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Cost Comparison of Expendable, Hybrid and Reusable Launch Vehicles

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COST COMPARISON OF EXPENDABLE,
HYBRID, AND REUSABLE LAUNCH
VEHICLES

THESIS

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Abstract

This study compares the developmental, production, and maintenance costs (DPM) of two-stage-to-orbit (TSTO) expendable (ELV), hybrid (HLV), and reusable (RLV) launch systems. This comparison was accomplished using top level mass and cost estimating relations (MERs, CERs). Mass estimating relationships were correlated to existing launch system data and ongoing launch system studies. Cost estimating relations were derived from Dr. Dietrich Koelle's "Handbook of Cost Engineering for Space Transportation Systems". Hybrid launch vehicles appear to be preferable if current or modest increases in launch rates are projected while reusable launch vehicles appear preferable for large projected increases in launch rates.

Acknowledgments

I would like to thank everyone who made it possible for me to complete this graduate thesis. First, I would like to convey gratitude to Dr. Milton Franke, my graduate advisor, for guiding me through the thesis process. His teachings in Rocket Propulsion were instrumental in completing this project. Secondly, I would like to offer thanks to John Livingston from ASC/XREC. His mentoring and expertise in rocket design made it possible for me to get started, let alone complete my research. I would also like to thank the rest of the individuals who assisted me during my research. They include, Mike Snead, Alecia Hartong, Brendon Rooney, Antony Susainathan, Barry Hellman, Zac Proano, Danielle Tallman, Megan Edgar, and Brian Hirsch. Each of these individuals offered guidance and assistance during some portion of my research.

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Nomenclature

Symbol	Description
AOA	Analysis of Alternatives
ARES	Affordable Responsive Spacelift
ASC/XREC	Aeronautical Systems Center/Future Systems Concepts
CER	Cost Estimating Relationship
DPM Cost	Developmental, First Unit Production, and Maintenance Costs
DOC	Direct Operating Costs
ELV	Expendable Launch Vehicle
FUPC	First Unit Production Cost
GSO	Geostationary Orbit
HLV	Hybrid Launch Vehicle
LCC	Life Cycle Costs
LEO	Low Earth Orbit
MER	Mass Estimating Relationship
MYr	Man Year
RLV	Reusable Launch Vehicle
RMLS	Responsive Military Launch System
SSTO	Single-Stage-to-Orbit
TPS	Thermal Protection System
TSTO	Two-Stage-to-Orbit

COST COMPARISON OF EXPENDABLE, HYBRID, AND REUSABLE LAUNCH VEHICLES

1. Introduction

1.1 Motivation:

The United States space launch market requires low cost access to space. The argument over whether an expendable, hybrid, or reusable launch system should be used remains an ongoing debate. All current launch systems (other than the Space Shuttle) are expendable launch vehicles (ELVs). ELVs are less expensive and are economically lower risk to develop. However, the total life cycle cost (LCC) for ELVs rises dramatically for increasing launch rates.

Hybrid launch vehicles (HLVs) are defined here to be a first-stage reusable, second-stage expendable, launch system. HLV development costs are higher than ELVs due to fact that the first-stage booster is reusable. HLVs offer higher reliability than ELVs due to airframe robustness and system efficiency. The analysis of alternatives (AOA) performed by Aerospace Corporation concluded that the HLV is the preferred option based on current launch needs [12].

The last alternative is developing reusable launch vehicles (RLVs). RLVs are estimated to be significantly more expensive to develop than HLVs or ELVs. However, RLVs provide the capability to meet both current and future needs of U.S. space launch [1]. RLVs can be designed to be more responsive and operable than expendable counterparts, providing aircraft-like operations from military installations.

1.2 Research Objectives:

The purpose of this research is to compare the developmental, production, and maintenance costs (DPM) of expendable, hybrid, and reusable launch systems. Individuals and groups have evaluated expendable and reusable launch systems but never all three systems together. It is for this reason that Dr. Mark Lewis, the Chief Scientist of the Air Force, requested that someone compare the three launch vehicle alternatives [10].

This comparison was accomplished using top level mass and cost estimating relations (MERs, CERs). Mass estimating relations were correlated to existing launch system data and ongoing launch system studies. Cost estimating relations were derived from data and existing CERs provided by Dr. Dietrich Koelle's "Handbook of Cost Engineering For Space Transportations Systems". Launch rate, vehicle launch life, and system lifetime were varied to compare their effects on system costs.

1.3 Research Focus:

For this research, each launch system is a two-stage-to-orbit (TSTO), hydrocarbon fueled, vertically launched system. The HLV and RLV are both horizontal landing systems and therefore require wetted aero surfaces and landing gear [10]. The maximum vehicle life for the reusable vehicles is set at 200 launches and the total system life is 20 years. Development and first unit production costs are functions of stage dry mass. Maintenance cost is a function of wetted area and engine dry mass. Maintenance relations were developed with the assistance of Brendon Rooney and Barry Hellman of Aeronautical Systems Center (ASC) [6, 12].

1.4 Methodology:

The program used for the majority of this study was Mathsoft's MathCad 13. MathCad 13 is a powerful mathematical tool that allows a user to perform a multitude of operations such as solving mathematical calculations to graphing functions. MathCad 13 was used in this study to build files for MERs, CERs, and the comparison model. Payload mass, launch rate, and launch system life were varied and graphed to observe their impact on DPM.

1.5 Thesis Overview:

This thesis is structured into five chapters. Chapter 2 reviews relevant literature pertaining to different launch systems including past U.S. Air Force involvement with RLV programs. Chapter 3 presents the research methodology with an in-depth discussion of the MER, CER, and the comparison models. Chapter 4 discusses the results of the comparison model, with a thorough sensitivity analysis of DPM costs for each of the options. Chapter 5 provides the overall conclusions of this study, followed by recommendations for how future launch vehicle development should continue. The conclusion will also address risks and payoffs associated with each launch system that needs to be dealt with by future decision makers. English units were observed to be industry standard and all data will be referenced in English units.

2. Literature Review

This chapter reviews the background of government and industry development efforts of reusable launch vehicles (RLVs). The second section discusses rationale for HLVs and RLVs and arguments that individuals and groups involved in the launch market offer for remaining a competitive space-faring nation. The third section examines future space access and how HLV and RLVs offer responsive spacelift.

2.1 Launch System Background

Historically, except for the Space Shuttle, all launch vehicles have been expendable [14]. The United States and other nations have each developed a series of expendable launch systems that have provided the desired worldwide launch rates. Current expendable systems launch a wide variety of payloads to low Earth orbit (LEO) and geostationary orbit (GSO). At the current launch rate, approximately 18 per year in the U.S. and 50 worldwide, expendable launch vehicles remain sufficient for current launch requirements [2]. However, the increasing launch rates of the future would prosper from a safer and more responsive launch system, which are two traits not inherent in current expendables.

The United States has been pursuing RLVs for the past five decades. In the 1950-1960s, the X-20 Dyna-Soar (Dynamic Soaring) was designed to be a reusable orbiter launched into low Earth orbit via an expendable booster. The X-20 was the first step towards military use of a manned space plane. Later versions of the X-20 were envisioned for satellite inspection, use as mini space stations, and use as a strategic orbital bomber [15]. The X-20 program was cancelled in 1963, but not at a total loss. Much of the research and technology regarding heat-resistant material went into the Space Shuttle [15]. A drawing of the X-20 can be viewed in Figure 1.

Figure 1. Drawing of Dyna-Soar In Orbit [14]

Starting in 1972, the Space Transportation System (STS), also known as the Space Shuttle, began development. Initially the Space Shuttle was intended to be a low cost-to-orbit, fully reusable launch system, but due to budgeting issues, NASA was forced to decrease the cost of development [18]. This move eliminated building a fully reusable first stage booster and instead focused on a reusable second stage orbiter. The design was changed to launching the second stage into orbit using cheap solid rocket boosters firing in parallel with the space shuttle main engine (SSME), as seen in Figure 2.

Figure 2. Space Shuttle Orbiter Separating from Solid Rocket Motors [18]

The use of an expendable fuel tank and the massive maintenance and inspection times drove the cost per launch of the Space Shuttle far beyond the intended low-cost design. Currently the Space Shuttle is the highest cost-per-launch, heavy lifter in the United States launch fleet [18]. NASA is planning to replace the Space Shuttle with a fully reusable launch system but, as of present, has failed to complete that task.

The X-30, National Aerospace Plane (NASP), as seen Figure 3, was a joint development project between NASA and the United States Air Force. Proposed to be a single-stage-to-orbit (SSTO) spacecraft, NASP would have been a hypersonic airbreathing launch system that would carry cargo and passengers to LEO at an inexpensive rate [16]. The X-30 was doomed from the beginning since it required propulsion and propellant storage technology that was many years down the road. Also, due to the SSTO design, NASP required airbreathing turbine engines to boost the vehicle to Mach 5, at which the hypersonic engines would take over. This SSTO design drove the weight of the vehicle up to the point that it was no longer feasible [5]. The NASP program was finally terminated in 1993 amid budget cuts.

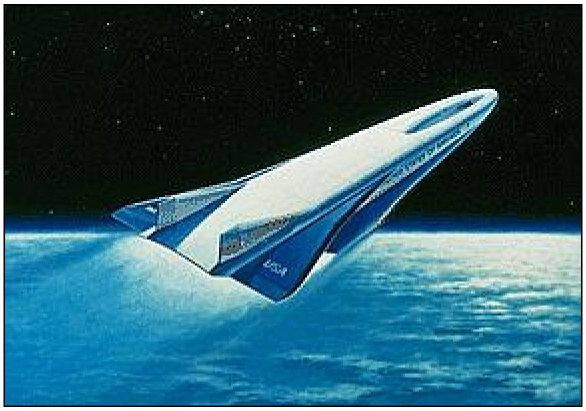

Figure 3. Drawing of National Aerospace Plane [16]

Currently, RLV development is no longer focused on using state-of-the-art technology, but rather proven technology such as rocket engines. The company, Space Exploration Technology, Space X for short, is developing the Falcon, a two-stage-to-orbit expendable launch system. The Falcon is planned to be a low-cost launch system that, once proven, would allow access to LEO for half the cost of current launch systems [19]. After becoming operational, Space X plans to investigate making the Falcon into an HLV by reusing the booster [19]. Figure 4 shows the Falcon I readying for launch at Vandenberg Air Force Base.

Figure 4. Falcon I on Launch Pad at Vandenberg Air Force Base [19]

Space X is not alone in the effort to design a low cost reusable launch system. Kistler Aerospace has been also developing a variant of a TSTO rocket-rocket launch system. The Kistler K-1 launch vehicle, seen in Figure 5, is designed to be completely reusable. The low development cost and minimal launch preparations of the Kistler K-1 would provide a low cost alternative to current services provided by Lockheed and Boeing [17]. However, due to investor difficulties, Kistler has been forced to put development of their vehicle on hold until further notice.

Figure 5. Drawing of Kistler K-1 Launch Vehicle During Launch [17]

HLVs and RLVs are not a new idea for delivering payloads to orbit. As discussed, their concepts have been researched and developed by both government and industry since the 1950s. The current expendable launch systems have been sufficient to this point but as the demand for lower cost per launch options increases, HLV and RLV systems will begin to be developed and employed. The next section will review the arguments that other authors offer for why RLVs and HLVs should or should not be developed.

2.2 Rational for Reusable Launch Systems

The mission needs statement for Operationally Responsive Spacelift, AFSPC 001-01, states that the United States Air Force requires the "capability to rapidly put payloads into orbit and maneuver spacecraft to any point in earth-centered space, and to logistically support them on orbit or return them to earth" [1]. The mission needs statement also states that the system must include cost effective means of executing DoD missions. These requirements, as well as others that are not listed here, all point to some sort of reusable launch system.

Hybrid and reusable launch vehicles would provide responsive launch capabilities. Unlike current expendable systems whose test flight is the mission, hybrid and reusable launch vehicles would be undergo flight testing. Also each reusable vehicle would be maintained after each flight allowing for defects to be identified and fixed. Finally, RLVs and HLVs are more robust systems with multiple redundant systems. The following drawing, Figure 6, is an artist rendition of the ARES launch vehicle on the launch pad.

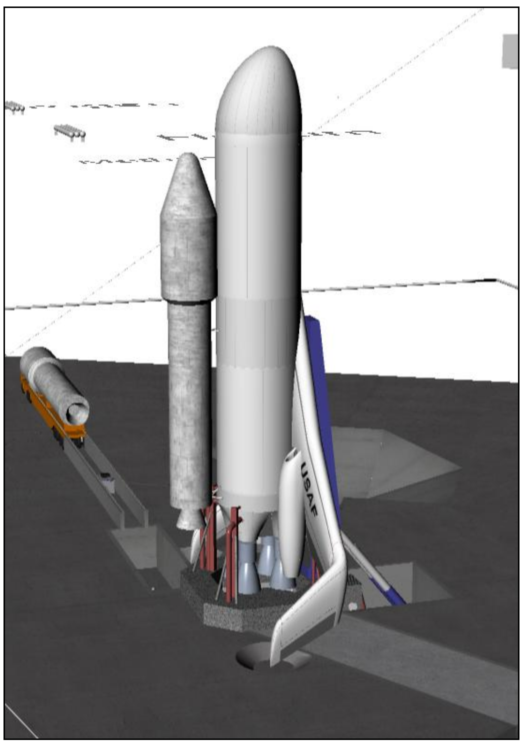

Figure 6. Drawing of Ares Launch Vehicle On Launch Pad [12]

Reusing engines is a first step in developing an HLV. An expendable launch vehicle uses multiple engines, each ranging in cost from 5-50 million dollars or more [10]. Reusing engines would be an excellent first step in lowering launch costs. Space Exploration Technologies plans to explore reusing the engines from the first stage booster on its Falcon launch vehicle [19]. A study done by Jason Mossman and David Perkins on the rocket propulsion technology impact on launch cost concludes that that reusability of rocket engines is the most important parameter in cutting launch costs with performance improvements being a distant second [11].

The average price-per-pound of payload to LEO for the United States is $12,000, while other countries, like Russia, China, and India, average $6,000 [3]. This disparity in launch costs is primarily due to the lower labor and infrastructure costs. This cost difference affects the United States when businesses are deciding which company to use to launch a satellite. The U.S. needs to recapture the launch market and the only way to do so is lowering the cost of launch. Many individuals similar to John Livingston, of the Air Force Aeronautical Systems Center (ASC), share this belief. Mr. Livingston argues that developing a Hybrid Launch System is the first step for the United States to recapture the world launch market [10].

2.3 Future Access to Space

The United States military and industry require assured access to space. To achieve this goal of safety and security, future launch systems need to be reliable and require aircraft like operations. Aircraft like operation do not mean that the vehicle must take off horizontally and land like an airplane. It simply means, that the vehicle will be dependable, easily maintainable at a low cost, and most of all, safe. Similar to current aircraft, future space vehicles will be designed so that in the event of a system failure, they will safely deliver the payload or abort mission and return the payload. Current aircraft are designed such that engine failure or bird strikes do not cause a catastrophic failure. Aircraft are robust enough and operate with redundant safety systems. Even after loss of a vital system, most aircraft can land safely. Aircraft are able to fly thousands of hours before a single overhaul. Future spacecraft will require similar system designs. Unlike the Space Shuttle, which requires tens of thousands of hours of maintenance and testing before and after each launch, future space vehicles will be lower cost to launch and more reliable than current expendable systems [13]. RLVs are also inherently safer than ELVs. Unlike expendable launch systems whose maiden flight is the payload delivery flight, a reusable launch vehicle is flown, tested, and proven to be launch capable [13].

3. Methodology

This chapter discusses the methodology used to develop the mass and cost estimating relation models and the comparison model. This chapter details how these three models were used to analyze system costs for the three launch system alternatives. Sensitivity analyses were performed to understand how payload and launch rate affected costs. Detailed discussion of cost analysis is found in Chapter 4: Results and Analysis.

3.1 Transcost 7.1 Best Fit Methodology

A large portion of the work done in this study builds upon the methodology established in "The Handbook of Cost Engineering for Space Transportation Systems" by Dr. Dietrich Koelle. Koelle uses data from historical launch systems to develop best fit curves to approximate development cost, first unit production costs, and other factors pertaining to launch systems [9]. This study builds upon Koelle's work and uses the data assembled to generate best fit curves which approximate development and first unit production costs. K-Factors, also known as correlation factors, were applied when deemed applicable. Maintenance costs were approximated using relations provided by Brendon Rooney of ASC/XREC.

3.2 Mass Estimating Relations

The first step for this study was construction of a mass estimating model (Appendix A). ELV, HLV, and RLV masses were approximated using standard rocket equations found in any space propulsion textbook. The MER model was sufficient for this study; however future users of the MER model methodology will most likely generate their own MER model for approximation of vehicle dry mass. A detailed step-by-step explanation of the MER model can be found in Appendix A.

Assumptions were made for the total change in velocity (delta V) required by the launch vehicle to reach low Earth orbit to be 30,000 ft/s [7]. This assumed delta V accounts for aero, gravity, and back pressures losses experienced during launch. For the ELV, the assumed first and second stages Isp were 300s and 320s respectively [10]. The ELV stage Isp used were consistent with current expendable engines. The RLV used 320s and 350s for the Isp of the first and second stages while HLV used 320s for the Isp of both stages [10]. HLV first stage and both RLV stages can afford using a more efficient engine due to their reusability. However, the MER model is sensitive stage Isp. Isp can be input by future users if a different stage Isp is preferred for the alternatives. It was also assumed that the first stage completed 40% of the required delta V and the second stage completed the remained 60% to place the vehicle into LEO. A structural mass fraction of 0.045 was used for ELVs [7]. The HLV and RLV structural mass fractions were approximated via summarizing the mass fractions for wings and landing gear, stack, and thermal protection system (TPS).

ELV dry mass predicted by the MER model (Appendix A) was compared to the dry mass of existing ELVs used by industry [13]. Table 1 includes the names of the expendable vehicles and their corresponding masses. Figure 7 illustrates how well the model approximated total dry mass. The data points correspond to the current expendable vehicles from Table 1. The blue line is the total dry mass of the vehicle with respect to the payload mass. The red line is the dry mass of the second stage. The first stage dry mass can be found by subtracting the second stage dry mass (red line) from the total dry mass (blue line). Also note, Figure 7 describes how dry mass changes with respect to change in stage Isp.

Table 1. Expendable Launch Vehicle Data [14]

Vehicle	Payload (lbm)	Total Dry (lbm)
Angara 1.1	4409	25574
Angara 1.2	8157	27238
Atlas I	8003	21676
Delta IV Medium	18960	65279
Titan II	4189	20150
Zenit 2	29762	82894

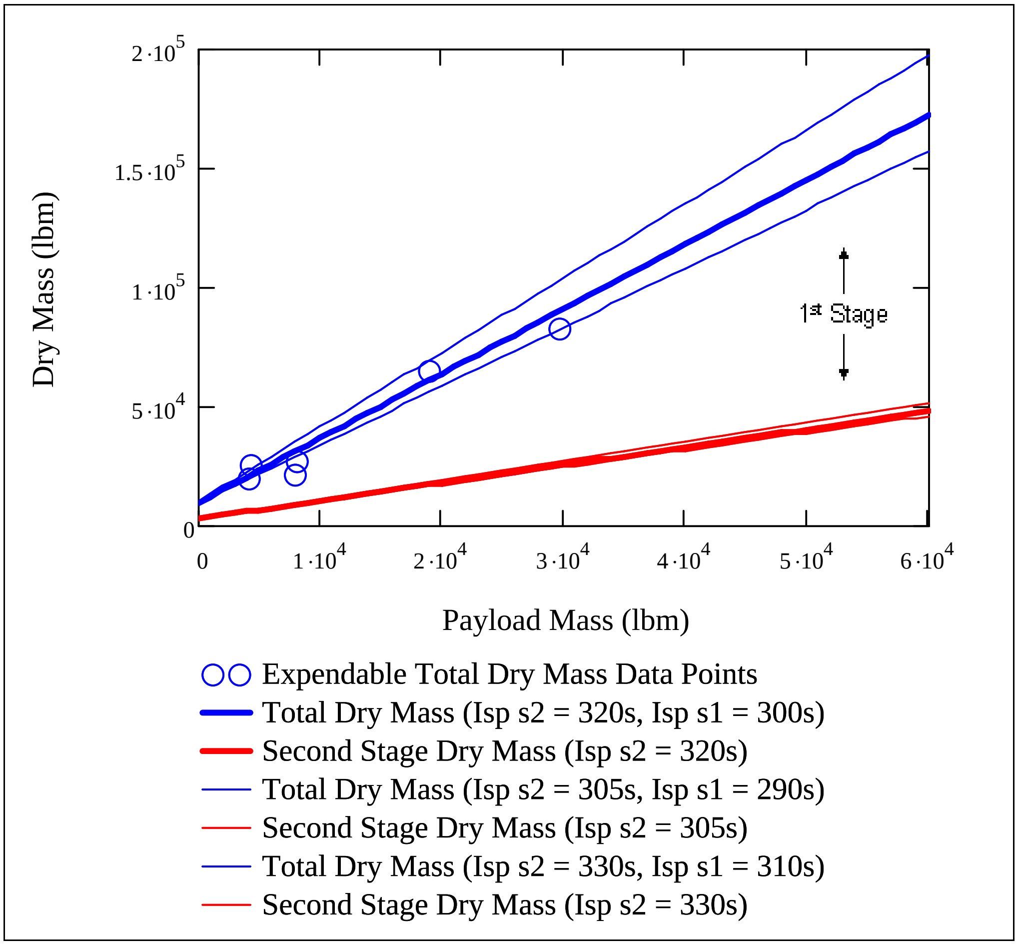

Figure 7. ELV Total Dry Mass versus Payload Correlated To Existing ELVs

The same process was completed for both HLVs and RLVs. Figures 8 and 9 detail how well the model approximates HLV and RLV total dry mass. The HLV and RLV models were correlated to Responsive Military Launch System (RMLS) studies performed by both government agencies and industry. The sharp decrease in dry mass at small payloads is due to the square-cubed relation of TPS. At very high payloads, the TPS mass fraction approaches zero [10]. Tables 2 and 3 include the names of the Hybrid and Reusable launch vehicles and their corresponding masses.

Table 2. Reusable Launch Vehicle RMLS Data [4]

Vehicle	Payload (lbm)	Total Dry (lbm)
RMLS-102--5kpyld-rprp-v7k-fb-s	5000	147618
RMLS-102-rprp-v7k-fb-s	15000	230705
RMLS-108-ch4ch4-fb-s	15000	232578

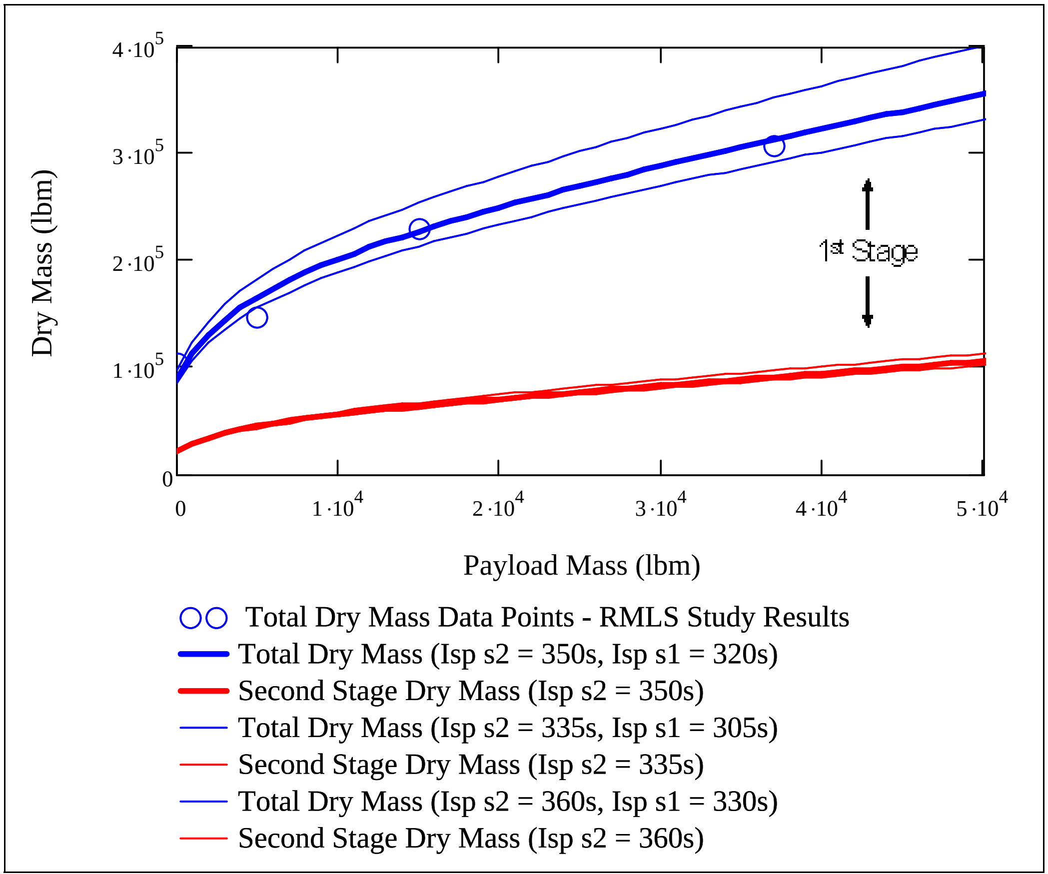

Figure 8. RLV Total Dry Mass versus Payload Correlated To RMLS Studies

Table 3. Hybrid Launch Vehicle RMLS Data [4]

Vehicle	Payload (lbm)	Total Dry (lbm)
RMLS 107-2750	2750	49433
RMLS 107-rpsol	15000	110140
RMLS 107-rprp	15000	99937
RMLS 107-rplh	15000	85226

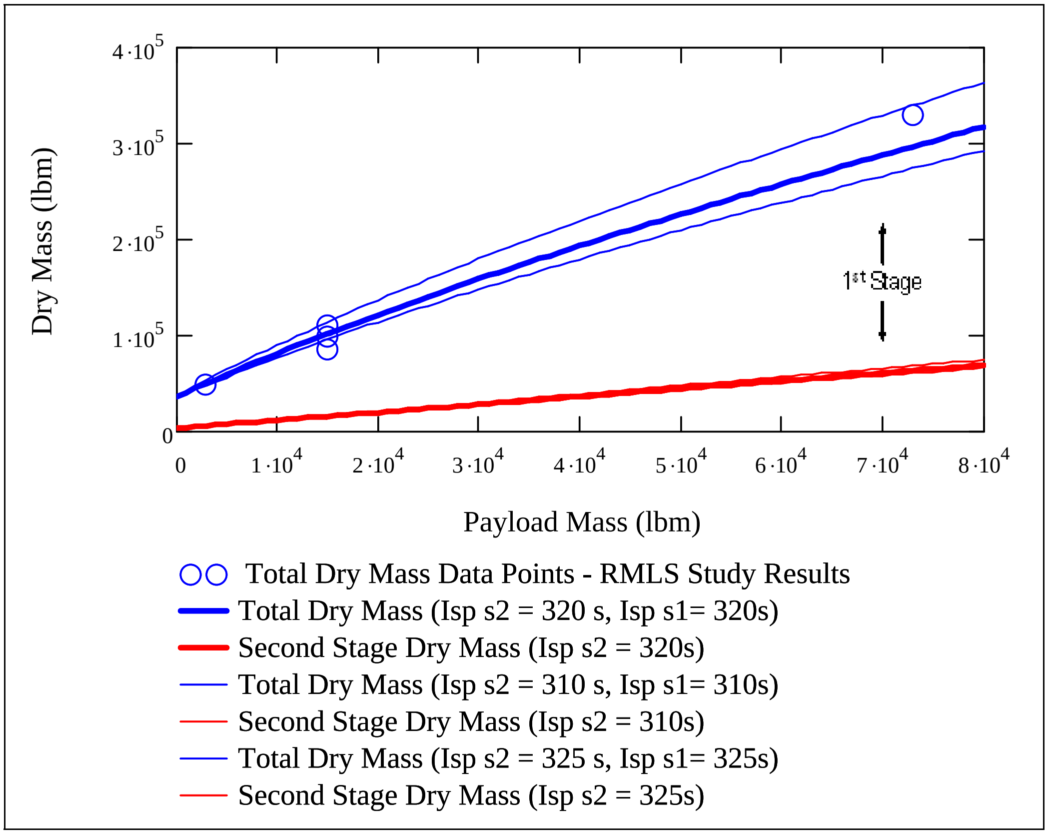

Figure 9. HLV Total Dry Mass versus Payload Correlated To RMLS Studies

3.3 Cost Estimating Relationships

The following sections cover the cost estimating relations for development, first unit production, and maintenance costs of ELV, HLV, and RLV airframes and engines. Costs from the CER model (Appendix B) are outputted in Man Years (MYRs) but can be converted to present dollars; one MYr was approximately $230,000 in 2004. Figure 10 details the different dollar equivalent of one MYr for the past 60 years [9: 19]. A detailed step-by-step explanation of the CER model can be found in Appendix B.

