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The Lowest Cost Rocket Propulsion System

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Low cost rocket propulsion is a fundamental assumption in all low cost launch vehicle and low cost access to space concepts. The actual costs of launch vehicles and developing and deploying launch systems are confounding and the data is highly malleable. Numerous claims for low cost propulsion applications are continuously being made and a clear market driven winner has not been found. A logically rationale for understanding launch vehicle and propulsion systems costs is discussed to illustrate the factors that drive cost and how these factors can be analyzed for less conventional ways to achieve low cost. Candidate low cost propulsion system criteria are proposed and a logical cost argument is described to justify a low cost concept.

Nomenclature

AP = Ammonium Perchlorate
CPI = Consumer Price Index
CPIA = Chemical Propulsion Institute Agency
DARPA = Defense Advanced Research Project Agency
DESC = Defense Energy Support Center
DoL = Department of Labor
DTIC = Defense Technical Information Center
EPA = Environmental Protection Agency
EWR = Eastern Western Range
FAR = Federal Acquisition Regulations
Fee % = Profit or Fee (%)
FFP = Firm Fixed Price
G&A = General and Administrative
G&A % = General and Administrative Rate (%)
GFE = Government Furnished Equipment
GFP = Government Furnished Propellant
GSE = Ground Support Equipment
H2O2 = Hydrogen Peroxide
ICBM = Intercontinental Ballistic Missile
IRFNA = Inhibited Red Fuming Nitric Acid
LH2 = Liquid Hydrogen
LO2 = Liquid Oxygen
MDA = Missile Defense Agency
MON = Mixed Oxides of Nitrogen
MMH = Monomethylhydrazine
N2H4 = Hydrazine

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ODC = Other Direct Cost
OSHA = Occupational Safety and Health Agency
Overhead% = Overhead Rate (%)
PPI = Producer Price Index
RP-1 = Rocket Propellant 1
SEC = Securities and Exchange Commission
TVC = Thrust Vector Control
ULA = United Launch Alliance
US = United States
USA = United Space Alliance
USD = United States Dollars

I. Introduction

THE launch vehicle and rocket propulsion community continuously pursues the nebulous low cost launch vehicle[1]. Numerous attempts have been made and will continue to be made to create low cost launch capability. Various factors drive cost such as cost of materials, labor rates, non-recurring work, recurring cost, market capture, market size, system functionality and others. These factors are unclear and some are intimately bound together. A logical basis for describing launch vehicle and rocket propulsion cost is discussed with relevant data used to sanity check assumptions and claims. Based on a logical cost driven argument, factors that promote a low cost concept are developed and features of a conceptual low cost system can be assessed. A candidate low cost rocket propulsion system is described as an example of a low cost launch system.

Many design decisions for launch vehicle propulsion are made by engineers with little to no knowledge of how that decision affects the overall cost of the product. This creates an environment where staff is driven to make a low cost design but are not given the tools or knowledge to make correct decisions. The end results are poor design choices which are not low cost. An understanding of launch vehicle costs and prices will help the engineer intelligently choose true low cost solutions. All cost examples in this paper will be in US dollars.

Launch vehicle propulsion systems account for 40% to 60% of the launch system hardware costs and structures account for an additional approximately 25% to 50% of the cost[1]. Most launch vehicle structure is for propellant containment, so it is reasonably seen that rocket propulsion makes up by far the largest hardware cost on launch vehicles. Low cost launch vehicles are synonymous with low cost propulsion. Once solutions for low cost propulsion are found, low cost access to space will occur. In terms of total launch system costs, the launch vehicle hardware cost (which is primarily propulsion system and tank mass) accounts for 60% to 80% of the total vehicle costs with launch services accounting for 15% to 20% and government support and range costs accounting for the remainder[1]. Propulsion hardware, by far, leads as the primary cost driver for launch systems.

The definition of launch system costs and price is ambiguous and many claims for means and methods of low cost launch capability have been proposed, and some have been developed and implemented. The price of launch costs is still considered to be high and further efforts and interest are being pursued to try and lower access to space. The basic methods of pricing and cost estimating have confounding features which make the assessment and analysis of various claims hard to comprehend, nor is it clear from cost and price analysis what the lowest cost solution(s) should be. A discussion of the various features of launch system price and costs analysis is provided as a tool with which one can scrutinize various launch system concepts. Criteria are developed from this analysis to provide features of what a low cost launch system would be like. These criteria are sometimes in conflict, so the true low cost solutions will be an optimal solution in a multi-variable design space. Non obvious parameters such as pre-existing developed assets and both direct and indirect government subsidies increase the design space and it is likely that there will be multiple solutions as well as a scale dependency. A proposal for one small-scale solution is provided.

II. Rate Structures

The price of launch systems is complex and involves many parameters and features which make a rigorous study difficult, if not impossible. For example, different launch system suppliers may have different costs due to specific historical aspects of their respective businesses. This paper will provide some simple techniques and tools such that a rationale means and method can be applied to either an existing launch system or a proposed new launch system to ascertain if the cost and price are reasonable and to assist in the decision making process to permit a rationale development of true low cost launch systems.

The price of any commodity or service is composed of two basic elements: The cost of the product and/or service and the profit or fee.

$$\text{Price} = \text{Cost} + \text{Profit}$$

Businesses that operate at zero or negative profit for extended durations of time are either non-profit or not-for-profit entities. Examples of such organizations are amateur rocket societies, academic institutions and governments. The latter claim of government organizations seems like a paradox since virtually all launch systems incur some degree of government involvement or subsidy and in fact this is a probable contributor to the non-clarity of launch system costs.

Profit or fee is generally dictated by the negotiation of the market place and in general, a company tries to maximize profit while maintaining competitive strength. Profits can be used for various purposes such as reinvestment into the company via capitalization, research and development, stock buy back, employee compensation etc... Very high profits are not necessarily good as they indicate that the company may not be making enough investment to remain competitive for the future. Very low profits indicate a failing business. The business then tries to find the safest stable zone of optimized profit. Commercial businesses have profits that range from less than 5% to perhaps as high as 10%. Some extraordinary businesses may have much larger profits; however most businesses that have a large enough and competitive market place will tend to converge towards a common profit zone. The United States (US) aerospace and defense industry makes most of its sales to the US government which tries to constrain the profit to negotiated limits. In addition, US government procurement law, Federal Acquisition Regulations (FAR), limits profit for most procurement to no more than 26% and in practice most government contracts offer profit less than 15% and more likely less than 10%. This paper will assume a typical government profit or fee of 7% as a reasonably high fee or profit.

$$\text{Fee } \% = 7\%$$

In addition, with government procurement, based on the contract style, a portion of the fee may be consumed to account for errors. For example, if the procurement is Firm Fixed Price (FFP), cost overruns will be covered by loss in fee or profit to the seller. For a Cost Plus Fixed Fee (CPFF) contract, cost overruns may be paid for by the customer, but the overall profitability of the company suffers. And for all contract types, cost elements that are disallowed after the execution of the contract become fee losses. So there are various forces which can erode profit in government procurement which are sometimes not well controlled.

A potential means to control profit is to engage in competitive Firm Fixed Price contracts. In both government and commercial practices this permits a seller to negotiate and compete in the market place for the market price of a commodity or service. Once a buyer and seller agree upon a price, the seller has the latitude to manipulate their costs to increase profit. This is the most attractive option for profit potential but also has the greatest risk of severe loss thru the competitive determination of the price. It is possible for companies to “buy-in” to contracts to establish market control and force competitors to incur losses by matching their low prices. This creates a war of business attrition to see which entity can provide the same goods or services at the lowest prices for the longest time and survive. Some of the US procurement laws are structured to prevent this from happening. Examples of this are frequently seen in commercial price wars between groceries, airlines, retail gasoline and many others.

III. Cost Elements

Costs are generally grouped into various categories and these can vary widely from organization to organization. A simple cost model description is provided to help organize the arguments for understanding cost.

Costs can be largely grouped in the categories: Labor Cost, Overhead, Direct Material Cost, and General and Administrative (G&A) Costs. Labor costs are all of the cost that is directly paid as wages to staff that are working directly on the creation of the product or service. These are unsurprising called direct employees. Overhead includes all costs required to create the product or service less the purchased Materials costs. Overhead includes such cost elements as factory floor space lease costs or amortized real estate cost, equipment costs (amortized capital expenses, lease costs, or one-time incurred expenses), manufacturing consumables such as machining lubricants, consumable tools, in-process use of chemicals and many others. Direct Materials include all materials which are purchased which are made part of the delivered product such as raw materials; like metals, plastics, chemicals; components such as electronics, purchased piece parts, purchased assemblies (valves, actuators, nozzles, tanks, etc…), and others. General and Administrative (G&A) costs are all costs required to operate the business which are NOT directly related to the product or service, such as management compensation, administrative salaries or wages, accounting expenses, legal expenses, debt interest payments, material procurement, shipping and receiving, office operational costs for administrative and management functions and other costs. In a like manner to direct costs, the staff which is paid under G&A is called indirect labor.

Sometimes one also groups some costs as Fringe Costs which are typically expenses for staff that include vacations, sick and personal paid compensation, health benefits, and other benefits which are related to staff. Fringe Costs will of course apply to both direct and indirect staff and will differ, sometimes significantly in the type and amount of the fringe benefit. In this paper we will assume that the fringe costs are included appropriately in the overhead and G&A costs. In addition, some other costs are also grouped as a category termed Other Direct Costs (ODC). This analysis will also assume that the ODC is already included in one of the previously discussed groups of cost.

The cost of a product is created by the addition of these various cost elements. Some of these cost elements do not lend themselves to being simply allocated to a specific product. For example, if the company produces various products or is in engaged in various types of work such as product development as well as production, then some of the cost elements such as G&A and Overhead will not be easy to directly assign to a specific project or to a specific product. Some cost elements like direct materials that are used on a specific product or direct labor consumed on a specific product could be tracked and identified to that product and thus the true cost of the direct materials and labor may be assignable to a specific product.

The common method is to analyze the company's financial data to create a Rate Structure. This Rate Structure creates basic building blocks of Direct Labor, Overhead, G&A, and Fee which can then be used to create costs and prices. There are many variations on how this is done and the US government has particular guidelines on how this data can be organization and analyzed. This paper does not attempt to explain the details of how to develop or create rates, but provides a simple example which can be used as a tool for assessing costs for design evaluation purposes.

A simple rate structure includes:

Direct Labor Hourly Rate.

Overhead Rate (Overhead %) assumed to be a percent of the Direct Labor Cost.

G&A Rate (G&A %) assumed to be a percent of the Direct Labor Cost, Overhead, and Direct Material Cost.

Profit or Fee (Profit %) which is a percent of the total cost.

Before showing how these rates are used to create a price, a more detailed discussion of each item will be provided.

The Overhead and G&A costs are typically assigned as a percent of the Direct Labor and/or Material Cost. Which implies that the supporting cost of making the product (Overhead) and the costs of operating the business (G&A) are directly proportional to the direct costs of the product. In general this is a fairly true statement. It will always take some equipment and some sort of a facility to make a product and it will always take some staff and resources to make a business operate. A larger business requires larger buildings and larger management staff and has a corresponding larger total cost for Overhead and G&A; however the percent of the Overhead and G&A, within some reasonable bound, may be fairly stable. This is especially true for companies that are large, have stable sales, and have significant product lines which are large in comparison to new product development. Rate structures are more volatile and fluctuate more significantly for smaller companies or companies in volatile markets or entrepreneurial companies making large investments in product development. Extremely small businesses encounter another problem in that many of the Overhead and G&A resources have minimum sizes. For example management members are integers, when one needs a new upper executive manager this can incur a G&A cost increase that is significant in comparison to the G&A base costs. Accounting costs or public companies requirement to comply with SEC regulations are likewise not scale dependent and may be significant costs in comparison to the existing G&A baseline. Acquisition of new property, new equipment, or other additional resources can have a likewise effect on Overhead. As a small business grows into a larger businesses, various laws such as labor laws, Occupational Safety and Health Administration (OSHA), Environmental Protection Agency (EPA), and others require more and more new functions which generally incur higher Overhead and G&A costs. In another way, as a business ages, the staff and corporate culture may change generally in the direction of increasing employee benefits and the acquisition of property and capital. Depending on the management of the company, Overhead and G&A may creep upwards overtime and in the event of a market down turn a company may find itself with much unused capital and high labor and related costs. These costs are reduced reluctantly so a company may operate for significant periods of time under a non-optimal rate structure. This problem tends to penalize a larger company more severely than a smaller company. Smaller companies tend to have more volatile rate structures but greater control over changing the basis of the rate structure.

