Sec. 2, we are generally concerned with the total cost of launch, i.e., the sum of amortization of the non-recurring development cost, production cost of the expendable or reusable vehicle, launch operations, recovery and refurbishment for the reusable vehicle, insurance costs, and, of course, the cost of inventory for the responsive vehicles. The results of this total cost assessment are given in Sec. 5.1. However, it is often the case that the non-recurring development cost is paid separately (typically as government-funded R&D), and the only cost "charged" to a satellite to be launched is the recurring cost, i.e., the sum of all the costs other than non-recurring development. The results in terms of recurring costs only are discussed in Sec. 5.2.

5.1 Total Cost Comparison

Figure 2 shows the results of the Baseline scenario in terms of cost per launch vs. annual launch rate for a traditional, "non-responsive" small launch vehicle putting 400 kg (1,000 lb) in LEO. This can be compared with Fig. 1, which shows equivalent results for a larger (5,000 kg ~ 11,000 lb to LEO) system. As one would expect, the values change because of the different size launch, but the general shape of the curves and the overall conclusions remain the same. The expendable vehicle remains cheaper than the reusable over the full range of launch rates considered — up to at least 10 times the maximum expected launch rate for any near term or medium term launch system. Although the relative importance of various elements changes with launch rate, the learning curve is the driving characteristic that reduces the cost per launch for all of the systems in approximately the same way. A higher launch rate will reduce the cost per launch of reusable systems, but there is no fundamental reason to believe that the learning curve process will be any more or less effective for reusable or expendable systems. All systems will cost less per launch as the launch rate increases.

Given the baseline system described above and the various responsive scenarios defined in Sec. 4, we can use the RLCM to estimate the cost of responsiveness. This is done by computing the cost increase, relative to the baseline for each of the responsive scenarios. The results are shown in Fig. 3A, 3B, and 3C for the Commercial, FALCON, and Full Responsiveness scenarios. Note that these results are given as percentage increases for the responsive system such that a given cost increase will have a lower percentage impact on an inherently more expensive system. Thus, the curves for low-cost and moderate cost systems will sometimes cross in terms of percentage increase.

Several general characteristics are apparent from the curves. The cost of responsiveness tends to be higher for a low launch rate because of the need to keep vehicles in inventory simply to accommodate the responsiveness requirement. Also, the relative cost of responsiveness depends strongly on the required level of responsiveness, ranging from only a few percent for an inventory of 3 vehicles (commercial scenario), to 30% to nearly 80% for the full responsiveness scenario.

For purposes of comparison, Fig. 4 shows the total launch cost curve for the FALCON scenario. The objective of the FALCON program was to have a launch cost of less than $5 million, which appears to be possible with the assumed input parameters. To provide a direct comparison of the various responsiveness scenarios, Fig. 5 shows the low-cost expendable model (i.e., the lowest cost of the various sets of curves) for the 4 scenarios.

Finally it is convenient to look at representative values in tabular form. This is done in Table 2 for 5, 10, 20, and 100 launches per year for each of the scenarios. The results are shown to the nearest 0.1 million to make the comparisons easier. This precision is certainly not a measure of the accuracy of the model. The model accuracy depends almost entirely on the input parameter ranges that are used. While we have tried to provide a realistic range, others will almost certainly have very different ranges in mind. The range given in the table is between the low-cost and moderate-cost models.

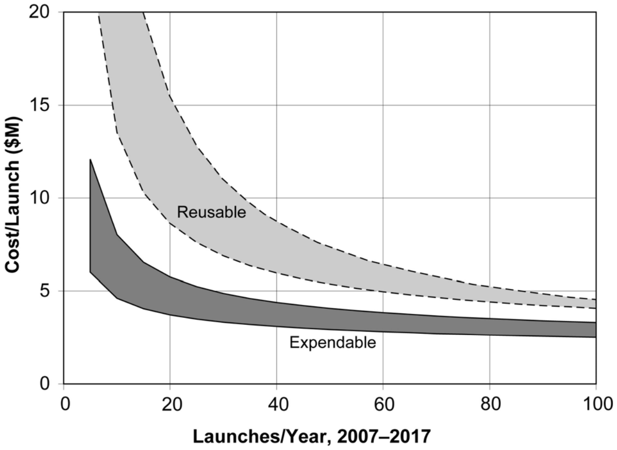

Fig. 2. Baseline Scenario for a Traditional, Non-Responsive Launch System. Uses similar parameters as Fig. 1 except that launch is for 400 kg (1,000 lb) to LEO amortized over 10 years.