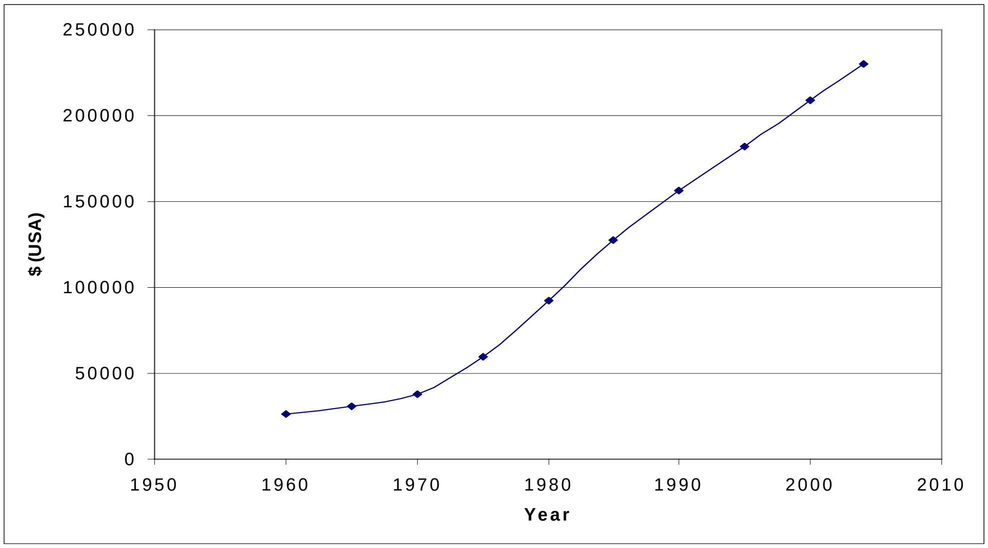

Figure 10. Man Year Costs over the Past 60 Years [9]

3.3.1 Airframe Development CER

Airframe development CERs were derived from best fit of data provided by Koelle's "Handbook of Cost Engineering for Space Transportation Systems" [9: 52-70]. Airframe development is a function of stage dry mass. The CERs developed in the CER model (Appendix B) for expendable and reusable airframe development costs are given in equations (1) and (2).

$$\text{Development}_{\text{airframe expendable}} = 150 \times \text{Mass}_{\text{stage}}^{0.48} \tag{1}$$

$$\text{Development}_{\text{airframe reusable}} = 250 \times \text{Mass}_{\text{stage}}^{0.48} + 2000 \tag{2}$$

These expendable and reusable airframe development CERs differ from Koelle [9]. When compared, the reusable and expendable airframe development CERs developed by Koelle showed an inconsistent trend for increasing stage dry mass. The difference between the reusable and expendable airframe development CERs decreased as stage dry mass increased. For this reason, two new curves were generated that better approximate development effort as a function of dry mass. Refer to Figures 11 and 12 for illustration of airframe development versus stage dry mass.

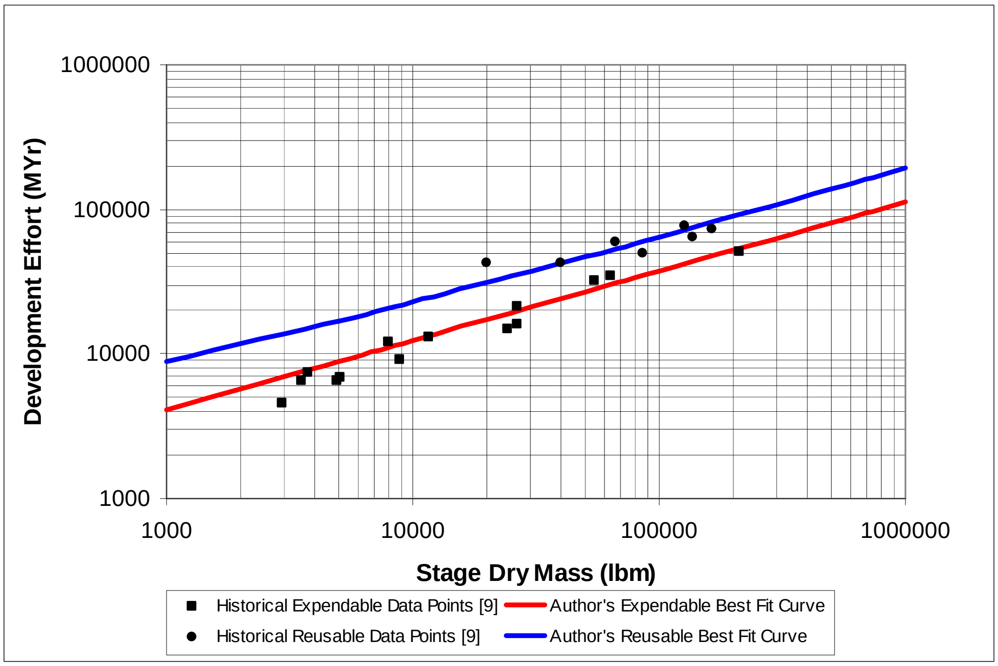

Figure 11. ELV and RLV Stage Development Cost on Log-Log Plot [9]

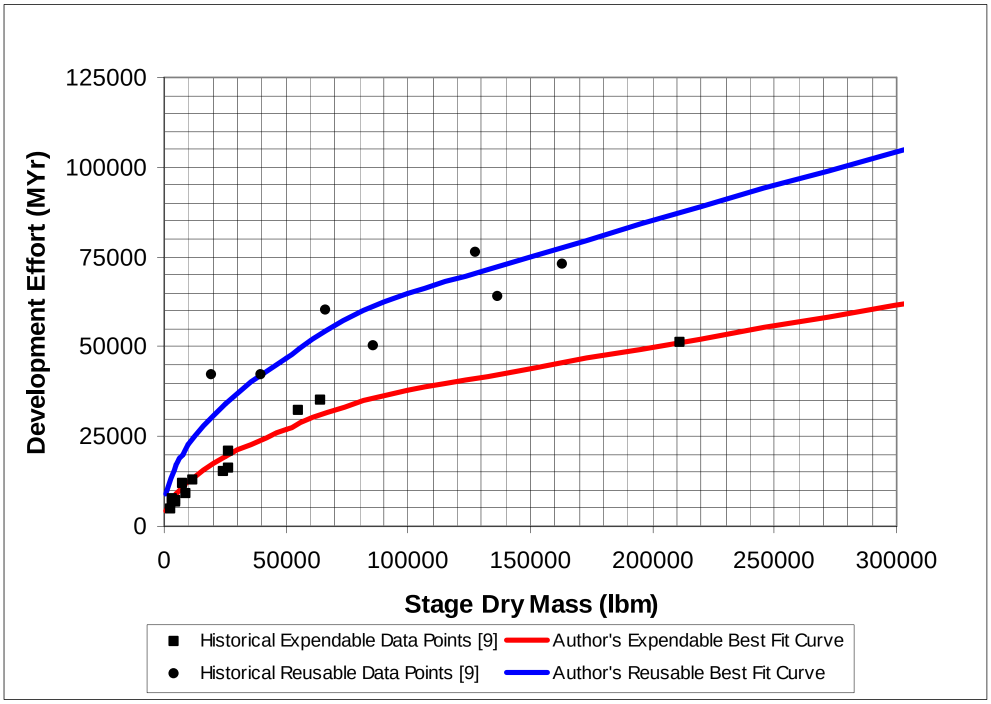

Figure 12. ELV and RLV Stage Development Cost on Linear Plot [9]

HLV development costs are calculated using the same RLV first stage and ELV second stage development CERs. The reason for this is because of the definition of HLVs used in this study. HLVs are defined to have a first stage reusable booster and second stage expendable orbiter.

3.3.2 Airframe First Unit Production CER

Airframe first unit production costs (FUPC) were determined via the same method as airframe development costs [9: 120-130]. Existing FUPC data was correlated with a best fit power curve. The CER model (Appendix B) approximates expendable and reusable airframe FUPC using equations (3) and (4).

$$\text{FUPC}_{\text{Expendable}} = 0.62 \times \text{Mass}_{\text{stage}}^{\ 0.63} \tag{3}$$

$$\text{FUPC}_{\text{Reusable}} = 1.1 \times \text{Mass}_{\text{stage}}^{\ 0.62} \tag{4}$$

Stage mass, calculated by the MER model (Appendix A), was input for each airframe FUPC CER. As for airframe development costs , the hybrid airframe FUPC uses the RLV first unit production CER for the first stage and the ELV first unit production CER for the second stage. The reusable airframe FUPC CER developed by Koelle's was found to be inconsistent with the expendable FUPC CER, as seen in the CER model (Appendix B). Comparison of the two CERs on the same graph revealed that Koelle's predicted reusable airframe production was less than expendable vehicles with the same stage dry mass for low sizes. This was invalid due to the increase in system and airframe robustness required by reusable vehicles. To correct for this error, a new best fit curve was developed, equation (4). The trend of the updated FUPC CERs can be observed in Figures 13 and Figure 14.

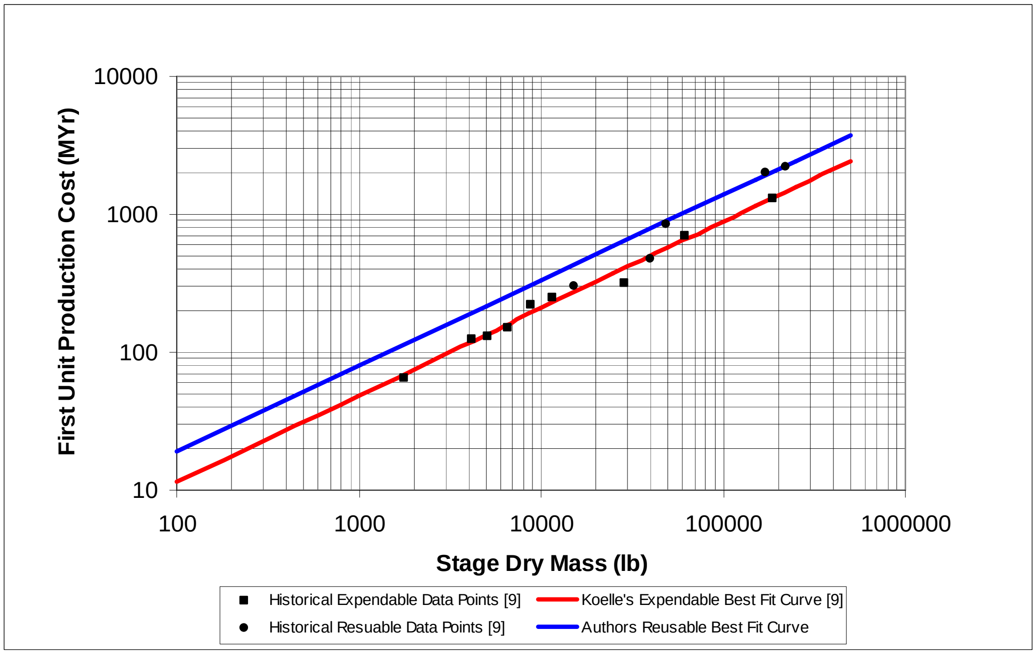

Figure 13. ELV and RLV First Unit Stage Production Cost on Log-Log Plot [9]

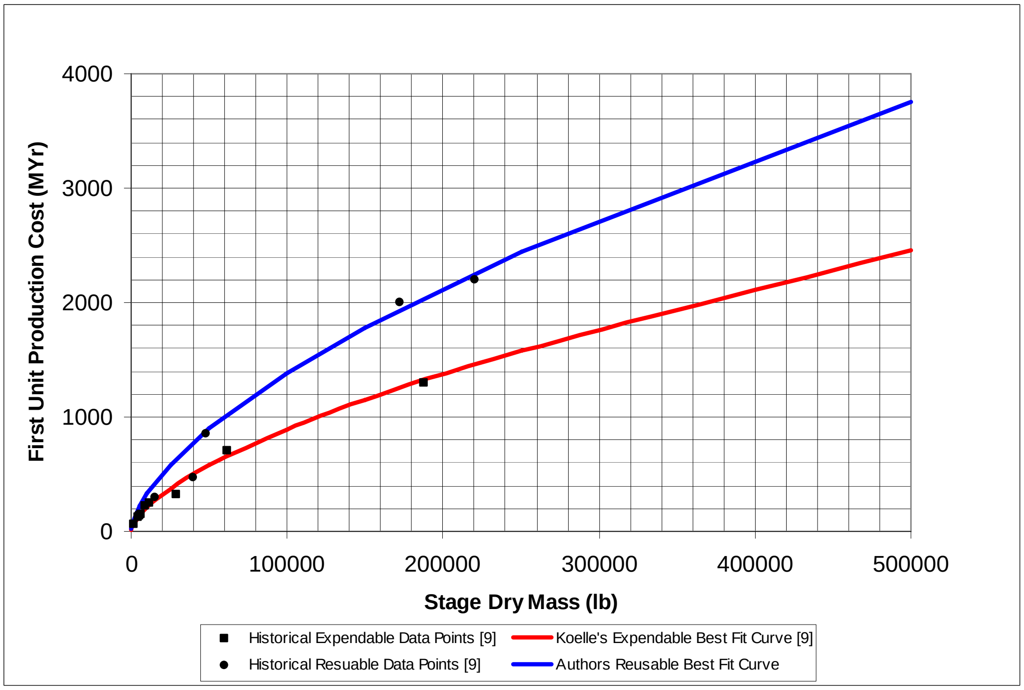

Figure 14. ELV and RLV First Unit Stage Production Cost on Linear Graph [9]

Since a new ELV must be manufactured for each launch, the cost for production decreases as launch rate increases. A common learning factor used for launch vehicles is every time you double production, the cost of each vehicle produced is roughly 90%-95% of the previous group [9: 125]. This learning factor also holds for the second stage of the HLV since it too is expendable. Equation (5) is the learning factor used for airframe production. A learning factor of 95% would result in a 29% reduction of FUPC after the 100th unit produced.

$$\text{Learning Factor} = \#_{\text{Launches}} \times \frac{\ln(\%\ \text{Reduction})}{\ln(2)} \tag{5}$$

The HLV first stage and the RLV use a fleet of vehicles to complete the required number of launches. As the number of launches increase, so does the fleet size required to complete the desired number of launches. The equation used to calculate fleet size is as follows:

$$\text{Fleet Size} = ceil\left(\frac{\text{Life}_{\text{Launch System}} \times \text{Launch}_{\text{rate}}}{\text{Maximum Launch Life}} + \text{Life}_{\text{LaunchSystem}} \times \text{Launch}_{\text{rate}} \times \text{Losses Per Launch}\right) \tag{6}$$

Fleet Size is a ceiling function that takes the minimum number of reusable vehicles required for the system lifetime based on the maximum launch life of each vehicle and adds to it extra vehicles for replacing vehicles lost due to random catastrophic events. The equation for fleet size and the assumed inputs can be found in the Comparison Model (Appendix C)

3.3.3 Engine Development CER

Engine development costs were also derived from Koelle's work [9:35-40]. Existing engine data points were correlated with a best-fit power curve and a sanity check applied to the resulting relations. Engine development costs are dependent on the engine dry mass [9]. To calculate engine dry mass, vacuum thrust is determined using equation (7). The vacuum thrust level is calculated by multiplying vacuum thrust correction factor, 1.55, by the gross mass of the launch vehicle and dividing by the number of engines for that stage [10].

$$\text{Thrust}_{\text{vacuum}} = \frac{1.55 \times \text{Gross Mass}}{\#_{\text{Engines}}} \tag{7}$$

Koelle described that engine dry mass is roughly related to the vacuum thrust, equation (8) [9]. Engine dry mass is a best fit of existing data points as can be seen in Figure 15.

$$\text{Engine Dry Mass} = 0.17 \times \text{Vacuum}_{\text{Thrust}}{}^{0.80} \tag{8}$$

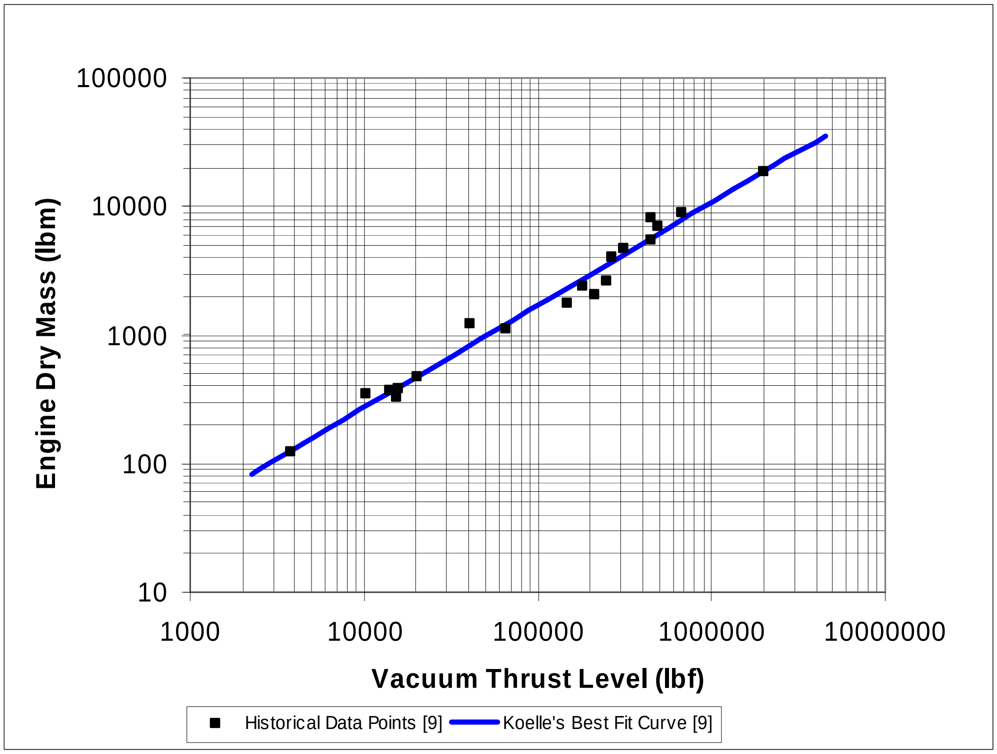

Figure 15. Engine Dry Mass Versus vs. Thrust Level [9]

After calculation of engine dry mass, equations (9) and (10) relate engine development cost to engine dry mass. A best fit power curve was used for the engine development CERs [9]. A K-factor of 1.5 is included in the reusable engines to account for extra development needed to produce an engine with a higher reliability. Both equations for engine development are illustrated in Figure 16.

$$\text{Engine Development}_{\text{Expendable}} = 124 \times \text{Engine Dry Mass}^{0.52} \tag{9}$$

$$\text{Engine Development}_{\text{Reusable}} = 1.5 \times 124 \times \text{Engine Dry Mass}^{0.52} \tag{10}$$

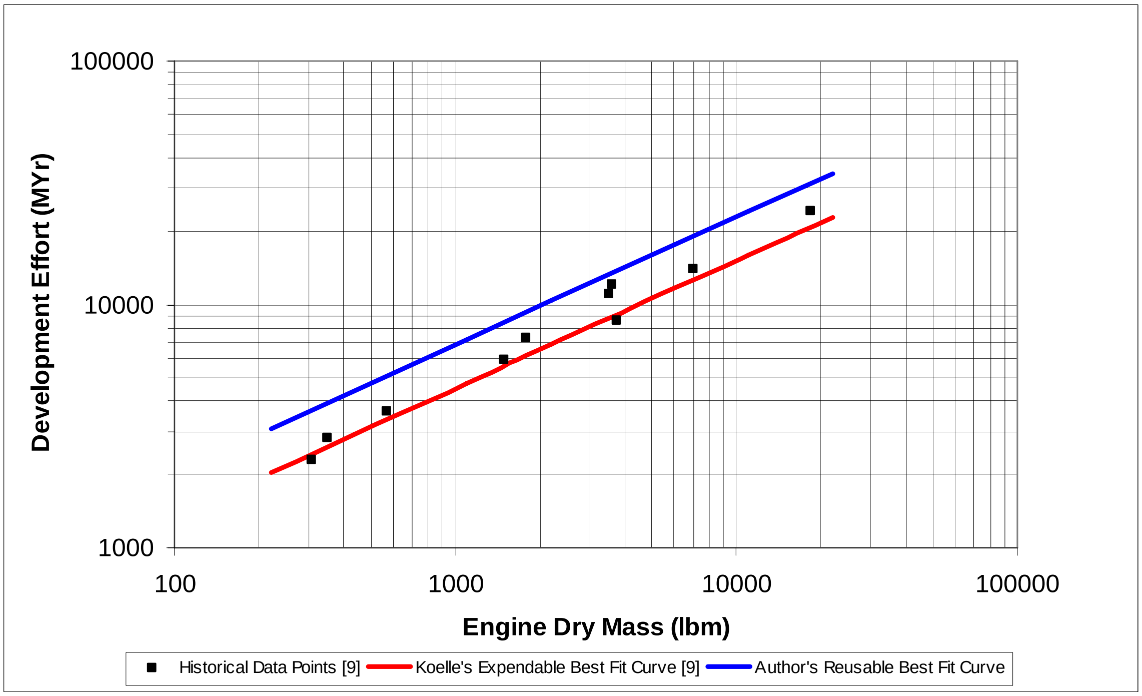

Figure 16. Engine Development Effort vs. Engine Dry Mass [9]

3.3.4 Engine First Unit Production CER

Engine first unit production costs are related to engine dry mass [9: 124-130]. Equations (11) and (12) detail the relationship of engine first unit production cost to engine dry mass. A K-factor of 1.3 is included in CER for engine first unit production costs of RLV and first stage of HLV to account for production of a more reliable and robust engine. Figure 17 illustrates the trend of the engine FUPC CER.

$$\text{Engine FUPC}_{\text{expendable}} = 3.72 \times \text{Engine Dry Mass}_{\text{expendable}}{}^{0.45} \tag{11}$$

$$\text{Engine FUPC}_{\text{reusable}} = 1.3 \times 3.72 \times \text{Engine Dry Mass}_{\text{expendable}}{}^{0.45} \tag{12}$$

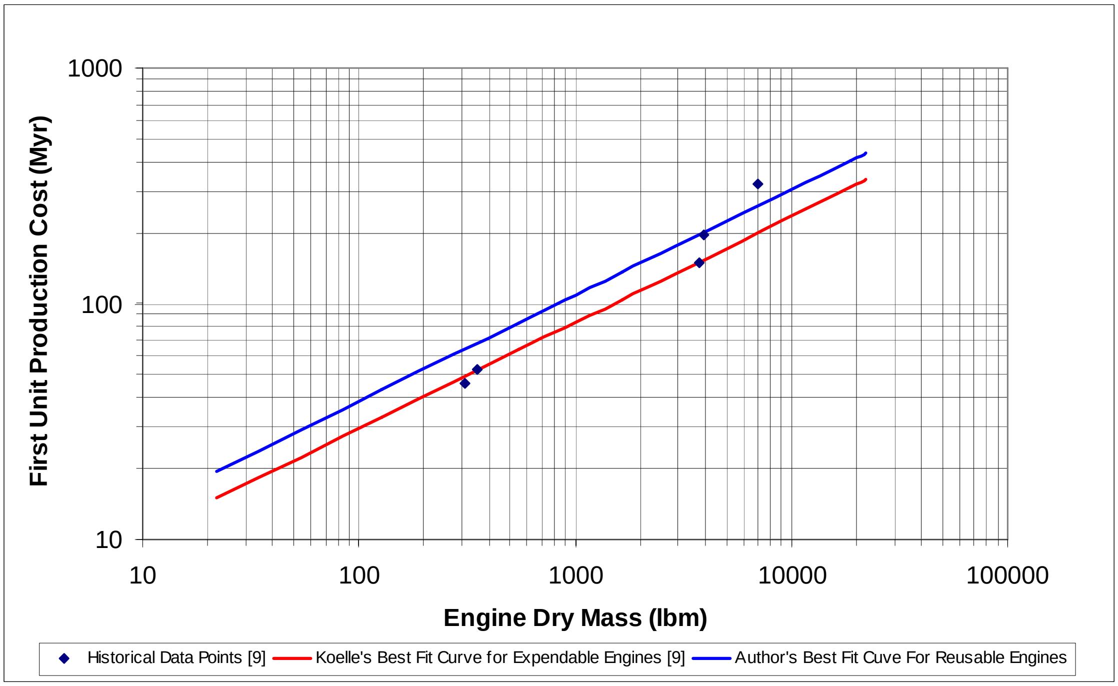

Figure 17. Engine First Unit Production Cost vs. Engine Dry Mass [9]

Both ELV stages and the second stage of the HLV will require the purchasing of new engines for every flight while the RLV and the first stage of the HLV will reuse engines for a given amount of launches. A learning factor, equation (13), is applied to the engine FUPC CER [9]. Figure 18 details the trend of the engine production learning factor.

$$\text{Learning Factor}_{\text{Engine Production}} = -0.553 \times \ln(\text{Engines}_{\text{Produced}}) + 1.0011 \qquad (13)$$

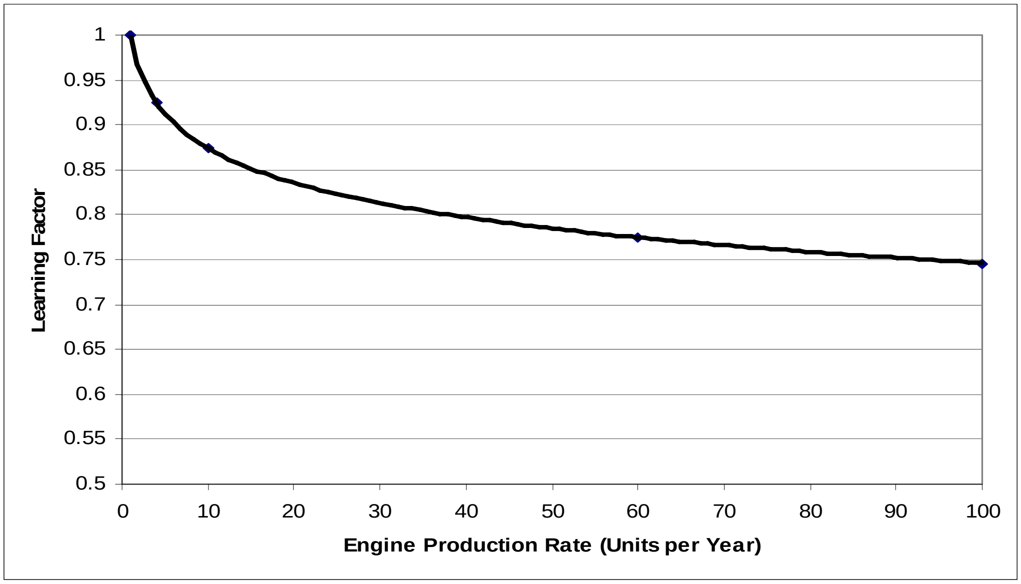

Figure 18. Learning Factor vs. Engine Production Rate [9]

3.3.5 Vehicle Maintenance CER

Vehicle maintenance includes airframe, engine, and subsystems for the reusable and hybrid launch vehicles. Since the HLV first stage and RLVs are launched more than once, the cost for turning the vehicle around must be included for DPM analysis. Also, vehicle maintenance is important when designing a military system. Maintenance time helps determine the fleet size required to carry out military-like operations with bomber-like sortie rates [10]. The engine maintenance CER was developed by Brendan Rooney of ASC/XRE [12]. Subsystem maintenance was assumed to be 250 man hours for first stage booster and 500 man hours for the second stage orbiter [12]. Airframe maintenance is related to wetted area of the vehicle. To calculate area maintenance, relationships of TPS area percentages were derived from calculated maintenance times from previous work done by Mr. Rooney. A more detailed breakdown of all maintenance costs can be found in Appendix B: Cost Estimating Relations. It is important to note that maintenance costs are very uncertain since no hybrid or reusable vehicles have been developed that provide accurate data. For this reason, maintenance costs must be viewed as being a best-guess estimate.

