A.9.0 Costing Methods

A.9.1 Introduction

Our cost analysis is a made up of many parts. We have compiled here a summary of our methods in order to create transparent cost functions that can be easily understood. We understand that there is a high degree of uncertainty in any cost estimate performed this early in design.

Additional costs can be added to those presented here and many of the variables can be modified in order to account for more precise estimates as they become available. Our hope is that the framework we have in place will be a stepping-stone for any subsequent design on this topic. We feel that our numbers provide an estimated magnitude for cost.

Author: Alan Schwing

A.9.2 Design Methods

A.9.2.1 Avionics Cost

To approach a cost model for our avionics design, we combine several different methodologies based on available data. Many of the companies we contacted refused to answer questions regarding pricing and exact specifications for their products. In order to develop an approximate cost budget for the project, we took the prices we could find, and when a price was unavailable, we used approximations based on input from people experienced in the field.

We budget $10,000 for the telecommunications system onboard the vehicle. This assumes commercial grade components and little to no radiation hardening procedures. Unofficially, we are told by Honeywell International that a generic, space-grade radio component would cost on the order of $400,000 to $600,000. The company currently supplies components like this to launch vehicles such as the Atlas family of rockets. At the other end of the spectrum, the Purdue University Cube-Sat project, organized by Professor David Filmer, includes an onboard telecommunications package that budgets less than a thousand dollars on hardware.[1] Our vehicle will spend very little time outside of the protection of the atmosphere, so we believe radiation issues can be compensated for with the use of redundant hardware and software mechanisms. To budget for our telecommunications system, we assumed a base hardware set similar to that used by the Cube-Sat project, and multiplied it by a factor of ten to account for redundant hardware and an extended software development cycle to support the vehicle’s mission.

The power distribution system on our launch vehicle is modeled after the Vanguard family of rockets. We are budgeting $500 for the materials used in the power distribution.[2] This number is determined using pricing data from a modern supplier of MIL-W-16878 specification wiring for the volume of wiring selected in the design. For installation costs associated with the power distribution system, we are budgeting $7,500. We calculate this cost estimate from extrapolating four weeks of billable work out of the median salary for an aircraft electrician.[3] Four weeks was assume as an adequate assembly time during which the power distribution components can be installed, tested, and checked off for flight readiness.

Table A.9.2.1.1 Range Safety Subsystem Cost

No. Units	Component	Manufacturer	Unit Cost	Total Cost
1	Global Positioning Unit	Garmin	$50.00	$50.00
2	S-Band Encrypted Transceiver	Aerocomm	$200.00	$400.00
2	S-Band Antenna	Syntronics	$250.00	$500.00

The costs of a basic non-space rated range safety subsystem is broken down in Table A.9.2.1.1. The table presents a component type, manufacturer, number of units, unit cost, and total cost. The number of units concerning the transceiver and antenna is mainly for redundancy. This table does not comprise a complete subsystem, just the main and separate components comprising this system. The subsystem also uses components from the rest of the avionics package, costs are presented in earlier sections.

Table A.9.2.1.2 Ground Tracking Stations Cost

Component	Estimated Costs
Radio	$1200
Antennas	$500
Computer	$2000
Misc	$500

The costs of a basic non-space rated ground tracking station are presented in Table A.9.2.1.2. The costs presented are core components that make up the simplest of stations. The costs in the table are those of the Purdue University Satellite Control Equipment which are housed at the Purdue airport. The airport station is used for satellite research and its functionality is assumed to be viable for our application.

In accordance with the information presented in Section A.2.2.1, we have decided to use non-space-rated sensors in our vehicle design. Typical prices for these sensors are shown in Table 9.2.1.3.

Table A.9.2.1.3 Non-space-rated sensors costs

Sensor type	Part number	Manufacturer	Unit price
Thermal	TS3-85	Cantherm	$10.29
Pressure	2000260	Measurement Specialties Inc.	$104.06
Flow	26616	Gems Sensors, Inc.	$154.95
Force	FSS1500NSR	Honeywell Sensing and Control	$46.56

We have budgeted $789.65 to account for the sensors on our vehicle. Included in this estimate are 2 non-space-rated sensors of each type (thermal, pressure, flow, and force) and a safety factor of 1.25 to account for any inaccuracies.

Table A.9.2.1.3 Avionics cost summary

Unit	**Costs**
Wiring – Materials	$500
- Installation	$7,500
CPU	$10,000
IMU	$3,300
Sensors	$790
Battery (BST System)	$10,000
Range Safety	$20,000
Ground Tracking	$10,000
Telecom	$10,000
Installation –telecom	$7,500
Total	**$79,590**

References

[1] Filmer, David. "Link Budget Analysis," AAE 450 Lecture, Department of Aeronautical and Astronautical Engineering, Purdue University. 23 January, 2008.

[2] TexWire Wire and Cable, personal communication, 04 March, 2008.

[3] "Average Aircraft Electrician Salary." *Salary.com* [online], Jan. 2008. URL: http://swz.salary.com/salarywizard/layouthtmls/swzl_compresult_national_SC16000294.html [cited 21 February 2008].

[4] "BST Products." *BST Systems, Inc.*[online], URL: http://www.bstsys.com [cited 25 March 2008].

[5] "L-3 Space and Navigation." *L-3 Communications* [online], URL: http://www.l-3com.com/spacenav/space_and_nav/products.htm [cited 26 February 2008].

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A.9.2.2 Engine Cost

Rocket engines by nature tend to account for a significant portion of the total cost of the launch system. Depending on the type of propulsion system we select (usually based off the chosen propellant) the complexity and cost of the engine can increase dramatically.

Bipropellant systems have piping, pumps, tubes, valves, and gauges. In the case of cryogenic bipropellants, additional systems to manage extremely cold temperature fuels and oxidizers are required. Large injectors are necessary to inject the propellants into the combustion chamber. The required additional components to make bipropellant engines are very expensive to design, manufacture, or purchase. Bipropellant engines will be amongst the highest costing engines available.

Solid Rocket Motors (SRMs) are much simpler than bipropellant systems because they do not have piping or duct work. After casting the grain into the motor case and attaching a nozzle and igniter the launch vehicle is essentially ready to fire. Therefore the cost of an SRM is in casting of the propellant and the construction of the nozzle. The nozzle may not be an insignificant cost because complex bore patterns in the grain can lead to higher manufacturing costs. Also the nozzle of the SRM can be costly as it must withstand erosion by solid particles of propellant that were not burned completely in the combustion port. However, the lack of any complex piping or feed systems greatly reduces their cost when compared with bipropellant engines.

Hybrid engine systems are a combination of a SRM and a liquid propellant system. Along those lines we anticipate the cost of a hybrid system to lie somewhere in between a bipropellant and SRM. Hybrids contain at least one liquid system, usually the oxidizer, which will require a piping system and injector. They also have solid fuel cast into the motor case which helps to reduce the cost of the overall propulsion system as compared to bipropellants.

Therefore, when examining the costs of different engine systems it becomes clear that for engines producing the same level of thrust a bipropellant system is the most expensive, followed by a hybrid system, and an SRM is the least expensive. However, this does not necessarily mean that to accomplish our mission we desire an entirely solid system to reduce costs. The higher performance of hybrid and bipropellant systems can reduce cost compared to a SRM when achieving certain mission requirements. The Model Analysis our team performs determines which combination of engine systems will provide the lowest cost launch vehicles and which engine systems will be chosen.

There were four potential fuel combinations chosen to undergo Model Analysis. They are as follows:

1. Cryogenic Bipropellant – Liquid Oxygen and Liquid Hydrogen
2. Storable Bipropellant – Hydrogen Peroxide and RP-1
3. Hybrid – Hydrogen Peroxide and HTPB
4. Solid Rocket Motor – HTPB/AP/Al

Finding a method to cost the engines for the thousands of possible designs created by the Model Analysis groups proved difficult. After lengthy research a series of equations were found that enabled estimation of the engine cost based off currently available data.

The formulations found for estimating cost of the engine were determined from historical data based upon engine performance parameters and propellant type. A paper written by John S. Nieroski and Edward I. Friedland of the Aerospace Corporation provides us with equations to estimate the cost of our propulsion systems (not including propellant cost).[1] We found the cost of an engine (produced in quantity), C_N, is found using the following equations.

$$C_N = 604 w_{dry}^{2.012} F_{vac}^{-0.373} \dot{m}^{-0.733} \quad \text{(A.9.2.2.1)}$$

$$C_N = 54700 w_{dry}^{1.726} F_{vac}^{-0.971} \dot{m}^{0.03} \quad \text{(A.9.2.2.2)}$$

$$C_N = 1780 w_{dry}^{0.658} \quad \text{(A.9.2.2.3)}$$

where w_{dry} is the dry weight of the engine, F_{vac} is the vacuum thrust produced by the engine, and $\dot{m}$ is the mass flow rate of propellant through the engine.