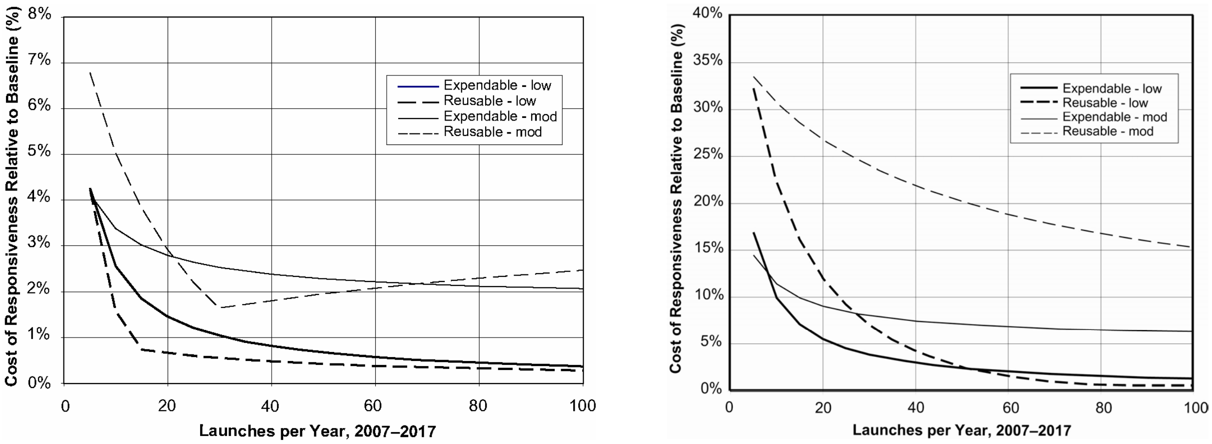

Fig. 3A. Commercial Scenario (LR = 3).

Fig. 3B. FALCON Scenario (LR =16).

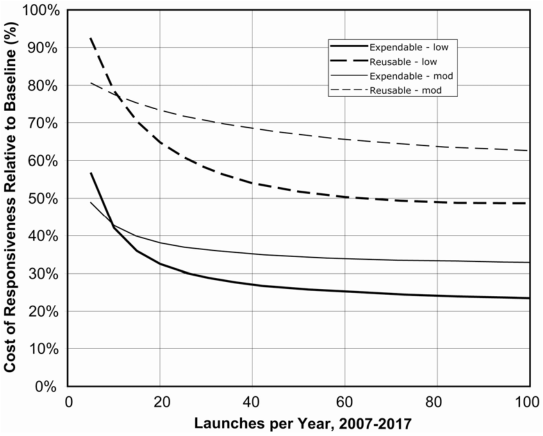

Fig. 3C. Full Responsiveness (LR = 32)

Fig. 3. The Cost of Responsiveness. Charts show the relative cost between the responsive scenarios and the baseline, traditional mission. See text for discussion.

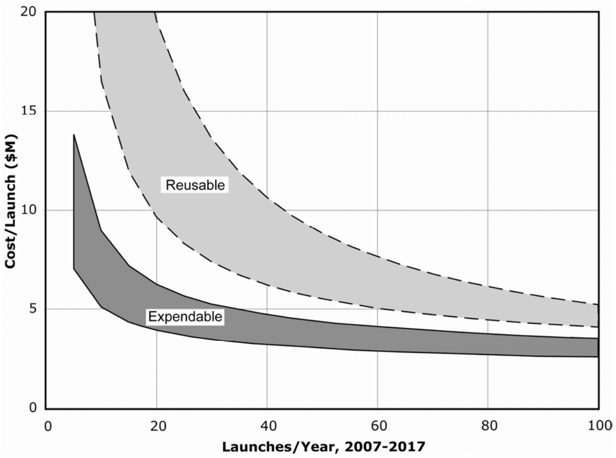

Fig. 4. Cost of Launch vs. Launch Rate for the FALCON scenario (LR = 16). Compare with the Baseline scenario in Fig. 2. Table 2 gives specific numerical results