3.4 Comparison Model

The comparison model (Appendix C) incorporates both the MER and CER models (Appendices A and B). The comparison model requires user input regarding launch system lifetime, launch rate, payload mass, and max vehicle life of HLV first stage and RLVs. The model calculates the stage dry mass for each vehicle type and uses those masses to determine the development effort, first unit acquisition costs, and maintenance costs. The model compares the different life cycle costs of the different vehicle options for a series of development scenarios. For this study, life cycle costs will consist of development, first unit production, and maintenance costs (DPM). Life cycle costs are described this way because ground launch costs and vehicle decommissioning costs are not included in the model. The scenario comparisons will be discussed further in Chapter 4: Results and Analysis.

4. Results and Analysis

The following chapter discusses the results and analysis from the study. The research done through this study was completed to assist ASC/XRE in the costing of the ARES (Affordable Responsive Spacelift) hybrid launch vehicle, as seen in Figure 6. A payload mass of 15,000 lbs was used for a majority of the calculations. Results were calculated using the MER, CER, and comparison models, found in Appendices A, B and C. Appendix A contains the documented methodology for the MER model. Appendix B contains the CER model and Appendix C contains the comparison model. The Comparison model includes the assumptions used for this study and the corresponding calculations for mass and costs.

4.1 Vehicle Sizing

Vehicle size for each alternative was predicted using the MER model (Appendix A). The MER model uses payload mass and stage Isp to calculate vehicle dry mass. As discussed in section 3.2, the MER model correlates well to existing launch vehicle data from industry and RMLS data produced by both industry and government. Table 4 contains the stage Isp used for each vehicle alternative. Table 5 details predicted vehicle dry mass while Figure 19 graphically displays the predicted dry masses for each alternative sized for a payload mass of 15,000 lbs.

Table 4. Stage Isp for Each Vehicle Alternative

Vehicle Type	1st Stage (s) Isp	2nd Stage Isp (s)
Expendable	300	320
Hybrid	320	320
Reusable	320	350

Table 5. Vehicle Sizing @ Payload of 15,000 lbs

Vehicle Type	1st Stage Dry (lbm)	2nd Stage Dry (lbm)	Total Dry (lbm)
Expendable	35996	13950	49946
Hybrid	86273	15109	101382
Reusable	163551	63673	227224

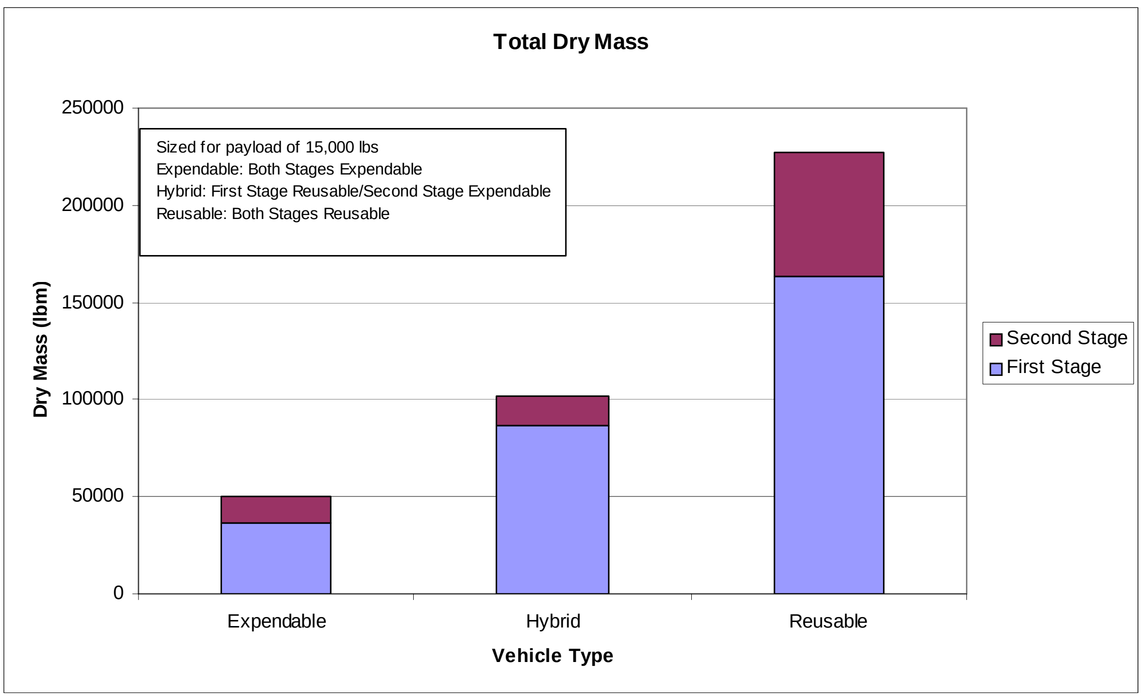

Figure 19. Dry Mass for Each Vehicle Type

The HLV and RLV are both more massive than the expendable. The HLV is roughly two times, while the RLV over four times the mass of the ELV. The reason for the increased dry mass is due to the aero surfaces, TPS, and landing gear required by the first stage for the HLV and both stages for the RLV.

4.2 Airframe Development Effort

The development efforts for vehicles sized with a payload mass of 15,000 lbs are found in Table 6. Development effort was calculated using the CER model (Appendix B). The ELV development effort converted to 2004 U.S. currency is $8.7 billion. The HLV is roughly twice and the RLV is about 3.5 times that of the ELV alternative. Figure 20 illustrates airframe development versus payload mass. Figure 20 was generated using the comparison model (Appendix C) by plotting development effort against payload mass.

Table 6. Airframe Development Effort @ Payload of 15,000 lbs

Vehicle Type	Airframe Development Cost (2004 $)
Expendable	8.7 billion
Hybrid	17.4 billion
Reusable	30.8 billion

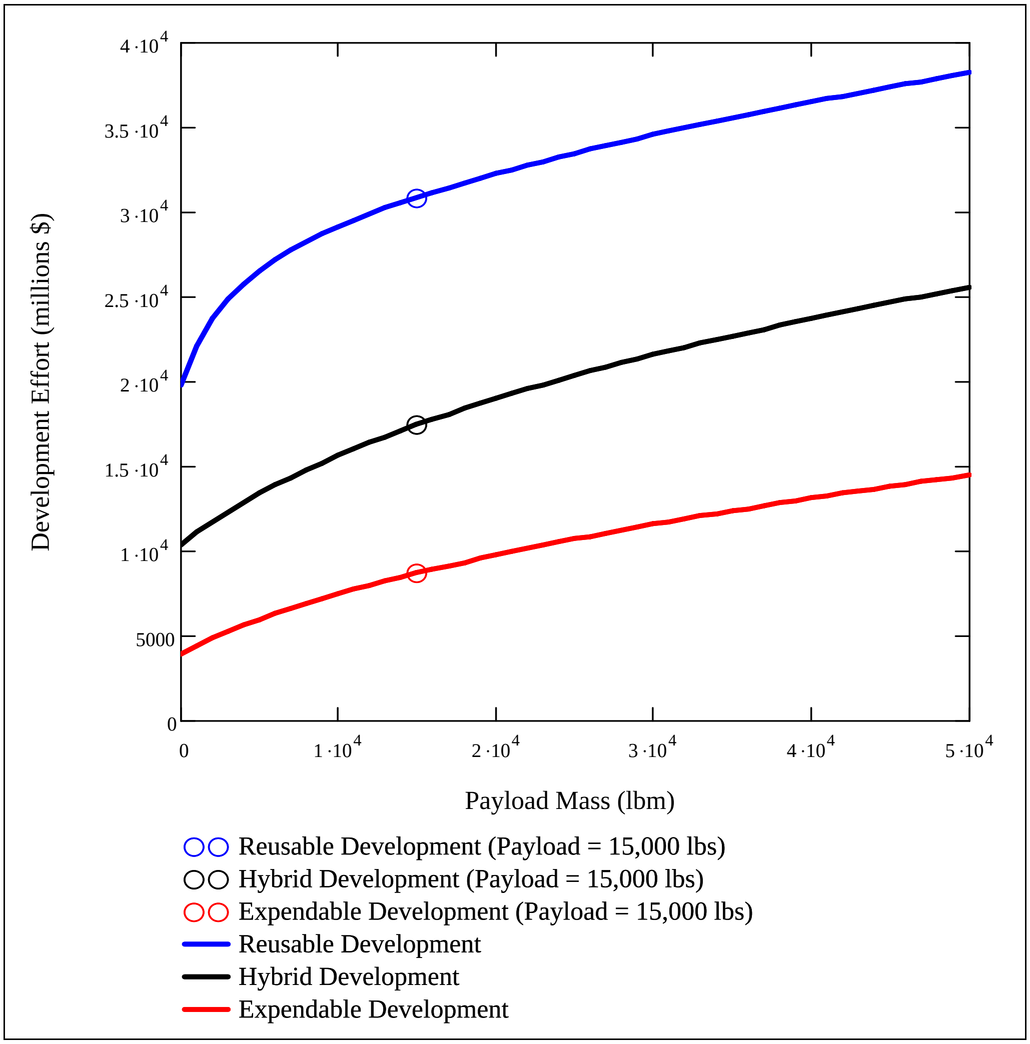

FIGURE 20. Development Effort vs. Payload Mass for Each Vehicle Option

4.3 Airframe First Unit Production Costs

First unit production costs are the price tag of building the first unit. Production costs decrease as more vehicles are manufactured through application of a production learning factor. A production learning factor is significant for an expendable vehicle due to the requirement of a new vehicle for each launch. The CER model predicts an ELV airframe cost of $167 million. For a learning factor of 95%, the production cost will decrease to 71% of the FUPC after the 100th vehicle is produced. A Delta IV Medium launch vehicle delivers an equivalent payload for a launch cost of $130 million in 2004 dollars [14]. With the application of a learning curve, the CER model predicts a similar production cost. The learning factor also applies to the second stage of the HLV since that stage is expendable. Table 7 contains the FUPC of the different vehicle options sized for a payload of 15,000 lbs and Figure 21 illustrates FUPC versus payload mass. Both Table 6 and Figure 21 were developed using the CER and comparison models (Appendices B and C).

Table 7. Airframe First Unit Production Costs @ Payload of 15,000 lbs

Vehicle Type	First Unit Production Cost (2004 $)
Expendable: Total	167 million
Hybrid: First Stage	290 million
Hybrid: Second Stage	62 million
Reusable: Total	673 million

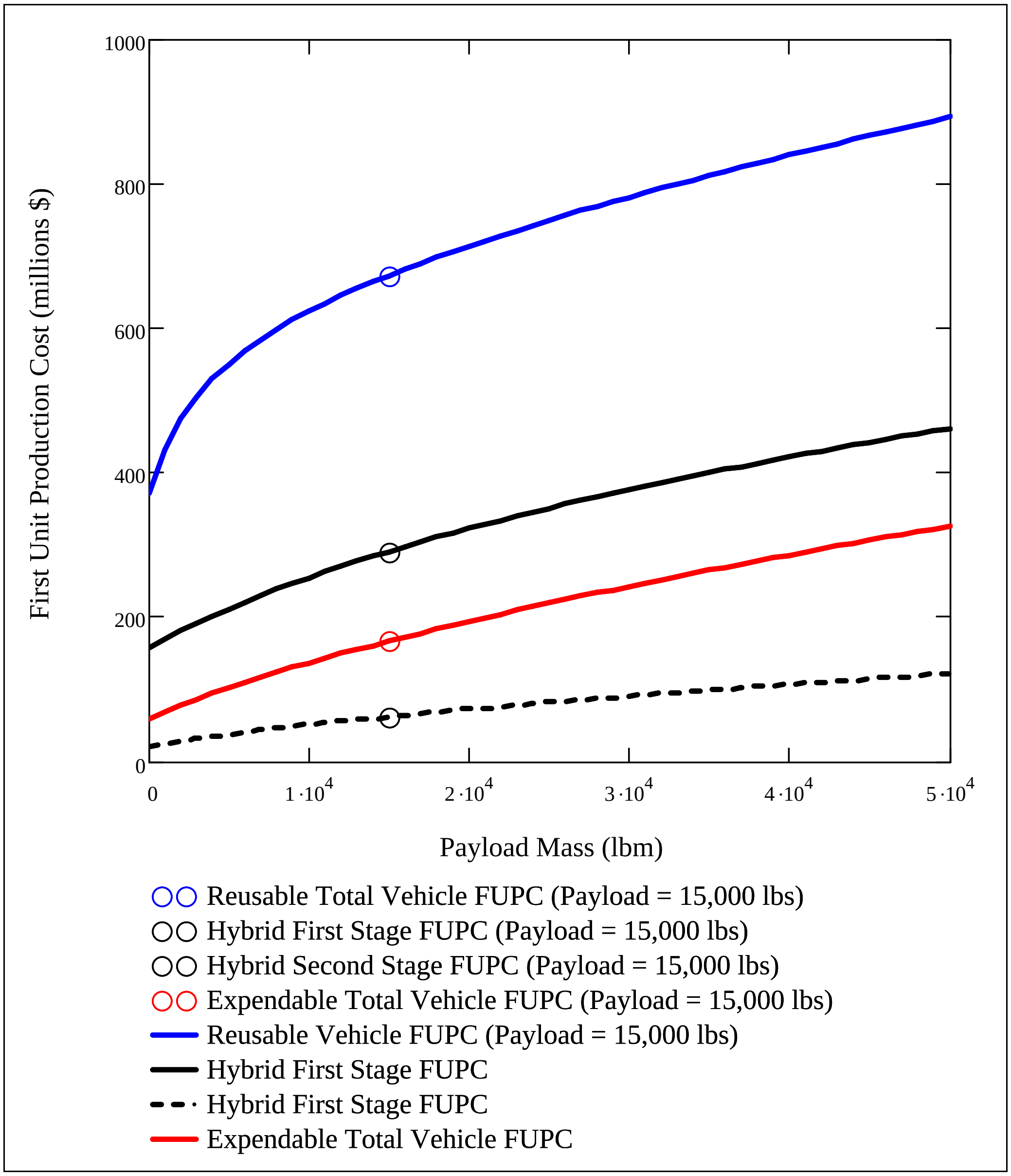

Figure 21. First Unit Production Costs vs. Payload Mass for Each Vehicle Option

4.4 Engine Development Effort

Engine development is related to the size of the engines. A launch system can use smaller engines which cost less to develop but will require more engines per stage, increasing production costs. As stated earlier in the section 3.3.3, the reusable engines development effort is increased by a K-Factor of 1.5 to account for the extra reliability required for engine reusability. That K-Factor is included in the equation for reusable engine development. Table 8 and Table 9 detail engine sizing and the corresponding engine development effort, in 2004 dollars, predicted by the CER model for each alternative. Refer to the CER model (Appendix B) for the methodology of engine development costs and the comparison model (Appendix C) for the exact development effort calculated for the given inputs.

Table 8. Engine Size @ Payload of 15,000 lbs

Vehicle Type	Number of Engines First Stage	First Stage Engine Thrust (lbf)	Number of Engines Second Stage	Second Stage Engine Thrust (lbf)
Expendable	1	1079433	1	182100
Hybrid	4	320248	1	63130
Reusable	4	682726	3	142055

Table 9. Engine Development Costs @ Payload of 15,000 lbs

Vehicle Type	First Stage Engine Development (2004 $)	Second Stage Engine Development (2004 $)	Total Engine Development (2004 $)
Expendable	3.68 billion	1.75 billion	5.43 billion
Hybrid	3.33 billion	1.78 billion	5.11 billion
Reusable	4.56 billion	2.37 billion	6.93 billion

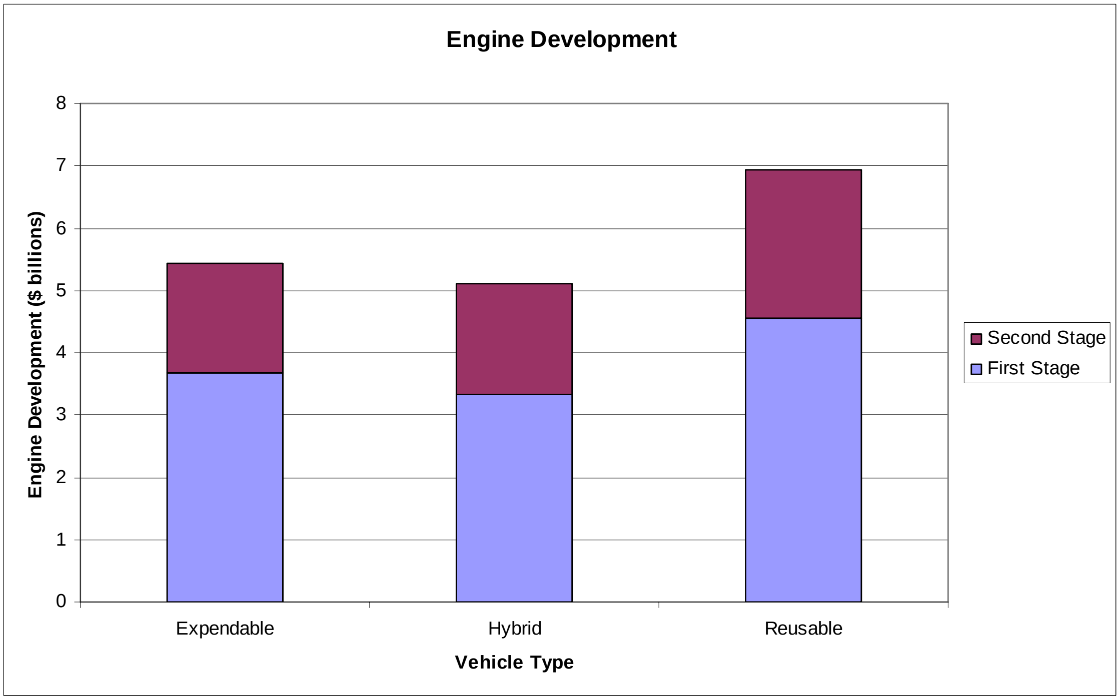

Figure 22. Engine Development for Payload Mass of 15,000 lbs

4.5 Maintenance Costs

Maintenance costs were included in the examination of DPM cost. The maintenance calculated using the comparison model (Appendix C) to turn the vehicles for launch was found to be minimal, around $1 million for the reusable and $270,000 for the hybrid. These costs corresponded to 6,000 and 1,330 hours respectively. Figure 23 shows the minuscule impact of varying maintenance time on DPM. To understand the impact of maintenance, a high approximation of 10,000 hours per launch for the reusable and 3,800 hours per launch for the hybrid were used for the comparison. The total cost for the 10,000 hour maximum maintenance time equated to $80 million dollars after 400 launches for the reusable launch vehicle. This is pennies compared to the total cost of the system. However, as stated earlier, maintenance time does affect fleet size. For military applications, during a surge in launch requirement, fleet size will need to be increased to provide the required sortie rates. The following example illustrates how maintenance time impacts fleet size.

A reusable vehicle sized for a payload mass of 15,000 lbs is estimated to require a total of 6,000 hours of maintenance time after each flight. If the maximum number of people able to work on the vehicle at any one time was limited to 50 individuals, then a vehicle could be ready for flight after a minimum of 120 hours. This would include vehicle and engine inspection, replacing broken TPS panels, and other activities. If surge operations dictated launch rates of 1-3 launches per day, then a small fleet size of 3 vehicles would be insufficient to accomplish mission needs. Instead fleet size would need to consist of 5-20 vehicles since each vehicle would be under maintenance for roughly 5 days and therefore, unable to launch.

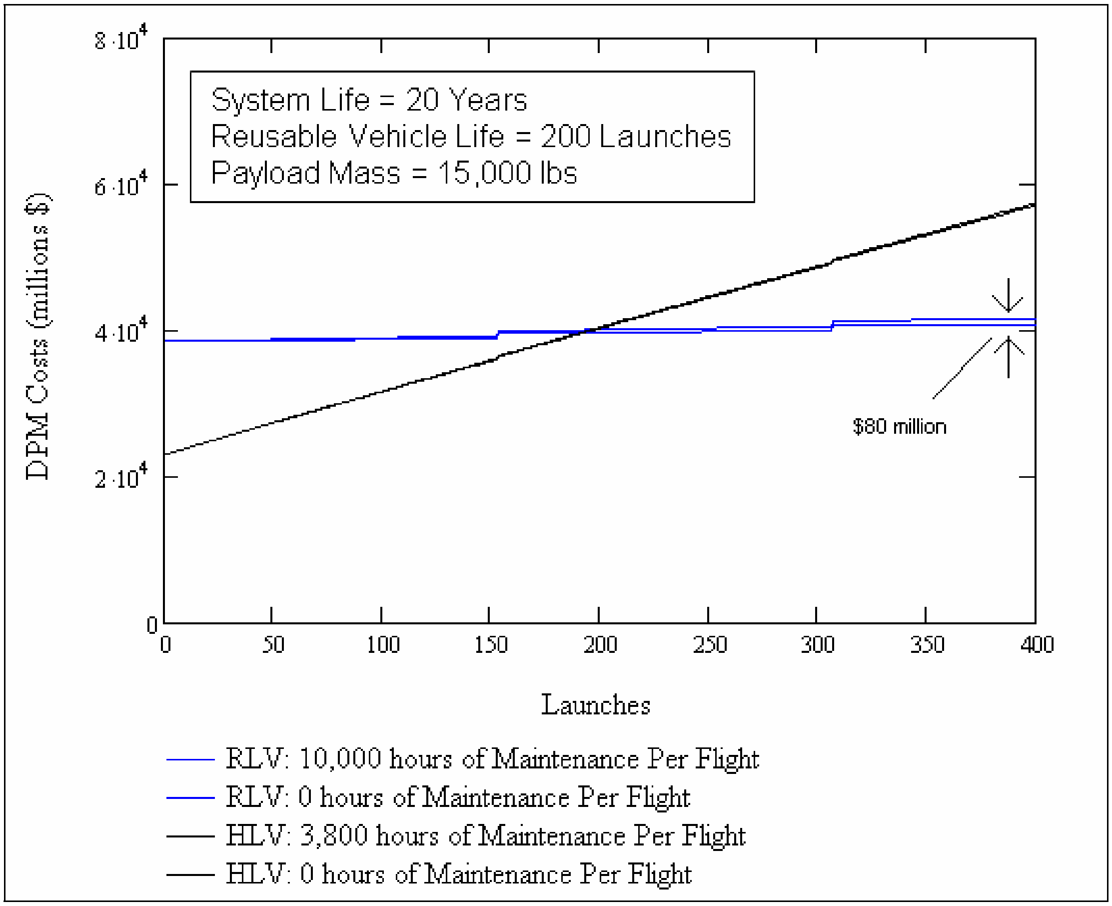

Figure 23. Effect of Maintenance on DPM Costs

4.6 Cost Analysis: Total DPM Comparison

The following analysis compares DPM costs if each vehicle alternative were to undergo complete development and production for an assumed system life of 20 years. Figure 24 illustrates the DPM comparison and the preferential launch regions for each vehicle alternative for a system life of 20 years. Figure 25 includes the same information; however, DPM is plotted against an average launch rate per year. Each Figure was generated using the comparison model (Appendix C) via summarizing DPM costs over a system life of 20 years. As stated earlier, a reusable vehicle, (HLV first-stage, both RLV stages) has a maximum life of 200 launches.

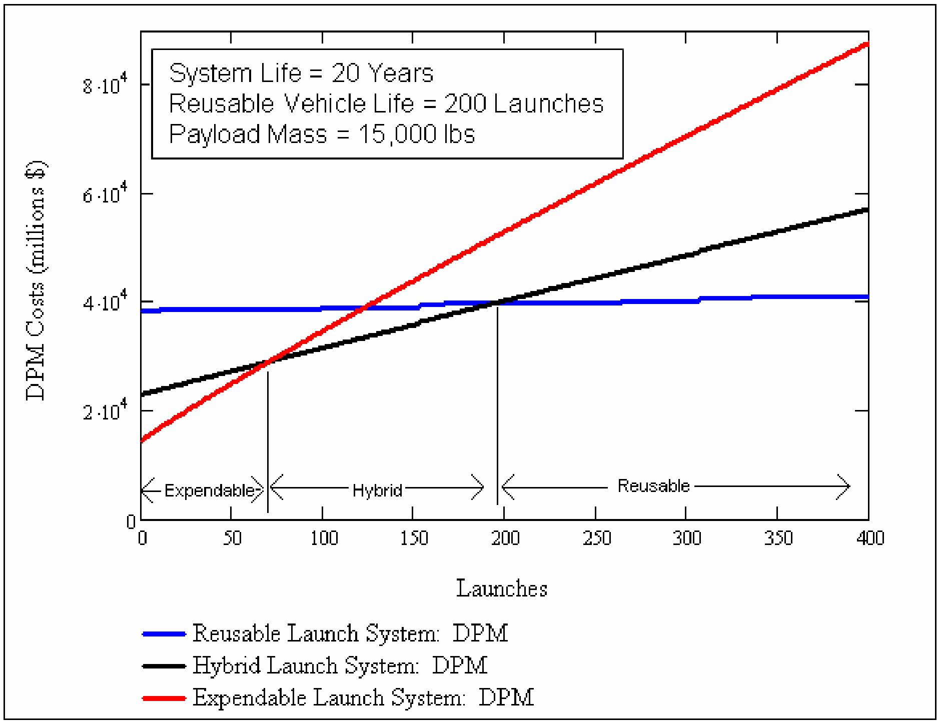

Figure 24. Total DPM Costs vs. Number of Launches

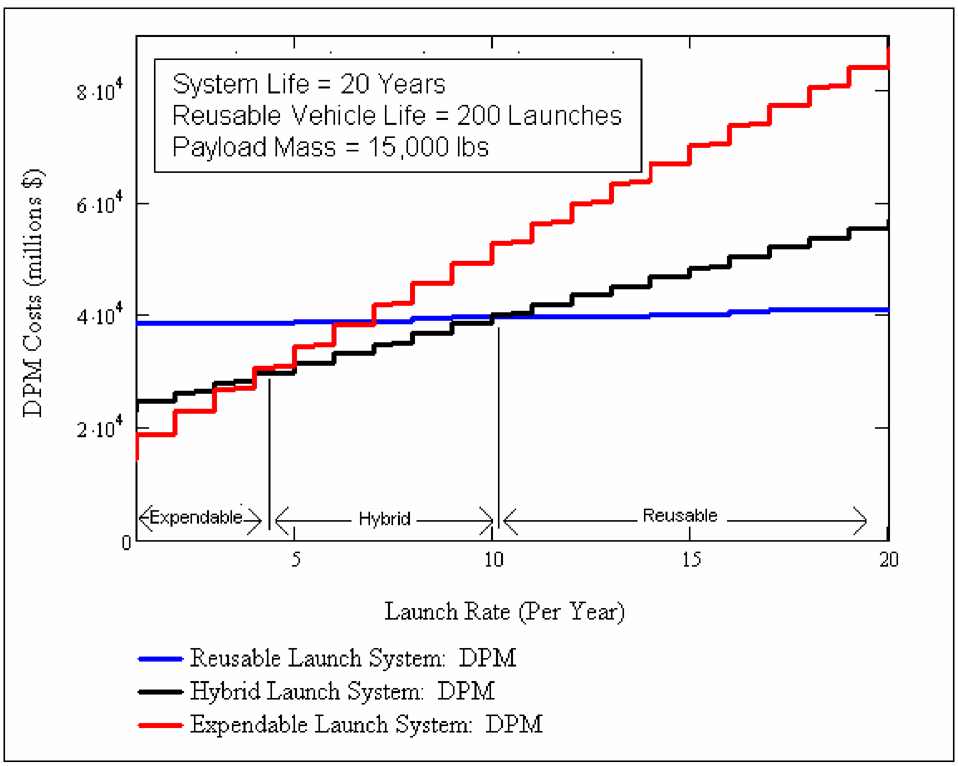

Figure 25. Total DPM Costs vs. Average Launch Rate Per Year

If each system underwent complete development and production then the expendable vehicle would be preferable for lower than 75 launches over a 20 year system life. The hybrid vehicle would be preferable for 75 – 200 launches and the RLV is preferred for launches greater than 200 launches over 20 years. The slopes of alternative in Figure 24 and step sizes in Figure 25 describe the cost for each additional launch. ELVs have lower development costs compared to hybrid and reusable vehicles but require new vehicles for each launch. Nonetheless, as the number of launches over the system life increase, the higher production costs outweigh the lower development costs after an average of 5 launches per year. Similarly, the lower development costs of the HLV compared to the RLV is outweighed by the production costs for average launch rates greater than 10 per year. The RLV curve consists of maintenance costs and new vehicle production amortized over the vehicle life of 200 launches, therefore the slop is close to linear. This comparison is valid only if each system undergoes total DPM. However, since expendable vehicles currently exist, no new expendable development needs to be completed. Therefore, further analysis will compare the different vehicle alternatives for a real world scenario.