Rate structures are also scale dependent. Larger companies have economies of scale. For example a management team may be able to manage a company with large increases in sales by hiring more sales personnel and acquiring more manufacturing resources without significantly increasing management. G&A rates for larger companies tend to be smaller than the G&A rates for smaller companies. Larger companies are also better able to more fully utilize capital equipment and it is possible for a larger company to have lower Overhead than a smaller company. In practice this is not always true since smaller companies will elect to out-source specialized work to companies that already have amortized resources. In the US aerospace business this behavior is also becoming more common with larger companies; however many of the larger companies already have significant capital investments.

Rate structure ranges for G&A tend to vary from roughly 15% to 25% and are highly dependent on the style and size of the business. Overhead rates can vary from 50% to 200%. For this paper we will assume a nominal G&A rate of 20% and an Overhead rate of 100%. These are summarized in Figure 1.

The cost of a product can be created using this rate structure by this algorithm:

Known: Direct Labor Hours, Direct Hourly Labor Rate, Direct Material Cost, Overhead Rate, G&A Rate, Profit

Labor Cost = Direct Labor Hours X Direct Labor Rate

Overhead Cost = Overhead % X Labor Cost

G&A Cost = (Labor Cost + Overhead Cost + Direct Material Cost) X G&A %

Total Cost = Labor Cost + Overhead Cost + Direct Material Cost + G&A Cost

Profit = Profit % X Total Cost

Price = Profit + Total Cost

Using our assumed rate structure, we can do a simple example of what a product made with 1 hour of labor at a base labor rate of $15/hour with $1.00 of direct materials. Our example rate structure is 100% Overhead, 20% G&A and 7% profit.

Labor Cost = $15.00 = 1.0 hours Direct Labor X $15/hr Direct Labor Rate

Overhead Cost = $15.00 = 100% Overhead Rate X $15 Labor Cost

G&A Cost = $6.20 = ($15.00 Labor Cost + $15.00 Overhead Cost + $1.00 Direct Material) X 20% G&A %

Total Cost = $37.20 = $15.00 Labor Cost + $15.00 Overhead Cost + $1.00 Direct Material + $6.20 G&A Cost

Profit = $2.60 = $37.20 Total Cost X 7% Profit %

Price = $39.80 = $37.20 Total Cost + $2.60 Profit

So our fictitious product using 1 hour of labor and $1.00 in materials has a price of $39.80. One can now quickly see what parameters one could try to manipulate in order to control or lower the price: Profit, Labor Cost, Materials, Overhead, and G&A. In this example, if one assumed that the company was matured, then the ability to significantly change the Overhead and G&A would be limited. The material cost is very small in comparison to the

Price. Likewise lowering the profit has little to no effect, leaving the Direct Labor as the most attractive target, and in many US companies improvements in staff efficiency are vigorously pursued.

Figure 2 shows the parametric effect of a fictitious product price as the labor rate and direct material cost vary. One sees from this graph that if the labor rate is high and material cost low then using the rate structure in Figure 1, the product prices all tend to converge. As the material cost increases the product price is driven by labor when the labor cost is noticeably greater than the material cost. One can conclude from this that 1) Labor costs drive prices when material costs are LOW; 2) High price labor has little impact on the price of the product when using very high cost materials; and 3) the best value with low priced labor is to use low cost materials. The product price is driven by labor when the material cost is much less than the labor cost. When labor costs are high in comparison to materials costs, **then the labor that is used to increase the value of the material, or the value added to the material, drives the cost**.

IV. Cost and Price Modeling

There are many forms of cost modeling and in general companies rightly so jealously guard the secrets of their cost models as they contain historical data, rate data, and other information which can used by competitors to gain advantages. Protection of corporate cost data often prevents engineering staff from having access to the information needed in order to formulate correct decisions. This paper attempts to offer some general data and approaches which engineers can use to assist in making more effective cost design decisions in the absence of actual cost and rate data. This paper does not provide a rigorous treatment of cost models but provides a simple framework which can be used to assess cost, cost bases and provide guidance on making design choices that will incur cost effects. In general most entities model cost in one of two ways: Parametric Modeling or Grass Roots Cost Estimates. Both have advantages and disadvantages.

Parametric cost modeling normally takes the historical experience of the company and attempts to find parameters that are similar and scaleable between products or projects such that prior expertise, experience, and cost history can be used to predict what future costs will be. The advantages of a parametric model is that they can account for cost elements that are difficult or impossible to define. It accounts for the cultural behavior of a company (if a company takes a certain amount of labor to set-up a machine, release a drawing, conduct a test, etc.. then it is likely to do the same in the future), it is traceable to prior historical data, and it provides a deterministic price and it is fast and easy to implement once the parametric model is developed. The parametric price can also be manipulated to account for different wage base rates, changes in Overhead and G&A rate structures, changes in profit, and various inflation factors for labor, material, and other cost elements. As such, parametric modeling is quite attractive and commonly used. A simple parametric model is used when any company makes many parts of the same part number. Historical data is collected and over time one can track and analyses the true costs of a product and then improve functions and resources to drive cost downward. This is a common practice in commercial companies. Parametric models are disadvantages if the product is significantly different from the prior data or if the data is so old that the company may not behave as it did in the past. Changes in company staff, resources, intellectual property, and capital equipment can all alter a parametric cost. Parametric modeling is very good for similar products with relatively young historical data. Parametric modeling also will not provide a radical change in pricing because by definition it is an extrapolation of past pricing. If a company wants to radically change the cost of a product, then a parametric model will not be helpful, even if it is truthful. This is a key point. If a company wishes to make a radical departure in pricing and it has a parametric model that predicts it to be otherwise, that indicates that some factor imbedded in the model is either wrong (which is unlikely) or that some factor about the company or product must change (more likely). In general companies are not prone to radical changes in behavior or products because this incurs risk. Large companies, especially public traded companies are less likely to incur radical risk that smaller or newer companies that are entering the market place.

Grass Roots cost estimating is the rigorous practice of trying to identify all of the cost elements in a product or project and then developing the cost from an essentially clean sheet of paper. This is a very laborious and tedious process and more difficult to implement the larger and more complex the product becomes. Smaller projects, such as commercial practices of building, repair, and simple commercial products can be estimated reliably using this method, especially if the company has prior experience in estimating similar products. The benefit of a Grass Roots model is that for a new company without any prior experience, it is the only means to estimate cost. It allows a more accurate description of a new project or product, however there is an inherent and common fallacy which generally renders the costs from this method inaccurate and under estimated.

V. The Fallacies of Grass Roots Pricing

The fallacy arises because one generally engages in a Grass Roots cost estimate for one of two reasons: Reason 1) A company with a parametric cost model does not want to use the parametric price because it is too high and they believe they will be unable to compete at the higher price. Therefore, a Grass Roots cost is used to justify the business decision to enter into a business area which is not viable with parametric pricing. This has a hidden assumption that somehow the company will change its behavior to become able to operate like the Grass Roots cost model. Often this is untrue and costs overrun. Reason 2) A company without historical price data wants to enter into a market place and knows what the current market price point is. They develop a Grass Roots cost model that permits the price to be competitive. There is a psychological bias towards creating a cost model that does not exceed the market price point because that signals that the business is a failure. This fallacy is manifested in Grass Roots models that are too simple and thereby forget to include cost elements which are necessary and later come into the project and are then considered overruns. Often under these circumstances these cost models may be developed by a hand full of people with limited knowledge of the overall complexity of the project and the costs for the elements outside of one expertise are simple not included. To an outside observer this is also hard to assess because very few people have the expertise to fully assess a Grass Roots cost model for a product as complex as launch vehicle services. A comparative analysis with a parametric model may have value, but more than likely a parametric model will predict a higher price and it will be hard or difficult to reconcile the differences between the two prices.

The authors experience with Grass Roots pricing and modeling suggests that most organizations price following a common approach. The product or project is broken into elemental cost components such as a list of parts and materials, and/or a list of tasks. These components are broken down into some level such that one could conceivably estimate the individual cost element value by looking up prices in a catalog, requesting quotations from suppliers, estimating labor costs for tasks, and estimating costs of various equipment, resources, and facilities.

As previously mentioned, this form of pricing is generally terminated prematurely because it is driven by the psychological desire to keep the cost below the known market price point. This tends to create costs which are too low for several reasons.

The market price point may be low already and not readily or even feasible to under cut. Especially in the launch vehicle business, some of the major cost elements may be subsidized by the government or development costs may have been funded by the government and are not seen as an amortized cost. The product may be derived from prior products which are already fully amortized. Many incumbent US launch system companies were created by the government in the 1940's and 1950's using very aggressive procurement practices and were essentially created thru large amounts of cost type contracts. These companies have a significant advantage in size, capital, technical expertise, technology, and resources, most of which were funded through government contracts. Even new low cost launch system companies are commonly staffed by personnel whom were trained by working for a larger company under one of these larger government funded programs. So while one may actually provide a true lower total recurring cost product, the market price point may low due to these various factors. A common feature of this is the use of government facilities, government equipment, and government employees. The cost of these items may be either at no cost to the company or they may be at a reduced cost. A company may conduct business in a government facility which will lower overhead. A launch vehicle may operate out of a government range where the land is provided at lower than commercial costs for a similar resource. Launch systems may use government furnished equipment (GFE) which could be very expensive to capitalize commercially. Most if not all of the current low cost commercial launch systems are also using government funded resources in some form, although it may not always be obvious to either the launch vehicle company or an outside observer. For example Space Ship One is being developed on a public airport which is well suited for this type of research. The airport was originally built as a military air base and the capital cost of the airport was funded by the government thereby creating a valuable resource which has assisted numerous companies, including the author's company, to provide quality products and services at a cost lower than what would be possible without the government's development of that resource. The true cost of any company's product becomes less clear and the price can be quite specific to what government resources are best utilized by the company. Other examples of such indirect subsidy of low cost launch systems include the use of the McGregor test facility by Beal Aerospace and SpaceX, the use of the Stennis Space Center by Lockheed-Martin for commercial hybrid motor development, the use of Edward's Air Force Base by AMROC for commercial hybrid motor development, and numerous others. This is not an indictment of this practice, and in fact the author encourages all governments to provide resources like these to help low cost launch systems become more viable. However these costs are non-trivial and depending on what launch platform a company chooses to pursue, the use of government subsidized resources can be pivotal.

Grass Roots cost estimates also fail in addition to being both incomplete and psychological truncated, because often the justifying costs bases are weak. Assuming that one had done a fairly accurate job of defining all of the cost components such as all of the parts, raw material, and labor elements, one then needs to assign an accurate value to each of these items. The task of acquiring all of this cost data may be comparable or greater to the task of creating the list initially. This requires finding suppliers and preferably more than one supplier for each component, specifying the needed part, getting quotations and then analyzing the quotation. This task often fails because of lack of effort whereby cost elements are justified not by a rigorous approach but by the euphemism of "engineering estimate", which is a guess and often by the wrong person (an engineer) who unlike a professional buyer is not necessarily the one that knows what items cost. Vendors also affect the price by failing to fully quote the true cost. When given a poorly or incomplete request for quotation, a supplier will provide the lowest price that meets what is requested, and often that this is NOT what is needed. Market driven economics creates this behavior which almost assures later overruns. Many cost elements such as shipping costs, modification costs, accelerated schedule needs, additional customer support, and specific test requirements arise later on after they are more fully defined.

Grass Roots costs also evolve with time. This will occur no matter what as the project proceeds because the undefined or ill defined cost estimates will become true costs when they are finally realized. For example, a Grass Roots cost estimate for a rocket would start as one item, a rocket, and one could assign a value to this part, say $60M. Subsequent evolutions of this cost model would break the rocket into stages, then parts of stages like tanks, nozzles, separation systems, avionics, power, Thrust Vector Control (TVC), telemetry, etc… The next generation of cost estimates would further sub-divide the system into valves, electronic boxes, major component assemblies, tank shell elements, rocket engine components, and others. Finally at a detailed design level ready to build a system one would have minimum level procurement items as called out on a released engineering drawing parts lists like fasteners, spools of wire, electrical connectors, specialty out-sourced services (welding, consulting, etc…), fabricated piece parts, billets of raw material, containers of chemicals, and countless others. The overall complexity of the cost model grows very quickly with each iteration and eventually terminates prior to completion of the full price list due to some constraining event like the market price bias, time, funds, etc… If the price model is allowed to mature and one tracks the overall price, one generally sees that the price rises quite dramatically at first and if the cost model is allowed to proceed without being terminated, the price will peak and then stabilize and either decrease and/or begin to slowly creep towards what is the true price.