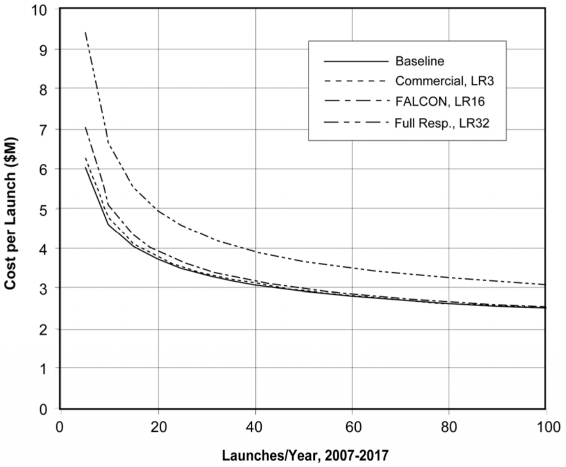

Fig. 5. The Cost of Responsiveness for the Low-Cost Expendable Model. This is generally the lowest cost within each scenario. The other curves have a similar behavior.

Scenario	5 launches/yr	10 launches/yr	20 launches/yr	100 launches/yr
Baseline (LR = 0)				
Expendable	6.0 – 12.1	4.6 – 8.0	3.7 – 5.7	2.5 – 3.3
Reusable	22.7 – 54.5	13.5 – 28.6	8.6 – 15.4	4.1 – 4.5
Commercal (LR = 3)				
Expendable	6.3 – 12.6	4.7 – 8.3	3.8 – 5.9	2.5 – 3.4
Reusable	23.7 – 58.2	13.7 – 30.0	8.7 – 15.9	4.1 – 4.6
FALCON (LR = 16)				
Expendable	7.0 – 13.8	5.1 – 8.9	3.9 – 6.3	2.5 – 3.5
Reusable	30.0 – 72.7	16.5 – 37.3	9.7 – 19.6	4.1 – 5.2
Full Responsiveness (LR = 32)				
Expendable	9.4 – 18.0	6.6 – 11.4	4.9 – 7.9	3.1 – 4.4
Reusable	43.7 – 98.4	24.1 – 50.7	14.2 – 26.8	6.0 – 7.3

Table 2. Representative Cost Results for the Various Responsive Scenarios. All costs are in millions of FY04$. See text for discussion.

5.2 Recurring Cost Comparison

This section provides the same cost results as in Sec. 5.1, but with the amortization of the non-recurring development cost omitted. In some ways, this is a fairer comparison of cost and in some ways, less fair. For most launch vehicles, the non-recurring development cost is paid for as part of an initial R&D government-funded investment. Consequently, launches are typically sold and accounted for in terms of recurring launch cost. For example, the development of the Space Shuttle was about $50 billion in today's dollars [Apgar, 1999]. If we were to cover only the interest on this money, and not amortization, it would add $1 billion to $2 billion to the cost of each Shuttle launch. What is already the most expensive cost/lb to orbit would become dramatically more expensive. Recurring cost is a fairer approach when we are comparing proposed vehicles with other, similar vehicles or trying to estimate the launch cost to be assigned to individual payloads.

Conversely, if we are to get a true sense of the cost of launch, then the approach of Sec. 5.1 provides a more correct picture. Ultimately, if space launch is to become a commercial activity, the cost of developing new vehicles must be recovered by their use, just as is the case for airplanes or automobiles. In addition, if the government is to fund launch vehicle development, it isn't economically justifiable to spend $10 billion in order to reduce the cost of launch by $1 million for 100 launches (although it is a good approach for continued aerospace employment).