Equation (A.9.2.2.1) is a general equation for the cost of a rocket engine without regard to the type of propellants being used. Since no direct cost relation was available for either the dual cryogenic or hybrid propulsion systems the general equation is used. For the storable bipropellant system Eq. (A.9.2.2.2) was found specifically for storable liquid engines. Finally as no cost relation was found for solid rocket motors Eq. (A.9.2.2.3) is selected as it is a more general cost relation for all engine categories than Eq. (A.9.2.2.1).

The mass of the engine depends on the type of engine being used. In Eq. (A.9.2.2.1) and Eq. (A.9.2.2.2) (for cryogenic bipropellant, storable bipropellant, and hybrid) the mass of the engine is determined by summing the mass of the nozzle and the mass of the injector system. For the Eq. (A.9.2.2.3) (the SRM) there are no injectors and therefore the only mass associated with the engine is that of the nozzle.

A fault with this method is a lack of a combustion chamber mass. Both of these bipropellant systems would require a section of engine in which to mix and combust the two fuels. During preparation for model analysis it became apparent that we would not be able to design a combustion chamber for each iteration. Combustion chamber design requires very detailed design and experimentation for just one iteration. If we consider a pressure fed fuel system (which both of our bipropellant designs are) then the mass of the combustion chamber is generally on the order of only 6.7% of the total mass of the engine.[2] Therefore we conclude that the mass of the combustion chamber is negligible when considering mass for the cost of the engine.

With the team having performed all of the model analysis and the mission analysis required to determine our three launch vehicles the final cost of the engines for each system. Keep in mind that the costs in Table 9.2.2.1 are for the engine components only and do not included any propellant or pressurant costs.

Table 9.2.2.1 Engine Cost

Payload Mass	1st Stage Engine Cost	2nd Stage Engine Cost	3rd Stage Engine Cost	Total Engine Cost
200g	$679,720	$263,690	$79,930	$1,023,340
1kg	$634,090	$209,930	$86,860	$930,880
5kg	$1,138,700	$339,700	$80,900	$1,559,300

Footnotes: 1st stage in all rockets is a Hybrid motor and all other stages are SRM

As can be seen from the table above we are able to cost all of the engines for each of our three launch vehicles. The engine costs for each of the three payloads make up nearly half of the total cost of the launch vehicle.

References

[1] Nieroski, John S., and Friedland, Edward I., "Liquid Rocket Engine Cost Estimating Relationships," AIAA Paper 65-533, July 1965.

[2] Humble, Ronald W., Henry, Gary N., and Larson, Wiley J., "Estimating the Mass of the Thrust Chamber," *Space Propulsion Analysis and Design*, 1st ed. Revised, McGraw-Hill Companies, New York, 1995, pp. 226-229

Author: Stephen Bluestone

A.9.2.3 Propellant Cost Methods

The cost of propellants is relatively small in comparison to ground and handling costs of propellants, but nonetheless important in our analysis. The cost of the propellant is calculated simply by knowing the mass of the propellant needed. Throughout our project we have defined the term propellant to include fuel and oxidizer.

In order to calculate the costs of systems that require both fuel and oxidizer, the optimum oxidizer to fuel ratio must be found. Our task is completed by running the NASA Chemical Equilibrium with Applications code. Once completed, we plot the ratios versus specific impulse to find the maximum specific impulse. The total mass of propellant is found using the sizing codes. After finding the maximum oxidizer to fuel ratio and mass of propellant, we find the masses with the following two equations.

$$m_{fuel} = \frac{m_{prop}}{(1+\eta)} \tag{A.9.2.3.1}$$

$$m_{oxidizer} = \frac{m_{prop}\eta}{1+\eta} \tag{A.9.2.3.2}$$

where m_{fuel} is the total mass of the fuel, $m_{oxidizer}$ is the total mass of the oxidizer, m_{prop} is the total mass of propellant, and η is the oxidizer to fuel mass ratio.

We note that solid rocket motors do not contain oxidizer, therefore the total mass of fuel is the total mass of propellant. In Eqs. (A.9.2.3.1) & (A.9.2.3.2), we can see that the above statement is true when η is equal to zero.

Once the masses of the oxidizer and fuel are known, we find the cost of the total propellant in each stage using the following equation.

$$C_{total} = m_{oxidizer} D_{oxidizer} + m_{fuel} D_{fuel} \tag{A.9.2.3.3}$$

where C_{total} is the total cost, $D_{oxidizer}$ is the cost per kilogram of oxidizer, and D_{fuel} is the cost per kilogram of the fuel.

While finding the liquid propellant costs is relatively easy, finding costs for solid fuels is more difficult. However, the cost of solid rocket propellant is estimated at approximately $5/kg.[1] The pricing method we use includes the casting of solid rocket fuel in the motor. The rest of the propellant and oxidizer costs are found using a list of military prices which include transportation to site, but not handling at site.[2] Table A.9.2.3.1 includes all prices found for propellants chosen.

Table A.9.2.3.1 Cost of Fuel and Oxidizer per Kilogram

Propellant	Fuel ($/kg)	Oxidizer ($/kg)
LOX / LH2	6.61 [a]	0.13 [a]
H2O2 / RP-1	3.26 [a]	10.36 [a]
H2O2 / HTPB	8.00 [b]	10.36 [a]
AP / HTPB / Al	5.00 [b]	N/A

[a] bulk prices used
[b] includes casting

In the above Table A.9.2.3.1, we can see that liquid oxygen and liquid hydrogen are one of the least expensive. Final propellant costs for each launch vehicle can be found in Table A.9.2.3.2.

Table A.9.2.3.2 Mass and Cost per Launch Vehicle

Payload	Stage	m_{prop}	C_{total}
200 g	1	1462.0	$14,650
	2	566.6	$2,833
	3	37.3	$187
	Total	2065.9	$17,670
1 kg	1	947.9	$9,500
	2	336.9	$1,685
	3	45.1	$226
	Total	1330.0	$11,410
5 kg	1	4122.2	$41,320
	2	1009.2	$5,046
	3	38.4	$192
	Total	5169.8	$46,560

The cost of the propellant is calculated using a simple correlation between the oxidizer and fuel. Solid fuels prove to be the easiest to calculate as they have no oxidizer to split the propellant costs between. While our propellant costs are tens of thousands of dollars, they are small in comparison to the total cost of the launch vehicle. However, all costs must be taken into account.

References

[1] Heister, Stephen D., Personal Contact., Purdue University, West Lafayette, IN, 1/13/08.

[2] "Missile Fuels Standard Prices Effective Oct 1, 2007.", Defense Energy Support Center, Fort Belvoir, Virginia, July 2007. [http://www.desc.dla.mil/DCM/Files/MFSPFY08_071107.pdf. Accessed 1/15/08.]

Author: Nicole Wilcox

A.9.2.4 Pressurant Cost Methods

The cost of pressurants is relatively small in comparison to the structural cost of holding the pressurant. Heavier tanks are needed for pressurant due to the pressurant contained at high pressures. The cost of the pressurant can be calculated simply by knowing the mass of the pressurant needed and the cost per kilogram of the gas used.

After finding the mass of the pressurant, we use Eq. (A.9.2.4.1) to calculate the total cost of the pressurant.

$$C_{pressurant} = m_{pressurant} D_{pressurant} \quad \text{(A.9.2.4.1)}$$

where $C_{pressurant}$ is the total cost, $m_{pressurant}$ is the mass of the pressurant, and $D_{pressurant}$ is the cost per kilogram of oxidizer.

The pressurant selected was nitrogen with a cost of $0.50/kg. Table A.9.2.3.1 includes all of the vehicle pressurant masses required.

Table A.9.2.3.1 Pressurant Mass and Cost per Launch Vehicle

Payload	Pressurant Mass (kg)	Pressurant Cost ($)
200 g	59.0	$29.50
1 kg	38.2	$19.10
5 kg	166.3	$83.15

Cost of pressurant is based on our use of diatomic gaseous nitrogen. Other gasses could have been selected that were lighter, but would incur higher costs. The mass of the pressurant is only located in the first stage of the rocket due to the presence of a liquid oxidizer for the hybrid engine. Costing methods for pressurants are simple in comparison to the propellant due to a direct relationship between the total cost and mass.