Another common failure in Grass Roots cost modeling is to assume that the costs that are necessary are not necessary. These tend to be items like Ground Support Equipment (GSE) ("It's not part of the rocket right?"), design rigor ("We are doing it differently and we don't need to do all of the analysis."), redundancy, and the involvement of the customer. GSE can be quite significant and complex and can be more complex and sophisticated than the launch vehicle itself. In fact, that should be the case, since it should be easier to force a function onto GSE rather than place it on the vehicle and have to carry mass, cost, and complexity on the launch vehicle. So GSE tends to become complicated because one tries to make the launch vehicle simple by making the GSE complex. GSE is also a cost element that can be heavily influenced by the availability of GFE.

Launch vehicles that fly within the control of the US need to conform to the basics of the range safety document EWR 127-1. This document provides much guidance and has been established based on the vast history of the launching process by the US. Numerous requirements are defined by the range and require some minimal level of engineering and design in order to make a reasonably safe vehicle. These requirements are often ignored as being either obvious or superfluous and the implications are later considered as cost increases. Since EWR 127-1 has and does change with time, prior experience and prior launch platforms are NOT necessarily accurate examples of what can be expected today. For example the Atlas MA-5A and Delta RS-27 rocket engines were designed and developed while EWR 127-1 was also being developed. These engines would be developed differently today if they started with the more mature form of EWR 127-1.

Redundancy is often ignored since this has a multiplying effect on cost and mass. A common behavior is to state that all systems are at the lowest level of redundancy until some requirement (often not known at the early stages of a project) forces the redundancy to be used. This creates a bias towards system with artificially low redundancy at the initial Grass Roots pricing phase.

Launch vehicle customers often have payloads which are very important to them for either financial or application needs. The customer may have specific needs for analyses, payloads environments, payload processing, orbit insertion needs which require more specialized attention. What costs are considered to be a reasonable cost and customer's needs costs that are additional is less clear.

VI. Propellant Cost Fallacy

A common argument used in launch vehicle costs is that the cost of the propellant has some, generally implied important, effect on price. This is routinely seen with claims that a low cost launch system uses low cost propellants. This is patently false and misleading. This is caused by two factors: 1) Engineers are defining cost drivers and engineers know what they know which is how to estimate the mass of objects much better than the cost. This is an artifact that the propellant mass by virtue of the rocket equation is probably the one analytic number that engineers known the best. The propellant mass has a better accuracy than even the inert mass since the inert mass requires a detailed design in order to converge. Note that many parametric cost models use the inert mass as a basis for cost. The propellant mass is also proportionally large, so psychologically it appears that one has solved much of the cost problem once one has identified the major mass element and assigned a cost to it. Propellant is also easy to price as established prices exist for many rocket propellants in various quantities and some of these prices are known for both government procurement prices and commercial equivalent prices. Also during development operations, significant amounts of propellant are consumed and handled making it the big object both physically and to a lesser extent financially on system non-recurring cost. And lastly, many launch systems use relatively cheap chemicals such as liquid oxygen (LO2) and kerosene (RP-1). These chemicals have a large commercial market base which permits the suppliers to have large capacity (economies of scale) production facilities and commercial markets which help provide the lowest possible prices. This IS a highly desirable feature for a low cost launch system however for the current market price points for launch services; the propellant cost is inconsequential especially for the lower cost chemicals. The argument goes that one of, if not the most attractive, feature of a low cost launch system is the very low cost of the propellants. The implied argument is that higher cost propellants will incur HIGHER launch costs. In fact most propellant costs are so small that even a significant increase in the cost of the propellant will not unduly change the launch price. Note that the argument that a low cost propellant is important would imply that rising energy costs would increase launch costs and low cost launchers that use low cost propellant would inflate in price with energy costs. That does not and will not happen because the energy cost of the propellant is trivial in comparison to the true cost of a launch vehicle.

A simple means to illustrate this effect is to look at a hypothetical case of the Delta II launch vehicle. The Delta II launch system use low cost propellants (LO2 and RP-1) and has a long history of usage. The Delta II is a derived vehicle from the Thor Intermediate Range Ballistic Missile and the company has had a long history of the product evolution and development. It is reasonable to assume that the Delta II price is representative of the recurring cost of the system and that the pricing and costs are very mature and stabilized. For our example we will assume the price of the Delta II with four (4) GEM 40 solid rocket motors is \$60M[2]. The true price may vary and could be less since Delta II can be configured for more solid motors and the \$60M price point is the expected top end of the Delta II pricing.

The price of propellant varies whether the propellant is provided by the government, Government Furnished Propellant (GFP), or if the propellant is procured commercially. Figure 3 shows some historical pricing for various propellants from the Defense Energy Support Center (DESC)[3,4,5,6,7].These prices are for fully delivered propellant at point of use, which includes many costs such as shipping, special safety requirements during shipping, boil-off during shipment, and some handling equipment costs such as shipping containers. Commercial pricing often does not include these costs since these are specific negotiated terms and could vary substantially from user to user. Regardless, these prices are commonly available and will serve as example of what propellant prices can and could be. Propellant prices which are substantially cheaper than Figure 3 will not change the conclusion of this argument but actually make it stronger. One sees from Figure 3 that propellant prices are generally flat and vary based on the chemistry. LO2 and RP-1 are much cheaper than other propellants and storables are more expensive than other propellants. Note that the pricing can fluctuate substantially due to the non-profit nature of DESC which passes on cost savings or overruns to consumers in future pricing. This can create an aberrant price such as the temporary very low cost of hydrazine. Note that the nominal propellant cost for LO2 is \$0.38/lbm and RP-1 is \$0.41/lbm. Figure 4 shows the propellant masses for each of the three stages and four boosters[2]. The stage 1 propellant load is 146,499 lbm of liquid oxygen and 65,401 lbm of liquid kerosene[2]. The total stage 1 propellant cost for this launch system is \$84,917 or 0.14% of the launch price. One sees that the propellant cost would need to increase by a factor of 70 times in order to change the launch price by 10%. Similar arguments can be made for other launch systems.

We can also analyze this further for the case of the Delta II. As seen earlier with the analysis of the first stage propellant cost effect, we can ask the question, what the propellant cost would be if the propellant accounted for some percent of the launch system price. Figure 4 shows us that the Delta II could have a propellant mass of 333,281 lbm. Figure 5 calculates how much the propellant cost would be per pound if the propellant cost accounted for some percent of the launch system price. One sees that if the propellant accounted for 10% of the launch system price, then the propellant would cost \$18.00/bm. Another way to look at this is to ask what would happen if the price of the Delta II propellants increased to \$18.00/lbm and the answer would be a slight increase in price.

Alternately we can consider a radical new launch system which has the same capability as the Delta II but has a launch price 10 times lower or \$6M per launch. The same analysis for the propellant cost per lbm is shown in Figure 6 and now the propellant cost has dropped. It is reasonable that as the cost of a launch vehicle drops that the relative fraction of the propellant to the launch system price should increase. Commercial airline propellant costs range from 20-25% of their operating costs[8] and it could be reasonable to assume that our radical new launch system may have similar cost allocations. In this case if the propellant is 25% of the launch costs then the propellant can still cost \$4.50/lbm. In both cases for a current market price point for a Delta II and for a futuristic very low cost Delta II like vehicle, the effect of the propellant price is slight. Almost all propellants are viable choices for launch systems in terms of the chemical cost. A key question to be made is if there is some feature of the chemical that drives another cost element that DOES increase the cost. If that is the case then the feature of the propellant that drives the other cost element is more important that the chemical cost of the propellant. Or, a higher cost propellant could provide lower launch costs because it controls other cost elements which are more important.

An example of how this could happen is to compare cryogenics (LO2, LH2, and others) with storable propellants (NTO, MMH, RP-1, H2O2, IRFNA, Solid propellants, and others). Storable propellants can be loaded far in advance of a launch window. This removes the propellant handling operations from other time constrained launch operations and reduces the need for more complex flight and GSE to accommodate the unique operational needs of cryogenics. In some sense storable propellants are cheaper than cryogenics for some cost elements of operation. For example, cryogenic requirements like anti-geyser systems, insulation, anti-icing, some purging, hydrogen safety, propellant conditioning, boil-off, hydrogen flaring, and others are essentially eliminated, creating a wholesale elimination of some cost elements. The storable propellant could also introduce some cost elements not seen with cryogenics such as disposal, toxic vapors, and special handling equipment. The propellant chemistry can thereby affect the system price in many other ways other than its own cost and these other less clear relationships may actually incur far greater cost impacts. Solid rocket propellant is by far an extreme example of this. The propellant is in such a state that many operations and components that exist with liquid propellants are completely eliminated. This is done at the expense of having a fully loaded and powerful charge of propellant always in the system.

Other launch platforms may use different chemicals such as Monomethylhydrazine (MMH), Mixed Oxides of Nitrogen (MON), liquid hydrogen (LH2), ammonium percholrate (AP), hydrazine (N2H4) and others. The costs for these propellants are significantly higher than LO2 and RP-1 due to their specialized usage in the rocket propulsion industries and there are limited, and some cases, only one supplier and limited users for these chemicals. The costs for these propellants should have a more profound impact on the launch system cost however even with much more expensive chemistry the launch system cost as previously shown may not be driven by the cost of the propellant. This begs the question that if not propellant, what really drives launch system cost and does the choice of the propellant actually incur any cost savings? Our intuition says that it should but the market price point and the actuals costs of the chemicals tell us otherwise. We know for example that in other propellant uses, such as automotive travel, trucking, boat shipping, and air transportation, that the propellant cost is important, why should this not be the same for rockets? What cost element drives the high cost of rocket propulsion?

VII. Prior Claims for How to Achieve Low Cost

Many prior claims and current claims for a low cost launch capability have been made[1,9]. It is likely that this will continue to be the case for the foreseeable future as the industry continues to mature. In a market driven economy normally industries tend to converge over time towards the most cost optimal solution. For example the very large worldwide hydrogen peroxide industry started roughly 100 years ago using a batch process using one form of chemistry. This evolved over time into several different inorganic, organic, and electrochemical processes and has now converged on a specific organic process. This evolution of the manufacturing process was extensive and significant investments were made and in many cases abandoned in favor of the more optimal approaches. Companies were started, failed, and were absorbed by competitors. Similar events occur in all industries and the launch vehicle industry is still in the early stages where the preferred embodiment of the optimal solution may not have been realized. A very important feature of the launch industry is that the more common architectures and technologies are all derived from ballistic missile weapon technologies. Weapons are generally not designed and built to be cost effective versus being technically viable. It is much more important that a weapon work than what it costs. A low cost non-functional or slightly unreliable weapon is not worth having. As such all of our launch systems have a heritage which is uniformly and inherently technically optimized but not necessarily cost optimal.

A. Low Cost Reason #1 – We Are Different.

This is a very attractive concept and the general claim is that since the status quo is de facto expensive, then anything that is different has the potential of being better and thereby lowers cost. This assumes that the status quo is in fact expensive, which may not be true. This also assumes that the difference provides some fundamental means to provide a significant benefit that will incur a lower cost. A reasonable analysis of this claim is what are those differences and how do those differences create a lowering of cost. For example is the Direct Labor Rate, Overhead, G&E or Fee lower? Is there some cultural feature that reduces one or more cost elements? Is it made in a lower business cost location? Is there some resource like automation which could incur lower cost? If the staff is somehow different, are they different enough to make a significant change in cost? Are they ten time faster? Ten times smarter? This argument is attractive because it fits the prior condition that in order to make a radical departure from the existing market price point, one needs a different approach.

B. Low Cost Reason #2 – We Use Low Cost Components.

This is a more conservative idea where one decides to build a launch system using materials which are lower in price. This normally accepts some loss in performance in that the parts may be of lower quality, heavier, or require more redundancy. This is a common evolutionary process which is adopted by many industries. This has a natural limit whereby when the parts get so cheap they fail to function and the launch system becomes dysfunctional.