With the above caveat, Fig. 6 shows the recurring cost curves corresponding to the Baseline model, and Fig. 7 shows the same data for the FALCON (LR = 16) scenario. Fig. 8 shows the low-cost expendable model (i.e., the lowest cost of the various sets of curves) for the 4 scenarios that have been evaluated for comparison with the total cost curves in Fig. 5.

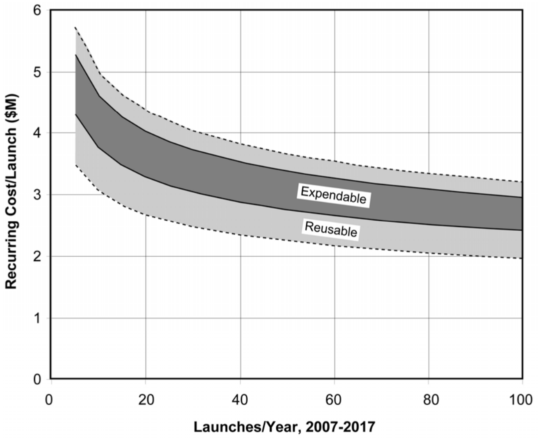

Fig. 6. Recurring Cost Only for a Traditional, Non-Respon-sive Launch System. Uses the same data as for Fig. 2, but omitting the amortization of the non-recurring development cost. See text for discussion of limitations on the use of this data.

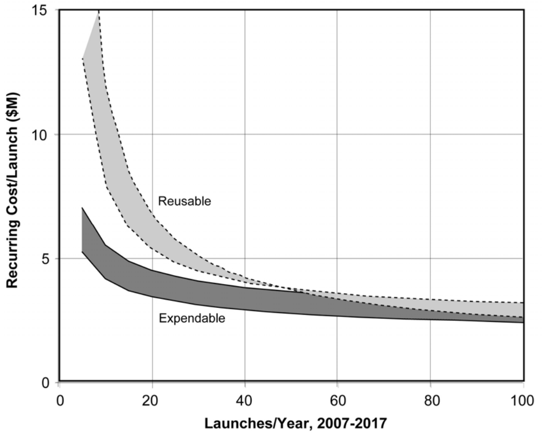

Fig. 7. Recurring Cost Only for the FALCON Responsive Launch Scenario, LR = 16. Uses the same data as for Fig. 3, but omitting the amortization of the non-recurring development cost. See text for discussion of limitations on the use of this data.

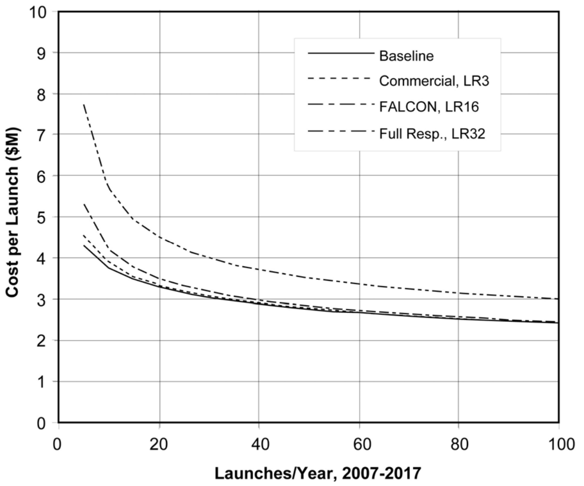

Fig. 8. The Recurring Cost of Responsiveness for the Low-Cost Expendable Model. This is generally the lowest cost within each scenario. The other curves have a similar behavior.

Finally, Table 3 presents the recurring cost in tabular form corresponding to Table 2 for the total cost. As in Table 2, the cost range is between the low-cost and moderate-cost models. However, for the reusable vehicles, the objective of spending more on non-recurring development is to reduce the recurring cost. Therefore, for some of the reusables, the recurring cost in the moderate-cost model is less than that in the low-cost model.

6. "Opportunity Value" — the Benefits of Responsiveness

Ultimately, the economic cost of responsiveness must be balanced against the benefits to determine whether it is worthwhile. While we can at least estimate the economic cost, it is much harder to quantify the benefits of responsiveness. This is normally done via mission utility analysis [Wertz and Larson, 1999]. While this can produce a variety of measures of effectiveness, it typically does not result in an economic value measured in dollars.