4.7 Cost Analysis: Payload Size Impact for Total DPM

Figure 26 illustrates how total DPM is affected by varying payload mass for a system life of 400 launches over 20 years. As payload mass increases, the vehicle dry mass increases and subsequently, so do development, production, and maintenance costs. Figure 26 was developed using the comparison model (Appendix C) and shows how the number of launches required for an HLV or RLV system to be preferred decreases as payload mass increases. Simply put, large payloads favor HLVs and RLVs sooner compared to expendable vehicles when each alternative undergoes complete development and production.

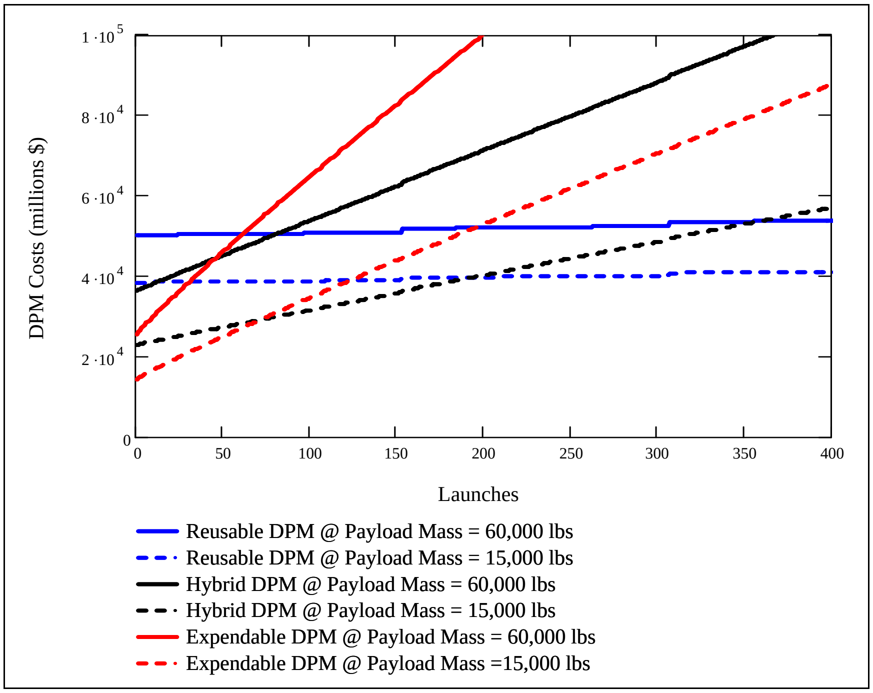

Figure 26. Total DPM for Increasing Payload Size

4.8 Real World Scenario: DPM Comparison

As described earlier, expendables are currently in use today and therefore do not require further development. Also, the hybrid vehicle is planned to use existing second stage engines and require minimal second stage airframe development due to use of an expendable second stage. For these reason, a comparison of current expendables was completed against a reusable vehicle and the ARES, a RMLS hybrid vehicle being designed by the U.S. Air Force [10]. Figures 27 and 28 detail the preferential launch regions for the real world scenario.

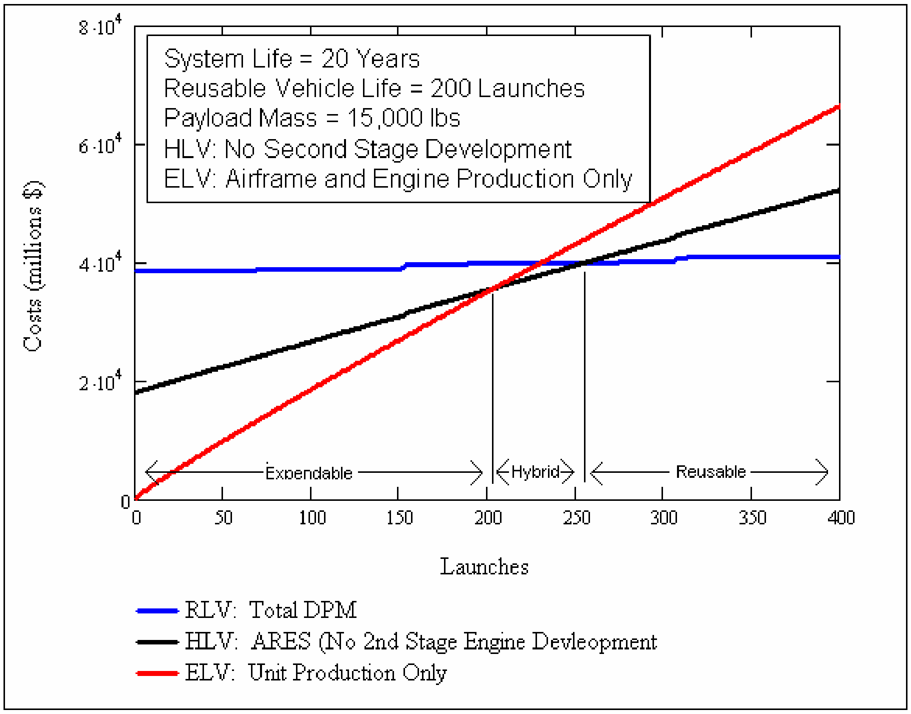

Figure 27. Real World DPM Comparison vs. Number of Launches

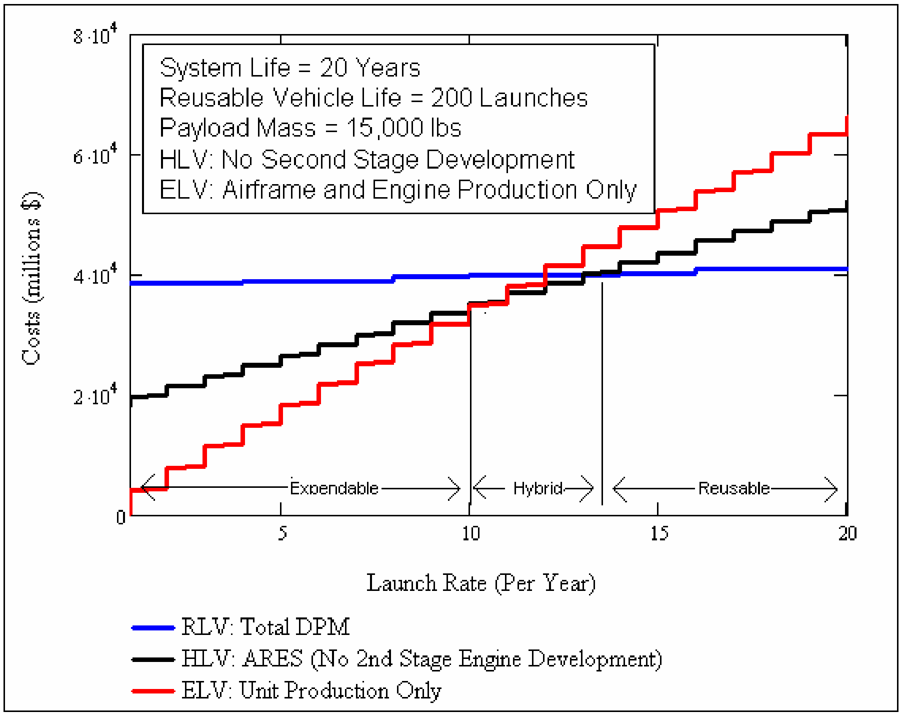

Figure 28. Real World DPM Comparison vs. Average Launch Rate Per Year

On the basis of DPM costs, the ARES hybrid launch system preferable for 200 – 260 launches, or roughly 10 – 13 launches per year over 20 years. The reusable system, with its lower cost per launch, dominates the ARES for launches greater than 260 over 20 years and current expendable systems for launches greater than 225 over 20 years. Again, this real world scenario includes limited development for the hybrid vehicle. If complete development were to take place, then the hybrid launch vehicle would not be preferable against the expendable and reusable launch vehicles. Being said, both the hybrid and reusable systems have lower direct operating costs (DOC) than the expendable alternative. Analysis of DOC will be further discussed in a later section. The following section will address total cost-per-pound of payload for the real world scenario.

4.9 Real World Scenario: Cost-Per-Pound of Payload

Figure 29 describes how the total cost-per-pound of payload decreases as the number of launches during the system lifetime increases. The DPM costs for the real world scenario were amortized over the amount of payload lifted to low Earth orbit. The blue oval corresponds to current world launch costs of $12,000 per pound of payload for the U.S. and $6,000 per pound for non western countries. The oval was plotted for 120 launches. This number of launches corresponds to the six missions the U.S. military carried out in 2005 [10].

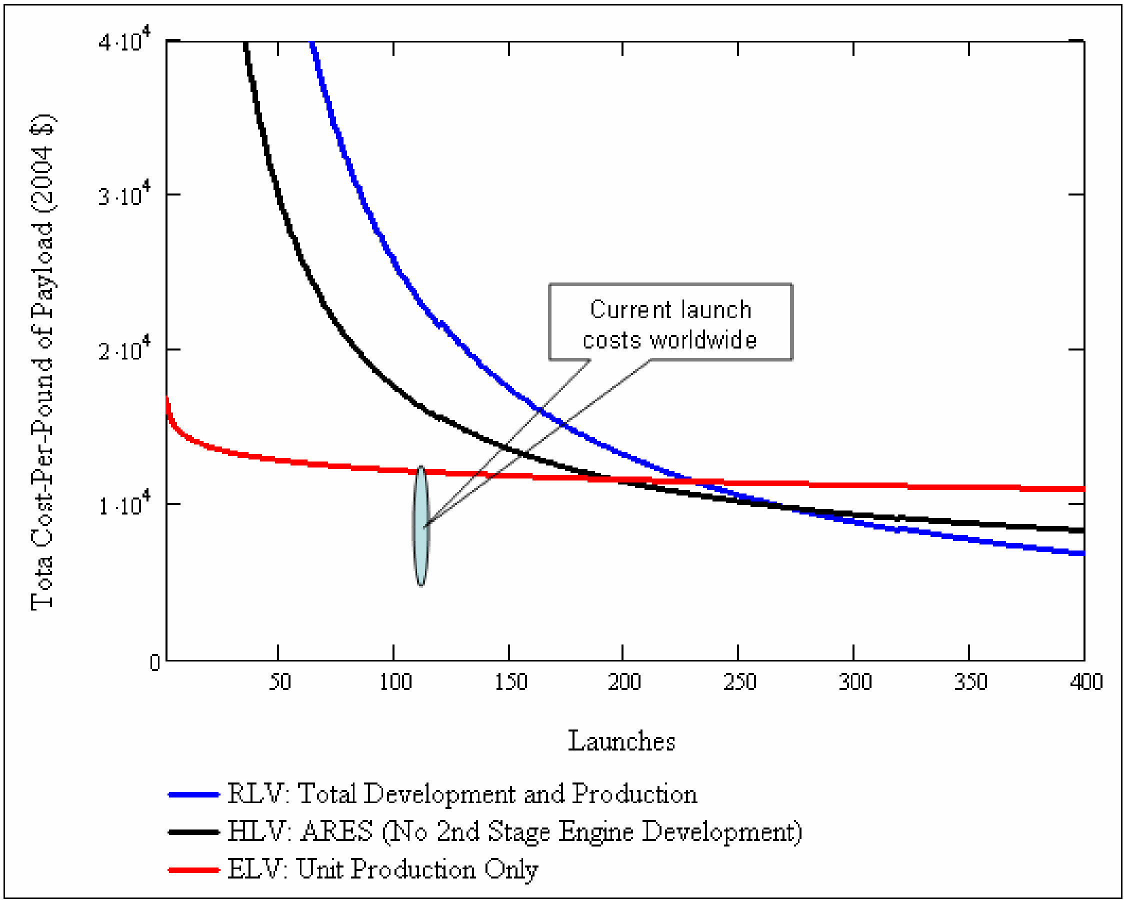

Figure 29. Total Cost-Per-Pound of Payload for Real World Scenario

The expendable cost-per-pound of payload trend predicts current launch costs well. Figure 29 illustrates low cost-per-pound of payload requires a large number of missions for hybrid and reusable systems. The HLV and RLV systems included development and therefore a larger number of launches needs take place before the total cost-per-pound of payload falls below current expendables.

4.10 Direct Operating Costs

Development is an indirect cost while production and maintenance are direct costs. It is the direct costs that affect an organization's operating budget. Therefore they are known as direct operating costs (DOC). Figure 30 displays the DOCs trends for the different launch vehicles alternatives. Figure 30 was generated using the comparison model (Appendix C) by summarizing production and maintenance costs for each alternative and plotting them against the number of launches.

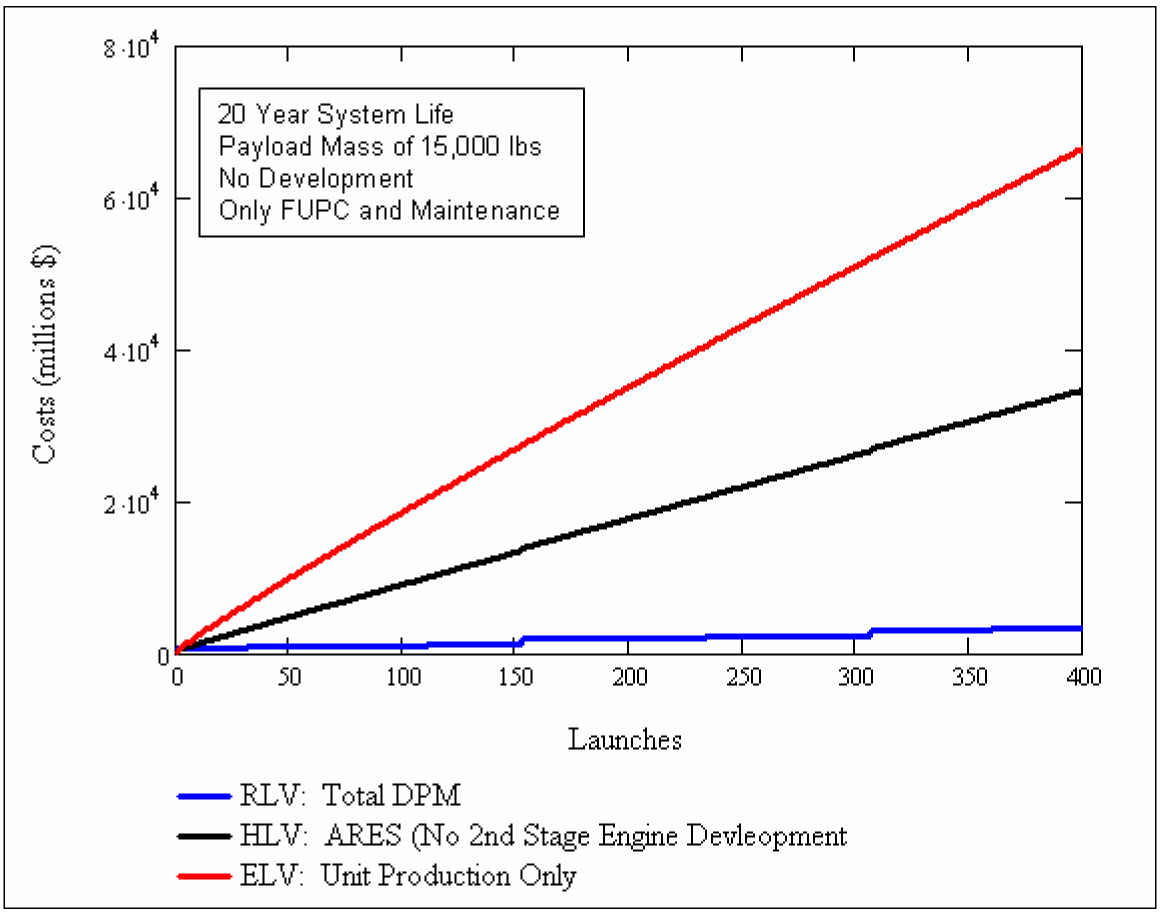

Figure 30. Direct Operating Costs vs. Number of Launches

The direct operating costs for expendable and hybrid vehicles rise dramatically for increasing number of launches. Each launch requires the production of a new ELV or HLV second stage. The DOC for the RLV remains almost flat consisting of maintenance costs and RLV vehicle production costs amortized over the vehicle life of 200 launches.

Lower DOC allows for greater mission flexibility. A decision maker can afford to send multiple sorties using RLVs to complete a mission and still spend less than one launch using a current ELV. For that reason, RLV allows for greatest mission flexibility of the three alternatives. HLVs are ranked second best with a DOC of roughly half of ELVs.

4.10 DOC: Cost-Per-Pound of Payload

If government were willing to pick up the development costs for a hybrid or reusable system then industry would see launch costs similar to those found in Figure 31. An analogy for a situation where industry profited from government developed system is the Boeing 707 spin off from the KC-135. Boeing was able to save billions in development by using the design of the KC-135 in when developing the Boeing 707 and subsequent aircraft.

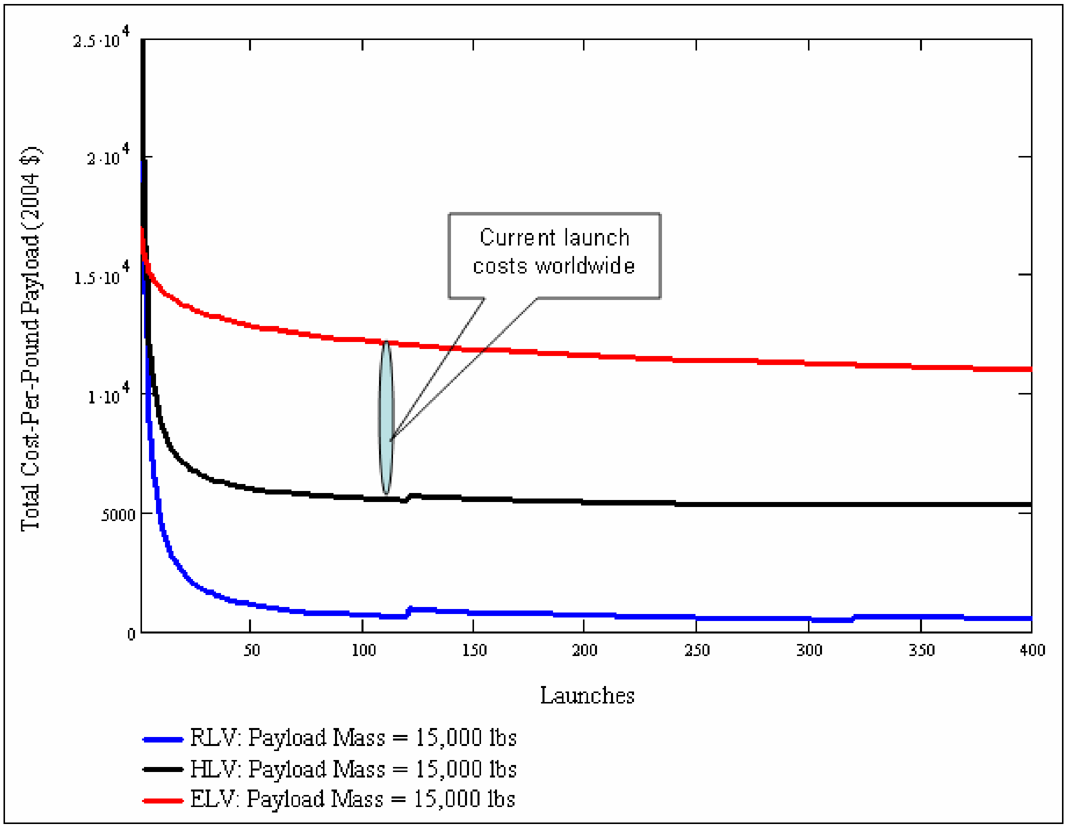

Figure 31. Total Cost-Per-Pound of Payload for DOC

Figure 31 details how the U.S. space industry would be able to offer launch costs on the order of $1,000 per pound of payload for RLVs and $6,000 per pound of payload for HLVs. This reduction in launch costs would make the U.S. competitive with other nations in the space launch market. HLV launch costs of $6,000 per pound of payload would be similar to those offered by non western nations using current expendable vehicles. However, the RLV launch costs of $1,000 per pound would allow for U.S. to recapture of the world launch market. Not only would the cost-per-pound be lower than current worldwide expendable systems, but the vehicles would be more reliable due to flight testing and maintenance. This decrease in launch costs would open the space market to any who could afford a payload.

5. Conclusion and Recommendations

5.1 Expendable Launch Systems

Expendable launch systems have relatively low development costs and are well understood. Except for the Space Shuttle, all other current launch vehicles are expendable systems. ELVs can be designed to launch in a few hours, but have high direct operating costs and long production times that limit their ability to take on more missions if needs develop. In the case of a surge in launch requirements, it is necessary to have a stockpile of complete systems available which to draw from. Expendable systems are preferable for predictable, low launch rate missions, but will have trouble responding to higher launch rates.

5.2 Hybrid Launch Systems

Hybrid launch systems will cost roughly twice as much to develop due to the complexity and cost of the reusable booster. A hybrid system is well within current technology. Development risks are slightly higher than expendable systems, but direct operating costs are lower, by about half, due to the reusable first stage. Additional development effort is needed to insure that the booster is sufficiently reliable and that the system as a whole is more responsive. Unlike the expendable system, only upperstages need to be stockpiled for surge requirements. Hybrid systems are preferable over expendables for current or modest increases in predicted launch rates.

5.3 Reusable Launch Systems

Reusable launch systems have the highest development costs and technical risks of the three alternatives analyzed in this research due to booster and orbiter complexity, but the technology is within current state of the art. The extremely low direct operating costs quickly outweigh the high development costs for launch rates above about 20 per year. A reusable system is the more flexible system due to their extremely low direct operating costs. They require only stockpiling of payloads to support surge operations. Reusable launch systems are the systems of choice if it is believed that future launch rates will increase significantly and will require responsive and flexible launch capabilities.

5.4 Recommendations from Study

As launch rates increase it is imperative that the United States develop a reusable launch system capable of delivering medium to heavy payloads to low Earth orbit. Though a reusable launch system would have a higher development cost than the other alternatives, for launch rates greater than 20 a year, the RLV would be preferable over ELV and HLV systems with similar operational capabilities. Also, systems developed to launch larger payloads would be capable of delivering a series of smaller payloads to LEO. This would provide operation flexibility with rapid decrease in cost per pound of payload. It is for these reasons that development and production of a reusable system is vital to future space exploration and logistics as well as recapturing the space launch market.

A hybrid system would offer a second best alternative. If Congress or investors are not willing to appropriate the funds required for the development of a reusable system, then the hybrid would offer a lower development cost substitute without sacrificing in the means of responsive operations with low direct operating costs. Either way, it is imperative that the United States begin development of a Hybrid or Reusable System. Both systems are technically feasible and would reduce current launch costs, thus enabling the United States to be competitive in the world launch market. Also, an HLV or RLV would provide the operationally responsive spacelift requirement laid out in the mission needs statement for Operationally Responsive Spacelift, AFSPC 001-01.

Appendix A: Mass Estimating Model

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Expendable Launch System MER

The following worksheet is designed to size TSTO expendable launch systems for any given payload. These expendable TSTO launch systems have liquid propulsion with a default first and second stage Isp of 300 and 320 respectively. Theoretically the Δv required to get to orbit is 24,934 ft/s. To account for aero, drag, and back pressure losses, the Δv design for in this worksheet is 120% of the theoretical. Therefore a $\Delta v_{required}$ of 30,000 ft/s is used. Secondly, it is assumed that the first stage completes the first 40% of the desired $\Delta v_{required}$ and the second stage completes the other 60%. Information in green stands for equations developed for the model. Light blue stands for industry standard information and should not be changed by the user. Yellow stands for inputs that users can change.

Industry Launch Systems (Payload Weight, Total Dry Weight)

The following Matrix is comprised of TSTO rocket based expendable launch systems from industry. The first column is payload of the launch system in pounds, and the second column is the total dry mass of the launch system, also in pounds.

$$points_{exp} := \begin{pmatrix} 4409 & 25574 \\ 8157 & 27238 \\ 8003 & 21676 \\ 18960 & 65279 \\ 4189 & 20150 \\ 29762 & 82894 \end{pmatrix}$$

Vehicle Information

Total Delta V required for Low Earth Orbit (accounts for gravity, aero, and back pressure losses)

$$\Delta v_{Total.exp} := (1.2) \cdot 24934 \frac{ft}{s}$$

Delta V required from First Stage

$$\Delta v_{s1.exp} := 0.4 \Delta v_{Total.exp}$$

Delta V required from Second Stage

$$\Delta v_{s2.exp} := 0.6 \Delta v_{Total.exp}$$

Isp of First Stage (Default Values. Model allows for user input Isp)

$$Isp_{s1.exp} := 300 \cdot s$$

Isp of Second Stage

$$Isp_{s2.exp} := 320 \cdot s$$

Second Stage Sizing

Propellant Mass Fraction for Expendable Second Stage

$$f_{p2.exp}(Isp_{s2.exp}) := 1 - e^{\frac{-\Delta v_{s2.exp}}{Isp_{s2.exp} \cdot g}}$$

Structural Mass Fraction for Expendable Second Stage

$$f_{struc2.exp} := 0.045$$

Vehicle Fixed Mass for Expendable Second Stage (Roughly 30% of Payload plus 2000 lbs to account for avionics and extras)

$$m_{fixed.s2.exp}(m_{pay}) := 0.3\,m_{pay} + 2000$$

Initial Mass of Expendable Second Stage (includes fuel, payload, structure, etc)

$$m_{02.exp}(m_{pay}, Isp_{s2.exp}) := \frac{m_{pay} + m_{fixed.s2.exp}(m_{pay})}{1 - f_{struc2.exp} - f_{p2.exp}(Isp_{s2.exp})}$$

Dry Mass of Expendable Second Stage

$$m_{s2.exp}(m_{pay}, Isp_{s2.exp}) := m_{02.exp}(m_{pay}, Isp_{s2.exp}) \cdot f_{struc2.exp} + m_{fixed.s2.exp}(m_{pay})$$

First Stage Sizing

Mass Payload of First Stage (Equal to Initial Mass of Second Stage)

$$m_{pay.s1.exp}(m_{pay}, Isp_{s2.exp}) := m_{02.exp}(m_{pay}, Isp_{s2.exp})$$

Vehicle Fixed Mass (Roughly 30% of Stage's Payload plus 3000 lbs to account for avionics)

$$m_{fixed.s1.exp}(m_{pay}, Isp_{s2.exp}) := .01\, m_{pay.s1.exp}(m_{pay}, Isp_{s2.exp}) + 3000$$

Propellant Mass Fraction of Expendable First Stage

$$f_{p1.exp}(Isp_{s1.exp}) := 1 - e^{\frac{-\Delta v_{s1.exp}}{Isp_{s1.exp} \cdot g}}$$

Structural Mass Fraction of Expendable First Stage

$$f_{struc1.exp} := 0.045$$

Initial Mass of Expendable First Stage

$$m_{01.exp}(m_{pay}, Isp_{s2.exp}, Isp_{s1.exp}) := \frac{m_{pay.s1.exp}(m_{pay}, Isp_{s2.exp}) + m_{fixed.s1.exp}(m_{pay}, Isp_{s2.exp})}{1 - f_{struc1.exp} - f_{p1.exp}(Isp_{s1.exp})}$$

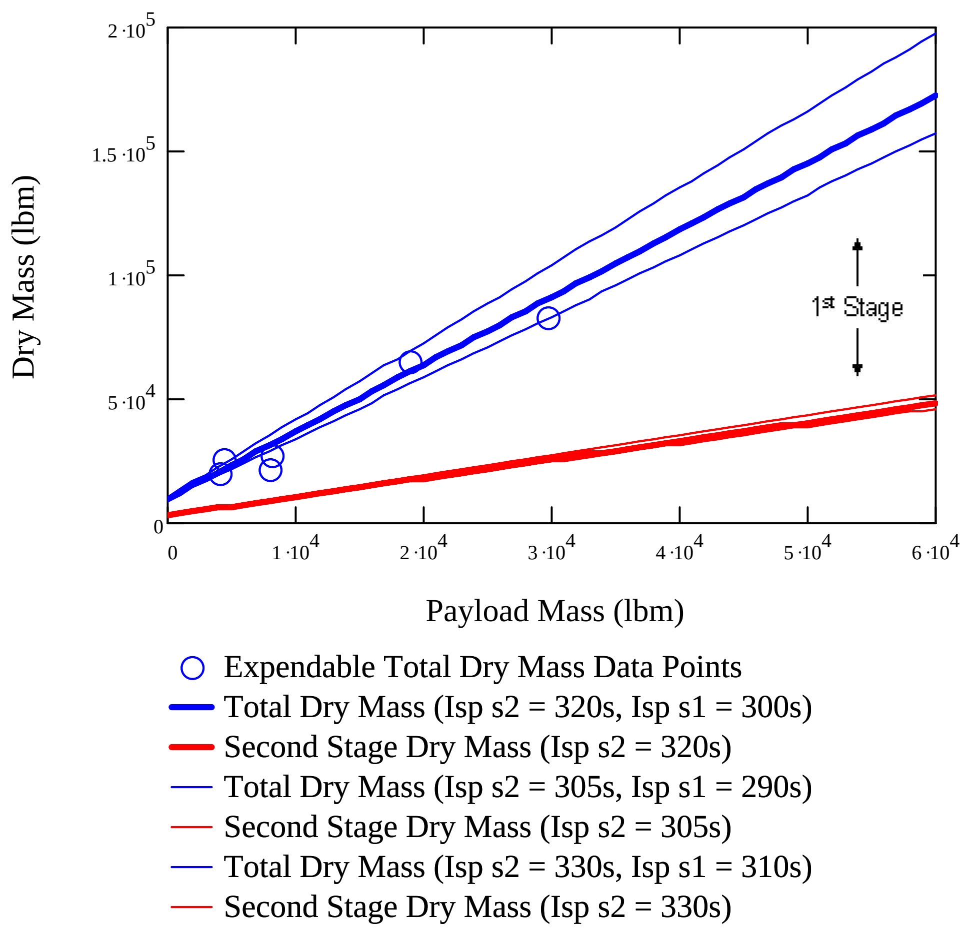
Dry Mass of Expendable First Stage

$$m_{s1.exp}(m_{pay}, Isp_{s2.exp}, Isp_{s1.exp}) := m_{01.exp}(m_{pay}, Isp_{s2.exp}, Isp_{s1.exp}) \cdot f_{struc1.exp} + m_{fixed.s1.exp}(m_{pay}, Isp_{s2.exp})$$

Total Dry Mass of Both Expendable Stages

$$m_{dry.exp}(m_{pay}, Isp_{s2.exp}, Isp_{s1.exp}) := m_{s1.exp}(m_{pay}, Isp_{s2.exp}, Isp_{s1.exp}) + m_{s2.exp}(m_{pay}, Isp_{s2.exp})$$

$m_{pay} := 0, 1000 .. 60000$



Reusable Launch System MER

The following worksheet is designed to size TSTO reusable launch systems for any given payload. These reusable TSTO launch systems have liquid propulsion with a first and second stage Isp of 320 and 350 respectively. As stated earlier, the MER model allows for user input stage Isp. Theoretically the Δv required to get to orbit is 24,934 ft/s. To account for losses, the Δv design for in this worksheet is 120% of the theoretical. Therefore a $\Delta v_{required}$ of 30,000 ft/s is used. Secondly, it is assumed that the first stage completes the first 40% of the desired $\Delta v_{required}$ and the second stage completes the other 60%. Information in green stands for equations developed for the model. Light blue stands for industry standard information and should not be changed by the user. Yellow stands for inputs that users can change.