C. Low Cost Reason #3 – Our System is Simple.

This argument's merits are based on the concept that complexity drives cost either in total system piece parts or the processing of these piece parts[10,11,12]. Various ideas like stacks of solid rockets, single stage to orbit, reduction in the number of stages, non-toxic propellants, reduction in fluids, big dumb booster, hybrid rockets and numerous others all try to make the systems simpler and safer thereby reducing the amount time and the part count necessary to build and operate the system. This argument merits some inspection because if two systems are of the same size and mass, then the one with the lesser parts and simpler design SHOULD be the cheaper of both designs, to develop, build, and operate. If one eliminates a hydraulic system, then by definition the need for all of the cost elements associated with that system are gone. More over, the hazard of failing to price the system is also gone since one cannot overrun a cost for something that does not exist.

D. Low Cost Reason #4 – Our System Does Not Use the Expensive Part.

This argument makes a claim that there is some aspect of the status quo that is inherently expensive and that by using a new approach that eliminates this expensive item or items, that a new paradigm is created that enables low cost. Examples of this are hybrid rockets (AMROC and Virgin) to replace liquid bi-propellant or solid rocket motors and the Roton vehicle which eliminated turbo-pumps. Microcosm's low cost engine, nozzle, and tanks and various other low cost platforms. All small companies claim that they inherently have a very small staff that replaces the very large standing army.

E. Low Cost Reason #5 – Our System is Reusable.

Reusability is a natural choice and our best example of this concept is the US Space Shuttle, which is generally considered to not be very low cost, although it certainly was conceived as such initially and was a different approach to radically change the cost of access to space. Reusable systems work well for systems that don't require a lot of maintenance, which is one area that Shuttle has failed in comparison with a commercial airplane. Shuttle's failure as a low cost launch system is immensely valuable. The Shuttle program has created enormous amounts of technology and defined the limitation of what technology can do with reusability. Many lessons are available from Shuttle on how to create a reusable launch system and Shuttle helps support the important infrastructure of people, expertise, companies, suppliers, facilities and resources that the current commercial low cost launch providers take advantage of. Much of our corporate technical knowledge, expertise, and skills come from the government supported training of engineers and technicians when working on these platforms. If one could develop a reusable launch system that had the same operational needs as a commercial airplane, then one could envision a very low cost launcher. That solution does not appear to have been found yet. There are many features of a reusable rocket which differ from an airplane such as much different mass fractions, less industry experience with rocket building than airplanes, much more exotic environment for a launcher, less experience in mass production of rockets, and much tighter design criteria for orbital vehicles than for aircraft.

VIII. Consideration of Global Prices

The foregoing arguments are more difficult to make when comparing launch system between different countries. Since launch capability has a strong national character, it is hard, if not impossible, to segregate government influence over the price of launch systems. Launch system technology is useful for developing global reach of weapons and provides countries with many advantages. National pride helps governments continue to fund launch capacity even when the need for such services are financially unnecessary. The world currently has numerous rockets and launch systems many of which are being funded either directly or indirectly thru government support. Moreover the laws and relative costs to conduct such work will also vary from country to country, leading to further confounding in launch system costs. The world governments are somewhat in a free market competition with each other; however each government skews that market price point by subsidizing its indigenous industry and requiring the use of its launchers for critical spacecraft. The consideration of non-US pricing is too confusing to be of value to this argument, however the general theme of this paper should hold for other countries which have market based economies. Figure 7 shows the general mapping of launch system costs for various sized payloads[2]. One sees that the variation in price is significant with roughly one order of magnitude spread in pricing for equivalent payload sizes. This is highly inequitable and does not reflect a true free market economy of pricing for launch systems. Figure 8 shows the same data but only for US launch systems[2]. This helps normalize the data and permits this information to be more consistent with the other mostly US data in this paper. Note the examples of potentially new low cost launch systems on Figure 8 of the yet unflown Kistler K-1 and the in-development DARPA Falcon system.

IX. Commercial Price Guidelines

Commercial industries are rife with examples of quality functional products of various complexities that are at various prices. These products often confuse and distort our impression of what things should and actually do cost. Low cost consumer products are commonly being made in markets with very low cost labor and associated business expenses. We see our consumer products regularly (clothing, electronics, home goods, etc…) and these products have prices with which we are familiar and comfortable, however many of these are made but people and companies very different from what is experienced in more developed countries. These create a false sense and understanding of what the cost BASIS is for a product. It may take an American and a Chinese worker the same amount of time to assemble a desk top stapler, so the labor hour cost basis is the same, but the rate structure is radically different. In launch systems we often cannot out-source the manufacturing labor to a labor pool of very low cost for various reasons: incorrect skill level, legal constraints, quality control risk, impractical for container business practices, etc…

Commercial products are also often made in relatively large quantities such as much greater than hundreds of parts per year and are made by companies that have evolved the production of such parts over time. So these companies have spent a large amount of human thinking in how to lay out plants, make tooling, and design parts. An excellent example is any car. Almost all cars are made by companies that have been making cars for a long time. They have capital equipment which is well amortized. They have staff that has been making variants of the same basic car for years. Car models evolve slowly. Rarely does an auto maker come up with something completely new. The tooling and automation of the assembly process is complex and was created thru many generations of learning. These are well made products. A typical car could cost approximately $15,000 which is quite cheap for the complexity of the product. If the average fully burdened labor rate for an automotive assembler is $75/hr., then even if all of the parts are free the car is fully assembled in 200 man-hours of labor which is roughly 1 person in one month. A feat which is quite remarkable. In reality the car components do have value and in fact quite a bit. The cars components will cost 50% to 90% of the final cost. If the car is 50% material it is being built in 100 man-hours and if the car price is 90% material then it is being built in 20 hours. In the aerospace industry one can conduct a simple business meeting or present a technical paper that incurs more labor than that used to build the car you drove to work in. Our valuation of things, like cars, that we perceive as having noticeable value, are in fact aberrant in comparison to the means that the launch vehicle business operates and are misleading if used as guides.

Commercial products do provide some ideas as to how costs for products should be allocated. G&A expenses for commercial businesses should be comparable. It is reasonable that overhead expenses may also be comparable. Many simple commercial products use a rule of thumb that the direct labor cost should be approximately 10% of the cost and the remainder of the cost is direct material, G&A, Overhead, and Profit. Another benchmark value is that the gross margin of the cost before G&A and profit should be 40%. A reasonable commercial profit is 5% to 10%.

X. Labor Rates

As discussed earlier, the labor cost of a launch system can be quite variable especially when one considers international standards. Labor rates are set by local market conditions and will change over time as the local economy has normal supply and demand forces. There is an enormous amount of labor data available in the US from the US Department of Labor (DoL) which organizes and publishes historical labor data for a large class of skills based upon payroll data. This information is available for different geographic areas and levels of expertise. This information will be used to determine reasonable labor rates for the various skill sets that one would use in the production of a launch system.

A review some current DoL statistics shows that these skills had labor rates as shown in Figure 9[13-20]. The current actual rates will be slightly different that the historical data but one could consider trends of the historical data or the use of indices such the Producer Price Index (PPI) or Consumer Price Index (CPI) as a means to adjust these rates for more accurate labor rate data predictions.

Two general skill sets of "Engineering" and "Precision Production" were selected as representative of the bulk of the labor costs associated with rocket vehicle research and development, production, and operation. The ranges of 10%, 50% and 90% provides a distribution of the labor rate for each skill set in a particular demographic area. One sees from this data that there is a rough spread of labor costs of a factor of 1.5 to 2 between different demographic areas and some areas are noticeably different in labor cost. The bolded values in Figure 9 show the maximum and minimum rates, and the italicized values show the rates which are closest to the average rate for all areas considered. For example overall southern California has a higher labor rate than Cincinnati, Ohio. Companies will often also base cost decisions on other important factors such as availability and size of a qualified and skilled labor pool and access and availability of qualified and skilled suppliers, vendors, and services. So for example, while southern California has a high labor rate, it also has a large pool of skilled aerospace engineers, technicians, suppliers, and related services, providing an attractive venue for rocket launch vehicle work, which helps support some businesses which operate in this area despite the higher labor costs. Similar clustering of labor pools and supporting companies occurs in other industries such as the Silicon Valley for electronics and information systems and the "Rust Belt" for automotive and heavy industries. Over time some migration of industries including labor pools and companies also occurs such as the exodus of aerospace and defense industries from southern California to various other locations.

The effective cost of the labor portion of a product can be estimated by creating a fully burdened or wrapped labor rate. One takes the base labor rate and then applies the various rate structures to create an hourly labor rate which includes all of the cost elements for that company's means of conducting business. Figure 10 shows an example of what some fully burdened labor rates might be based on the DoL labor rates and our assumed model company rate structure provided in Figure 1. We will assume that our primary touch labor skill is a Rocket Assembly Technician whose base labor rate is the same as the DoL skill set "Precision Production". The average labor rate for this skill is approximately \$20.00/hr which is rounded up from the average 50% labor rate of \$19.91/hr. for all locations in Figure 9.

How does this labor rate compare with expected labor rates? Hawkins and Shirouzu provide labor rates for two commercial companies both providing similar capabilities in the same demographic area: GM and Toyota automotive assembly labor in Arlington, TX which is a suburb of Dallas, TX[21]. Our demographic data in Figure 9 suggests that our estimated baseline labor rate of \$20.00/hr is not too dissimilar than the Houston, TX 50% rate of \$18.61/hr.

Company	Base Rate (\$/hr.)	Rate with benefits (\$/hr.)
GM	26.50 to 30.50	81.18
Toyota	15.50 to 25.00	35.00

GM Average Base Rate	\$28.50/hr
Toyota Average Base Rate	\$20.25/hr

One sees that the two companies have base rates which are between the 50% to 90% ranges of the Houston, TX rate range, so these rates are competitive and reasonable. GM is a unionized company with an older facility and a mature work force, whereas Toyota is non-union with a new younger work force. GM's labor costs are high due to the older more experience workers and also possibly due to the influence of the labor union on negotiating higher wages. Moreover, the more mature GM plant has had time for various benefit costs such as health care and pensions to impact the fully wrapped labor cost, which suggests that over time a company's fully wrapped rate can escalate due to both an aging and more experienced work force. A conclusion that one can draw from this is that newer companies could have inherently lower labor costs due to a younger less experienced staff and less benefit creep. While this may be a cost benefit, a younger less experienced staff may also make more mistakes or lack the technical depth to make a reliable product. Older companies can and have exploited this by creating separate cost centers, divisions and the like which have a different costs basis, different benefits to create lower cost labor and rate structures to become more competitive. This effect is non-trivial: Toyota's labor cost is over ½ of that of GM's.

XI. Analysis of Launch System Prices

Current launch systems have the potential price range from \$5M (The desired range for some new launch systems like the SpaceX Falcon I and the AirLaunch QuickReach^{TM}.) to approximately \$60M for various mid range launch systems and as high as hundreds of millions for some very large launch systems. We will use a typical mid range price point of the Delta II as an example of what the price data can tell us. We can apply a possible commercial rate structure to these prices to determine what may be driving the price.

Assume a commercial pricing structure with:

Profit 7%

Direct Labor Cost is 10% of the Product Cost

Material Cost is the remaining cost

The launch vehicle price is \$60M

Profit = \$4.2M = 7% X \$60M

Cost Before Profit = \$55.8M = \$60M - \$4.2M

Direct Labor = \$5.58M = 10% X \$55.8M

The direct labor man-hours are then \$5.58M divided by \$51.36/hr.= 108,645 man-hours, which looks like a lot of people.

The average person works roughly 2000 hrs per year, so this is also equivalent to 54 people for one year. So would it be reasonable for a company composed of 54 people to build and launch one Delta II class rocket once a year. Yes, it is reasonable, and in fact when we think about the company that builds and launches Delta II rockets, the Boeing Company, we are quite confident that there are in fact MORE than 54 people involved in that operation. What if we bound the problem on the other side and assume that 90% of the rocket cost is labor:

Direct Labor = \$50.22M = 90% X \$55.8M

The direct labor man-hours are then 977,804 man-hours or 489 man-years. This is quite a few more people but still probably less than the number employed to launch Delta rockets. This makes sense in that the Delta program historically launched more often than once a year. Let us assume that the Delta program employs 1000 people. This provides 2M man-hours of labor or the potential sale of:

\$102.72M = 1000 people X 2000 hours/year X \$51.36/hr.

The range in direct labor cost is \$5.58M to \$50.22M so the range in delivered launches is then at least 2 to 18 which are similar to a typical range of launches per year for Delta II. One can estimate that the Boeing Company probably employs hundreds to perhaps thousands of people on the Delta program and the labor cost is probably greater than 10% of the product cost.