When assets are not available, the economic or utility consequences are often referred to as "Opportunity Cost." For example, the Opportunity Cost associated with a spacecraft or launch failure could include the inability to provide adequate surveillance or communica-tions during a war or the loss of the customer base for a commercial communications system. While these may be hard to quantify, they are very real. One of the most obvious examples of a high Opportunity Cost is the bankruptcy of the Iridium program due at least in part to delays in system implementation, which allowed terrestrial cell phones to take over the potential Iridium market.

The converse of Opportunity Cost is what I would like to call "Opportunity Value," i.e., the benefit gained by being able to respond immediately, having assets available in a short time, or being able to conduct immediate, short-term missions or experiments.

Scenario	5 launches/yr	10 launches/yr	20 launches/yr	100 launches/yr
Baseline (LR = 0)				
Expendable	4.3 – 5.3	3.8 – 4.6	3.3 – 4.0	2.4 – 3.0
Reusable	3.5 – 5.7	3.1 – 5.0	2.7 – 4.4	2.0 – 3.1
Commercal (LR = 3)				
Expendable	4.6 – 5.8	3.9 – 4.9	3.3 – 4.2	2.4 – 3.0
Reusable	6.7 – 7.2	4.5 – 5.2	3.1 – 4.4	2.1 – 3.2
FALCON (LR = 16)				
Expendable	5.3 – 7.0	4.2 – 5.5	3.5 – 4.6	2.4 – 3.2
Reusable	13.0 – 21.8	8.0 – 11.8	5.4 – 6.8	2.7 – 3.2
Full Responsiveness (LR = 32)				
Expendable	7.7 – 11.2	5.7 – 8.0	4.5 – 6.2	3.0 – 4.0
Reusable	26.7 – 47.4	15.6 – 25.2	10.0 – 14.0	4.8 – 5.2

Table 3. Representative Recurring Cost Results for the Various Responsive Scenarios. All costs are in millions of FY04$. Compare with Table 2 for the total cost. See text for discussion.

Examples of the benefit gained by having responsive missions include:

- Assets safely deployed in CONUS can reach any location in the world in 45 minutes from launch
- Assets can be assigned to operational commands for tactical applications
- Ability to monitor inherently hazardous environments
  - Monitoring on the ground or even with UAVs causes inherent risk of dispersal of toxic material and may endanger operations personnel
  - Monitoring from space eliminates or reduces the need to put personnel in hazardous environments
- Ability to overfly hostile territory:
  - Without warning
  - Without being a hostile act
  - With little or no chance of being shot down
- Consequences of a launch failure are minimized
  - Launch failure of a traditional surveillance satellite may cost $100's of millions and take months or years to replace
  - Launch failure of a small space mission will cost <$20 million, can be replaced in hours, and minimizes collateral damage
  - Failure of ground or air assets may cause unintended casualties or compromise operational systems, which is unlikely in the case of failure of a space asset

The impact of responsiveness will be felt in nearly all areas of space exploration and exploitation. By creating a system which is inherently not responsive, all of us in aerospace share, to some degree, the responsibility for the death of the original Iridium program and the LEO commercial communications revolution. Conversely, examples of the Opportunity Value of responsiveness in specific areas include:

- Military missions — rapid and continuous battlefield intelligence that's "responsive and flexible" (quote from Gen. Tommy Franks assessment of the strategy for the Iraq war — March 22, 2003)
  - Without responsiveness, space will be less relevant to future military users
- Commercial Missions — ground-based (rather than space-based) sparing, 0-g manufacturing based on needs defined today
  - For space to remain relevant, the next major set of commercial systems must succeed
- Science — observations of transient phenomena; responsive science with tomorrow's experiment based on today's results
- Education — experiments launched while the student is still a student, or at least still in astronautics
- Crewed Missions — can we make them safer by having responsive launch available?
  - Consumables brought up as needed to extend on-orbit life
  - Inspection missions launched when needed to evaluate potential problems
  - "Spare parts" brought up to mitigate any launch or on-orbit failures