Industry Launch Systems (Payload Weight, Total Dry Weight)

The following matrix is comprised of TSTO rocket based reusable launch systems launch system studies both by industry and government agencies. The first column is payload of the launch system, in pounds, and the second column is the total dry mass of the launch system, also in pounds.

$$points_{reus} := \begin{pmatrix} 0 & 105000 \\ 5000 & 148000 \\ 15000 & 230000 \\ 37000 & 307000 \\ 61700 & 362000 \end{pmatrix}$$

Vehicle Information

Total Delta V required for Low Earth Orbit (accounts for gravity, aero, and back pressure losses)

$$\Delta v_{Total.reus} := (1.2)\cdot 24934\frac{ft}{s}$$

Delta V required from First Stage

$$\Delta v_{s1.reus} := 0.4\Delta v_{Total.reus}$$

Delta V required from Second Stage

$$\Delta v_{s2.reus} := 0.6\Delta v_{Total.reus}$$

Isp of First Stage

$$Isp_{s1.reus} := 320\cdot s$$

Isp of Second Stage

$$Isp_{s2.reus} := 350\cdot s$$

Second Stage Sizing

Propellant Mass Fraction of Reusable Second Stage

$$f_{p2.reus}\left(Isp_{s2.reus}\right) := 1 - e^{\frac{-\Delta v_{s2.reus}}{Isp_{s2.reus} \cdot g}}$$

Calculating structural mass fraction for reusable launch systems requires a summation of smaller mass fractions. Stack mass fraction and wing/landing gear mass fraction are discrete values but TPS mass fraction needs vary with vehicle size. For smaller vehicles the TPS mass fraction needs to be higher and as the size of the vehicle increases, TPS mass fraction should Reusable Second Stage. Summation of stack mass fraction, wing and landing gear mass fraction, and TPS mass fraction should decease till it becomes negligible for large vehicles

Stack Mass Fraction for Reusable Second Stage

$$f_{stack.s2.reus} := .065$$

Wing and Landing Gear Mass Fraction for Reusable Second Stage

$$f_{wing.s2.reus} := .01$$

Mass Payload Half is a constant value that assists in the development of the TPS Mass fraction

$$m_{pay.half.s2.reus} := 30000$$

TPS Mass Fraction Calculation for Reusable Second Stage

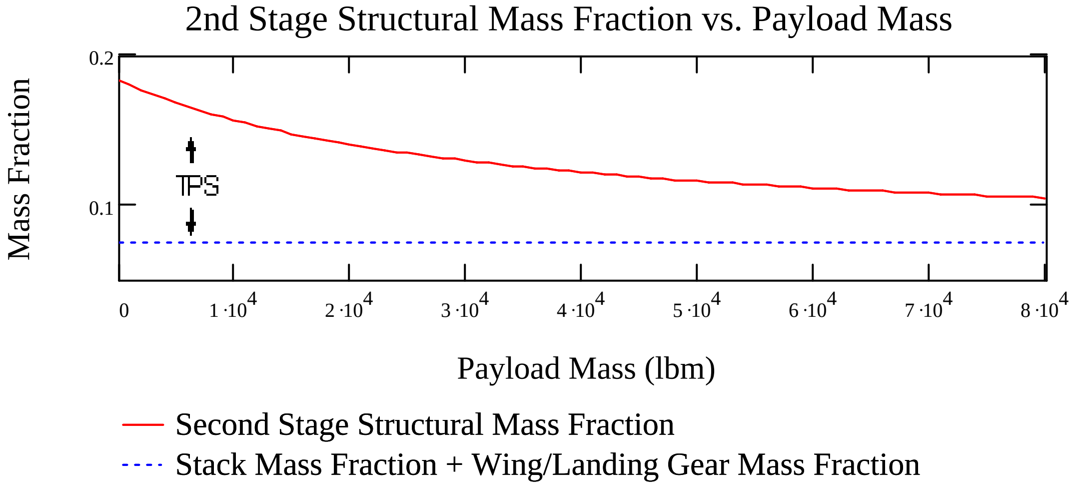
$$f_{TPS}\left(m_{pay}, Isp_{s2.reus}\right) := \frac{.85\, m_{pay.half.s2.reus} \cdot \left(1 - f_{p2.reus}\left(Isp_{s2.reus}\right) - f_{stack.s2.reus} - f_{wing.s2.reus}\right)}{m_{pay} + m_{pay.half.s2.reus}}$$

Structural Mass Fraction for Reusable Second Stage

$$f_{struc2.reus}\left(m_{pay}, Isp_{s2.reus}\right) := f_{stack.s2.reus} + f_{wing.s2.reus} + f_{TPS}\left(m_{pay}, Isp_{s2.reus}\right)$$

The following chart shows how Structural Mass Fraction decreases as payload mass increases. This is due to the fact that square-cubed relation of TPS.

$$m_{pay.a} := 1, 1000 .. 80000$$



Vehicle Fixed Mass for Reusable Second Stage (Roughly 30% of Payload plus 2000 lbs to account for avionics and extras)

$$m_{fixed.s2.reus}(m_{pay}) := 0.3\, m_{pay} + 2000$$

Initial Mass of Reusable Second Stage

$$m_{02.reus}(m_{pay}, Isp_{s2.reus}) := \frac{m_{pay} + m_{fixed.s2.reus}(m_{pay})}{1 - f_{struc2.reus}(m_{pay}, Isp_{s2.reus}) - f_{p2.reus}(Isp_{s2.reus})}$$

Dry Mass of Reusable Second Stage

$$m_{s2.reus}(m_{pay}, Isp_{s2.reus}) := m_{02.reus}(m_{pay}, Isp_{s2.reus}) \cdot f_{struc2.reus}(m_{pay}, Isp_{s2.reus}) + m_{fixed.s2.reus}(m_{pay})$$

First Stage Sizing

Mass Payload of Reusable First Stage (Equal to Initial Mass of Second Stage)

$$m_{pay.s1.reus}(m_{pay}, Isp_{s2.reus}) := m_{02.reus}(m_{pay}, Isp_{s2.reus})$$

Vehicle Fixed Mass for Reusable First Stage (Roughly 30% of Stage's Payload plus 18,000 lbs to account for avionics)

$$m_{fixed.s1.reus}(m_{pay}) := 18000$$

Propellant Mass Fraction of Reusable First Stage

$$f_{p1.reus}(Isp_{s1.reus}) := 1 - e^{\frac{-\Delta v_{s1.reus}}{Isp_{s1.reus} \cdot g}}$$

Stack Mass Fraction for Reusable First Stage

$$f_{stack.s1.reus} := .038$$

Wing/Landing Gear Mass Fraction for Reusable First Stage

$$f_{wing.s1.reus} := .004$$

Mass Payload Half is a constant value that assists in the development of the TPS Mass fraction.

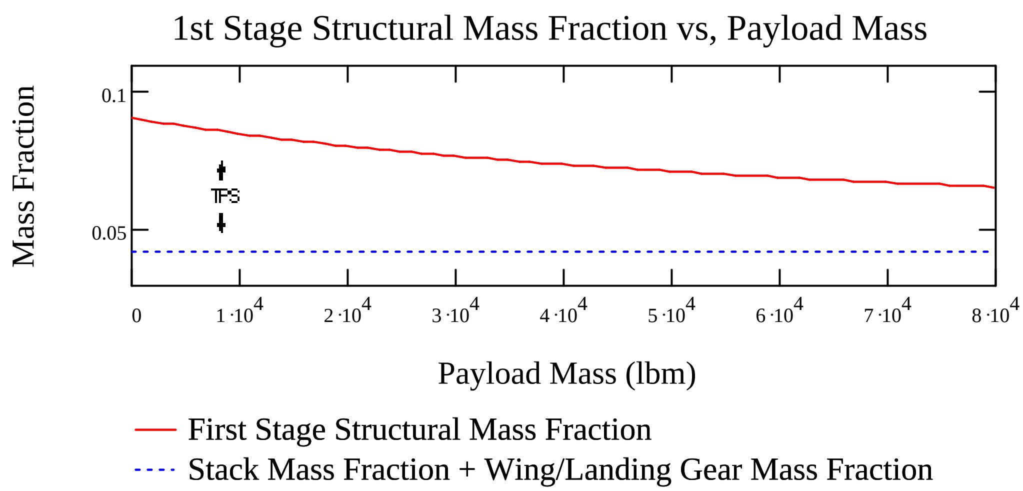
$$m_{pay.half.s1.reus} := 75000$$

TPS Mass Fraction Calculation for Reusable First Stage

$$f_{TPS.s1.reus}(m_{pay}, Isp_{s2.reus}, Isp_{s1.reus}) := \frac{0.18\, m_{pay.half.s1.reus} \cdot \left(1 - f_{p1.reus}(Isp_{s1.reus}) - f_{stack.s1.reus} - f_{wing.s1.reus}\right)}{m_{pay} + m_{pay.half.s1.reus}}$$

Structural Mass Fraction for Reusable First Stage

$$f_{struc1.reus}(m_{pay}, Isp_{s2.reus}, Isp_{s1.reus}) := f_{stack.s1.reus} + f_{wing.s1.reus} + f_{TPS.s1.reus}(m_{pay}, Isp_{s2.reus}, Isp_{s1.reus})$$



Initial Mass of Reusable First Stage

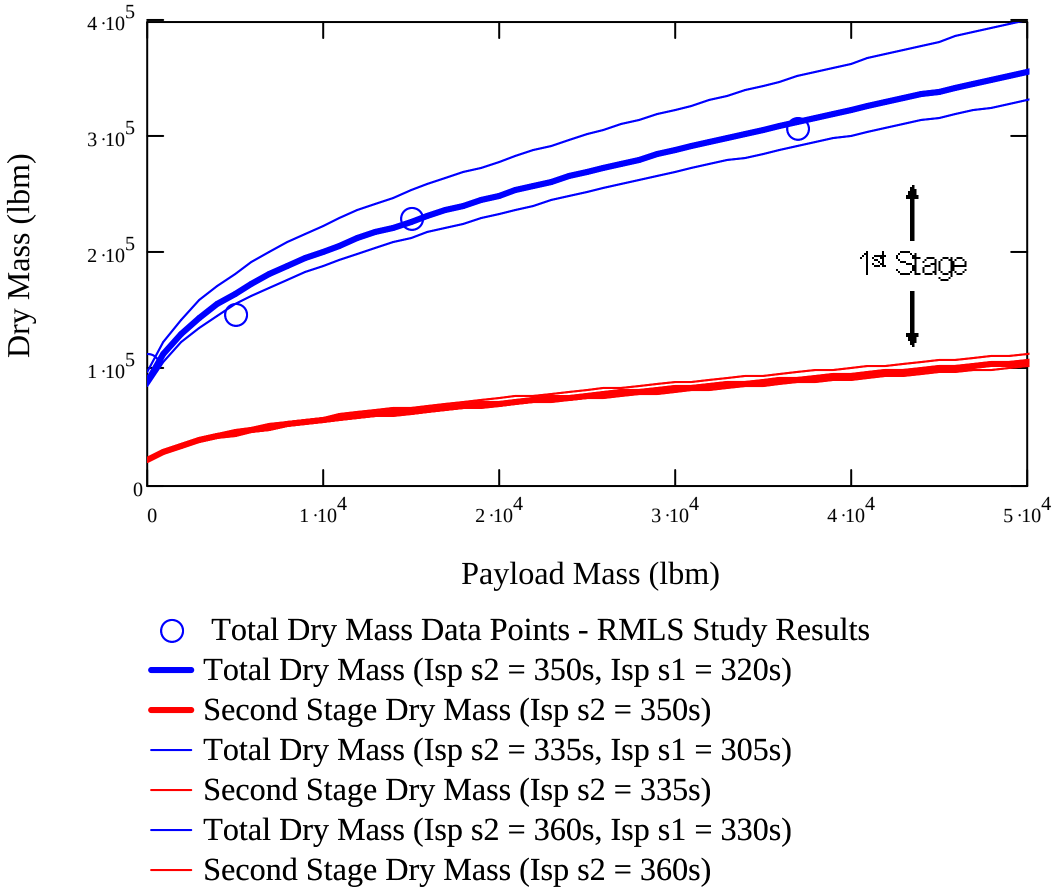
$$m_{01.reus}(m_{pay}, Isp_{s2.reus}, Isp_{s1.reus}) := \frac{m_{pay.s1.reus}(m_{pay}, Isp_{s2.reus}) + m_{fixed.s1.reus}(m_{pay})}{1 - f_{struc1.reus}(m_{pay}, Isp_{s2.reus}, Isp_{s1.reus}) - f_{p1.reus}(Isp_{s1.reus})}$$

Dry Mass of Reusable First Stage

$$m_{s1.reus}(m_{pay}, Isp_{s2.reus}, Isp_{s1.reus}) := m_{01.reus}(m_{pay}, Isp_{s2.reus}, Isp_{s1.reus}) \cdot f_{struc1.reus}(m_{pay}, Isp_{s2.reus}, Isp_{s1.reus}) + m_{fixed.s1.reus}(m_{pay})$$

Total Dry Mass of Both Reusable Stages

$$m_{dry.reus}(m_{pay}, Isp_{s2.reus}, Isp_{s1.reus}) := m_{s1.reus}(m_{pay}, Isp_{s2.reus}, Isp_{s1.reus}) + m_{s2.reus}(m_{pay}, Isp_{s2.reus})$$



4·10^5
3·10^5
2·10^5
1·10^5
0
Dry Mass (lbm)
0
1·10^4
2·10^4
3·10^4
4·10^4
5·10^4
1st Stage
Payload Mass (lbm)
Total Dry Mass Data Points - RMLS Study Results
Total Dry Mass (Isp s2 = 350s, Isp s1 = 320s)
Second Stage Dry Mass (Isp s2 = 350s)
Total Dry Mass (Isp s2 = 335s, Isp s1 = 305s)
Second Stage Dry Mass (Isp s2 = 335s)
Total Dry Mass (Isp s2 = 360s, Isp s1 = 330s)
Second Stage Dry Mass (Isp s2 = 360s)

Hybrid Launch System MER

The following worksheet is designed to size TSTO hybrid launch systems for any given payload. These hybrid TSTO launch systems have liquid propulsion with a first and second stage Isp of 320 and 350 respectively. Theoretically the Δv required to get to orbit is 24,934 ft/s. To account for losses, the Δv design for in this worksheet is 120% of the theoretical. Therefore a $\Delta v_{required}$ of 29,921 ft/s is used. Secondly, it is assumed that the first stage completes the first 40% of the desired $\Delta v_{required}$ and the second stage completes the other 60%. Information in green stands for equations developed for the model. Light blue stands for industry standard information and should not be changed by the user. Yellow stands for inputs that users can change.

Industry Launch Systems (Payload Weight, Total Dry Weight)

The following matrix is comprised of TSTO hybrid based launch systems from launch system studies both by industry and government agencies. The first column is payload of the launch system, in pounds, and the second column is the total dry mass of the launch system, also in pounds.

$$points_{hyb} := \begin{pmatrix} 2750 & 49433 \\ 15000 & 85226 \\ 15000 & 99937 \\ 15000 & 110140 \\ 73000 & 330000 \end{pmatrix}$$

Vehicle Information

Total Delta V required for Low Earth Orbit(accounts for gravity, aero, and back pressure losses)

$$\Delta v_{Total.hyb} := (1.2)\cdot 24934\cdot\frac{ft}{s}$$

Delta V required from First Stage

$$\Delta v_{1.hyb} := 0.4\Delta v_{Total.hyb}$$

Delta V required from Second Stage

$$\Delta v_{2.hyb} := 0.6\Delta v_{Total.hyb}$$

Isp of Hybrid First Stage

$$Isp_{s1.hyb} := 320\cdot s$$

Isp of Hybrid Second Stage

$$Isp_{s2.hyb} := 320\cdot s$$

Second Stage Sizing

Propellant Mass Fraction of Hybrid Second Stage

$$f_{p2.hyb}\left(Isp_{s2.hyb}\right) := 1 - e^{\frac{-\Delta v_{2.hyb}}{Isp_{s2.hyb} \cdot g}}$$

Structural Mass Fraction of Hybrid Second Stage

$$f_{struc2.hyb} := .05$$

Vehicle Fixed Mass for Hybrid Second Stage (Roughly 30% of Payload plus 2000 lbs to account for avionics and extras)

$$m_{fixed.s2.hyb}\left(m_{pay}\right) := 0.3\,m_{pay} + 2000$$

Initial Mass of Hybrid Second Stage

$$m_{02.hyb}\left(m_{pay}, Isp_{s2.hyb}\right) := \frac{m_{pay} + m_{fixed.s2.hyb}\left(m_{pay}\right)}{1 - f_{struc2.hyb} - f_{p2.hyb}\left(Isp_{s2.hyb}\right)}$$

Dry Mass of Hybrid Second Stage

$$m_{s2.hyb}\left(m_{pay}, Isp_{s2.hyb}\right) := m_{02.hyb}\left(m_{pay}, Isp_{s2.hyb}\right) \cdot f_{struc2.hyb} + m_{fixed.s2.hyb}\left(m_{pay}\right)$$

First Stage Sizing

Mass Payload of Hybrid First Stage (Equal to Initial Mass of Second Stage)

$$m_{pay.s1.hyb}\left(m_{pay}, Isp_{s2.hyb}\right) := m_{02.hyb}\left(m_{pay}, Isp_{s2.hyb}\right)$$

Vehicle Fixed Mass for Hybrid First Stage(Roughly 18000 lbs to account for avionics and other extra weights)

$$m_{fixed.s1.hyb}\left(m_{pay}\right) := 18000$$

Propellant Mass Fraction of Hybrid First Stage

$$f_{p1.hyb}\left(Isp_{s1.hyb}\right) := 1 - e^{\frac{-\Delta v_{1.hyb}}{Isp_{s1.hyb} \cdot g}}$$

Calculating structural mass fraction for hybrid launch system first stage requires a summation of smaller mass fractions. Stack mass fraction and wing/landing gear mass fraction are discrete values but TPS mass fraction needs vary with vehicle size. For smaller vehicles the TPS mass fraction needs to be higher and as the size of the vehicle increases, TPS mass fraction should Reusable Second Stage. Summation of stack mass fraction, wing/landing gear mass fraction, and TPS mass fraction should decease till it becomes negligible for large vehicles

Stack Mass Fraction for Hybrid First Stage

$f_{stack.s1.hyb} := .038$

Wing/Landing Gear Mass Fraction for Hybrid First Stage

$f_{wing.s1.hyb} := .004$

Mass Payload Half is a constant value that assists in the development of the TPS Mass fraction.

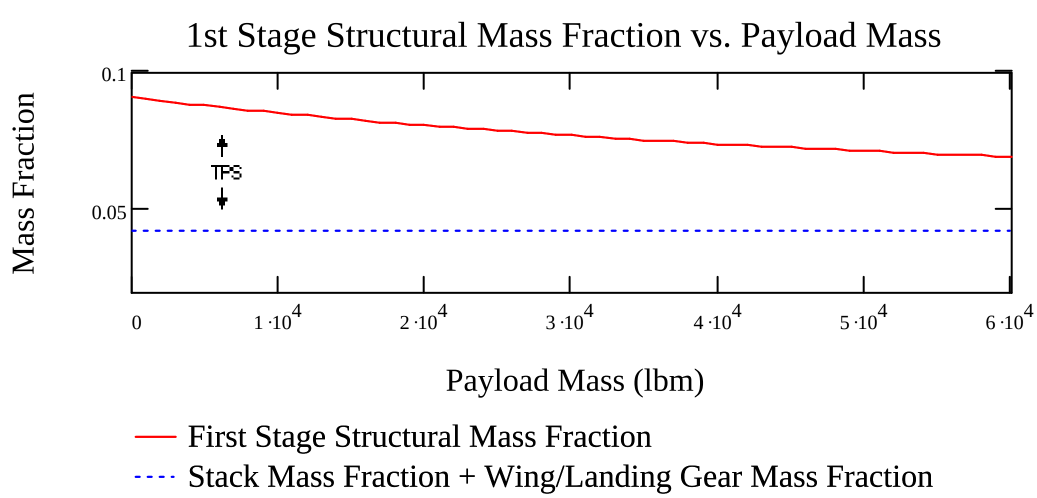
$m_{pay.half.s1.hyb} := 75000$

TPS Mass Fraction Calculation for Hybrid First Stage

$$f_{TPS.s1.hyb}\left(m_{pay}, Isp_{s1.hyb}\right) := \frac{.18\, m_{pay.half.s1.hyb} \cdot \left(1 - f_{p1.hyb}\left(Isp_{s1.hyb}\right) - f_{stack.s1.hyb} - f_{wing.s1.hyb}\right)}{m_{pay} + m_{pay.half.s1.hyb}}$$

Structural Mass Fraction for Hybrid First Stage

$$f_{struc1.hyb}\left(m_{pay}, Isp_{s1.hyb}\right) := f_{stack.s1.hyb} + f_{wing.s1.hyb} + f_{TPS.s1.hyb}\left(m_{pay}, Isp_{s1.hyb}\right)$$



Initial Mass of Hybrid First Stage

$$m_{01.hyb}(m_{pay}, Isp_{s2.hyb}, Isp_{s1.hyb}) := \frac{m_{pay.s1.hyb}(m_{pay}, Isp_{s2.hyb}) + m_{fixed.s1.hyb}(m_{pay})}{1 - f_{struc1.hyb}(m_{pay}, Isp_{s1.hyb}) - f_{p1.hyb}(Isp_{s1.hyb})}$$

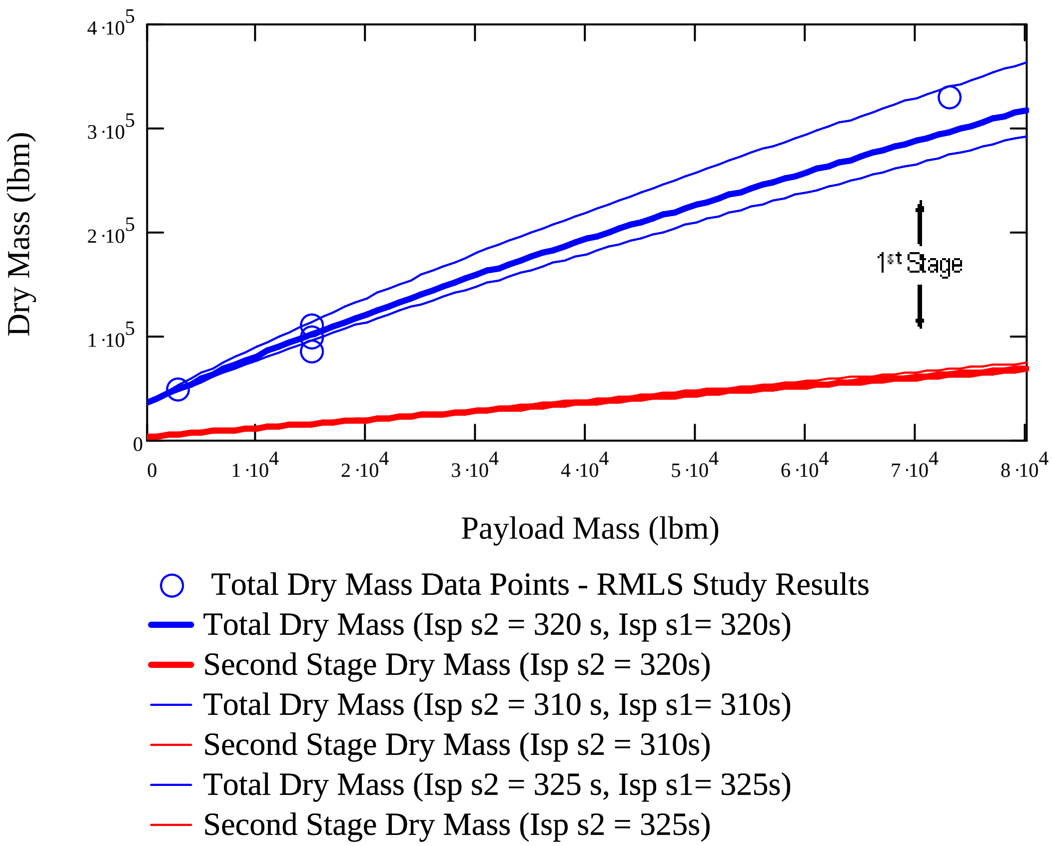
Dry Mass of First Stage

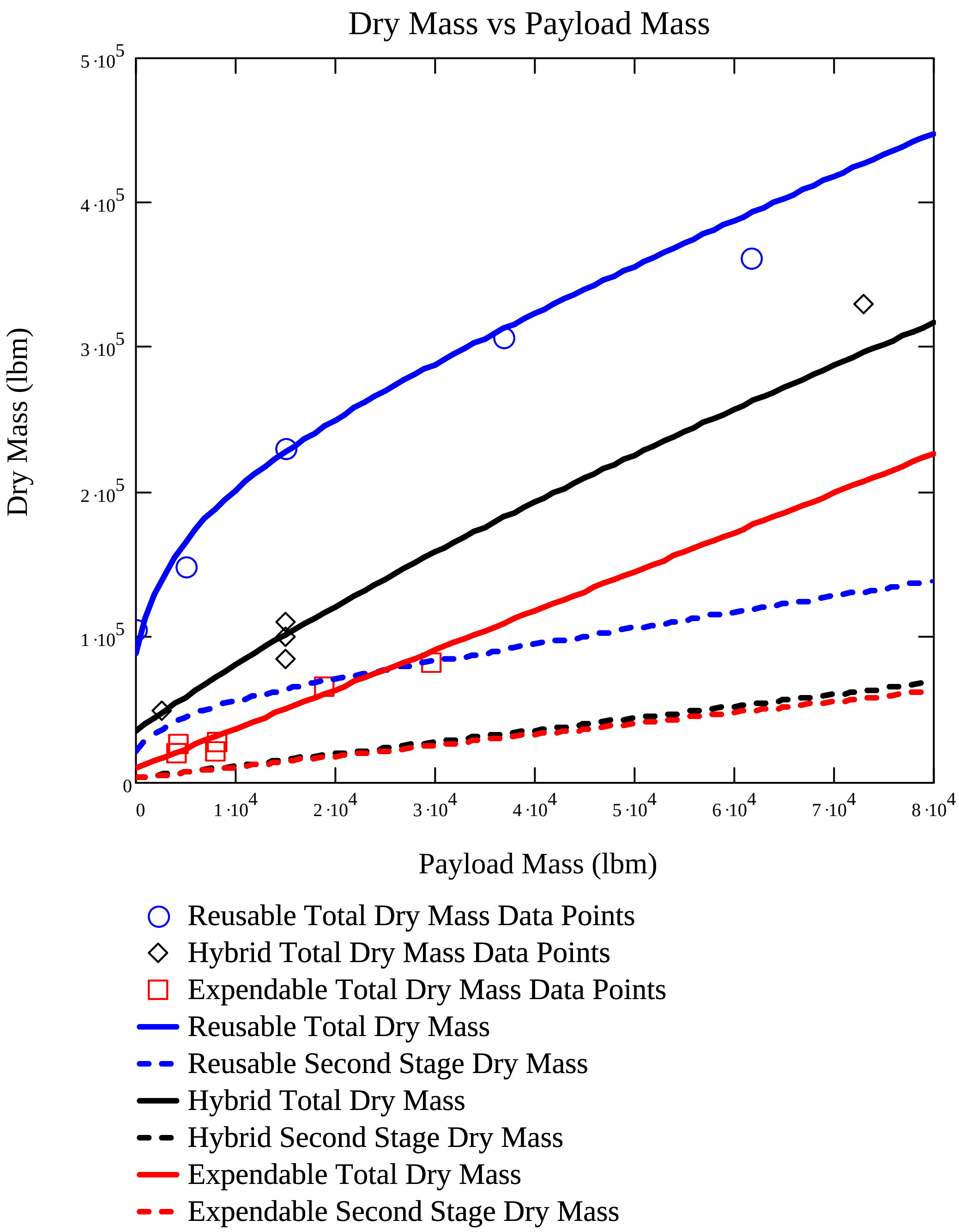
$$m_{s1.hyb}(m_{pay}, Isp_{s2.hyb}, Isp_{s1.hyb}) := m_{01.hyb}(m_{pay}, Isp_{s2.hyb}, Isp_{s1.hyb}) \cdot f_{struc1.hyb}(m_{pay}, Isp_{s1.hyb}) + m_{fixed.s1.hyb}(m_{pay})$$

Total Dry Mass of Both Hybrid Stages

$$m_{dry.hyb}(m_{pay}, Isp_{s2.hyb}, Isp_{s1.hyb}) := m_{s1.hyb}(m_{pay}, Isp_{s2.hyb}, Isp_{s1.hyb}) + m_{s2.hyb}(m_{pay}, Isp_{s2.hyb})$$

$m_{pay.h} := 0, 1000 .. 80000$




Dry Mass vs Payload Mass
Dry Mass (lbm)
Payload Mass (lbm)
5·10^5
4·10^5
3·10^5
2·10^5
1·10^5
0
0
1·10^4
2·10^4
3·10^4
4·10^4
5·10^4
6·10^4
7·10^4
8·10^4
Reusable Total Dry Mass Data Points
Hybrid Total Dry Mass Data Points
Expendable Total Dry Mass Data Points
Reusable Total Dry Mass
Reusable Second Stage Dry Mass
Hybrid Total Dry Mass
Hybrid Second Stage Dry Mass
Expendable Total Dry Mass
Expendable Second Stage Dry Mass

Appendix B: Cost Estimating Model

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The following model approximates development, first unit production, and maintenance costs for expendable, hybrid, and reusable launch vehicles. The different costs cover both airframe and engines for each type of launch vehicle.