If we take the same rocket and look at the direct material cost we can deconstruct the pricing the same way except we need to remove the G&A cost to see the material cost basis. Let us assume that the material cost plus the G&A cost is also either 10% or 90% of the cost of the system. We will then remove the 20% G&A cost from these values to find the direct material cost basis.

Low Cost Estimate of Material Cost Plus G&A	$5.58M
High Cost Estimate of Material Cost Plus G&A	$50.22M

Low Cost Estimate of Material Cost Minus G&A	$4.46M
High Cost Estimate of Material Cost Minus G&A	$40.28M

One way to look at this cost is to see if the material cost is reasonable. In commercial products, the product cost is heavily driven by the raw material costs, so emphasis is placed on using low cost materials. Let us examine how expensive the material costs are. The Delta II inert masses are[2]:

GEM	2900 lbm
Stage 1	12,200 lbm
Stage 2	2095 lbm
Stage 3	457 lbm
Total Stack	17,652 lbm

Dividing the material costs without G&A (that would be the actual procurement material direct cost) by the inert mass of the Delta II gives a material cost per lbm in the range of $210/lbm to $1897/lbm. (Note that by our prior argument, propellant cost has been shown to be inconsequential.) This looks quite expensive. It is common that when raw materials are processed especially into high technology products that there is a significant mark-up in price and this is to be expected with a launch vehicle. The Delta II is primarily made from materials like aluminum, steel, stainless steel, plastics, and to a lesser extent more exotic materials like precious metals. The cost per lbm of some of these materials is:

Material	Price Per lbm ($/lbm)
Aluminum	1.50
Steel	0.38
Stainless steel	2.50
Plastic	2.00
Silver	192.00
Gold	10,400.00

One can see that the inert cost of the Delta II rocket is comparable to the precious metal raw material costs and since it is made from materials of much lesser cost than precious metals, there must be **a significant increase in the value added to the raw material**. Another counter argument could be that the cost to operate the vehicle is the primary cost driver and that while the launch vehicle is cheap the operations costs are high. This is the standing army fixed operating cost claim. While this may be true, several examples show that that is not always true. Intercontinental Ballistic Missiles are launched with a minimal launch crew and the launch crews for the missile versions of Delta were likewise small. In a like argument to the fallacy of propellant cost, the raw material cost of a rocket is likewise very cheap and unlike commercial products, it is the value added to the raw material that drives the cost. Note that a rocket system integrator may purchase many materials which already have value added in them such as a fabricated component, in which case the value added may have been made by a supplier. This is worthy of an example since it influences some basic business and design decisions.

XII. A Very Expensive Fastener

We will analyze the pricing of a notional fastener to illustrate how the multiple effect of buying and selling of a fastener dramatically changes the end price to the customer. A launch vehicle (called the LV Co.) buys a rocket engine from the RE Co and that rocket engine has a thruster vector control system which the rocket company buys from the TVC Co. The TVC Co. buys an electromechanical actuator from the EM Co. which in turns buys an electronic control box from the EB Co. The EB Co. buys an electrical connector from an electronics supplier (the ES Co.) who in turns buys the connector from a distributor, the ED Co. The ED Co. buys the connector from the Original Equipment Manufacturer for the connector the EC Co. The EC likewise buys a threaded fastener for the electrical connector from a supplier (FS Co.), who buys from a fastener distributor (FD Co.), who buys from the fastener manufacturer (FOEM Co.). FOEM then buys the raw metal material from a supplier (MS Co.) who buys from a distributor (MD Co.) who buys the raw material from a steel mill. We'll assume the steel mill owns the mine where the steel comes from though that may be untrue. Each transaction between these companies will add value to the fastener by incurring at least G&A and profit as the material moves forward. The fastener manufacturer would also add some labor cost say 10% of the raw material costs. Let us follow the cost of the fastener. We will assume that for each transaction up to the sale of the fastener from the TVC Co. to the RE Co. that each company doubles the price based upon its costs, which is a common practice in commercial businesses. Each transaction from the TVC Co. to the customer has the same rate structure and rolls up the costs by 20% G&A and 7% profit for each transaction. Figure 11 shows the impact of this accumulation of value added for the very expensive fastener as the price of the fastener to the customer is 4000 times more than the original raw material costs. The original raw material cost is $0.02 and the delivered price to the customer and a launch system is $82.37. Our analysis of the Delta II vehicle shows value added of roughly 100 to 1000 times higher than some raw material costs (the price per pound of the Delta II vehicle ranges from $200 to $2000/lbm where as some of the raw material costs are on the order of $1 to $2/lbm), which is comparable to our very expensive fastener. While this example is extreme it shows the basic process which incurs costs for launch systems and one of the driving forces behind pulling manufacturing in-house to control costs and this process does occurs to some degree on all launch systems. Note that this can also been seen as 14 layers of management for the production of one part, a fastener. Some industries, such as automotive industries have historically tried to chase these costs literally back to the mines the metals come from. Since it is impractical for a launch system company to make everything, a cost compromise must be made.

XIII. Life Cycle Cost

Because the expected production rate of almost any conceivable launch system is quite low, the effect of the non-recurring product development cost is non-trivial. For some businesses, one can do a simple business model and estimate that if some amount of money is invested and the product is deployed into a market, the expected sales will generate enough monies to cover the development costs relatively quickly and then subsequent sales are primarily driven by the recurring cost of making and selling the product. Launch systems do not necessarily follow that pattern and the development costs may be large in comparison with the expected production rate.

Further many launch systems are based or derived from prior launch vehicles, like ballistic missiles, so the true non-recurring cost is less clear and the selection of an existing asset which is included into a new launch system may be highly advantageous in reducing the non-recurring cost. An excellent example of this is the use of the Zenit rocket when integrated into the Sea Launch launch system. The very extensive and expensive development effort of the Zenit rocket is fully exploited by using this well developed asset in a new novel launch system. So the selection of existing developed components can mitigate non-recurring costs and non-recurring risks for the trade-off of losing control of the component which conflicts with the goal of more vertical integration to reduce material value added costs.

Most business models assume that the investment in a new business should be profitable or provide a return on investment to the investors. Common bench marks for determining the viability of an investment are a reasonable pay back period such as less than 7 years and a return on investment that would at least be as good as a stock market. If some criteria such as these cannot be met, the investor would be better off using that capital in some other manner unless of course that is not the goal as in a non-profit, government program or academic institution. In fact, since the launch vehicle business is ripe with risk, it would be fair that the potential for return should be much greater than one could get otherwise to justify the risk, so these criteria of a notional 7 year pack back and better than average market returns can very much be viewed as a minimum criteria for viability.

The rocket business is risky. It is highly probably that within the first 3-5 flights all launch systems will fail. This failure tends to kick off a failure investigation that will find numerous other problems all of which are now solved at the worst possible time; when the company has a peak product development team and is at the end of it financial clock for turning from red to black. If the vehicle and company can survive, then the vehicle reliability improves, launch failures drop, and typically price moves upward. The maturation in reliability and price of the Pegasus is a good modern example. Some other systems such as Conestoga were unable to survive the first launch failure. It is very healthy for a launch system company to recognize this known historical risk and have the financial resources to weather the first 5-10 flights. This is non-trivial and pushes to have the first launch occur early, such as in year three of a new launch system, to help provide a buffer to allow the company to begin becoming profitable within 5-7 years given a launch failure.

Since the non-recurring costs are also a major cost element, the expected launch rate also becomes important since that is the cash flow that will provide the pay back. This begs the major question of the industry of what does it cost to develop a rocket. It is very unclear and no one really knows, but we have some tantalizing clues as to what it should at LEAST cost. Some summarized estimated costs for launch systems which have failed or are not yet fully functional are:

AMROC	$20M
Beal Aerospace	> $100M
Space Ship One	$20M (1)
SpaceX	> $100M

(1) Note that Space Ship One has operated successfully but has two caveats: A) The first flights were in a sense experimental; and B) The vehicle is sub-orbital and therefore does not have the full development expense of an orbital launch system. One would expect that more money would be needed to continue and create an orbital system.

The development of a launch system appears to be on the order of hundreds of millions of dollars versus tens of millions of dollars. A simple reasonableness test can be applied to check these values. The development cost of a launch system is heavy on engineering. Using our fully wrapped engineering rate in figure 10 of $88.00/hr (without profit) we can estimate the monetary consumption of a fictitious company. Assume the organization is 200 people, the annual labor burn rate is:

$$\$35.2\text{M} = \$88.00/\text{hr} \times 200 \text{ people} \times 2000 \text{ hrs/year}$$

Much money will also be spent on non-recurring materials such as test articles, tests, and component procurement. Rocket engine development can be quite material consumptive. The author’s experience with these development recurring costs for combustion devices and rocket propulsion systems is that the material costs are at least as much as the labor costs, so a material expenditure of an equivalent $35.2M per year is possible. This yields a total yearly consumption $70.4M. This cost probably would ramp upwards during the first three years and plateau or grow less quickly as time proceeded. An estimated cash flow for this fictitious company is shown in figure 12.

If the company was ten times larger, the costs would be in the billions. It is unlikely that the company could be 10 times smaller which would be only 20 people. It would be reasonable for this price to vary by a factor of 2-5 about this estimated nominal range. This shows that in 3-4 years on could expect to consume hundreds of millions and possibly more.

The ability to make a return on this investment is then dependent on the ability to sell rides. The current launch vehicle market as previously described is quite large internationally and there is an excess supply of launch capacity. Given the expenditures by various governments and the very low rate structures of various countries it is unlikely that a US launch vehicle will be extremely attractive to an international customer, nor for that mater if another country has launch capacity will it be eager to use a competing platform. The most likely launch market is then the launch market of the country which has developed the system, unless the system provides some unusual capability like very low cost, very rapid service, unusual orbits or some other compelling feature.

Most modern launch systems have launch rates of several times per year. A radical departure from this launch rate would be to launch every month and a true paradigm would occur if one launched every week. For practical planning a system that launched every month would be vastly more successful than most current systems in terms of launch rate and this will be assumed to be a reasonably high launch rate. If one incurred a non-recurring cost of $200M in three years of development and then recovered this cost in 24 launches across two years such that at year 5 one had recovered the investment cost and had 1-2 years of margin to begin healthy returns on investment, the initial investment cost would add $8.3M to the price of each launch. Doubling or halving the initial investment impacts the time at which one becomes profitable and the time required to break even. And of course failure to capture the expected market share or a change in the market will have a similar major effect.

XIV. Operations Costs

Numerous studies in the past have focused on operations costs as a major driver of launch system costs. Especially in regards to Space Shuttle and large versions of Titan, the costs of handling and operating systems is significant. Extensive efforts have been made to identify features and criteria to create more operable systems[9-12]. Most of these studies assume that the methods of operating launch systems will not change appreciably and if the launch platforms remain similar to those currently in use, that is a reasonable and valid assumption. Expendable launch costs account for 20% to 30% of the launch vehicle costs whereas operations account for 50% to 60% of launch operations for reusable launch systems (the remaining 40% to 50% of costs for a reusable system are for hardware refurbusiment[1]).

High operations costs conflict with the known usage of military rockets such as military weapons and ballistic missiles, which by definition cannot be staffed with large numbers of people incurring large operational costs and must be operated in very short durations of time. So it is feasible to make launch systems which are highly operable and do not require large numbers of people in order to operate. The selection of the design can certainly help in this regard and a review of the various operations studies can provide guidance towards criteria for more operable systems. Some of these criteria are:

1. Minimize number of fluid systems.
2. Minimize hazardous operations, such as pyrotechnics.
3. Keep propulsion compartments open.
4. Minimize the number of parts.
5. Use non-toxic propellants or attempt to make the system safer to work with and around.

One could make the argument that launch vehicle costs are fundamentally driven by operations costs. If that is true, then designs should be highly focused on launch operations automation to reduce the number of personnel at launch operations, the use of storable propellants, possibly solids since a solid requires very little propellant handling at point of use (a fact well known and used by military organizations), the reduction in launch crews to that demonstrated on ICBM’s, the elimination of contractor staff in launch operations, and many other criteria which are commonly seen in commercial airline and military applications.

The prior analysis of launch system costs for both labor and material bounded the expected labor and material costs by 10% and 90%. One could also assume that some of the value added labor in this analysis is the labor required to launch the rocket. Even if the labor to launch the rocket is a significant portion of the total labor costs, the prior argument that labor costs for raw material value added is still valid but will be less significant.