References

[1] "Missile Fuels Standard Prices Effective Oct 1, 2007.", Defense Energy Support Center, Fort Belvoir, Virginia, July 2007. [http://www.desc.dla.mil/DCM/Files/MFSPFY08_071107.pdf. Accessed 1/15/08.]

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A.9.2.5 LITVC Cost

In our design, Liquid Injection Thrust Vector Control (LITVC) is used to control attitude during flight. The costing for the LITVC is broken up into several different sections due to the nature of the LITVC system. The main components of the LITVC that have costs associated are the hardware, tanks, and propellant.

The first part of the LITVC is the actual hardware of the LITVC system. This includes the valves, injectors, and tubing for the propellant. The only cost seen in this section is the valve cost. Several valves were looked at, and a price of $100 per valve was chosen due to the type of propellant used, H_2O_2, and the solenoid type of actuation needed. There are four valves per stage, and only stages one and two have LITVC. The cost for LITVC can be seen below in Table A.9.2.5.1.

Table A.9.2.5.1 LITVC Valve Costs

Payload	Stage 1	Stage 2	Stage 3	Total
200 g	$400	$400	$0	$800
1kg	$400	$400	$0	$800
5kg	$400	$400	$0	$800

The other pieces of the LITVC hardware are assumed to be a part of the engine cost. Our design is only a top level design, and due to the relatively low complexity of the LITVC system, the component cost can be assumed to be included the main engine cost.

The other parts of the LITVC that is assigned costs are the propellant and the tank. The propellant price is included in the main propellant cost and is not separated out as a separate cost. Cost for the second stage tank is already included in the tank section and is not explicitly priced in the LITVC cost.

A.9.2.6 Ground Support and Handling Cost

There are three basic techniques that can be used to develop cost models. The first is the bottom-up technique where the cost of each component and labor is estimated. This method is time consuming due to the research required to obtain data regarding each cost value.

The second method is an analogous estimation. This is where the cost of similar items are adjusted for complexity and used as an estimated cost. An example of this would be to use the commercial pricing of jet engines to approximate the cost of rocket engines where rocket engine pricing is not available. Although this method can be used for detailed analysis, the data obtained using this method is inflexible. An example would be if we were to consider using a more advanced engine rather than a simple rocket engine. It would be hard to readjust the cost estimate of the original engine.

The third method is the parametric estimation method. This is where past data is scaled according to size in order to obtain a cost estimate. This is a very useful method for large commercial companies. If a rocket engine manufacturer were asked to provide an estimate for a new larger rocket engine, they could simply scale up the associated costs of previous engines they have already manufactured in order to provide a very fast estimation.

The preferred form of cost estimation is a parametric cost model. Unfortunately, historical data is scarce and hard to come by. Instead, we must use a combination of the bottom-up and the analogous estimation methods.

We neglect the cost of transportation of fuel to the launch site due to the variability in transportation cost depending on our launch location. Instead, we assume that all fuel is ready at hand and only the cost of labor is required. We also assume that there will be no scaling of personnel requirements with the rocket size because our vehicle is assumed to not vary in complexity so much as to have different personnel requirements.
We also neglect the cost of possible labor and expenses required in the case of a failed launch or a discarded stage where debris and possibly hazardous material may require cleanup. The reason

for this is that we are interested in the cost required to launch the actual vehicle and not with any insurance and damage cost.

Looking at existing launch systems such as the SpaceX Falcon and the Orbital Science Corporation’s Pegasus, the prelaunch ground preparations are done in a period of two weeks prior to launch. Prior to this, work is also being done but cost estimates during that period will be included in our rocket construction cost. The ground support cost model only covers the two weeks prior to launch.

The cost estimate is broken into two main sections. The is a baseline cost which is consistent regardless of the launch vehicle design while the second is a specialist cost which varies depending on the fuel types used.

If we consider actually constructing and launching our vehicle, it would require a member from each technical group and our project manager to perform prelaunch tests and checkups. The technical groups are Aerothermodynamics, Avionics, Dynamics & Control, Propulsion, Structures & Materials and Trajectory Optimization. This means that there will be 7 normal engineers working at the launch site. The hourly rate of $75 per person as suggested by Larson, W.J. et al. is used for a 40 hour week.[1] This results in our baseline cost estimate of $42,000.

For our specialist cost estimate, we must look at the various propellants under consideration for our launch vehicle. These are cryogenic, storable, hybrid and solid propellants. We then estimate that four explosive technicians are required to handle solid propellants due to their dangerous nature, two cryogenic handlers for cryogenic systems due to the special training required to fuel up the vehicle and a single fuel technician for storable and hybrid systems since these systems are relatively easy and safe to fuel.

Based on job salaries for similar careers, a $100 per hour rate is used for each specialist. The total number of hours worked is also divided per stage as we assume that it would take 1/3 the time to fill a single stage as opposed to three stages.

The baseline and specialist cost can then be summed up to provide a cost estimate for the cost of ground support prior to launch. This cost is assumed to be constant regardless of the launch type. For example, if the launch vehicle were to be launched from a balloon, we assume that the specialists would have to perform the same tasks prior to launch. Hence, these costs would be in addition to any additional costs associated with a balloon or aircraft launch.

Our launch vehicles for all three payloads are based on the same architecture of a hybrid first stage and a solid second and third stage. Due to this, they all have the same ground support and handling costs which are listed in Table 9.2.6.1.

Table 9.2.6.1 Ground Support and Handling Costs

Cost Item	Cost
Personnel	$42,000
Stage 1 Handling	$2,000
Stage 2 Handling	$8,000
Stage 3 Handling	$8,000
Total	$60,000

References

[1] Larson, W.J., Wertz, J.R., "Space Cost Modeling," Space Mission Analysis and Design, 2nd ed., Microcosm, Inc., California and Kluwer Academic Publishers, London, 1992, pp. 715-731.

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A.9.2.7 Tubing Cost

To approximately determine the tubing cost of our launch vehicle, we must first look at the types of propellants in use, i.e. cryogenic, storable, hybrid and solid. Solid propellants do not require any tubing and so no tubing cost is associated with these propellants. We then scale the tubing cost with the length of the stage under the assumption that a tube the length of the stage will be sufficient for our needs.

After researching the cost of cryogenic tubing, we settled with Hose Master's G50CXG12 cryogenic tube at a cost of $78.20 per meter. This cryogenic hose is designed for liquid oxygen delivery and is made of Type 321 and Type 304 stainless steel.

For storable and hybrid propellants, we settled on the Gates 4698B, designed to transfer chemical products and is able to handle hypergolic propellants such as hydrazine. The Gates 4698B is available commercially at a cost of $141.70 per meter. In addition to a steel reinforcement, it is also designed with a Teflon tube stock to provide chemical resistance.

Our launch vehicles for all three payloads have solid second and third stages. Due to this, the only associated tubing cost is for the hybrid first stage. The length of the first stage and the tubing cost for each payload is listed in Table 9.2.7.1.

Table 9.2.7.1 First Stage Lengths and Tubing Costs for each Payload

Payload	First stage length (m)	Cost
200g	4.9429	$700
1kg	4.1555	$589
5kg	7.0718	$1,002

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A.9.2.8 Balloon Launch Cost Modifier

We derive the cost of the balloon launch platform in the following manner, where the cost of the balloon launch platform is divided between the lifting gas, the balloon, and the gondola.

The first part involves developing a physical model of the balloon. The derivation of this model can be found in Section A.4.2.1.2.2. Using the physical model, all dimensions for the balloon become readily available.

The total cost of the balloon launch is defined as,

$$C = C_{gas} + C_{balloon} + C_{gondola} + C_{extras} \qquad \text{(A.9.2.8.1)}$$

where $C_{balloon}$ is the cost of the balloon, $C_{gondola}$ is the cost of the gondola, $C_{per\ volume}$ is the cost per volume of the lifting gas and C_{extras} is the total cost for any additional requirements such as towing costs. For our study, the lifting gas chosen is helium.

Gas prices are usually provided per liter so we should express the cost in terms of the cost per liter of the lifting gas. By assuming the balloon to be a perfect sphere, a simple substitution for the ground volume of the balloon will result in the following equation,

$$C = \frac{\pi}{6} d^3 \times C_{per\ volume} + C_{balloon} + C_{gondola} + C_{extras} \qquad \text{(A.9.2.8.2)}$$

where d is the diameter of the balloon at sea level and $C_{per\ volume}$ is the cost per liter of lifting gas.

We can obtain the prices for the lifting gas per unit volume from military pricing.[1] For the lifting gas chosen (helium), the cost per cubic meter is $4.87.

Next, we must calculate the cost of the balloon. Our balloon costs are based on price quotes from Aerostar International.[2] These prices are listed in Table A.9.2.8.1.