Development and first unit production costs were derived from Dr. Koelle's "Handbook of Cost Engineering for Space Transportation Systems" [9]. His work details how to approximate the different costs for expendable and reusable systems. Best fit curves were applied to vehicle data assembled and adjusted by Dr. Koelle. For understanding purposes, all work was done in English Units and costs are outputted in Man Years.

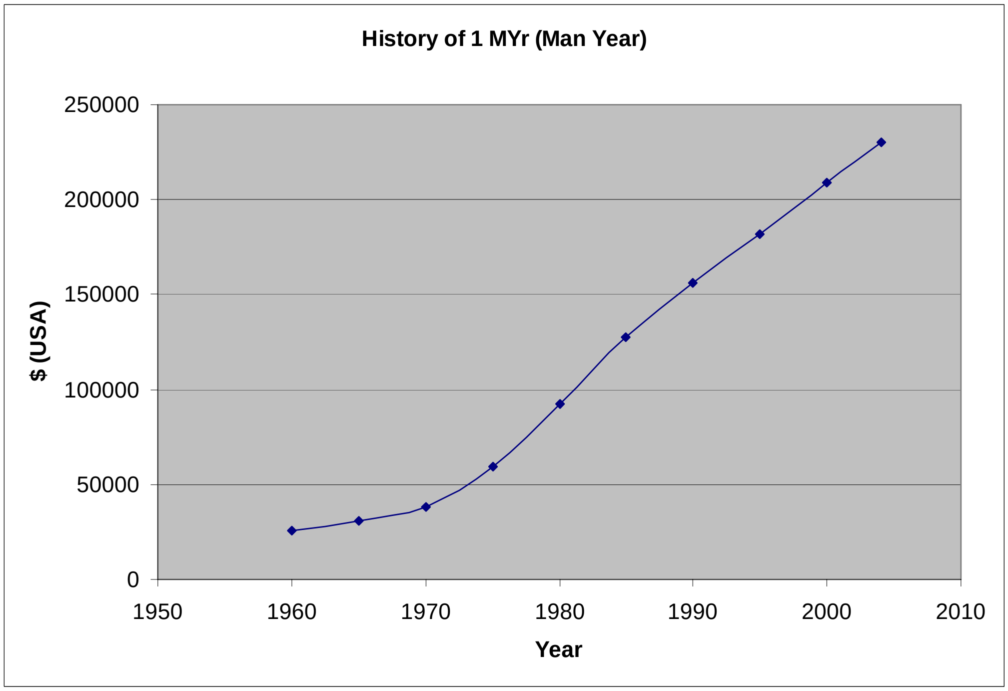
Maintenance relations were derived with the assistance of Brendan Rooney of ASC/XREC. The engine maintenance relation was taken from previous work done by Mr. Rooney. K-Factors were applied to the existing equations when deemed appropriate Airframe maintenance relations were developed from existing maintenance work done by Mr. Rooney. Data for existing vehicles was inspected and from which, area relations for the different type of thermal protection systems (TPS) developed. The area relations applied to calculated wetted area. The equations for wetted area were provided by Barry Hellman, also from ASC/XREC. Man hour approximations for each area relation were calculated and the summations of which were used for airframe maintenance. Approximations were checked with previous estimations, performed by John Livingston of ASC/XREC and deemed acceptable.

For the CER model the information is color coded with yellow, blue, and green. The yellow values are inputs for user to define. Blue stands for industry standard. These can be viewed as constants and should not be changed. Green are equations used by the model.

The CER model references the MER model (Appendix A)

Man Year Cost Information (Dollars)

$MYr_{2004} := 230000$



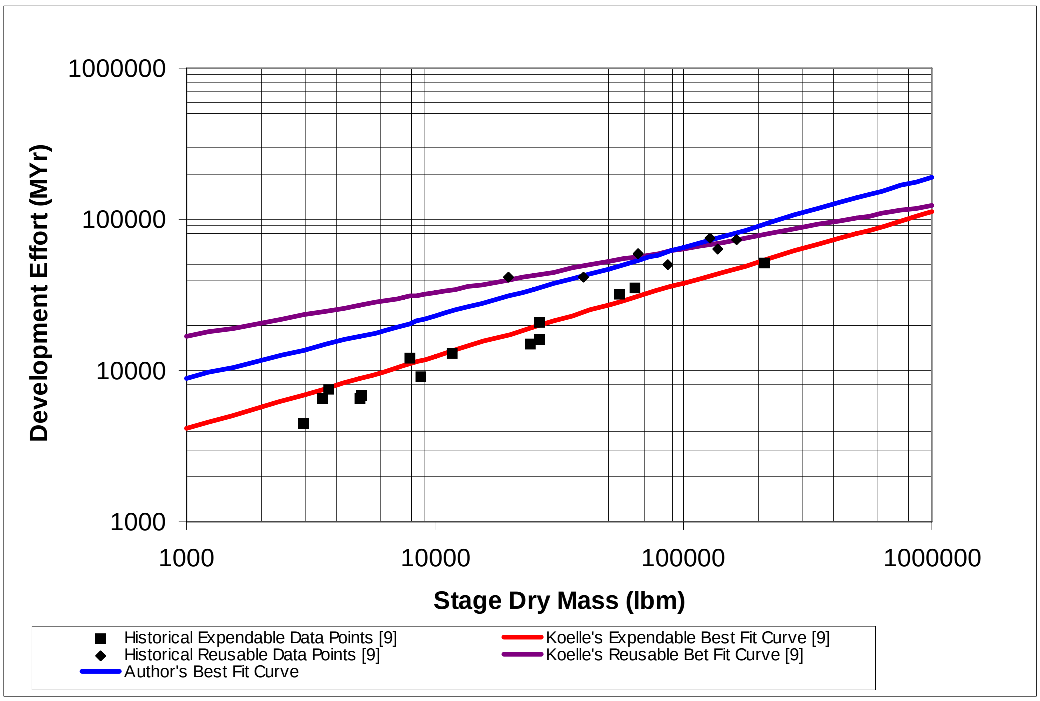
Production Cost Learning Factor @ Given Learning Factor

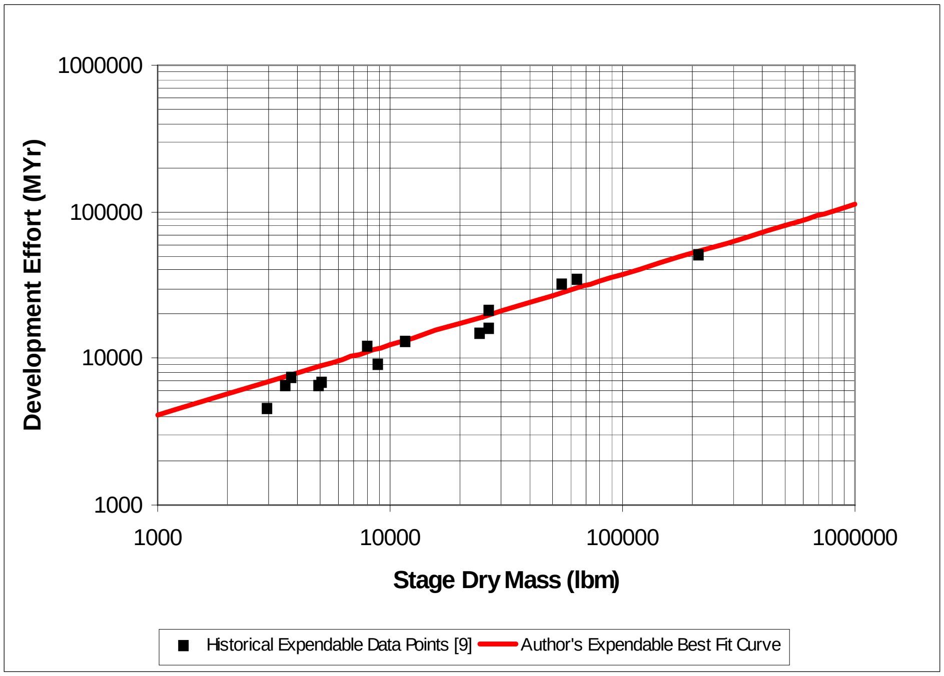
$$LF(Launches, Leaning_{Factor}) := Launches^{\frac{\ln(Leaning_{Factor})}{\ln(2)}}$$

Airframes

Development Cost - Expendable Airframe (MYr) [Excluding Engines]

Previous airframe development CERs developed by Dr. Koelle were redone to better capture the difference in development costs of expendable and reusable systems for increasing vehicle size. Previous CERs predicted a cross over in development costs for stage dry mass greater than 1 million pounds. Airframe development was plotted and correlated to better approximate the trend of airframe development.





The equations for expendable development costs are determined using best fit relationships based on a combination of existing expendable data provided in "Handbook of Cost Engineering for Space Transportation Systems" by Dr. Koelle [9].

Development Cost for Expendable Second Stage (MYr)

$$Develop_{s2.exp}\left(m_{pay}, Isp_{s2.exp}\right) := 150 \cdot m_{s2.exp}\left(m_{pay}, Isp_{s2.exp}\right)^{0.48}$$

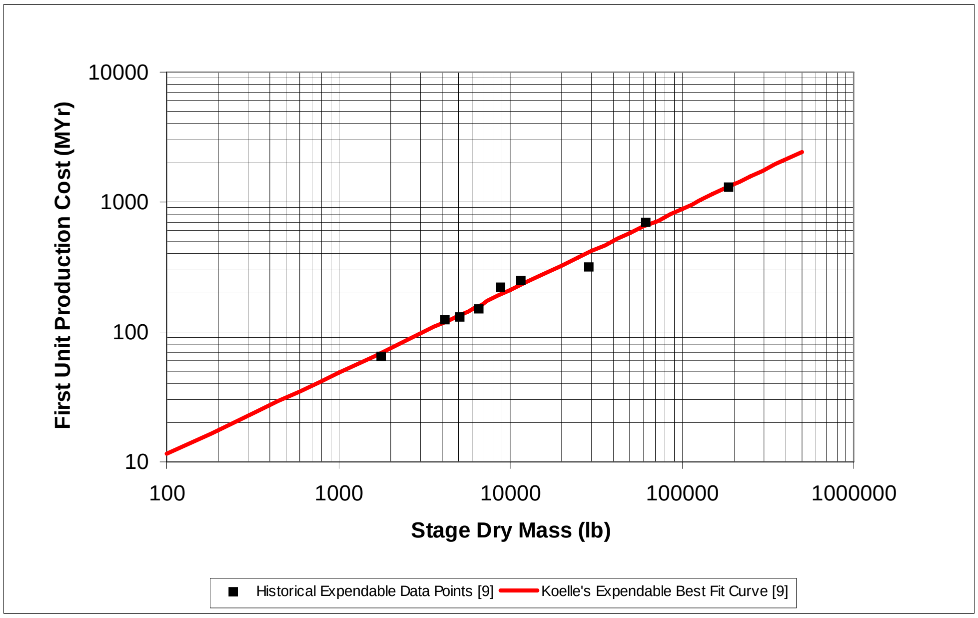
Development Cost for Expendable First Stage (MYr)

$$Develop_{s1.exp}\left(m_{pay}, Isp_{s2.exp}, Isp_{s1.exp}\right) := 150 \cdot m_{s1.exp}\left(m_{pay}, Isp_{s2.exp}, Isp_{s1.exp}\right)^{0.48}$$

Total Development Cost for Both Expendable Stages (MYr)

$$Develop_{total.exp}\left(m_{pay}, Isp_{s2.exp}, Isp_{s1.exp}\right) := Develop_{s1.exp}\left(m_{pay}, Isp_{s2.exp}, Isp_{s1.exp}\right) + Develop_{s2.exp}\left(m_{pay}, Isp_{s2.exp}\right)$$

First Unit Production Cost - Expendable Airframe (MYr)



The equations for expendable first unit production costs are determined using best fit relationships based on a combination of existing expendable data provided in "Handbook of Cost Engineering for Space Transportation Systems" by Dr. Koelle [9].

First Unit Production Cost for Expendable Vehicle Second Stage (MYr)

$$FUPC_{s2.exp}\left(m_{pay}, Isp_{s2.exp}\right) := 0.63 \cdot m_{s2.exp}\left(m_{pay}, Isp_{s2.exp}\right)^{0.63}$$

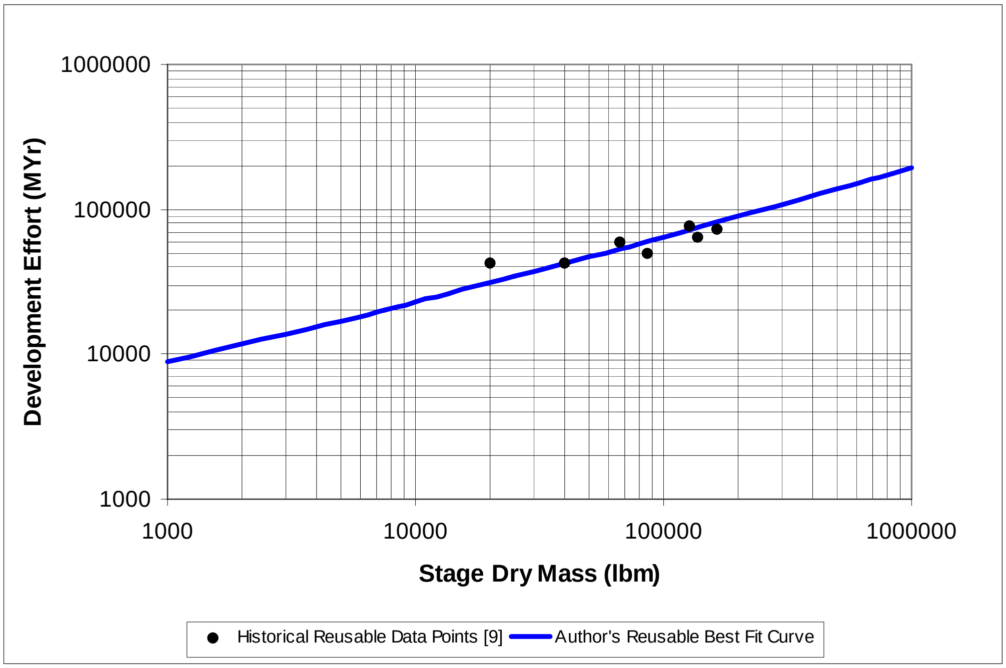
First Unit Production Cost for Expendable Vehicle First Stage (MYr)

$$FUPC_{s1.exp}\left(m_{pay}, Isp_{s2.exp}, Isp_{s1.exp}\right) := 0.63 \cdot m_{s1.exp}\left(m_{pay}, Isp_{s2.exp}, Isp_{s1.exp}\right)^{0.63}$$

Total First Unit Production Cost for Expendable Vehicle (MYr)

$$FUPC_{total.exp}\left(m_{pay}, Isp_{s2.exp}, Isp_{s1.exp}\right) := FUPC_{s1.exp}\left(m_{pay}, Isp_{s2.exp}, Isp_{s1.exp}\right) + FUPC_{s2.exp}\left(m_{pay}, Isp_{s2.exp}\right)$$

Developmental Cost - Reusable Airframe (MYr) [Excluding Engines]



The equations for reusable development costs are determined using best fit relationships based on a combination of existing expendable data provided in "Handbook of Cost Engineering for Space Transportation Systems" by Dr. Koelle [9]

Development Cost for Reusable Second Stage (MYr)

$$Develop_{s2.reus}(m_{pay}, Isp_{s2.reus}) := 250 \cdot m_{s2.reus}(m_{pay}, Isp_{s2.reus})^{0.48} + 2000$$

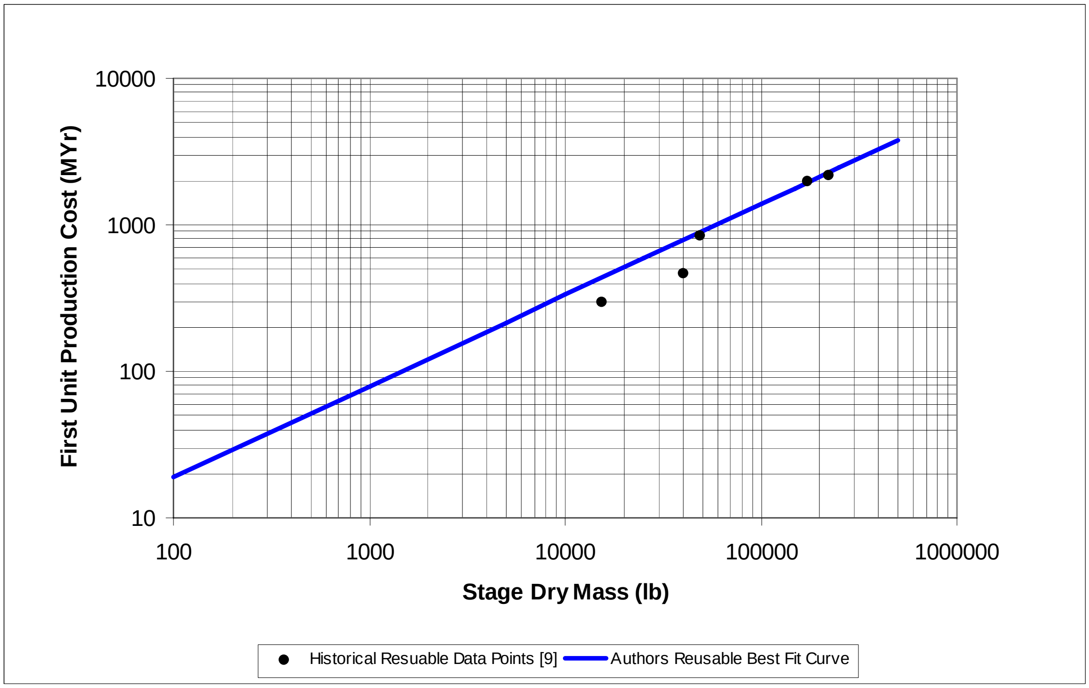
Development Cost for Reusable First Stage (MYr)

$$Develop_{s1.reus}(m_{pay}, Isp_{s2.reus}, Isp_{s1.reus}) := 250 \cdot m_{s1.reus}(m_{pay}, Isp_{s2.reus}, Isp_{s1.reus})^{0.48} + 2000$$

Total Development Cost for Both Reusable Stages (MYr)

$$Develop_{total.reus}(m_{pay}, Isp_{s2.reus}, Isp_{s1.reus}) := Develop_{s1.reus}(m_{pay}, Isp_{s2.reus}, Isp_{s1.reus}) + Develop_{s2.reus}(m_{pay}, Isp_{s2.reus})$$

First Unit Production Cost - Reusable Airframe (MYr)



The equations for reusable first unit production costs are determined best fit empirical relationships based on a combination of existing expendable data provided in "Handbook of Cost Engineering for Space Transportation Systems" by Dr. Koelle [9]

First Unit Production Cost For Reusable Second Stage

$$FUPC_{s2.reus}(m_{pay}, Isp_{s2.reus}) := 1.1 \cdot m_{s2.reus}(m_{pay}, Isp_{s2.reus})^{0.62}$$

First Unit Production Cost For Reusable First Stage

$$FUPC_{s1.reus}(m_{pay}, Isp_{s2.reus}, Isp_{s1.reus}) := 1.1 \cdot m_{s1.reus}(m_{pay}, Isp_{s2.reus}, Isp_{s1.reus})^{0.62}$$

Total First Unit Production Cost for Reusable Vehicle

$$FUPC_{total.reus}(m_{pay}, Isp_{s2.reus}, Isp_{s1.reus}) := FUPC_{s1.reus}(m_{pay}, Isp_{s2.reus}, Isp_{s1.reus}) + FUPC_{s2.reus}(m_{pay}, Isp_{s2.reus})$$

Developmental Cost - Hybrid Airframe (MYR) [Excluding Engines]

The equations for hybrid development costs are the development costs the reusable first stage and the expendable second stage.

Development Cost for Hybrid Second Stage (MYr)

$$Develop_{s2.hyb}(m_{pay}, Isp_{s2.hyb}) := 150 \cdot m_{s2.hyb}(m_{pay}, Isp_{s2.hyb})^{0.48}$$

Development Cost for Hybrid First Stage (MYr)

$$Develop_{s1.hyb}(m_{pay}, Isp_{s2.hyb}, Isp_{s1.hyb}) := 250 \cdot m_{s1.hyb}(m_{pay}, Isp_{s2.hyb}, Isp_{s1.hyb})^{0.48} + 2000$$

Total Development Cost for Hybrid Vehicle (MYr)

$$Develop_{total.hyb}(m_{pay}, Isp_{s2.hyb}, Isp_{s1.hyb}) := Develop_{s1.hyb}(m_{pay}, Isp_{s2.hyb}, Isp_{s1.hyb}) + Develop_{s2.hyb}(m_{pay}, Isp_{s2.hyb})$$

First Unit Production Cost - Hybrid Airframe (MYR)

The equations for hybrid first unit production costs are the first unit production costs for the reusable first stage and the expendable second stage.

First Unit Production Cost for Hybrid Launch Vehicle Second Stage

$$FUPC_{s2.hyb}(m_{pay}, Isp_{s2.hyb}) := 0.63 \cdot m_{s2.hyb}(m_{pay}, Isp_{s2.hyb})^{0.63}$$

First Unit Production Cost for Hybrid First Stage

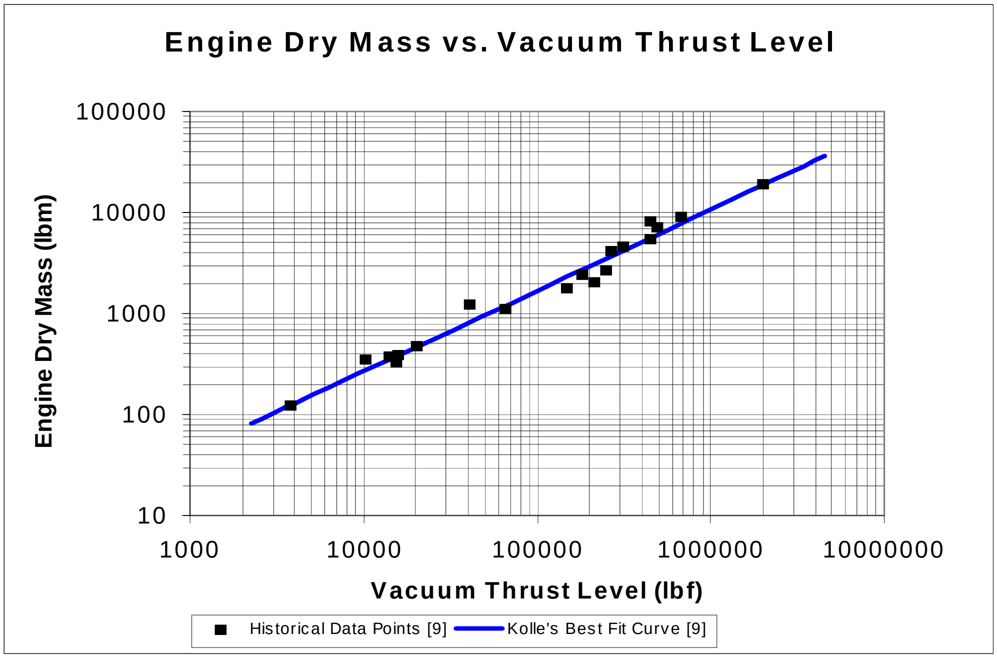
$$FUPC_{s1.hyb}(m_{pay}, Isp_{s2.hyb}, Isp_{s1.hyb}) := 1.1 \cdot m_{s1.hyb}(m_{pay}, Isp_{s2.hyb}, Isp_{s1.hyb})^{.62}$$

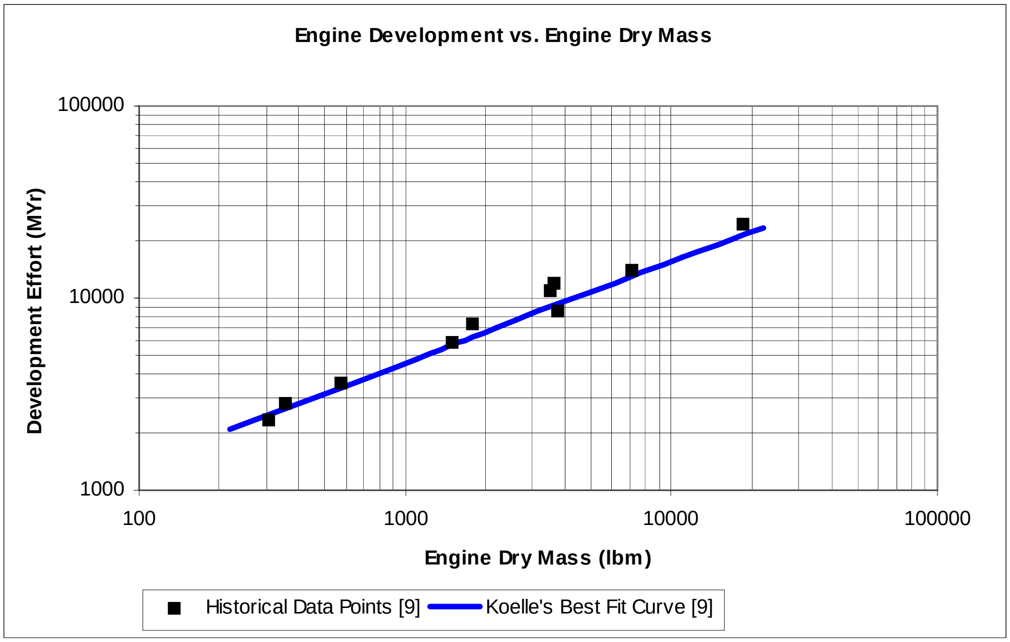
Total First Unit Production Cost for Hybrid Vehicle

$$FUPC_{total.hyb}(m_{pay}, Isp_{s2.hyb}, Isp_{s1.hyb}) := FUPC_{s1.hyb}(m_{pay}, Isp_{s2.hyb}, Isp_{s1.hyb}) + FUPC_{s2.hyb}(m_{pay}, Isp_{s2.hyb})$$

Engines

The following graphs are used for approximating engine development effort. These graphs are reproductions of graphs produced by Dr. Koelle in "Handbook of Cost Engineering for Space Transportation systems. The data has been converted to English Units.