Reusable systems however will need to be much more attentive to operations costs and these will become part of the recurring cost and our primary example of Space Shuttles shows us that the operational costs for a reusable launch vehicle can be quite significant. Byrd provides ground operational data for Space Shuttle that indicates the staff is quite large. The average number of man-hours of labor for operations in the Vehicle Assembly Building averaged 3636 for flights ST-14 to ST-33, and the number of man-hours at the pad averaged 15,943 for same series of flights[10]. The reusability requirements and specific design of the Space Shuttle do not lend themselves to very low costs.

XV. Discussion - What Features Does a Low Cost Rocket Have?

This analysis provides several features or criterion that a low cost launch system may have:

1) The primary cost driver is the value added to the inert raw material. Use components that have less value added and try to reduce the amount of value added put into the raw material.
2) Make the system simple. This also includes the product development process as well as the associated GSE. Wholesale elimination of cost elements like fluids, systems, GSE, operations, and non-recurring tasks inherently lowers cost.
3) Focus on reducing value added cost on material. This is can be done thru vertical integration and performing more cradle to grave material processing in-house to reduce the numerous wraps from lower tiered suppliers. This completely conflicts with the later defined goal of reducing Overhead. Note that this is probably an evolutionary process and the exact optimal solution is still being experimented with. For example, the auto industry initially expanded significantly into vertical integration and has later regressed in more horizontal integration business practices. The actual optimal solution will be some compromise on vertical integration. The time value cost of money is also an important parameter that conflicts with vertical integration.
4) Make investments in cultivating strong supplier chains with pre-negotiated prices. Negotiate preferential agreements to ensure the supplier can thrive and the customer gets the lowest possible price. This conflicts with the preferred US government practice of multiple competitive bids but is shown as a demonstrated method that auto makers reduced vertical integration and kept costs low. This also prefers to co-locate companies or to find a location where one can acquire most of the items needed for the system. This reduces shipping expenses and permits a close relationship between companies.

5) Use existing developed components, especially those that incur development costs and especially those that a company already makes in-house.
6) The choice of propellant does not necessarily indicate the lowest cost solution. Propellant costs will probably be between 0.25% to 25% of the launch costs. As systems become lower in cost, the percent of the propellant cost should increase from the lower end to the higher end of this range. In general a reasonable goal for selecting a propellant should be that it provides an overall system cost reduction and that the propellant cost is within this range trending towards the upper end. Current and projected future pricing suggests that propellant costs should be less than \$20/lbm for current pricing and less than \$5/lbm for future low cost pricing. Most current propellants meet these criteria with the exception that hydrazines may be unfavorable. The reduction in operation of Titan will probably also tend to increase the cost of hydrazines as the primary user of that family of propellants decreases. Hydrazines are still widely used for spacecraft and a like argument for spacecraft should show that the propellant cost is trivial and will not be a driver in determining what propellants go onto satellites.
7) Labor cost and rate structures in the US are relatively inflexible and this product does not lend itself to out-sourcing to low cost labor pools. Some variation in labor rate may be possible thru demographic selection or modifying the rate structures of Overhead and G&A. The most promising approach is probably to decrease direct labor. Since the launch vehicle production rate is low and probably will always be low in comparison to other mass manufactured items, it is unlikely that automation will provide reasonable reduction in direct labor since the production rate will not justify the amortized tooling and capitalization. This limits reductions in direct labor to reduction of assembly and operations procedures which are best done by making inherently simpler systems.
8) Organize companies with minimal G&A rates. This tends to prefer companies that are not too small to get some economy of scale and companies that are not too mature so that accumulated management costs and employee benefits are small. The inherent risk is that a mid-sized to small companies may not have the technical depth to execute a reliable product; however this is not currently well explored. Note that Orbital Sciences has implemented this model and has not created a radically lowered cost launch system.
9) Organize a company with low Overhead. This is a general trend of many companies including some of the larger launch system providers. Capital and facilities are being consolidated or reduced and more efforts are being out-sourced.

XVI. Proposed Low Cost Solution

The optimal solution for a low cost launch system is likely to be multiple solutions due to the confounding effects of pre-existing developed components and systems, the effect of government subsidy through facilities, GFE and the technology, and the inherent lack of long term experience in building variant systems due to the extreme costs and lead time for product development. In addition, technology will continue to change so optimal solutions will also probably change over time. Especially due to the reduced cost of existing assets and the influence of amortizing non-recurring costs, the optimal solution for a low cost launch system will probably be scale dependent and possibly application dependent. Some candidate concepts which exhibit some of these features are suggested as potential or reasonable low cost solutions and a proposal for a small scale low cost solution is offered.

A. Concept #1 – Use Existing Assets.

Find the most well qualified and developed launch system currently made in a low cost market place. Continue to build as much of the system in the low cost economy. Develop the means to provide the service of the launch system with the least amount of development necessary. This has the inherent risk of later price escalation which should occur as the low cost economy improves plus dependence on a major supplier who may chose to change the business relationship. An attractive feature of this system is that the pricing of the system may be market driven in which case if the market comes up with a new lower cost competitor, this concept could lower the price to maintain itself as low price leader.

B. Concept #2 – Make the system as simple as possible.

Minimize non-recurring cost and minimize all possible cost elements, such assembly operations and launch operations. A good example of this is the Orbital Pegasus. This system is noteworthy in that it exhibits many of the features of a low cost rocket: It is a novel concept to provide a paradigm change to lower the costs basis; It was a new small company; It is made with few parts as a stack of solids; It is robust so it should have been simple to develop and assemble. Pegasus had problems initially with launch reliability probably due to the rigorous control on staff size (reduced raw material value added) which did not invest the same degree of technical maturity that existing launch systems had. Pegasus could achieve lower cost if Orbital chooses to make solid rocket motors or Hercules chooses to become a launch system integrator. The segregation of rocket engines and propulsion from launch system integration in the US markets may not be the optimal solution and it is noteworthy that some newer companies are quite particular about integrating that work in-house as in the cases of Microcosm, SpaceX, Beal Aerospace, and Virgin. Alternate possibilities for some of the existing companies would be for a propulsion company to develop, acquire or merge with a system integrator.

C. Concept #3 – Reduce labor value added cost.

The easiest way to do this is to make the product simple. The cost of the raw materials and the cost of the propellant are inconsequential. If the choice of the raw material and the choice of the propellant reduces the labor value added, then a low cost solution has been found. This is one of the benefits of such ideas as reduction of stages, reduction in number of fluids, lower reliability (i.e. lower redundancy, less product development) in exchange for lower cost, and other architectural simplifying concepts.

The optimal low cost solution for a rocket is thus not a simple or clear answer. It is dependent on numerous factors which, over time will become known thru the trial and failure of systems. Some concepts are of value in an industrialized economy and will hold true, such as the need to reduce labor value added to raw materials and the lack of effect due to propellant and raw materials in general. A proposal for a potential low cost solution for a very small scale launcher is proposed.

XVII. Small Low Cost Launcher

This cost analysis shows us many features of what our low cost propulsion system should have. These features are:

1) Uses technology which has been previously developed reducing non-recurring costs.
2) Simple design wholesale eliminates cost elements:
    a. One stage
    b. Three fluids: Hydrogen peroxide, kerosene, and helium
    c. One piece of mechanical structure
    d. Reduces the number of items needed to be developed
3) Storable propellants reduces cryogenic GSE operations.
4) Non-toxic propellants reduces toxic propellant GSE operations.
5) Can be operated using existing government facilities and assets.
6) System is simple enough to allow most of the work to be brought in-house for more vertical integration.
7) Product is small enough that a separate cost center can be created to make this product.
8) Product is simple enough that the above cost center could be located in a low cost labor pool area.
9) Product part count is low enough to allow procurement of components closer to the raw material source.
10) Company makes as many parts as possible in-house from raw materials.
11) Company co-locates near its suppliers.
12) Reduces part counts for all parts to the lowest level possible at all scales.
13) Uses government launch facilities and GFE to maximum extent possible. System design fits into existing government assets.
14) Design product such that it can be operated with little to no support from the seller so that government personnel can completely operate the product.
15) Develop all local suppliers of components which are not made in-house.

A low cost very small nano satellite class launch system could be created using existing technology developed for interceptor vehicle applications. This concept would be a single stage vehicle which would deliver approximately 1 kg to orbit. The stage would use a high performance bi-propellant hydrogen peroxide kerosene rocket engine recently developed for interceptor vehicle applications. A cluster of these engines would be pump fed by a reciprocating pump also developed at the same time for similar applications. Hydrogen peroxide would be used for all fluid and power applications such as TVC, roll control, main propulsion, and orbit trim burns. The system would be storable and could be loaded with propellant long before use.

This launch system could be made in the industrial sector of Santa Ana, CA which is surrounded by quality suppliers of almost all materials and services used by the aerospace industries. Suppliers and companies from northern Los Angeles to San Diego are within a few hours of driving and most freight carriers deliver goods with 1-2 days of ordering. While the Los Angeles area has high labor rates, Santa Ana is a relatively lower cost region for both Overhead and labor pools. Labor pools for technician labor are extensive and are well supported by local industry. Nearby communities are filled with qualified engineers. The size of the rocket thrusters and the use of non-toxic propellants would permit engine testing in-house without undue constraints by the local community. New suppliers could be readily developed and located in nearby industrial zones.

Figure 13 shows the system concept and figure 14 provides an estimate of the system mass. Figure 15 shows the candidate thruster which has been under development. Using the parametric price model in Figure 8 and extrapolating the trend backwards to approximately 2 lbm (~ 1 kg), one finds a launch vehicle cost of $60,000.00 If the features of this concept can actually enable a change in the basis of pricing, then a possible reduction below $60,000 may be possible. The DARPA goal for Falcon is a rough reduction in launch cost by a factor of two for a reduction from $10,000/lbm of payload to $5000/lbm of payload at the 1000 lbm scale. Using the same logic, the proposed low cost launcher could have a price of $30,000 or ½ the parametric estimate of $60,000 Given reasonable production rates, it may not be impossible for a vehicle of this scale to be built for $30,000.

Applying the same pricing analysis of the $60,000 price we can ascertain what costs are necessary to achieve this price. Our total cost less profit is:

Profit = $4200 = 7% X 60,000

Total Cost = $55,800 = 60,000 - 4200

Our propellant load is 2736 lbm of H2O2 and 375 lbm of RP-1. Current market prices for propellant grade H2O2 vary from $0.75 to $5.00 per lbm. For this analysis we will assume the H2O2 propellant price is $4.50/lbm and the RP-1 is $0.41/lbm for a total propellant cost of:

Propellant Cost = $12,466 = 2736 lbm H2O2 X $4.50/lbm + 375 lbm RP-1 X $0.41/lbm

The $12,466 cost of the propellant is 22% of our total cost which is on the high side of the propellant cost allocated range and comparable to the current commercial airline propellant costs. We can then assume that 20% of the remaining cost is for operations and the other 80% is for the hardware.

Operations and Hardware Costs = $43,334 = 55,800 – 12,466

Operations Cost = 8,667 = 20% X 43,334

Hardware Cost = $34,667 = 80% X 43,334

The Operations cost of $8,667 is equivalent to 169 man-hours at $51.36/hr, or one man-month. So the system will need to be designed such that one person can service it and prepare it for flight and launch it in one month.

The Hardware has a dry mass of 131 lbm, so the cost per lbm of the vehicle is $264/lbm which is on the low end of what we estimated for the Delta II hardware costs. If the materials have very low value and all of the hardware costs are value added labor in-house, the system is being made in 844 hours at a rate of $51.36/hr. This is much more labor that what is expended on building a common car. Our nano class vehicle is arguably comparable to a car in terms of complexity and possibly much simpler.

An understanding of the non-recurring amortized cost is less clear. If our nano class launch vehicle flies often, such as 50 flights a year and we burdened the flights with a 25% premium for development costs, we would have $15,000 per flight of non-recurring capital per flight or $750,000/yr. If the vehicle were developed in 3 years, the maximum investment would be $2.25M. It is arguable as to whether a vehicle like this could be developed in 3 years for $2.25M. In this regard, support from a government development subsidy (i.e. a development contract), would mitigate that cost and permit a company to operate the system in a recurring operation.