Table A.9.2.8.1: Aerostar Cost Trends

Payload Mass(lbm)	Payload Mass(kg)	Cost
5,00	226.796185	$10,000
2,000	907.18474	$30,000
8,000	3628.73896	$100,000

The costs include the balloon material, as well as manufacturing and labor. Figure 9.2.8.1 details the cost trend of the given data in relation to the payload carried by the balloon.

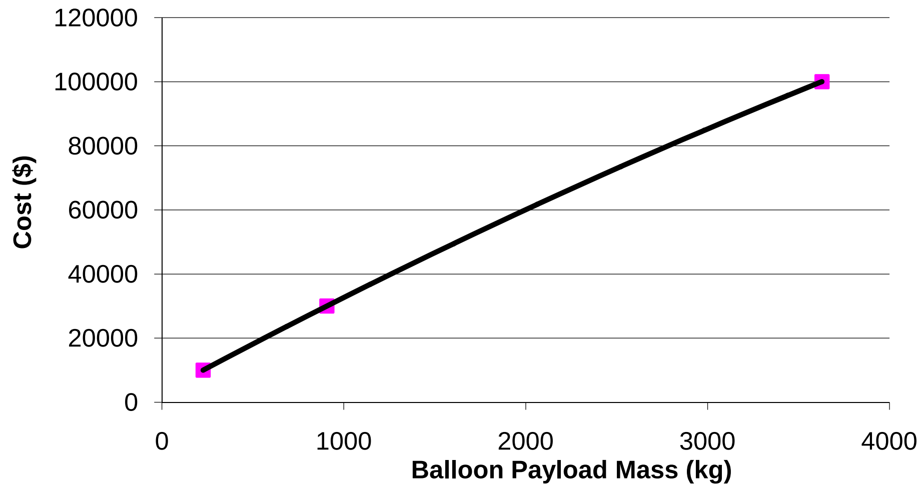

Figure 9.2.8.1: Cost Trend for Aerostar High Altitude Balloon.

Next, an equation for cost in relation to balloon payload can be found from Figure A.9.2.8.1. This equation is listed below.

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$$y = -0.0011x^2 + 30.62x + 3111.1 \qquad \text{(A.9.2.8.3)}$$

where y is the cost in dollars and x is the mass the balloon carries.

The next component of the balloon platform cost is the gondola. After designing the gondola, the costs were found by adding the cost of the material, welding, and riveting needed to construct it. For our design, the gondola cost remains fixed at $13,200. The gondola masses for each stage do differ. However, the cost does not vary because of aluminum's low cost.

Regarding towing costs, the design team understands that FAA regulations make launching from a balloon over land very difficult. We must therefore look into the cost feasibility of launching from a marine location. Through contacts with industry, we consider the cost of chartering a tugboat and a barge to a launch location approximately 200 nautical miles off the U.S. coast.

Our source, Jerry White, owns a small ocean towing company on the west coast, and notes that his cost estimates are just "ballpark" and prices could be as much as twenty percent greater on the gulf and east coasts.[3] For the purposes of the cost modifier, we assume a weight of 10,000 kg for the launch vehicle and all of its ancillary equipment. Furthermore, we recognize that a distance of 300 km is a reasonable distance for a tug and barge to cover in fair weather in one 24 hour period (1 "day", by industry pricing standards). We assume then a three day trip: one day out, one day for launch, one day back to port.

We note first that a small barge would initially cost about $4,000 to charter, and then approximately $1,000 a day afterwards. For a small launch vehicle, it may be feasible to mount the launch apparatus on the tugboat itself and forgo the barge. However, since this is a subjective measure, we choose to leave the barge costs in the modifier. So for a three day trip, barge costs come to about $7,000 dollars.

The tug itself is estimated to cost $12,000 per day for charter costs. The pricing of this is primarily due to fuel costs, with only about $2000 daily coming from crew and food costs. For a three day trip, this comes to $36,000. If delays are necessary due to weather or other miscellaneous events, the tug would cost approximately $200 hourly at the dock, or would be charged the day rate at sea, unless otherwise negotiated.

The initial cost modifier comes out to be $43,000 for a three day trip, and a more conservative estimate would be closer to $50,000. The cost quickly grows from there as delays and loading times are figured in to the overall cost.

For the purposes of the design project we neglect the towing cost modifier. Since the balloon project is on a smaller scale than originally estimated, and because the project is likely to be attempted by a college or university, it is considered likely that an FAA waiver could be obtained for many of their launch restrictions. This makes an ocean launch both unattractive and unnecessary, and so the cost is dropped from the overall estimates.

All variables associated with this cost analysis are now either known or can be solved. We have a simple code which inputs the launch vehicle mass and desired altitude and provides a total cost as the output. This method can be adapted to any lifting gas desired simply by providing the standard sea level density of the lifting gas.

Using the code, we are able to find that the cost of the lifting gas is a minor component of the total cost. Using hydrogen would pose major handling problems while only providing a very small financial advantage. Therefore, using helium as the lifting gas would be a more viable solution for our design.

The final costs of our balloon launch platforms are detailed in Table A.9.2.8.2 for each payload.

Table A.9.2.8.2: Final Costs of Balloon Launch Platform

Cost Item	200g case	1 kg case	5 kg case
Balloon	$82,007	$60,848	$157,070
Helium	$14,813	$10,644	$32,979
Gondola	$13,200	$13,200	$13,200
Total	$110,020	$84,692	$203,249

References

[1] Defense Energy Support Center, “MISSILE FUELS STANDARD PRICES EFFECTIVE 1 OCT 2007,” Aerospace Energy Reference, November 2007.

[2] Smith, Mike, Phone Conversation, *Aerostar International,* February 15, 2008

[3] White, Jerry, Cpt., Personal Phone Conversation, January 18, 2008

Author: William Yeong Liang Ling, Jerald Balta, Alex Woods

A.9.2.9 Aircraft Launch Cost Modifier

We determine that using the White Knight as a carrier aircraft could be the solution to our mission of a low-cost launch system. Scaled Composites gives the estimate of $5,030/hr total for leasing the aircraft. As quoted, the estimate includes fuel, crew and flight time. Not knowing how much time it would take for a launch, our research estimates the amount of time we need to lease the White Knight for each launch.

Since the L-1011 Stargazer with the Pegasus rocket is an existing aircraft launch system we use their mission timeline for reference.[1] The timeline for the Stargazer is very detailed and includes all aspects such as adapting the aircraft and repeated flight simulations. Since they require many more integration and testing days than we deem necessary for our smaller-scale launch, the prelaunch schedule is reduced to a 14 day window for a specific concentration on the launch preparation as seen in Table A.9.2.9.

Table A.9.2.9 Timeline for our Aircraft Launch System

Task	Timeline
Delivery to launch site	T-14 days
Rocket loading	T-13 days
Integration testing	T-12 days
Flight simulation	T-11 to 8 days
Contingency	T-7 to 4 days
Final Preparation	T-3 days
Launch	T-0 days

Using the 14 day timeline, we estimate that the aircraft will be in possession starting at the flight simulation task in Table A.9.2.9. The total cost modifier is calculated as an eight hour day, for three days of flight simulation and seven days of launch preparation, which gives a total of 80 hours at the cost of $5,030/hr. The total cost modifier is $402,400 for each launch. The cost modifier is added to the Model Analysis Code in the **Aircraft_Cost_Modifier.m** file.

The cost modifier for the aircraft launch system is a fixed price regardless of launch vehicle weight. Since there is a flat rate to lease White Knight, the cost is constant for each payload. Having a base cost seems like an advantage but the disadvantage is the amount of payload the aircraft can carry. The limiting payload weight of the White Knight is 3,629 kg and restricts the chance of the air launch being used. In the 5 kg payload case, the mass of the launch vehicle is 5,159 kg, which overweighs the limit of 3,629 kg. If the mass of the launch vehicle is greater than the maximum payload of the aircraft, then the White Knight isn't even considered for that payload case. The Stargazer is able to carry 36,800 kg which would suffice for the 5 kg payload launch vehicle, but the cost of purchasing the aircraft causes the aircraft to be eliminated when compared to balloon and ground launches.

The cost of insurance is also noted by Scaled Composites. In order to lease White Knight an insurance coverage of $5 million is needed.[2] As they have seen several plans, Scaled Composites gives a reference that it costs approximately $125,000 for a two-month coverage plan.[2] The insurance cost is in addition to the lease cost per hour. The cost of insurance is not included in the overall cost modifier since it varies with the type of launch vehicle and the length of the coverage plan. Even though this cost isn't included in the cost modifier it is very important to realize that it is an additional cost if this launch vehicle is used with White Knight.