Developmental Cost - Expendable Engine (MYr)

Expendable Input Parameters

Vacuum Thrust to Weight: First Stage Expendable

$TtoW_{vac.s1.exp} := 1.55$

Vacuum Thrust to Weight: Second Stage Expendable

$TtoW_{vac.s2.exp} := 1.1$

Number of Engines: First Stage

$EngineNumber_{s1.exp} := 1$

Number of Engines: Second Stage

$EngineNumber_{s2.exp} := 1$

Expendable Engine Calculations

Vacuum Thrust Level: First Stage (lbf)

$$VacuumThrust_{s1.exp}\left(m_{pay}, Isp_{s2.hyb}, Isp_{s1.hyb}\right) := \frac{TtoW_{vac.s1.exp} \cdot m_{01.exp}\left(m_{pay}, Isp_{s2.hyb}, Isp_{s1.hyb}\right)}{EngineNumber_{s1.exp}}$$

Vacuum Thrust Level: Second Stage (lbf)

$$VacuumThrust_{s2.exp}\left(m_{pay}, Isp_{s2.hyb}\right) := \frac{TtoW_{vac.s2.exp} \cdot m_{02.exp}\left(m_{pay}, Isp_{s2.hyb}\right)}{EngineNumber_{s2.exp}}$$

Engine Dry Mass: First Stage (lbm)

$$EngineDryMass_{s1.exp}\left(m_{pay}, Isp_{s2.hyb}, Isp_{s1.hyb}\right) := 0.17\, VacuumThrust_{s1.exp}\left(m_{pay}, Isp_{s2.hyb}, Isp_{s1.hyb}\right)^{0.80}$$

Engine Dry Mass: Second Stage (lbm)

$$EngineDryMass_{s2.exp}\left(m_{pay}, Isp_{s2.hyb}\right) := 0.17\, VacuumThrust_{s2.exp}\left(m_{pay}, Isp_{s2.hyb}\right)^{0.80}$$

Engine Development Effort: First Stage (MYr)

$$Develop_{engine.s1.exp}\left(m_{pay}, Isp_{s2.hyb}, Isp_{s1.hyb}\right) := 124.2 \cdot EngineDryMass_{s1.exp}\left(m_{pay}, Isp_{s2.hyb}, Isp_{s1.hyb}\right)^{0.52}$$

Engine Development Effort: Second Stage (MYr)

$$Develop_{engine.s2.exp}\left(m_{pay}, Isp_{s2.hyb}\right) := 124.2 \cdot EngineDryMass_{s2.exp}\left(m_{pay}, Isp_{s2.hyb}\right)^{0.52}$$

Engine Development Effort: Total (MYr)

$$Develop_{total.engine.exp}\left(m_{pay}, Isp_{s2.hyb}, Isp_{s1.hyb}\right) := Develop_{engine.s1.exp}\left(m_{pay}, Isp_{s2.hyb}, Isp_{s1.hyb}\right) + Develop_{engine.s2.exp}\left(m_{pay}, Isp_{s2.hyb}\right)$$

Developmental Cost - Reusable Engine (MYR)

Reusable Input Parameters

Vacuum Thrust to Weight: First Stage Reusable

$TtoW_{vac.s1.reus} := 1.55$

Vacuum Thrust to Weight: Second Stage Reusable

$TtoW_{vac.s2.reus} := 1.1$

Number of Engines: First Stage

$EngineNumber_{s1.reus} := 4$

Number of Engines: Second Stage

$EngineNumber_{s2.reus} := 3$

Reusable Engine Calculations

Vacuum Thrust Level: First Stage (lbf)

$$VacuumThrust_{s1.reus}\left(m_{pay}, Isp_{s2.reus}, Isp_{s1.reus}\right) := \frac{TtoW_{vac.s1.reus} \cdot m_{01.reus}\left(m_{pay}, Isp_{s2.reus}, Isp_{s1.reus}\right)}{EngineNumber_{s1.reus}}$$

Vacuum Thrust Level: Second Stage (lbf)

$$VacuumThrust_{s2.reus}\left(m_{pay}, Isp_{s2.reus}\right) := \frac{TtoW_{vac.s2.reus} \cdot m_{02.reus}\left(m_{pay}, Isp_{s2.reus}\right)}{EngineNumber_{s2.reus}}$$

Engine Dry Mass: First Stage (lbm)

$$EngineDryMass_{s1.reus}\left(m_{pay}, Isp_{s2.reus}, Isp_{s1.reus}\right) := 0.17\, VacuumThrust_{s1.reus}\left(m_{pay}, Isp_{s2.reus}, Isp_{s1.reus}\right)^{0.80}$$

Engine Dry Mass: Second Stage (lbm)

$$EngineDryMass_{s2.reus}\left(m_{pay}, Isp_{s2.reus}\right) := 0.17\, VacuumThrust_{s2.reus}\left(m_{pay}, Isp_{s2.reus}\right)^{0.80}$$

Engine Development Effort: First Stage (MYr)

$$Develop_{engine.s1.reus}\left(m_{pay}, Isp_{s2.reus}, Isp_{s1.reus}\right) := 1.5 \cdot \left(124.2 \cdot EngineDryMass_{s1.reus}\left(m_{pay}, Isp_{s2.reus}, Isp_{s1.reus}\right)^{0.52}\right)$$

Engine Development Effort: Second Stage (MYr)

$$Develop_{engine.s2.reus}\left(m_{pay}, Isp_{s2.reus}\right) := 1.5 \cdot \left(124.2 \cdot EngineDryMass_{s2.reus}\left(m_{pay}, Isp_{s2.reus}\right)^{0.52}\right)$$

Engine Development Effort: Total (MYr)

$$Develop_{total.engine.reus}\left(m_{pay}, Isp_{s2.reus}, Isp_{s1.reus}\right) := Develop_{engine.s1.reus}\left(m_{pay}, Isp_{s2.reus}, Isp_{s1.reus}\right) + Develop_{engine.s2.reus}\left(m_{pay}, Isp_{s2.reus}\right)$$

Developmental Cost - Hybrid Engine (MYr)

Hybrid Input Parameters

Vacuum Thrust to Weight: First Stage Hybrid

$TtoW_{vac.s1.hyb} := 1.55$

Vacuum Thrust to Weight: Second Stage Hybrid

$TtoW_{vac.s2.hyb} := 1.1$

Number of Engines: First Stage

$EngineNumber_{s1.hyb} := 4$

Number of Engines: Second Stage

$EngineNumber_{s2.hyb} := 1$

Hybrid Engine Calculations

Vacuum Thrust Level: First Stage (lbf)

$$VacuumThrust_{s1.hyb}\left(m_{pay}, Isp_{s2.hyb}, Isp_{s1.hyb}\right) := \frac{TtoW_{vac.s1.hyb} \cdot m_{01.hyb}\left(m_{pay}, Isp_{s2.hyb}, Isp_{s1.hyb}\right)}{EngineNumber_{s1.hyb}}$$

Vacuum Thrust Level: Second Stage (lbf)

$$VacuumThrust_{s2.hyb}\left(m_{pay}, Isp_{s2.hyb}\right) := \frac{TtoW_{vac.s2.hyb} \cdot m_{02.hyb}\left(m_{pay}, Isp_{s2.hyb}\right)}{EngineNumber_{s2.hyb}}$$

Engine Dry Mass: First Stage (lbm)

$$EngineDryMass_{s1.hyb}\left(m_{pay}, Isp_{s2.hyb}, Isp_{s1.hyb}\right) := 0.17\, VacuumThrust_{s1.hyb}\left(m_{pay}, Isp_{s2.hyb}, Isp_{s1.hyb}\right)^{0.80}$$

Engine Dry Mass: Second Stage (lbm)

$$EngineDryMass_{s2.hyb}\left(m_{pay}, Isp_{s2.hyb}\right) := 0.17\, VacuumThrust_{s2.hyb}\left(m_{pay}, Isp_{s2.hyb}\right)^{0.80}$$

Engine Development Effort: First Stage (MYr)

$$Develop_{engine.s1.hyb}\left(m_{pay}, Isp_{s2.hyb}, Isp_{s1.hyb}\right) := 1.5 \cdot \left(124.2 \cdot EngineDryMass_{s1.hyb}\left(m_{pay}, Isp_{s2.hyb}, Isp_{s1.hyb}\right)^{0.52}\right)$$

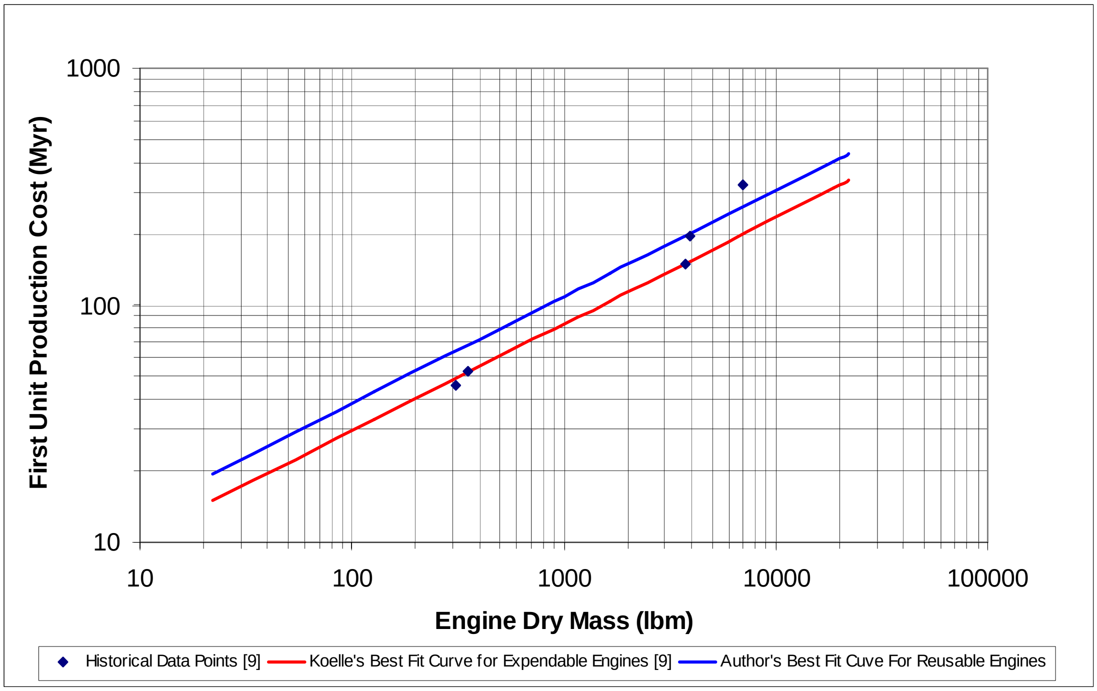
Engine Development Effort: Second Stage (MYr)

$$Develop_{engine.s2.hyb}\left(m_{pay}, Isp_{s2.hyb}\right) := 124.2 \cdot EngineDryMass_{s2.hyb}\left(m_{pay}, Isp_{s2.hyb}\right)^{0.52}$$

Engine Development Effort: Total (MYr)

$$Develop_{total.engine.hyb}\left(m_{pay}, Isp_{s2.hyb}, Isp_{s1.hyb}\right) := Develop_{engine.s1.hyb}\left(m_{pay}, Isp_{s2.hyb}, Isp_{s1.hyb}\right) + Develop_{engine.s2.hyb}\left(m_{pay}, Isp_{s2.hyb}\right)$$

First Unit Production Cost - Engine



Expendable Engine

Expendable Launch Vehicle 1st Stage Engine First Unit Production Cost

$$EngineCost_{s1.exp}(m_{pay}, Isp_{s2.exp}, Isp_{s1.exp}) := 3.72 \cdot EngineDryMass_{s1.exp}(m_{pay}, Isp_{s2.exp}, Isp_{s1.exp})^{0.45}$$

Expendable Launch Vehicle 2nd Stage Engine First Unit Production Cost

$$EngineCost_{s2.exp}(m_{pay}, Isp_{s2.exp}) := 3.72 \cdot EngineDryMass_{s2.exp}(m_{pay}, Isp_{s2.exp})^{0.45}$$

Total Expendable Launch Vehicle Engine First Unit Production Cost

$$EngineCost_{total.exp}(m_{pay}, Isp_{s2.exp}, Isp_{s1.exp}) := EngineCost_{s1.exp}(m_{pay}, Isp_{s2.exp}, Isp_{s1.exp}) + EngineCost_{s2.exp}(m_{pay}, Isp_{s2.exp})$$

Reusable Engine

Reusable Launch Vehicle 1st Stage Engine First Unit Production Cost

$$EngineCost_{s1.reus}(m_{pay}, Isp_{s2.reus}, Isp_{s1.reus}) := 4.84 \cdot EngineDryMass_{s1.reus}(m_{pay}, Isp_{s2.reus}, Isp_{s1.reus})^{0.45}$$

Reusable Launch Vehicle 2nd Stage Engine First Unit Production Cost

$$EngineCost_{s2.reus}(m_{pay}, Isp_{s2.reus}) := 4.84 \cdot EngineDryMass_{s2.reus}(m_{pay}, Isp_{s2.reus})^{0.45}$$

Total Reusable Launch Vehicle Engine First Unit Production Cost

$$EngineCost_{total.reus}(m_{pay}, Isp_{s2.reus}, Isp_{s1.reus}) := EngineCost_{s1.reus}(m_{pay}, Isp_{s2.reus}, Isp_{s1.reus}) + EngineCost_{s2.reus}(m_{pay}, Isp_{s2.reus})$$

Hybrid Engine

Hybrid Launch Vehicle 1st Stage Engine First Unit Production Cost

$$EngineCost_{s1.hyb}\left(m_{pay}, Isp_{s2.hyb}, Isp_{s1.hyb}\right) := 4.84 \cdot EngineDryMass_{s1.hyb}\left(m_{pay}, Isp_{s2.hyb}, Isp_{s1.hyb}\right)^{0.45}$$

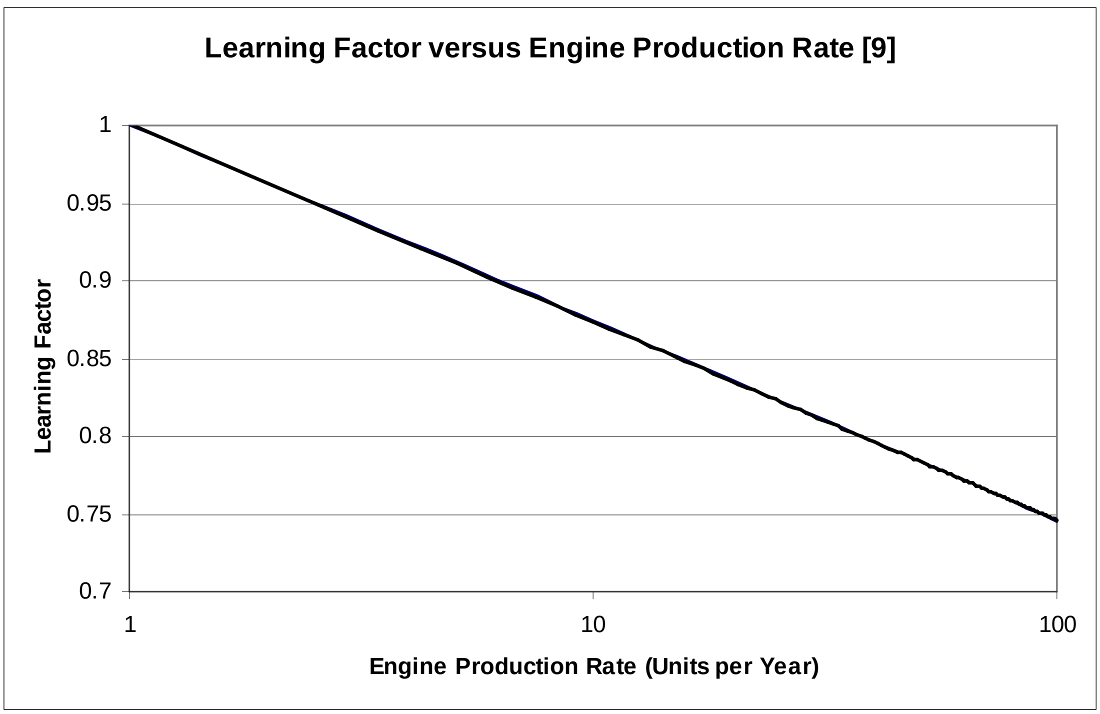
Hybrid Launch Vehicle 2nd Stage Engine First Unit Production Cost

$$EngineCost_{s2.hyb}\left(m_{pay}, Isp_{s2.hyb}\right) := 3.72 \cdot EngineDryMass_{s2.hyb}\left(m_{pay}, Isp_{s2.hyb}\right)^{0.45}$$

Total Hybrid Launch Vehicle Engine First Unit Production Cost

$$EngineCost_{total.hyb}\left(m_{pay}, Isp_{s2.hyb}, Isp_{s1.hyb}\right) := EngineCost_{s1.hyb}\left(m_{pay}, Isp_{s2.hyb}, Isp_{s1.hyb}\right) + EngineCost_{s2.hyb}\left(m_{pay}, Isp_{s2.hyb}\right)$$

Learning Factor for Engine First Unit Production Cost



Engine First Unit Production Cost Learning Factor

$$LF_{engine}(launches) := -.0553 \cdot \ln(launches) + 1.0011$$

Maintenance

Maintenance Costs are approximated using relations developed by Brendan Rooney of ASC/XREC. Engine maintenance is a function of vacuum thrust and TPS maintenance is a function stage gross mass. Subsystem maintenance is a given for each stage. First stage subsystems are assumed to have 250 man hours of maintenance and second stage subsystems are assumed to have 500 man hours. These subsystems maintenance times are best estimates. Maintenance in general is a best approximation. There is no real understanding of maintenance of a hybrid or reusable vehicle since no vehicles currently are in operation.

Hybrid Vehicle Maintenance

Engine Maintenance: Hybrid First Stage (Man Hours)

$$EngineMNX_{s1.hyb}\left(m_{pay}, Isp_{s2.hyb}, Isp_{s1.hyb}\right) := \left[140 + 92\cdot\left(\frac{VacuumThrust_{s1.hyb}\left(m_{pay}, Isp_{s2.hyb}, Isp_{s1.hyb}\right)}{650364}\right)^{.6}\right]\cdot\left(EngineNumber_{s1.hyb}\right)$$

Subsystems Maintenance: Hybrid First Stage (Man Hours)

$$SubSysMNX_{s1.Hyb} := 250$$

Wetted Area: Hybrid First Stage (ft^2)

$$WetArea_{s1.hyb}\left(m_{pay}, Isp_{s2.hyb}, Isp_{s1.hyb}\right) := SurfaceArea_{Total}\left(m_{01.hyb}\left(m_{pay}, Isp_{s2.hyb}, Isp_{s1.hyb}\right)lb, f_{p1.hyb}\left(Isp_{s1.hyb}\right), LOX\_LH2\right)$$

TPS Maintenance: Hybrid First Stage (Man Hours)

Advanced TPS Blankets = 25% of Wetted Area @ 0.15 Man Hour/ft^2
Windward TPS = 4% of Wetted Area @ 0.8 Man Hour/ft^2
Leeward TPS Blankets = 40% of Wetted Area @ 0.06 Man Hour/ft^2

$$TPSMNX_{s1.hyb}\left(m_{pay}, Isp_{s2.hyb}, Isp_{s1.hyb}\right) := \frac{\frac{WetArea_{s1.hyb}\left(m_{pay}, Isp_{s2.hyb}, Isp_{s1.hyb}\right)}{ft^2}}{\frac{1}{0.25}\frac{1}{0.15}} + \frac{\frac{WetArea_{s1.hyb}\left(m_{pay}, Isp_{s2.hyb}, Isp_{s1.hyb}\right)}{ft^2}}{\frac{1}{0.04}\frac{1}{0.8}} + \frac{\frac{WetArea_{s1.hyb}\left(m_{pay}, Isp_{s2.hyb}, Isp_{s1.hyb}\right)}{ft^2}}{\frac{1}{0.4}\frac{1}{0.06}}$$

Total Maintenance for Hybrid First Stage

$$MNX_{s1.hyb}\left(m_{pay}, Isp_{s2.hyb}, Isp_{s1.hyb}\right) := EngineMNX_{s1.hyb}\left(m_{pay}, Isp_{s2.hyb}, Isp_{s1.hyb}\right) + SubSysMNX_{s1.Hyb} + .1TPSMNX_{s1.hyb}\left(m_{pay}, Isp_{s2.hyb}, Isp_{s1.hyb}\right)$$

Reusable Vehicle Maintenance

Reusable First Stage

Engine Maintenance: Reusable First Stage (Man Hours)

$$EngineMNX_{s1.reus}(m_{pay}, Isp_{s2.reus}, Isp_{s1.reus}) := \left[140 + 92 \cdot \left(\frac{VacuumThrust_{s1.reus}(m_{pay}, Isp_{s2.reus}, Isp_{s1.reus})}{650364}\right)^{.6}\right] \cdot EngineNumber_{s1.reus}$$

Subsystems Maintenance: Reusable First Stage (Man Hours)

$$SubSysMNX_{s1.reus} := 250$$

Wetted Area: Reusable First Stage (ft^2)

$$WetArea_{s1.reus}(m_{pay}, Isp_{s2.reus}, Isp_{s1.reus}) := SurfaceArea_{Total}\left(m_{01.reus}(m_{pay}, Isp_{s2.reus}, Isp_{s1.reus})\,lb, f_{p1.reus}(Isp_{s1.reus}), LOX\_LH2\right)$$

TPS Maintenance: Reusable Second Stage (Man Hours)

Advanced TPS Blankets = 25% of Wetted Area @ 0.15 Man Hour/ft^2
Windward TPS = 4% of Wetted Area @ 0.8 Man Hour/ft^2
Leeward TPS Blankets = 40% of Wetted Area @ 0.06 Man Hour/ft^2

$$TPSMNX_{s1.reus}(m_{pay}, Isp_{s2.reus}, Isp_{s1.reus}) := \frac{\frac{WetArea_{s1.reus}(m_{pay}, Isp_{s2.reus}, Isp_{s1.reus})}{ft^2}}{\frac{1}{0.25}\cdot\frac{1}{0.15}} + \frac{\frac{WetArea_{s1.reus}(m_{pay}, Isp_{s2.reus}, Isp_{s1.reus})}{ft^2}}{\frac{1}{0.04}\cdot\frac{1}{0.8}} + \frac{\frac{WetArea_{s1.reus}(m_{pay}, Isp_{s2.reus}, Isp_{s1.reus})}{ft^2}}{\frac{1}{0.4}\cdot\frac{1}{0.06}}$$

Total Maintenance for Reusable First Stage (Man Hours)

$$MNX_{s1.reus}(m_{pay}, Isp_{s2.reus}, Isp_{s1.reus}) := EngineMNX_{s1.reus}(m_{pay}, Isp_{s2.reus}, Isp_{s1.reus}) + SubSysMNX_{s1.reus} + .1 TPSMNX_{s1.reus}(m_{pay}, Isp_{s2.reus}, Isp_{s1.reus})$$

Reusable Second Stage

Engine Maintenance: Reusable Second Stage (Man Hours)

$$EngineMNX_{s2.reus}(m_{pay}, Isp_{s2.reus}) := \left[140 + 92 \cdot \left(\frac{VacuumThrust_{s2.reus}(m_{pay}, Isp_{s2.reus})}{650364}\right)^{.6}\right] \cdot (EngineNumber_{s2.reus})$$

Subsystems Maintenance: Reusable Second Stage (Man Hours)

$$SubSysMNX_{s2.reus} := 500$$

Wetted Area: Reusable Second Stage

$$WetArea_{s2.reus}(m_{pay}, Isp_{s2.reus}) := SurfaceArea_{Total}\left(m_{02.reus}(m_{pay}, Isp_{s2.reus})\,lb, f_{p2.reus}(Isp_{s2.reus}), LOX\_LH2\right)$$

TPS Maintenance: Second Stage (Man Hours)

Advanced TPS Blankets = 25% of Wetted Area @ 0.15 Man Hour/ft^2
Windward TPS = 4% of Wetted Area @ 0.8 Man Hour/ft^2
Leeward TPS Blankets = 40% of Wetted Area @ 0.06 Man Hour/ft^2
RCC = 5% of Wetted Area @ 1.9 Man Hour/ft^2

$$TPSMNX_{s2.reus}(m_{pay}, Isp_{s2.reus}) := \frac{\frac{WetArea_{s2.reus}(m_{pay}, Isp_{s2.reus})}{ft^2}}{\frac{1}{0.25}\frac{1}{0.15}} + \frac{\frac{WetArea_{s2.reus}(m_{pay}, Isp_{s2.reus})}{ft^2}}{\frac{1}{0.04}\frac{1}{0.8}} + \frac{\frac{WetArea_{s2.reus}(m_{pay}, Isp_{s2.reus})}{ft^2}}{\frac{1}{0.4}\frac{1}{0.06}} + \frac{\frac{WetArea_{s2.reus}(m_{pay}, Isp_{s2.reus})}{ft^2}}{\frac{1}{0.05}\frac{1}{1.9}}$$

Total Maintenance for Reusable Second Stage (Man Hours)

$$MNX_{s2.reus}(m_{pay}, Isp_{s2.reus}) := EngineMNX_{s2.reus}(m_{pay}, Isp_{s2.reus}) + SubSysMNX_{s2.reus} + TPSMNX_{s2.reus}(m_{pay}, Isp_{s2.reus})$$

Total Reusable Vehicle

Total Maintenance for Reusable Launch Vehicle (Man Hours)

$$MNX_{total.reus}(m_{pay}, Isp_{s2.reus}, Isp_{s1.reus}) := MNX_{s1.reus}(m_{pay}, Isp_{s2.reus}, Isp_{s1.reus}) + MNX_{s2.reus}(m_{pay}, Isp_{s2.reus})$$

Appendix C: Comparison Model

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The following is a life DPM comparison between expendable, hybrid, and reusable two-stage to orbit launch systems. The life of each program is capped at 20 years. All systems are sized to carry a 15,000 lbm payload to low Earth orbit. The hybrid vehicle is a first stage reusable and a second stage expendable launch system. The reusable vehicle fully reuses both stages. The weight relationships between expendable, hybrid, and reusable vehicles were approximated using physics based mass estimating relations that were correlated to industry and government vehicle and RMLS data. Also it is assumed that reusable vehicles operate for a maximum of 200 launches and launch rate is approximated to be 20 launches a year.

Maintenance costs were approximated using relations developed Brendan Rooney. A detailed breakdown of the maintenance costs can be found in Appendix B: Cost Estimating Model

First unit production costs for each launch system are based on data assembled and adjusted by Dr. Dietrich Koelle in "The Handbook of Cost Engineering for Space Transportation Systems" for expendable and reusable launch systems. Hybrid launch systems are a combination of the two. More information on first unit production cost can be found in Appendix B: Cost Estimating Model

For the comparison model the information is color coded with yellow, blue, and green. The yellow values are inputs for user to define. Blue stands for industry standard. These can be viewed as constants and should not be changed. Green are equations used by the model.