The deconstruction of the pricing for the nano class launch system shows that it is reasonable that such a system could be made to meet the recurring cost. It would need to satisfy some very specific design requirements: 1) Must be fully operated in less than 169 hours of labor; 2) must be able to built from raw materials in less than 844 hours of direct labor; 3) value added material costs must be less than $264/lbm; and 4) propellant costs must be less than approximately 25% of the total cost. These provide quantitative design metrics which have been derived independently from analysis of the price and cost data. Violation of these metrics will incur an increase in price. The means to track these metrics will require the development of an engineering tool that tracks and analyzes these metrics which is not commonly done, but is necessary if one truly wishes to deterministically find low cost solutions.

XVIII. Conclusion

Pricing practices and cost modeling were used to analyze price data and methods of pricing to find a set criteria and guidelines that would help the decision making process in creating and developing low cost launch systems. The results of this analysis have shown that the primary cost driver is value added to inert materials, that the propellant material cost is not a cost driver, that labor costs are controllable but not enough to create a radical price change, and that numerous other tangible and intangible factors also control cost. These other cost factors include government assistance both direct and indirect, access to existing technology, supplier relationships, and the amount of vertical integration of the company. The goal of reducing access to space is worthy to pursue and more interestingly there will probably be more than one solution and this solution will be scale and time dependent. The means to define this solution conclusively and deterministically are probably not possible; however time and experience will eventually drive the market towards the optimal solution. Current efforts can be accelerated by the consideration of the primary cost drivers and a continual analysis of the costs to create the criteria used by designers and engineers to more quickly find optimal solutions.

Acknowledgments

General Kinetics would like to thank the many pioneering companies and supporting governments that continue to search and explore as pioneers the means to which we can access and utilize space more effectively. Our admiration and truly altruistic support goes to these companies who choose or have chosen to try, knowing full well the potential for failure: AMROC, EER (Conestoga), SpaceX, Microcosm, Virgin, Blue Origin, Orbital Sciences, Beal Aerospace and many others. The true cost and price of launch vehicles is and will probably remain unclear for the foreseeable future. The sometimes made assumption that the current suppliers do not or cannot find the optimal solution may be incorrect, so we also believe that similar but different attempts by the more traditional entities are also necessary and valuable in the search for more cost effective access to space, such as the USA and ULA consortiums, Lockheed's Athena, Orbital Science's Taurus, and many others. Last but certainly not least, the various government agencies and organizations that provides the catalyst to make any of these a possibility thru the development of technology, creation of corporate and government resources, and the sustaining financial support of continual funding of existing and new launch systems. Access to space as we now know it would not be possible without the major efforts of the US Air Force, NASA, DARPA, MDA, CPIA, DESC, DTIC, and the voluminous government entities that have created the infrastructure of people, companies, laboratories, test and launch facilities, and technical data that the entire launch vehicle community uses for the advancement of access to space.

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Overhead %	100%
G&A %	20%
Profit	7%

Figure 1 - Notional Rocket Company Rate Structure

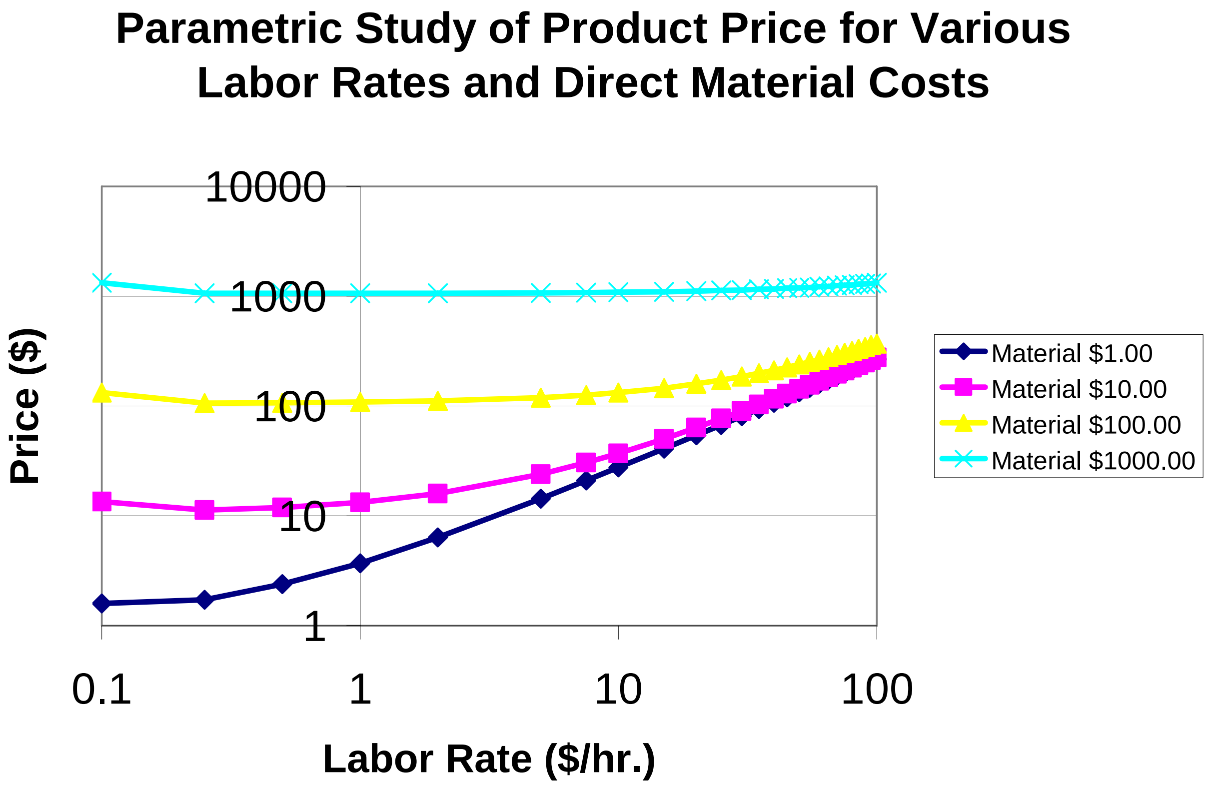

Figure 2 – Parametric Study of Product Price for Various Labor Rates and Direct Material Costs

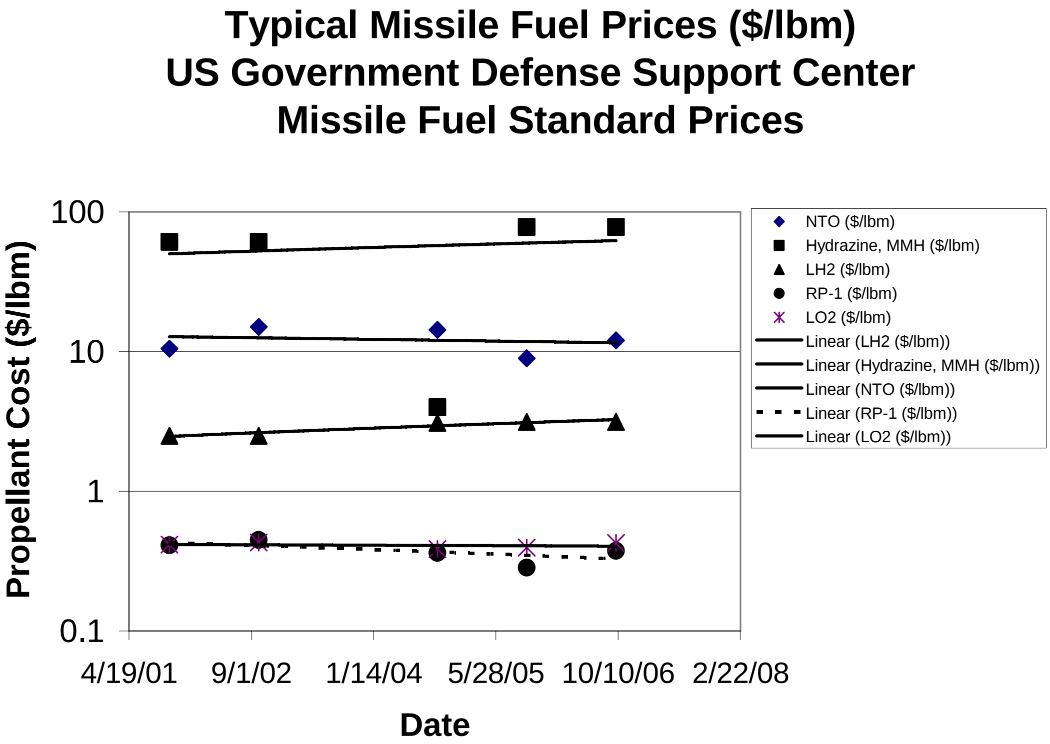

Figure 3 – US Propellant Prices from DESC

Delta II Propellant Masses

(4) GEM 40	47,060	kg.	103,720	lbm
Stage 1	96,143	kg.	211,900	lbm
Stage 2	6,004	kg.	13,233	lbm
Stage 3	2,009	kg.	4,428	lbm
Total	151,216	kg.	333,281	lbm

Figure 4 – Delta II with Four (4) GEM 40 Propellant Masses

Propellant 1%	1.80	$/lbm
Propellant 2%	3.60	$/lbm
Propellant 5%	9.00	$/lbm
Propellant 10%	18.00	$/lbm
Propellant 25%	45.01	$/lbm
Propellant 50%	90.01	$/lbm
Propellant 75%	135.02	$/lbm

Figure 5 – Propellant Cost for a Notional Launch System Like the Delta II with Four (4) GEM 40 SRB for Various Propellant Cost Percentages of the Total Price of $60M USD

Propellant 1%	0.18	$/lbm
Propellant 2%	0.36	$/lbm
Propellant 5%	0.90	$/lbm
Propellant 10%	1.80	$/lbm
Propellant 25%	4.50	$/lbm
Propellant 50%	9.00	$/lbm
Propellant 75%	13.50	$/lbm

Figure 6 - Propellant Cost for a Notional Low Cost Launch System Like the Delta II with Four (4) GEM 40 SRB for Various Propellant Cost Percentages of the Total Price of $6M USD

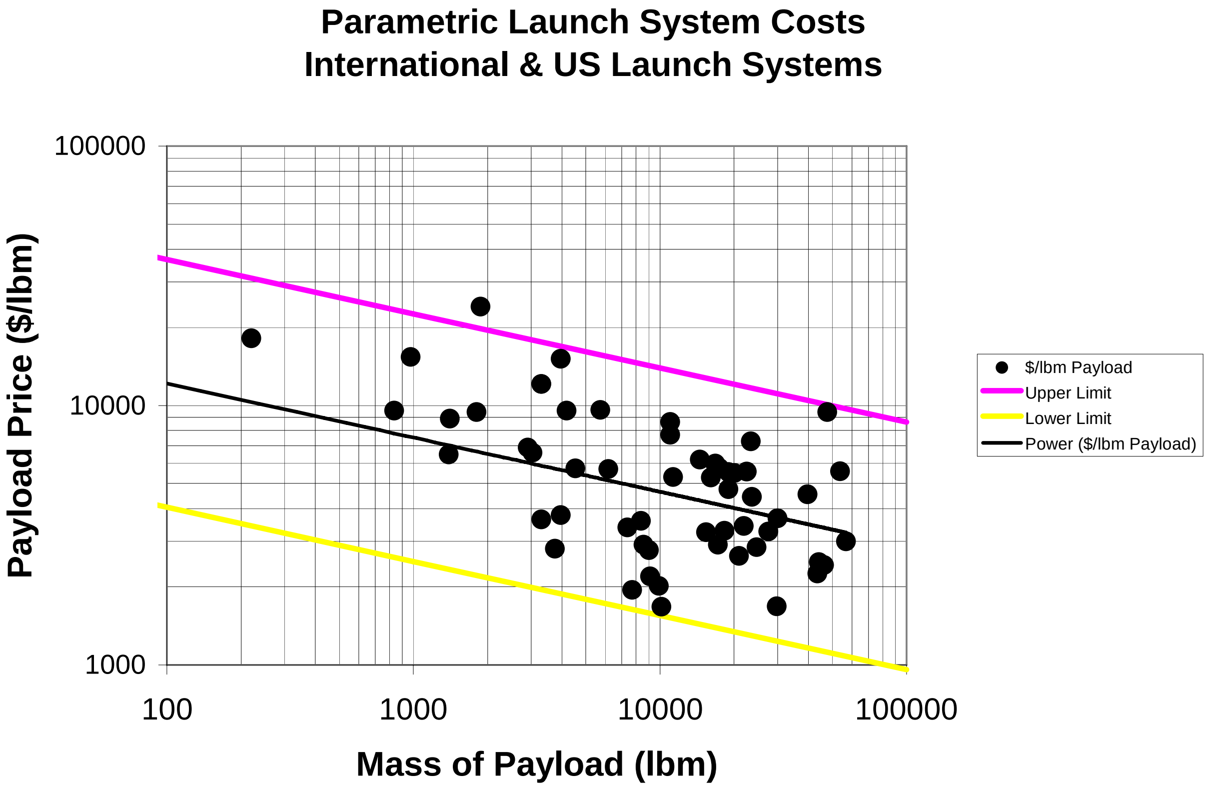

Figure 7 – Parametric Study of International Launch Cost versus Launch System Scale