References

[1] Dietz, William E., Suhs, Norman E. "Pegasus User's Guide". Stuart E. Rogers NASA Ames Research Center. [www.orbital.com/NewsInfo/Publications/peg-user-guide.pdf]

[2] Williams, Bob, Sales representative of Scaled Composites. "Email Conversation," Dates 1/22/08 through 1/31/08.

Author: Stephanie Morris

A.9.2.10 Material Cost

The cost of the structures is a major factor to the total final amount. The cost is driven by the price of the raw material, propellant tanks, and manufacturing which includes rivets, welding, rolling, and more for the structural components that do not involve the tanks. Figure A.9.2.10.1 presents the overview of how the costing breaks down within structures. Each subcategory calculates the cost based on the amount needed through constant variables and the dimensions that come from the launch vehicle's sizing functions.

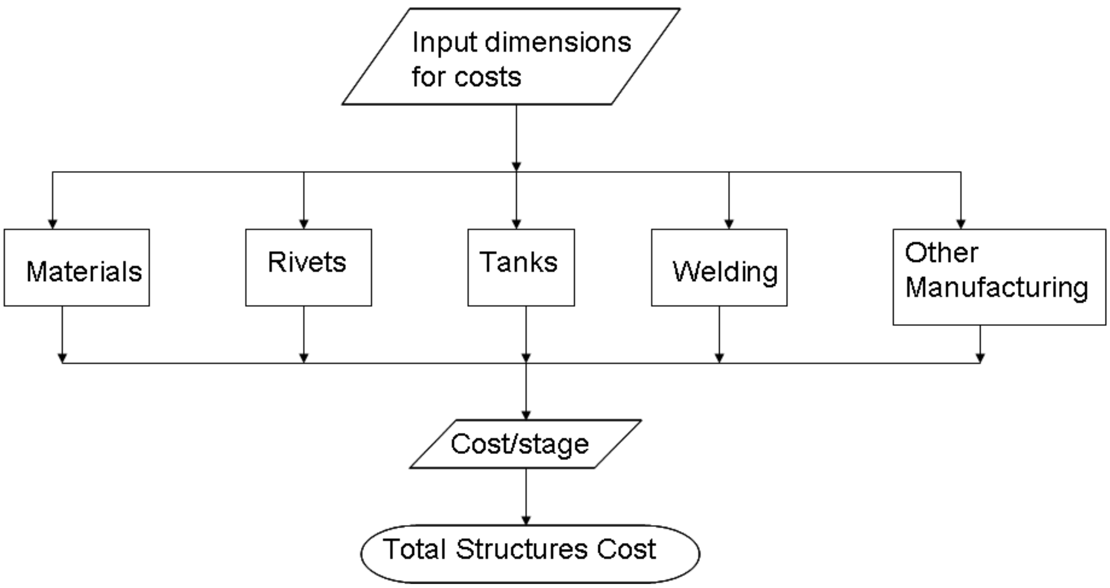


Figure A.9.2.10.1. Structures cost algorithm showing the breakdown of the costing sections. (David Childers)

The materials that we consider for the launch vehicle are titanium, aluminum, steel, and composites. Titanium is discarded as a major material because the costs needed to form the shapes and components is too great. Raw titanium is also expensive at $88.91/kg.[1]

Aluminum is not as expensive as titanium but it is still high since space grade aluminum must be used so the structure will withstand the affects of space flight. The cost of space grade aluminum is $13.23/kg.[1] If non-space grade aluminum is employed, then the cost would only be $2.30/kg.[2]

Steel is inexpensive at $0.23/kg.[2] Steel also does not cost any more to work with than aluminum. However, steel's density and weight rules out its application.

We are not implementing composites because the time frame and cost are much too high to be reasonable for the scope of this project. Speaking with Walter Tam of ATK, the creation of a low volume composite tank would take two years and $2 million to produce.[3] The $2 million includes the cost of manufacturing and building the tank. Once the tank is created, it must go through testing which can cost up to an additional $1 million. As a result of each of the material's factors, aluminum is the chosen material.

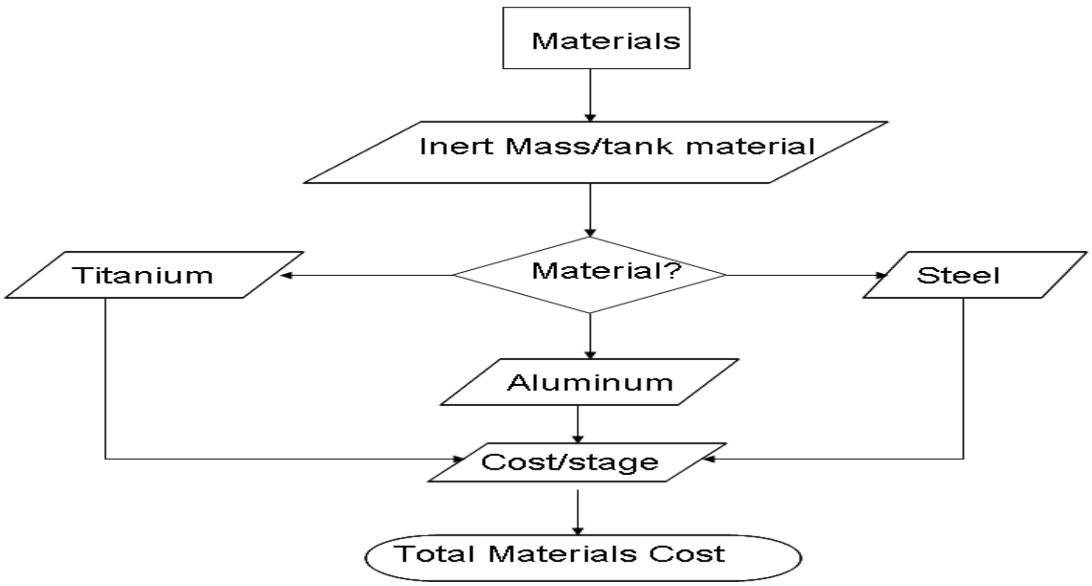


Figure A.9.2.10.2. Material cost algorithm for the structures cost. (David Childers)

In Fig. A.9.2.10.2, the method that we employ to find the cost of materials is shown. From the main cost function, the **materials.m** function is given the inert mass of the launch vehicle and the type of material that will be employed. Once the function is running, the cost of each stage, M_{cost} is calculated by employing Eq. (A.9.2.10.1) below.

$$M_{\cos t} = nM_{inert} \quad \text{(A.9.2.10.1)}$$

where M_{inert} is the inert mass of the stage (kg) and n is the cost of the material per kilogram.

From the equation, the variable n is $13.23/kg for space grade aluminum,[1] $88.91/kg for titanium,[1] and $0.23/kg for steel.[2] The results of the total material costs for each payload are in Table A.9.2.10.1. The cost of the 200g vehicle is greater than the 1kg payload vehicle because the 200g launch vehicle is larger than the 1kg. The total material cost is considerably small in comparison to the total structures costs. The cost in the table shows that the costs behind any project is not in acquiring the material needed, but in the formation and labor that has to be put into making the final product.

Table A.9.2.10.1 Total Material Cost for each Payload

Payload Mass	Cost
200g	$3,755
1kg	$2,490
5kg	$7,795

References

[1] Murphy , Mike. E-mail interview. 09 Feb 2008.

[2] "Metal Prices & News on the Internet," *MetalPrices.com* [online], URL: http://www.metalprices.com/ [sited 10 February 2008].

[3] Tam, Walter. Telephone interview. 10 Feb 2008.

Author: David Childers

A.9.2.11 Tank Cost

We explore two methods for pricing tanks. The first method employs cost values provided by Mike Murphy of Spincraft.[1] This method is not applicable because we are only given a fixed rate of $150/hr for materials aluminum and titanium. The lead time that Spincraft provides is 26 weeks for aluminum and 52 weeks for titanium. We assume that each week is a standard 40 hour week. Since the values we have from Spincraft do not provide any means of adjusting the totals for various shapes and sizes, we are stuck with a constant value for each tank that we would need. The constant value means that a small tank will cost the same as one that is several times larger.