The comparison model references both the MER model (Appendix A) and the CER model (Appendix B)

Life Cycle Information

Max Number of Launches Per Vehicle (Hybrid 1st Stage, Reusable 1st& 2nd Stage)

$Launch_{max} := 200$

Total Life of a Launch System Program (Years)

$Life_{LaunchSystem} := 20$

Launch Rate Per Year

$Launch_{rate} := 20$

Vehicle Losses Per Launch

Maximum vehicle launch rate, launch system lifetime, launch rate, and payload mass are inputs for the user define.

$LossesPerLaunch := 0.001$

Number of Launch Vehicles Required to be Built to complete Launch Objectives (For Hybrid/Reusable)

$$FleetSize := ceil\left(\frac{Life_{LaunchSystem} \cdot Launch_{rate}}{Launch_{max}} + Life_{LaunchSystem} \cdot Launch_{rate} \cdot LossesPerLaunch\right)$$

Payload Mass to LEO (lbm)

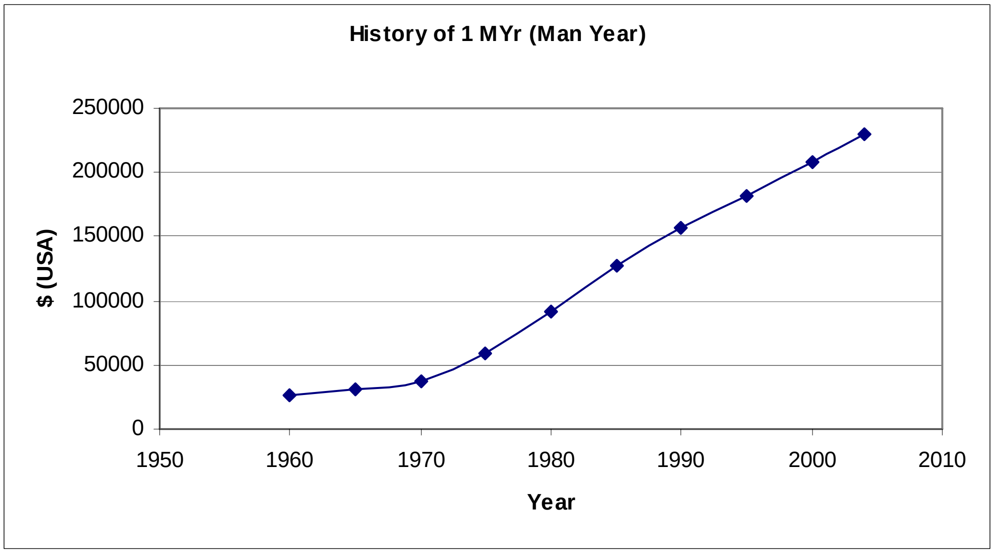
$Mass_{payload} := 15000$

Isp For Vehicle Alternatives

Expendable	Reusable	Hybrid
Expendable 2nd Stage Isp	Expendable 2nd Stage Isp	Expendable 2nd Stage Isp
$Isp_{2.exp} := 320s$	$Isp_{2.reus} := 350s$	$Isp_{2.hyb} := 320s$
Expendable 1st Stage Isp	Expendable 1st Stage Isp	Expendable 1st Stage Isp
$Isp_{1.exp} := 300s$	$Isp_{1.reus} := 320s$	$Isp_{1.hyb} := 320s$

Man Year Cost Information (Dollars)

$MYr_{2004} = 230000$



Airframe Developmental Cost (MYR) - Expendable

Expendable Launch Vehicle Weight Ratios (TWO STAGE TO ORBIT)

Payload Mass to LEO (lbm)

$Mass_{payload} = 15000$

The equations for stage dry mass are determined using a physics based model. For more information on mass determination, see Appendix A: Mass Estimating Model.

Dry Mass of Second Stage (lbm)

$m_{s2.exp}(Mass_{payload}, Isp_{2.exp}) = 13949.51$

Dry Mass of First Stage (lbm)

$m_{s1.exp}(Mass_{payload}, Isp_{2.exp}, Isp_{1.exp}) = 35993.83$

Development Cost for Expendable Airframe - Second Stage (MYr)

$Develop_{s2.exp}(Mass_{payload}, Isp_{2.exp}) = 14637.93$

Development Cost for Expendable Airframe - First Stage (MYr)

$Develop_{s1.exp}(Mass_{payload}, Isp_{2.exp}, Isp_{1.exp}) = 23071.76$

Total Development Cost for Expendable Airframes (MYr)

$Develop_{total.exp}(Mass_{payload}, Isp_{2.exp}, Isp_{1.exp}) = 37709.69$

Airframe First Unit Production Cost (MYr) - Expendable

First Unit Production Cost for Expendable Airframe - Second Stage (MYr)

$FUPC_{s2.exp}(Mass_{payload}, Isp_{2.exp}) = 257.28$

First Unit Production Cost for Expendable Airframe - First Stage (MYr)

$FUPC_{s1.exp}(Mass_{payload}, Isp_{2.exp}, Isp_{1.exp}) = 467.48$

Total First Unit Production Cost for Expendable Airframe (MYr)

$FUPC_{total.exp}(Mass_{payload}, Isp_{2.exp}, Isp_{1.exp}) = 724.77$

Engine Developmental Cost (MYr) - Expendable

Development Cost for Expendable Engine - Second Stage (MYr)

$Develop_{engine.s2.exp}(Mass_{payload}, Isp_{2.exp}) = 7625.06$

Development Cost for Expendable Engine - First Stage (MYr)

$Develop_{engine.s1.exp}(Mass_{payload}, Isp_{2.exp}, Isp_{1.exp}) = 15986.91$

Total Development Cost for Expendable Engines (MYr)

$Develop_{total.engine.exp}(Mass_{payload}, Isp_{2.exp}, Isp_{1.exp}) = 23611.97$

Engine First Unit Production Cost (MYr) - Expendable

First Unit Production Cost for Expendable Engine - Second Stage (MYr)

$EngineCost_{s2.exp}(Mass_{payload}, Isp_{2.exp}) = 131.21$

First Unit Production Cost for Expendable Engine - First Stage (MYr)

$EngineCost_{s1.exp}(Mass_{payload}, Isp_{2.exp}, Isp_{1.exp}) = 249$

Airframe Developmental Cost (MYr) - Reusable

Reusable Launch Vehicle Weight Ratios (TWO STAGE TO ORBIT)

Payload Mass to LEO (lbm)

$Mass_{payload} = 15000$

Dry Mass of Second Stage (lbm)

$m_{s2.reus}(Mass_{payload}, Isp_{2.reus}) = 63672.13$

Dry Mass of First Stage (lbm)

$m_{s1.reus}(Mass_{payload}, Isp_{s2.reus}, Isp_{1.reus}) = 163544.08$

The equations for stage dry mass are determined using a physics based model. For more information on mass determination, see Appendix A: Mass Estimating Model.

Development Cost for Reusable Airframe - Second Stage (MYr)

$Develop_{s2.reus}(Mass_{payload}, Isp_{2.reus}) = 52563.34$

Development Cost for Reusable Airframe - First Stage (MYr)

$Develop_{s1.reus}(Mass_{payload}, Isp_{s2.reus}, Isp_{1.reus}) = 81521.53$

Total Development Cost for Reusable Stage Airframes (MYr)

$Develop_{total.reus}(Mass_{payload}, Isp_{s2.reus}, Isp_{1.reus}) = 134084.87$

Airframe First Unit Production Cost (MYr) - Reusable

First Unit Production Cost For Reusable Airframe - Second Stage (MYr)

$FUPC_{s2.reus}(Mass_{payload}, Isp_{2.reus}) = 1046.75$

First Unit Production Cost For Reusable Airframe - First Stage (MYr)

$FUPC_{s1.reus}(Mass_{payload}, Isp_{s2.reus}, Isp_{1.reus}) = 1878.65$

Total First Unit Production Cost for Reusable Airframe (MYr)

$FUPC_{total.reus}(Mass_{payload}, Isp_{s2.reus}, Isp_{1.reus}) = 2925.4$

Engine Developmental Cost (MYr) - Reusable

Development Cost for Expendable Engine - Second Stage (MYr)

$Develop_{engine.s2.reus}(Mass_{payload}, Isp_{2.reus}) = 10314.98$

Development Cost for Expendable Engine - First Stage (MYr)

$Develop_{engine.s1.reus}(Mass_{payload}, Isp_{s2.reus}, Isp_{1.reus}) = 19819.52$

Total Development Cost for Expendable Engines (MYr)

$Develop_{total.engine.reus}(Mass_{payload}, Isp_{s2.reus}, Isp_{1.reus}) = 30134.5$

Engine First Unit Production Cost (MYr) - Reusable

First Unit Production Cost for Reusable Engine - Second Stage (MYr)

$EngineCost_{s2.reus}(Mass_{payload}, Isp_{2.reus}) = 156.11$

First Unit Production Cost for Reusable Engine - First Stage (MYr)

$EngineCost_{s1.reus}(Mass_{payload}, Isp_{s2.reus}, Isp_{1.reus}) = 274.71$

Maintenance Cost - Reusable

Maintenance Costs per Flight for Reusable Launch System (Man Hours)

$MNX_{total.reus}(Mass_{payload}, Isp_{s2.reus}, Isp_{1.reus}) = 5921$

Airframe Developmental Cost (MYr) - Hybrid

Hybrid Launch Vehicle Weight Ratios (TWO STAGE TO ORBIT)

Payload Mass to LEO (lbm)

$Mass_{payload} = 15000$

Dry Mass of Second Stage (lbm)

$m_{s2.hyb}\left(Mass_{payload}, Isp_{2.hyb}\right) = 15108.66$

Dry Mass of First Stage (lbm)

$m_{s1.hyb}\left(Mass_{payload}, Isp_{2.hyb}, Isp_{1.hyb}\right) = 86270.8$

The equations for stage dry mass are determined using a physics based model. For more information on mass determination, see Appendix A: Mass Estimating Model.

Development Cost for Hybrid - Second Stage (MYr)

$Develop_{s2.hyb}\left(Mass_{payload}, Isp_{2.hyb}\right) = 15209.67$

Development Cost for Hybrid - First Stage (MYr)

$Develop_{s1.hyb}\left(Mass_{payload}, Isp_{2.hyb}, Isp_{1.hyb}\right) = 60499.84$

Total Development Cost for Hybrid Stages (MYr)

$Develop_{total.hyb}\left(Mass_{payload}, Isp_{2.hyb}, Isp_{1.hyb}\right) = 75709.5$

Airframe First Unit Production Cost (MYr) - Hybrid

First Unit Production Cost For Hybrid Airframe - Second Stage (MYr)

$FUPC_{s2.hyb}\left(Mass_{payload}, Isp_{2.hyb}\right) = 270.55$

First Unit Production Cost For Hybrid Airframe - First Stage (MYr)

$FUPC_{s1.hyb}\left(Mass_{payload}, Isp_{2.hyb}, Isp_{1.hyb}\right) = 1263.65$

Engine Developmental Cost (MYr) - Hybrid

Development Cost for Expendable Engine - Second Stage (MYr)

$Develop_{engine.s2.hyb}(Mass_{payload}, Isp_{2.hyb}) = 7750.61$

Development Cost for Expendable Engine First Stage (MYr)

$Develop_{engine.s1.hyb}(Mass_{payload}, Isp_{2.hyb}, Isp_{1.hyb}) = 14465.35$

Total Development Cost for Expendable Engines Both Stages (MYr)

$Develop_{total.engine.hyb}(Mass_{payload}, Isp_{2.hyb}, Isp_{1.hyb}) = 22215.97$

Engine First Unit Production Cost (MYr) - Hybrid

First Unit Production Cost for Hybrid Engine - Second Stage (MYr)

$EngineCost_{s2.hyb}(Mass_{payload}, Isp_{2.hyb}) = 133.07$

First Unit Production Cost for Hybrid Engine - First Stage (MYr)

$EngineCost_{s1.hyb}(Mass_{payload}, Isp_{2.hyb}, Isp_{1.hyb}) = 209.18$

Maintenance Cost - Reusable

Maintenance Costs per Flight for Reusable Launch System (Man Hours)

$MNX_{s1.hyb}(Mass_{payload}, Isp_{2.hyb}, Isp_{1.hyb}) = 1326.93$

Summary

Inputs

Maximum Launches Per Vehicle (Reusable/Hybrid)

$Launch_{max} = 200$

Total System Life (Years)

$Life_{LaunchSystem} = 20$

Launch Rate Per Year

$Launch_{rate} = 20$

Payload Mass

$Mass_{payload} = 15000$

Isp For Vehicle Alternatives

Expendable

Expendable 2nd Stage Isp

$Isp_{2.exp} = 320\ s$

Expendable 1st Stage Isp

$Isp_{1.exp} = 300\ s$

Reusable

Expendable 2nd Stage Isp

$Isp_{2.reus} = 350\ s$

Expendable 1st Stage Isp

$Isp_{1.reus} = 320\ s$

Hybrid

Expendable 2nd Stage Isp

$Isp_{2.hyb} = 320\ s$

Expendable 1st Stage Isp

$Isp_{1.hyb} = 320\ s$

Expendable Launch System

Masses: Expendable

Dry Mass: 2nd Stage (lbm)

$m_{s2.exp}(Mass_{payload}, Isp_{2.hyb}) = 13949.51$

Dry Mass: 1st Stage (lbm)

$m_{s1.exp}(Mass_{payload}, Isp_{2.exp}, Isp_{1.exp}) = 35993.83$

Engine Info: Expendable

Number of Engines: 2nd Stage

$EngineNumber_{s2.exp} = 1$

Number of Engines: 1st Stage

$EngineNumber_{s1.exp} = 1$

Development Costs: Expendable Airframe

Development - Expendable 2nd Stage (MYr)

$Develop_{s2.exp}(Mass_{payload}, Isp_{2.exp}) = 14637.93$

Development - Expendable 1st Stage (MYr)

$Develop_{s1.exp}(Mass_{payload}, Isp_{2.exp}, Isp_{1.exp}) = 23071.76$

Development - Expendable Total Airframe (MYr)

$Develop_{total.exp}(Mass_{payload}, Isp_{2.exp}, Isp_{1.exp}) = 37709.69$

Development - Expendable Total Airframe (2004 Dollars)

$Develop_{total.exp}(Mass_{payload}, Isp_{2.exp}, Isp_{1.exp}) \cdot MYr_{2004} = 8.673 \times 10^{9}$

First Unit Production Costs: Expendable Airframe

First Unit Production - Expendable 2nd Stage (MYr)

$FUPC_{s2.exp}(Mass_{payload}, Isp_{2.exp}) = 257.28$

First Unit Production - Expendable 1st Stage (MYr)

$FUPC_{s1.exp}(Mass_{payload}, Isp_{2.exp}, Isp_{1.exp}) = 467.48$

First Unit Production - Expendable 2nd Stage Airframe (2004 Dollars)

$FUPC_{s2.exp}(Mass_{payload}, Isp_{2.exp}) \cdot MYr_{2004} = 5.92 \times 10^{7}$

First Unit Production - Expendable 1st Stage Airframe (2004 Dollars)

$FUPC_{s1.exp}(Mass_{payload}, Isp_{2.exp}, Isp_{1.exp}) \cdot MYr_{2004} = 1.075 \times 10^{8}$

Development Costs: Expendable Engines

Development - Expendable 2nd Stage (MYr)

$\mathrm{Develop}_{\mathrm{engine.s2.exp}}\left(\mathrm{Mass}_{\mathrm{payload}}, \mathrm{Isp}_{2.\mathrm{exp}}\right) = 7625.06$

Development - Expendable 1st Stage (MYr)

$\mathrm{Develop}_{\mathrm{engine.s1.exp}}\left(\mathrm{Mass}_{\mathrm{payload}}, \mathrm{Isp}_{2.\mathrm{exp}}, \mathrm{Isp}_{1.\mathrm{exp}}\right) = 15986.908$

Development - Expendable Total Engine (MYr)

$\mathrm{Develop}_{\mathrm{total.engine.exp}}\left(\mathrm{Mass}_{\mathrm{payload}}, \mathrm{Isp}_{2.\mathrm{exp}}, \mathrm{Isp}_{1.\mathrm{exp}}\right) = 23611.97$

Development - Expendable Total Engines (2004 Dollars)

$\mathrm{Develop}_{\mathrm{total.engine.exp}}\left(\mathrm{Mass}_{\mathrm{payload}}, \mathrm{Isp}_{2.\mathrm{exp}}, \mathrm{Isp}_{1.\mathrm{exp}}\right) \cdot \mathrm{MYr}_{2004} = 5.43 \times 10^{9}$

First Unit Production Costs: Expendable Engines

First Unit Production - Expendable 2nd Stage (MYr)

$\mathrm{EngineCost}_{\mathrm{s2.exp}}\left(\mathrm{Mass}_{\mathrm{payload}}, \mathrm{Isp}_{2.\mathrm{exp}}\right) = 131.21$

First Unit Production - Expendable 1st Stage (MYr)

$\mathrm{EngineCost}_{\mathrm{s1.exp}}\left(\mathrm{Mass}_{\mathrm{payload}}, \mathrm{Isp}_{2.\mathrm{exp}}, \mathrm{Isp}_{1.\mathrm{exp}}\right) = 249$

First Unit Production - Expendable 2nd Stage Engine (2004 Dollars)

$\mathrm{EngineCost}_{\mathrm{s2.exp}}\left(\mathrm{Mass}_{\mathrm{payload}}, \mathrm{Isp}_{2.\mathrm{exp}}\right) \cdot \mathrm{MYr}_{2004} = 3.02 \times 10^{7}$

First Unit Production - Expendable 1st Stage Engine (2004 Dollars)

$\mathrm{EngineCost}_{\mathrm{s1.exp}}\left(\mathrm{Mass}_{\mathrm{payload}}, \mathrm{Isp}_{2.\mathrm{exp}}, \mathrm{Isp}_{1.\mathrm{exp}}\right) \cdot \mathrm{MYr}_{2004} = 5.727 \times 10^{7}$

Reusable Launch System

Masses: Reusable

Dry Mass: 2nd Stage (lbm)

$m_{s2.reus}(Mass_{payload}, Isp_{2.reus}) = 63672.13$

Dry Mass: 1st Stage (lbm)

$m_{s1.reus}(Mass_{payload}, Isp_{2.reus}, Isp_{1.reus}) = 163544.08$

Engine Info: Reusable

Number of Engines: 2nd Stage

$EngineNumber_{s2.reus} = 3$

Number of Engines: 1st Stage

$EngineNumber_{s1.reus} = 4$

Development Costs: Reusable Airframe

Development - Reusable 2nd Stage (MYr)

$Develop_{s2.reus}(Mass_{payload}, Isp_{2.reus}) = 52563.34$

Development - Reusable 1st Stage (MYr)

$Develop_{s1.reus}(Mass_{payload}, Isp_{2.reus}, Isp_{1.reus}) = 81521.529$

Development - Reusable Total Airframe (MYr)

$Develop_{total.reus}(Mass_{payload}, Isp_{2.reus}, Isp_{1.reus}) = 134084.87$

Development - Reusable Total Airframe (2004 Dollars)

$Develop_{total.reus}(Mass_{payload}, Isp_{2.reus}, Isp_{1.reus}) \cdot MYr_{2004} = 3.084 \times 10^{10}$

First Unit Production Costs: Reusable Airframe

First Unit Production - Reusable 2nd Stage (MYr)

$FUPC_{s2.reus}(Mass_{payload}, Isp_{2.reus}) = 1046.75$

First Unit Production - Reusable 1st Stage (MYr)

$FUPC_{s1.reus}(Mass_{payload}, Isp_{2.reus}, Isp_{1.reus}) = 1878.65$

First Unit Production - Reusable Total Airframe (MYr)

$FUPC_{total.reus}(Mass_{payload}, Isp_{2.reus}, Isp_{1.reus}) = 2925.4$

First Unit Production - Reusable Total Airframe (2004 Dollars)

$FUPC_{total.reus}(Mass_{payload}, Isp_{2.reus}, Isp_{1.reus}) \cdot MYr_{2004} = 6.728 \times 10^{8}$

Development Costs: Reusable Engines

Development - Reusable 2nd Stage (MYr)

$\mathrm{Develop}_{engine.s2.reus}(\mathrm{Mass}_{payload}, \mathrm{Isp}_{2.reus}) = 10314.98$

Development - Reusable 1st Stage (MYr)

$\mathrm{Develop}_{engine.s1.reus}(\mathrm{Mass}_{payload}, \mathrm{Isp}_{2.reus}, \mathrm{Isp}_{1.reus}) = 19819.516$

Development - Reusable Total Engine (MYr)

$\mathrm{Develop}_{total.engine.reus}(\mathrm{Mass}_{payload}, \mathrm{Isp}_{2.reus}, \mathrm{Isp}_{1.reus}) = 30134.5$

Development - Reusable Total Engines (2004 Dollars)

$\mathrm{Develop}_{total.engine.reus}(\mathrm{Mass}_{payload}, \mathrm{Isp}_{2.reus}, \mathrm{Isp}_{1.reus}) \cdot \mathrm{MYr}_{2004} = 6.93 \times 10^{9}$

First Unit Production Costs: Reusable Engines

First Unit Production - Reusable 2nd Stage (MYr)

$\mathrm{EngineCost}_{s2.reus}(\mathrm{Mass}_{payload}, \mathrm{Isp}_{2.reus}) = 156.11$

First Unit Production - Reusable 1st Stage (MYr)

$\mathrm{EngineCost}_{s1.reus}(\mathrm{Mass}_{payload}, \mathrm{Isp}_{2.reus}, \mathrm{Isp}_{1.reus}) = 274.71$

First Unit Production - Reusable 2nd Stage Engine (2004 Dollars)

$\mathrm{EngineCost}_{s2.reus}(\mathrm{Mass}_{payload}, \mathrm{Isp}_{2.reus}) \cdot \mathrm{MYr}_{2004} = 3.59 \times 10^{7}$

First Unit Production - Reusable 1st Stage Engine (2004 Dollars)

$\mathrm{EngineCost}_{s1.reus}(\mathrm{Mass}_{payload}, \mathrm{Isp}_{2.reus}, \mathrm{Isp}_{1.reus}) \cdot \mathrm{MYr}_{2004} = 6.318 \times 10^{7}$

Maintenance Costs: Reusable

Maintenance - Reusable 2nd Stage (Man Hours)

$\mathrm{MNX}_{s2.reus}(\mathrm{Mass}_{payload}, \mathrm{Isp}_{2.reus}) = 4241.74$

Maintenance - Reusable 1st Stage (Man Hours)

$\mathrm{MNX}_{s1.reus}(\mathrm{Mass}_{payload}, \mathrm{Isp}_{2.reus}, \mathrm{Isp}_{1.reus}) = 1679.26$

Maintenance - Reusable Total Vehicle (Man Hours)

$\mathrm{MNX}_{total.reus}(\mathrm{Mass}_{payload}, \mathrm{Isp}_{2.reus}, \mathrm{Isp}_{1.reus}) = 5921$

Hybrid Launch System

Masses: Hybrid

Dry Mass: 2nd Stage (lbm)

$m_{s2.hyb}(Mass_{payload}, Isp_{2.hyb}) = 15108.66$

Dry Mass: 1st Stage (lbm)

$m_{s1.hyb}(Mass_{payload}, Isp_{2.hyb}, Isp_{1.hyb}) = 86270.8$

Engine Info: Hybrid

Number of Engines: 2nd Stage

$EngineNumber_{s2.hyb} = 1$

Number of Engines: 1st Stage

$EngineNumber_{s1.hyb} = 4$

Development Costs: Hybrid Airframe

Development - Hybrid 2nd Stage (MYr)

$Develop_{s2.hyb}(Mass_{payload}, Isp_{2.hyb}) = 15209.67$

Development - Hybrid 1st Stage (MYr)

$Develop_{s1.hyb}(Mass_{payload}, Isp_{2.hyb}, Isp_{1.hyb}) = 60499.836$

Development - Hybrid Total Airframe (MYr)

$Develop_{total.hyb}(Mass_{payload}, Isp_{2.hyb}, Isp_{1.hyb}) = 75709.5$

Development - Hybrid Total Airframe (2004 Dollars)

$Develop_{total.hyb}(Mass_{payload}, Isp_{2.hyb}, Isp_{1.hyb}) \cdot MYr_{2004} = 1.741 \times 10^{10}$

First Unit Production Costs: Hybrid Airframe

First Unit Production - Hybrid 2nd Stage (MYr)

$FUPC_{s2.hyb}(Mass_{payload}, Isp_{2.hyb}) = 270.55$

First Unit Production - Hybrid 1st Stage (MYr)

$FUPC_{s1.hyb}(Mass_{payload}, Isp_{2.hyb}, Isp_{1.hyb}) = 1263.65$

First Unit Production - Hybrid 2nd Stage Airframe (2004 Dollars)

$FUPC_{s2.hyb}(Mass_{payload}, Isp_{2.hyb}) \cdot MYr_{2004} = 6.22 \times 10^{7}$

First Unit Production - Hybrid 1st Stage Airframe (2004 Dollars)

$FUPC_{s1.hyb}(Mass_{payload}, Isp_{2.hyb}, Isp_{1.hyb}) \cdot MYr_{2004} = 2.906 \times 10^{8}$

Development Costs: Hybrid Engines

Development - Hybrid 2nd Stage (MYr)

$Develop_{engine.s2.hyb}(Mass_{payload}, Isp_{2.hyb}) = 7750.61$

Development - Hybrid 1st Stage (MYr)

$Develop_{engine.s1.hyb}(Mass_{payload}, Isp_{2.hyb}, Isp_{1.hyb}) = 14465.354$

Development - Hybrid Total Engine (MYr)

$Develop_{total.engine.hyb}(Mass_{payload}, Isp_{2.hyb}, Isp_{1.hyb}) = 22215.97$

Development - Hybrid Total Engines (2004 Dollars)

$Develop_{total.engine.hyb}(Mass_{payload}, Isp_{2.hyb}, Isp_{1.hyb}) \cdot MYr_{2004} = 5.11 \times 10^9$

First Unit Production Costs: Hybrid Engines

First Unit Production - Hybrid 2nd Stage (MYr)

$EngineCost_{s2.hyb}(Mass_{payload}, Isp_{2.hyb}) = 133.07$

First Unit Production - Hybrid 1st Stage (MYr)

$EngineCost_{s1.hyb}(Mass_{payload}, Isp_{2.hyb}, Isp_{1.hyb}) = 209.18$

First Unit Production - Hybrid 2nd Stage Engine (2004 Dollars)

$EngineCost_{s2.hyb}(Mass_{payload}, Isp_{2.hyb}) \cdot MYr_{2004} = 3.06 \times 10^7$

First Unit Production - Hybrid 1st Stage Engine (2004 Dollars)

$EngineCost_{s1.hyb}(Mass_{payload}, Isp_{2.hyb}, Isp_{1.hyb}) \cdot MYr_{2004} = 4.811 \times 10^7$

Maintenance Costs: Hybrid

Maintenance - Hybrid 1st Stage (Man Hours)

$MNX_{s1.hyb}(Mass_{payload}, Isp_{2.hyb}, Isp_{1.hyb}) = 1326.93$

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Vita

2nd Lieutenant Greg J. Gstattenbauer graduated from Western Albemarle High School in Crozet, Virginia in 1999. After High School, he completed his Associates Degree in Science at Piedmont Virginia Community College in Charlottesville, Virginia. Following his two years at Piedmont, he entered undergraduate studies at the University of Virginia in Charlottesville, Virginia where he graduated with a Bachelor of Science in Aerospace Engineering in My 2004. He was commission though the Detachment 890 AFROTC at the University of Virginia. His first assignment was to the Air Force Institute of Technology to pursue a Masters Degree in Space Systems. Upon graduation, he will be assigned to Air Force Space Command Detachment 12 Space and Missiles Systems Center.

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14. ABSTRACT

This study compares the developmental, production, and maintenance costs (DPM) of two-stage-to-orbit (TSTO) expendable (ELV), hybrid (HLV), and reusable (RLV) launch systems. This comparison was accomplished using top level mass and cost estimating relations (MERs, CERs). Mass estimating relationships were correlated to existing launch system data and ongoing launch system studies. Cost estimating relations were derived from Dr. Dietrich Koelle's "Handbook of Cost Engineering for Space Transportation Systems". Hybrid launch vehicles appear to be preferable if current or modest increases in launch rates are projected while reusable launch vehicles appear preferable for large projected increases in launch rates.

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