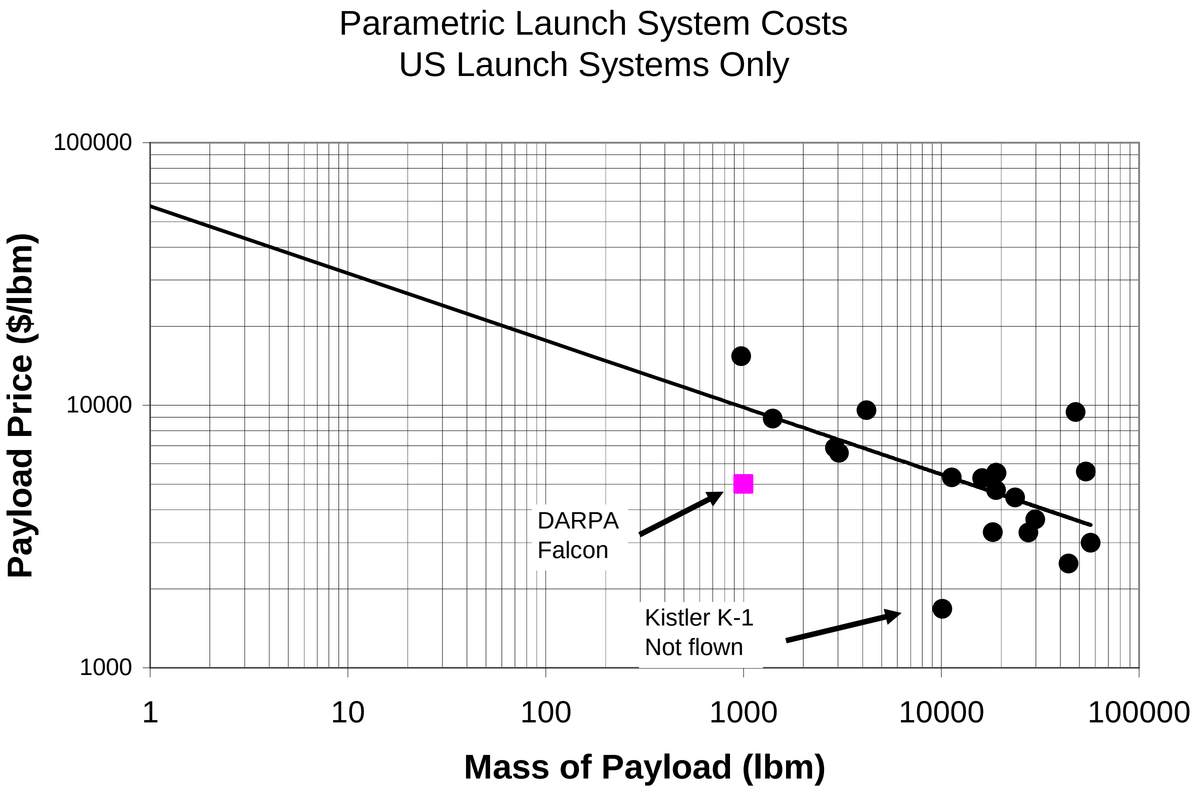

Figure 8 – Parametric Study of US Launch Cost versus Launch System Scale

Location	Engineering ($/hr.)			Precision Production ($/hr.)		
	10%	50%	90%	10%	50%	90%
Los Angeles-Riverside-Orange County, CA	39.68	52.25	**64.06**	11.00	23.53	**32.80**
Melbourne-Titusville-Palm Bay, FL	30.43	37.81	44.78	9.75	17.12	27.56
Denver-Boulder-Greely, CO	31.01	34.48	***50.59***	***11.50***	18.25	***30.40***
Huntsville, AL	***28.46***	***36.72***	52.60	**7.12**	17.04	30.57
Houston-Galveston-Brazoria, TX	24.60	39.92	55.35	12.00	***18.61***	28.70
Hartford, CT	25.00	30.95	41.82	12.75	22.50	30.39
Washington-Baltimore, DC-MD-VA-WV	19.25	30.29	46.35	13.00	21.75	30.00
Cincinnati-Hamilton, OH-KY-IN	**19.23**	30.96	42.79	13.79	20.45	28.87

Averages	27.21	36.67	49.79	11.36	19.91	29.91
Minimum	19.23	30.29	41.82	7.12	17.04	27.56
Maximum	39.68	52.25	64.06	13.79	23.53	32.80

Figure 9 – Labor Rates for Typical Skill Sets Used in Rocket Propulsion Systems

Rocket Assembly Technician

Base Labor Rate	$20.00/hr.
Overhead	$20.00/hr.
G&A	$8.00/hr.
Profit	$3.36/hr.
Fully Wrapped Rate	$51.36/hr.
Burdened Labor Cost without Profit	$48.00/hr.

Rocket Engineer

Base Labor Rate	$36.67/hr.
Overhead	$36.67/hr.
G&A	$14.67/hr.
Profit	$6.16/hr.
Fully Wrapped Rate	$94.17/hr.
Burdened Labor Cost without Profit	$88.01/hr.

Figure 10 – Rocket Assembly Technician and Engineer Labor Costs

Fastener Mass	0.05	lbm
Steel price per lbm	0.38	$/lbm
Fastener material cost	0.02	$
Steel Mill Price	0.02	$
Steel Mill to MD Co.	0.04	$
MD Co. to MS Co.	0.08	$
MS Co. to FOEM Co.	0.15	$
FOEM Co. to FD Co.	0.30	$
FD Co. to FS Co.	0.61	$
FS Co. to EC Co.	1.22	$
EC Co. to ED Co.	2.43	$
ED Co. to ES Co.	4.86	$
ES Co. to EB Co.	9.73	$
EB Co. to EM Co.	19.46	$
EM Co. to TVC Co.	38.91	$
TVC Co. to RE Co.	49.96	$
RE Co. to LV Co.	64.15	$
LV Co. to Customer	82.37	$

Figure 11 – Example of Impact of Supplier Chain Value Added on the Price of a Fastener

Year	Yearly Costs (M$)	Cumulative Costs (M$)
1	23.23	23.23
2	46.46	69.70
3	70.40	140.10
4	70.40	210.50
5	70.40	280.90
6	70.40	351.30
7	70.40	421.70

Figure 12 – Notional Estimate of Non-Recurring Costs for a New Low Cost Launch System

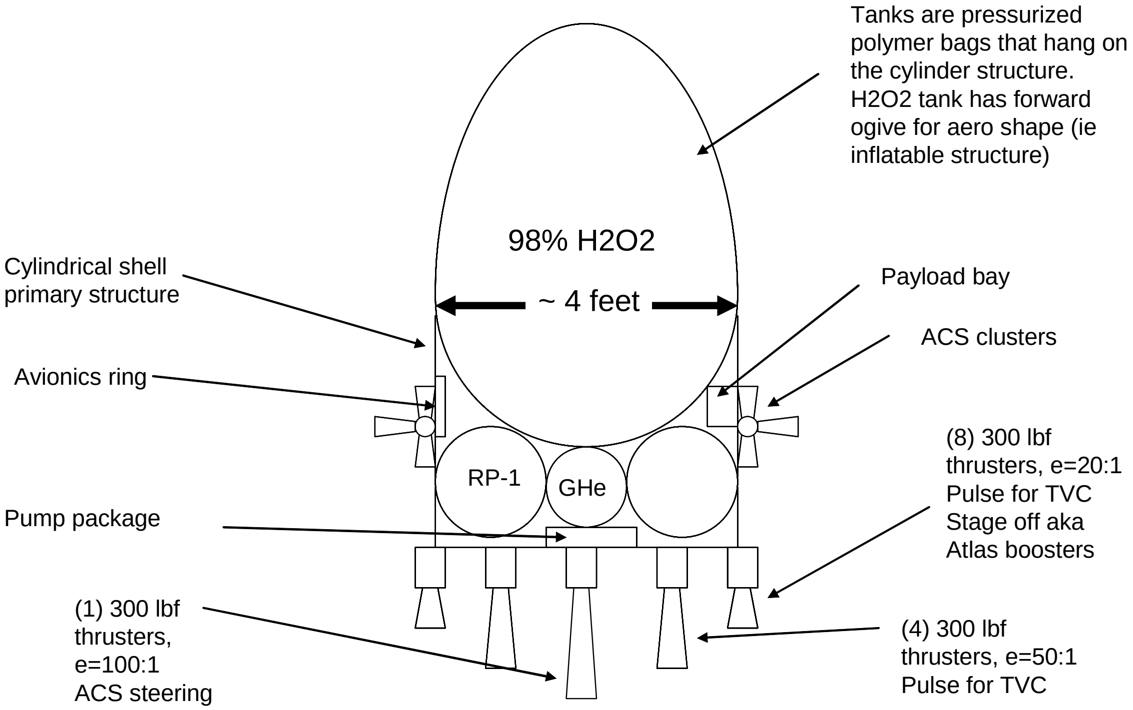

Figure 13 – Schematic of Low Cost Launch System

		Value	Units
Payload Mass		2.204	lbm
Burned Propellant Mass		3000	lbm
O/F Ratio		7	
Oxidizer			
	Booster mass	2625	lbm
	Sustainer mass		
	Gas generator mass	104.6025105	lbm
	Residual	6.5625	lbm
	Loaded oxidizer mass	2736.16501	lbm
	Oxidizer tank diameter	3.890558295	feet
	Oxidizer tank material		
	Oxidizer tank material yield stress	19950	psi
	Yield safety factor	10	
	Oxidizer tank pressure	25	psi
	Oxidizer tank wall thickness	0.012188466	inches
	Oxidizer tank surface area	6847.565873	square inches
	Oxidizer tank skin material volume	83.4613227	cubic inches
	Oxidizer tank material density	0.058051215	lbm/cubic inch
	Oxidizer Tank Shell Mass	7.025295256	lbm
Fuel			
	Booster mass	375	lbm
	Residual	0.375	lbm
	Loaded fuel mass	375.375	lbm
	Fuel Tank Minor Radius	0.5015	feet
	Fuel Tank Major Radius	1.443779147	feet
	Fuel tank pressure	25	psi
	Fuel Tank Shell Mass	16.53683371	lbm
Pressurant, Oxidizer			
	Ullage pressurant mass	0.435436232	lbm
Pressurant, Fuel			
	Ullage pressurant mass	0.101219096	lbm
Pressurant, Ghe			
	Pressurant tank diameter	11.722766	inches
	Pressurant tank mass	2.440833843	lbm
	Pressurant mass	1.749963024	lbm
Booster thrusters			
	Initial ~ T/W	1.5	
	Initial thrust	4500	lbf
	Thruster unit thrust	300	lbf
	Number of thrusters	15	
	T/W of thrusters	300	
	Mass of thrusters	15	
Pumps			
	Pump mass	16.875	lbm
	Pump system controls	4.21875	lbm
ACS thrusters		1	
	10 each		lbm
Electrical power		7.08	lbm
Avionics		5.9	
Secondary structure		7.08	
Primary structure		29.5	
Misc inerts		10	lbm
Burned Propellant Mass		3104.60251	lbm
Inert Mass		131.3441758	lbm
Payload Mass		2.204	lbm
GLOW w/o payload		3235.946686	lbm
GLOW w/payload		3238.150686	lbm
Stage Mass Fraction		0.959410896	
Stage Mass Fraction w/payload		0.958757887	
Burn-out mass with payload		133.5481758	lbm
Stage specific impulse		286.0167116	lbf-sec./lbm
Stage DV with payload		29339.65602	ft./sec.

Figure 14 – Small Low Cost Launch System Mass Properties

Figure 15 – Existing Thruster for Small Low Cost Launch Vehicle