The method that we apply in this project employs values from Walter Tam of ATK.[2] Table A.9.2.11.1 shows the tank volumes that ATK has available and the prices for those tanks

Table A.9.2.11.1 ATK Tank Volume

Tank	Volume (m^3)	Cost
Tank 1	0.461	$600,000
Tank 2	0.432	$400,000
Tank 3	0.229	$250,000
Tank 4	0.059	$250,000
Tank 5	0.015	$60,000

One note to point out about the propellant tanks that ATK makes is that the tanks are made for satellites and not launch vehicles. The different conditions that the two types of tanks undergo produce a difference in performance and likely cost. However, we are unable to find costs for actual launch vehicles due to prices being proprietary information within the aerospace industry. Companies do not divulge information due to the competitive nature of the industry. The difference between the tank types does not rule out the final result of the ATK values. It just means that the difference between satellite and launch vehicle tanks must be kept in mind when looking at the final cost values. The final tank costs that we find will be on the high end of actual costs because ATK has high standards from which they base their work.

We took the table values in Table A.9.2.11.1 and found a best fit line so that we can find the cost of our tank based on the volume that we are employing. The equation that we now apply to calculate the tank cost T_{cost} is Eq. (A.9.2.11.1) seen below.

$$T_{cost} = 157169\ln(x) + 714253 \qquad \text{(A.9.2.11.1)}$$

where x is the tank volume.

Equation (A.9.2.11.1) is a result of Fig. A.9.2.11.1 which show that curve fit that best fit the values that ATK gave us. The equation also provided reasonable values for volumes outside of the ATK numbers. The points in Fig. A.9.2.11.1 are the volume versus cost values in Table A.9.2.11.1. Because the equation is logarithmic, volumes less than 0.01m^3 are given a fixed cost of $60,000 to avoid obtaining a negative cost. We also have made sure that tanks that do not exist or have 0m^3 volume are priced at $0.

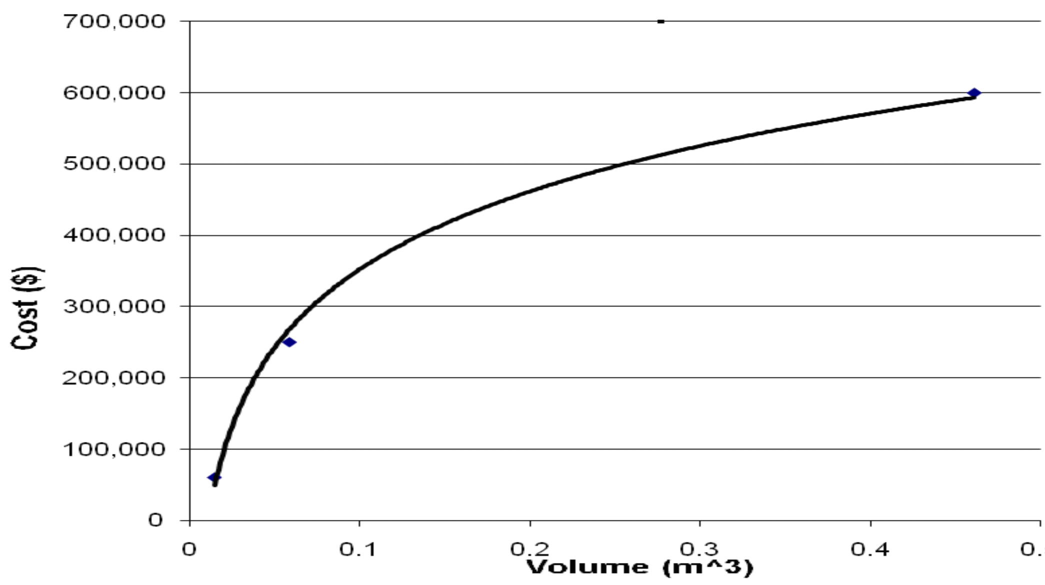


Figure A.9.2.11.1. Best fit curve of the ATK volume/cost values. (David Childers)

Each launch vehicle has the same number and types of tanks. The first stage has an oxidizer, fuel, and pressurant tank. Stage 2 has a fuel and LITVC tank. Stage 3 has a fuel tank. Figures

A.9.2.11.2 through A.9.2.11.4 show how the cost of our tanks compares to the ATK cost curve in Fig. A.9.2.11.1 for each payload mass.

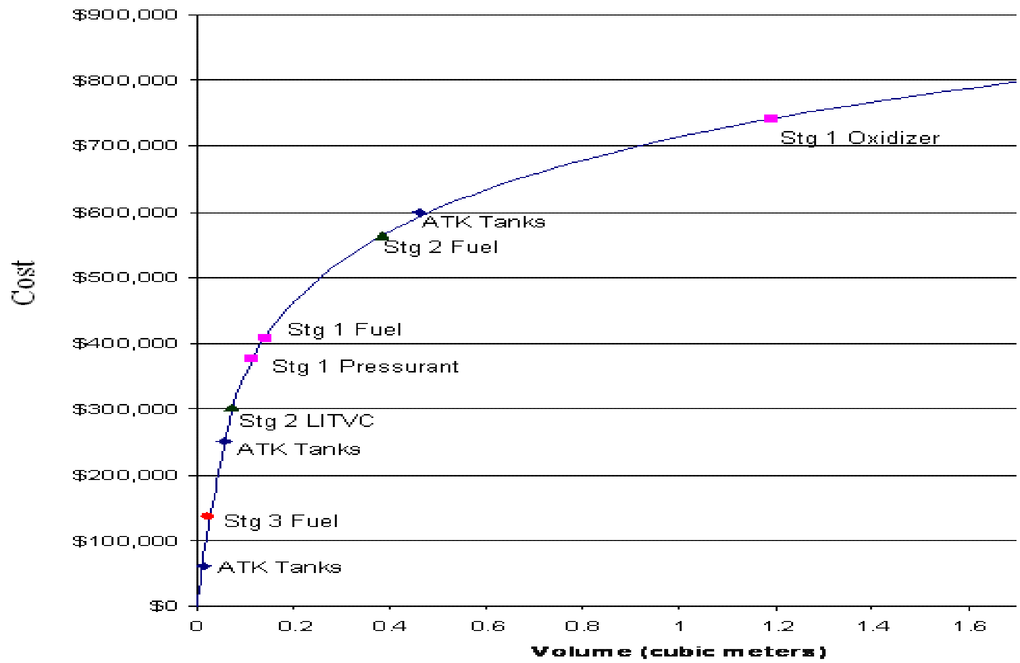


Figure A.9.2.11.2. Comparison of ATK curve fit and 200g payload vehicle tanks. (David Childers)

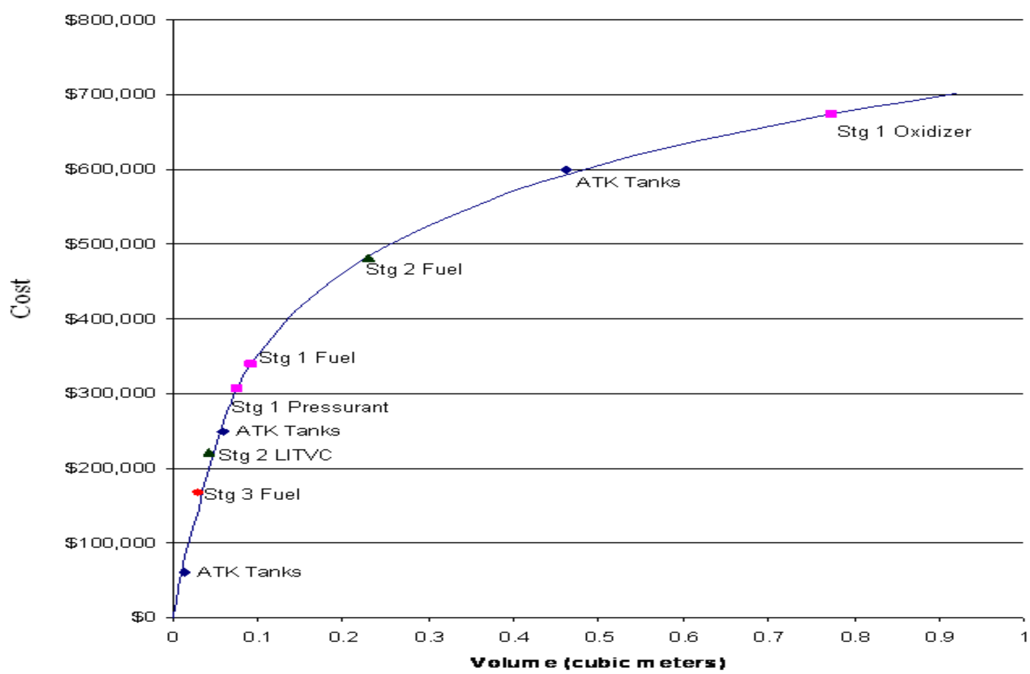


Figure A.9.2.11.3. Comparison of ATK curve fit and 1kg payload vehicle tanks. (David Childers)