In addition, there are specific missions that are enabled by responsive launch. While many such missions have yet to be invented, ones which have been considered include:

- Global Strike
  - Provides truly global reach
  - Can reach any location on Earth at any time more than 45 minutes after launch
- In-Space Inspection
  - Launched in response to foreign launch of unknown assets
    - Shadow at a distance, then close
  - Can typically launch at first or second pass over the launch site
  - Provides rapid examination, and potentially mitigation, of unknown space assets
- Responsive Communications
  - Single satellite or constellation launched to fill an immediate need
  - Altitude adjusted to balance coverage, power, and transmission duration

- Coordinated Missions
  - Launches can be timed to provide coordinated surveillance in conjunction with other space or ground assets
  - Example: coordinated attack on a target area with both visual observations and wind measurements prior to the attack, RF communications during the attack, and damage assessment afterward
- Search and Rescue
  - Very low cost RF system searching large areas for distress signals
  - Surveillance system can search very wide ocean areas
    - Use prograde orbit with inclination just above central search latitude
- Monitoring Natural Disasters
  - Volcanoes, floods, major storms, or fires
- Materials Processing in Space
  - Launch chemical or biological "processing labs" on demand and return products as soon as the processing is complete

Perhaps the largest Opportunity Value of responsiveness is the chance to truly change the way we do business in space. Prior to the first Responsive Space conference in April, 2003, one of the most compelling quotes was from Leonard David in Space News, "The U.S. Air Force has kick-started a major study on quick-to-launch boosters capable of enhancing the nation's warfighting abilities,... Given a Pentagon go-ahead and funding, the Air Force could first fly a multi-stage system by 2014." [David, 2003] It took 3 years less time to develop, build, test, and fly the Saturn V and use it to undertake mankind's first human trip to the Moon. Responsive space can help bring back a capability we have lost.

Finally, responsive, affordable access to space will impact traditional missions as well, fulfilling the adage "a rising tide raises all boats." Regularly scheduled space activities and traditional missions with long planning horizons will, nonetheless, benefit from lower cost, responsive launch. For example, back-up opportunities and low cost alternatives will become more common. More options will become available, to the benefit of most missions.

7. Conclusions

The estimate of the economic cost of responsive space systems is between 2% and 80% of the cost of launch, depending on the required level of responsiveness. Commercial responsiveness, i.e., launch-on-demand without a surge capability, has a very low cost, estimated at only 2% to 5% of the launch cost. A substantial surge capability requires that more vehicles be kept in inventory and more people be available to launch them with a corresponding cost increase. Depending on the surge capability required and the number of launches per year, the cost over the traditional, non-responsive baseline can increase by 5% to 80%. Generally, higher launch rates will result in lower added cost for responsiveness.

It is difficult to quantify the Opportunity Value of responsiveness, but it appears clear that the potential value far outweighs the cost. Responsiveness has substantial value for nearly all areas of space activity—military, commercial, education, scientific, and human spaceflight. For commercial activity, low-cost launch-on-demand enables ground-based sparing and ensures more nearly continuous service with minimal outages, which is key to making commercial space more competitive with non-space alternatives. For education, there is the hope of launching payloads while the students who built them are still students, i.e., real training rather than the traditional lesson in frustration and unfulfilled objectives. For scientific or civil activities, we can monitor natural disasters and real time events that we may, or may not, be able to observe today. For human flight, there is the potential to create a new element of safety by launching supplies or new equipment in response to emergencies.

For military missions, responsiveness and a corresponding surge capability enable new missions and provide a level of responsiveness to the warfighter that isn't currently possible. By enabling nearly immediate surveillance and global strike without putting lives at risk, overflying hostile territory, or moving large battle groups into harm's way, responsive missions can give us military and non-military options that can potentially prevent or shorten military conflicts and shorten the time from terrorist activity to consequences for those who orchestrated them. In summary, while it is hard to quantify directly, it is clear that the potential benefits of responsive missions dramatically outweigh their costs.

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