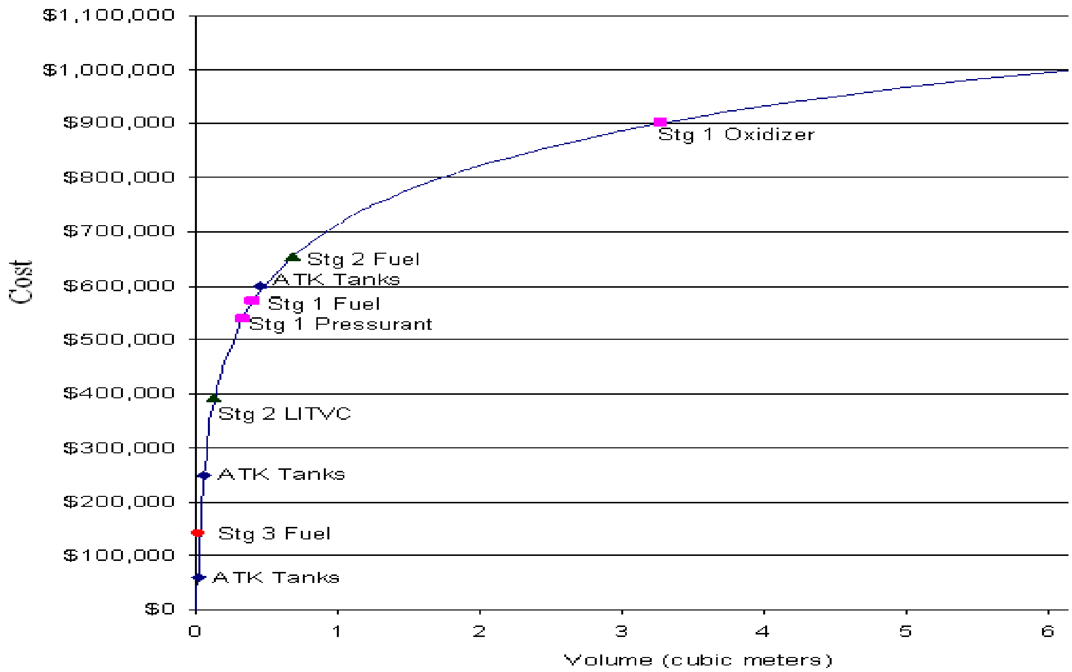


Figure A.9.2.11.4. Comparison of ATK curve fit and 5 kg payload vehicle tanks. (David Childers)

Figure A.9.2.11.5 shows the method for determining the cost for the tanks of the launch vehicle based on the values from ATK. There are two to three tanks per stage and as a result, ATK has a price reduction of 5 to 10% in the total cost.[2] We apply the 10% reduction to account for the number of tanks that we need and the tolerances that we have are not currently as stringent as the ones that ATK must meet.

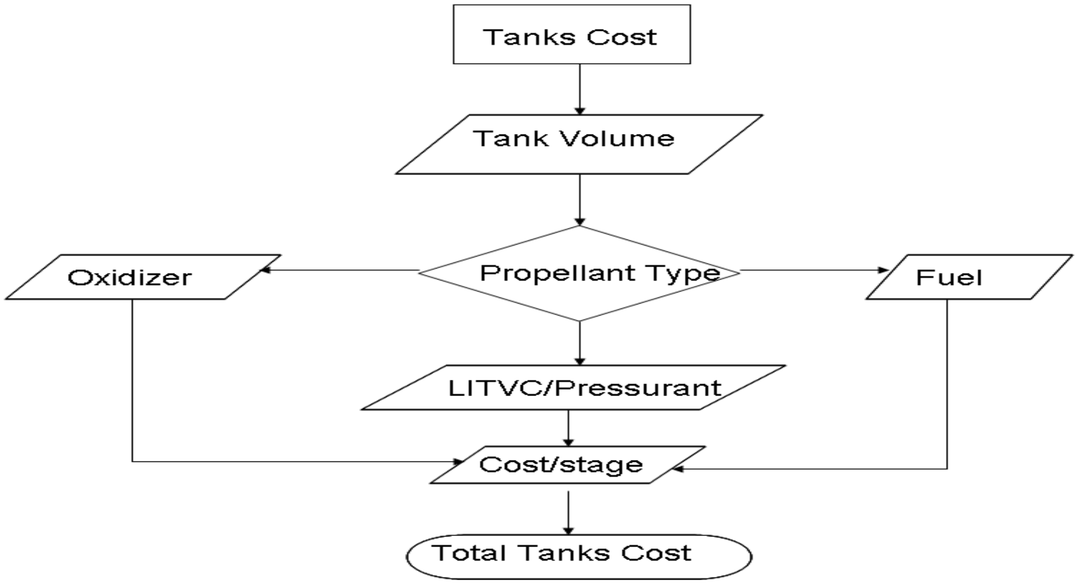


Figure A.9.2.11.2. Tank costing method that finds the cost of the tank based on volume. (David Childers)

Author: David Childers

With the ATK value method, we are able to obtain the tank costs in Table A.9.2.11.2.

Table A.9.2.11.2 Launch Vehicle Tank Costs for each Payload

Payload Mass	Tank Cost
200g	$2,275,400
1kg	$1,971,500
5kg	$2,879,100

The table shows that the 200g case costs more than the 1kg payload vehicle. This difference in cost is because the 200g launch vehicle is larger than the 1kg. As a result, the 200g launch vehicle has tanks with a larger volume which produces a higher cost. The cost shown in the table is the summation of each tank within the launch vehicle. The results also demonstrate that the tanks are a main factor in the total structures cost and the total cost of the entire launch vehicle.

References

[1] Murphy , Mike. E-mail interview. 09 Feb 2008.

[2] Tam, Walter. Telephone interview. 10 Feb 2008.

Author: David Childers

A.9.2.12 Manufacturing Cost

The manufacturing cost for the structures portion of the launch vehicle is categorized into three sections. The sections are rivets, welding, and other. The “other” category accounts for the rolling, drilling, and forming work that needs done to the structural components that do not involve the tanks. These components include the skirts, nose cone, and intertank skin. Figure A.9.2.12.1 shows the process of how the manufacturing costs are obtained. Each step main step is run from the main structure cost function which sends the necessary inputs to each function.

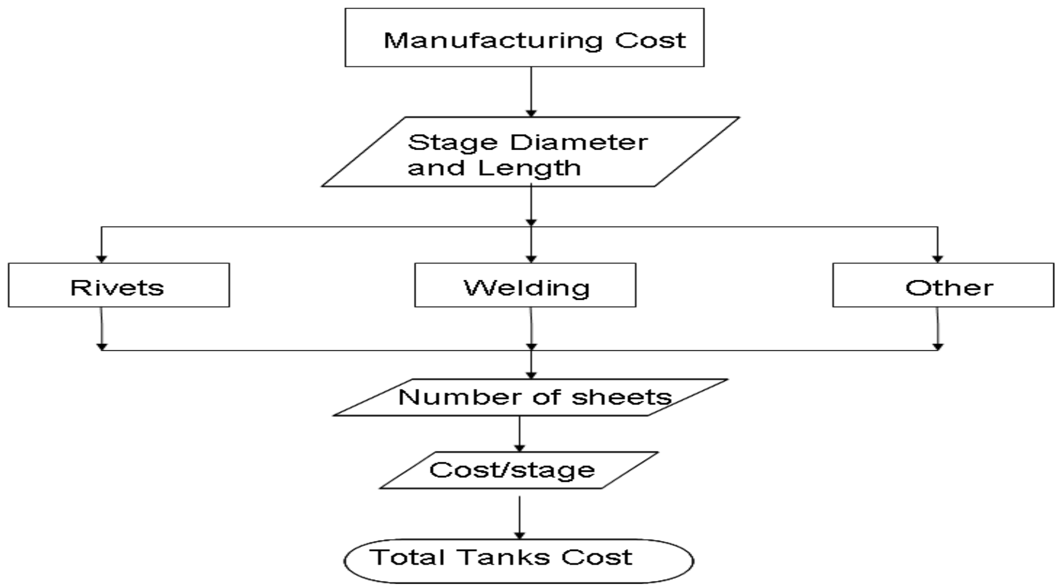


Figure A.9.2.12.1. Algorithm for the manufacturing cost of structures. (David Childers)

It is unreasonable to weld the entire launch vehicle. For this reason, rivets are employed to cover the gaps between different sections of the vehicle. We assume that there is 1 rivet for every 6 inches or 0.153 m.[1] We employ this assumption so that there is a reduction in the chances of cracks forming which can cause failure with the rivets being to close and being close enough so that there is enough strength to hold the vehicle together. We assume that we are placing rivets along the top and bottom of each stage and up the length of each skirt and the nose cone.

The total distance that has rivets is found by calculating the circumference of each stage and adding in the skirt length and nose length, if we are finding the length for the third stage as seen in Eq. (A.9.2.12.1).

$$L = 2\pi D + L_{skirt} + L_{nose} \quad \text{(A.9.2.12.1)}$$

where L is the length of material that will need rivets (m), D is the diameter of each stage (m), L_{skirt} is the length of the interstage skirts (m), and L_{nose} is the length of the nose cone (m).

For the third stage, L_{skirt} is zero and for the first and second stage, L_{nose} is zero. With the length found, the number of rivets R is calculated with Eq. (A.9.2.12.2).

$$R = L / 0.153 \quad \text{(A.9.2.12.2)}$$

where L is the riveted length (m) and 0.153 is the distance between rivets (m).

From this point, we can find the total cost of the rivets R_{cost} with Eq. (A.9.2.12.3)

$$R_{\cos t} = 0.73 * R + 52 * 0.049 * R \quad \text{(A.9.2.12.3)}$$

where R is the number of rivets 0.73 is the cost per rivet, 52 is the cost per hour, and 0.049 is the labor hour per rivet.

In Eq. (A.9.2.12.3), the total cost accounts for the cost of the rivets and the labor that is involved in working with the rivets which is shown in the constants within the equation.[2] The end result for the rivets is substantially smaller than the cost of the tanks as illustrated in Table A.9.2.12.1.

Table A.9.2.12.1 Rivet Costs for each Payload Launch Vehicle

Payload Mass	Cost
200g	$374
1kg	$327
5kg	$499

The welding costs are found in a similar manner as the rivets. For welding, we assume that there will be some need to weld areas that also have rivets. For this reason, Eq. (A.9.2.12.1) is part of the welding function. Since the overall cost of welding is substantially smaller than the tanks, we do not have to worry about any major change in the total cost from any significant excess in welding. The same thing is true for the cost of rivets. Using welding times of 0.6 m/hr for aluminum, 0.65 m/hr for steel, and 0.325 m/hr at a rate of $150/hr, we can calculate the cost to weld, W_{cost}, the launch vehicle with Eq. (A.9.2.12.4) below.[3]

$$W_{cost} = 150 * 1/(r * L) \quad \text{(A.9.2.12.4)}$$

where r is the welding time rates, L is the length of the weld (m), and 150 is the cost of labor rate. Since we are only using aluminum, r is always equal to 0.6 m/hr. The welding results are in Table A.9.2.12.2.

Table A.9.2.12.2 Welding Costs for each Payload Launch Vehicle

Payload Mass	Cost
200g	$4,345
1kg	$3,798
5kg	$5,797

The remaining manufacturing costs accounts for the rolling and forming of non-tank components. The values applied in this section are based on non-space grade manufacturing materials and techniques but because the industry is small and competitive, space values are hard to obtain. As a result, we apply calculations based on the capabilities of Gilchrist Metal Fabrication.[4] Gilchrist is able to roll a 10 ft^2 (9.29 m^2) metal sheet for $70/sheet and at a rate of 3 hrs/sheet for aluminum and 3.5 hrs/sheet for steel. Since we are using aluminum, the steel quantity can be ignored at this time. To employ these numbers, we find the number of sheets that we need by using Eq. (A.9.2.112.5) below.

$$N_{sheet} = (C * L_{stage}) / 9.29m^2 + 1 \quad \text{(A.9.2.12.5)}$$

where N_{sheet} is the number of sheets, C is the stage circumference (m), and L_{stage} is the length of each stage (m). We add an additional sheet to the actual number found from the first portion of the equation to cover any outside factors that would require more material.

The total cost of the remaining manufacturing, $C_{Manufacturing}$, is calculated with Eq. (A.9.2.12.6).

$$C_{Manufacturing} = 3 * N_{sheet} * H \quad \text{(A.9.2.12.6)}$$

where H is the number of labor hours that go into processing a single sheet.

The factor 3 is placed in the equation to account for each of the various other factors besides rolling, such as drilling, cooling, heating, and other formations that will be involved in forming the other structural components.[5] We base 20 hrs on the hours that Spincraft needs to produce their products.[6] This time covers may be low but the cost of manufacturing is small in comparison to the total cost for the entire launch vehicle. Further research into the time needed to produce each component will result in a more accurate final value for manufacturing. The end result of the remaining manufacturing is in Table A.9.2.12.3.

Table A.9.2.12.3 Other Manufacturing Costs for each Payload Launch Vehicle

Payload	Value
200g	$33,700
1kg	$29,400
5kg	$42,000

The results of the table show a much greater amount contributed to the overall cast than the welding and rivets provided. However, when we look at the total cost of the launch vehicles, the contributions are still relatively insignificant. The total manufacturing costs are in Table A.9.2.12.4.

Table A.9.2.12.4 Total Manufacturing Costs for each Payload Launch Vehicle

Payload	Cost
200g	$38,419
1kg	$33,525
5kg	$48,296

Comparing all of the manufacturing tables verifies that there is only a few thousand dollar increase from the manufacturing costs not including welding and rivets and the total final amount.

Author: David Childers

References

[1] Cyr, Kelley, "NASA New Start Index Inflation Calculator," Cost Estimating Web Site, NASA, May 2007. URL: http://cost.jsc.nasa.gov/inflation/nasa /inflateNASA.html [Sited 28 January 2008].

[2] Noton, Bryan R., "ICAM - Manufacturing Cost Design Guide," Paper 81-0855, AIAA, May 1981.

[3] Sutton, Mark. Telephone Interview. 17 Feb 2008.

[4] Morissette, Paul. Telephone interview. 10 Feb 2008.

[5] Green, E.A., and Coulon, J.F., "Cost Considerations in Using Titanium," Lockheed-California Company, Burbank, California v AlAA Paper.

[6] Murphy , Mike. E-mail interview. 09 Feb 2008.

Author: David Childers

A.9.3 User's Guides for Costing Methods Codes

User's Guide for *manufacture_ATK.m*

Written by David Childers
Revision 2.0 - 6 March 2008

Description:
Finds manufacturing and forming cost for non-tank components.

Assumptions:

Cost value covers rolling the sheet metal, drilling, forming, and other non-tank related costs of manufacturing.

Input Section:

The call line of the function is:

Man_Cost=manufacture_ATK(stages,tank_material,diameter,Length_stage)

All of the variables that are passed into the function are described below:

Variable Name	Description
stages	Number of stages
tank_material	Material of each stage
diameter	Diameter of stages [m]
Length_stage	Length of each stage [m]

Output Section:

Description of output.

Variable Name	Description
Man_Cost	Total manufacturing cost for each stage [USD]

User's Guide for *materials.m*

Written by David Childers
Revision 2.0 - 6 March 2008

Description:
Calculates the raw material cost for steel, aluminum, and titanium

Input Section:

The call line of the function is:
Mat_cst=materials(stages,tank_material,Mass_inert)

All of the variables that are passed into the function are described below:

Variable Name	**Description**
stages	Number of stages
tank_material	Material of each stage
Mass_inert	Inert mass of each stage [kg]

Output Section:

Description of output.

Variable Name	**Description**
Mat_cst	Material cost for each stage [USD]

User's Guide for *rivets.m*

Written by David Childers
Revision 2.0 - 6 March 2008

Description:

Calculates the number of rivets needed and finds the cost of the rivets along with the labor cost associated with each rivet.

Assumptions:

1 rivet for every 6 inches (.1524m)

Input Section:

The call line of the function is:
Rvt_Cost=rivets(stages,tank_material,diameter,L_skirt,L_cone)

All of the variables that are passed into the function are described below:

Variable Name	Description
stages	Number of stages
tank_material	Material of each stage
L_skirt	Length of each interstage skirt [m]
L_cone	Length of the nose cone [m]

Output Section:

Description of output.

Variable Name	Description
Rvt_Cost	Total cost for rivets/stage [USD]

User's Guide for *struc_cost_ATK.m*

Written by David Childers

Revision 2.0 - 6 March 2008

Description:

The code *struc_cost_ATK.m* is the calling function for the codes that calculate the structural cost of the launch vehicle. The function changes variable names that are taken from the workspace and adds up the total structure cost once the other functions have been called and ran.

Input Section:

This code takes values from the workspace that are available after running *main_loop.m* (MAT), *tanksv2.m,* and *LITCV.m.*

All of the variables that are passed into the function are described below:

Variable Name	**Description**
diameter	Diameter of stages [m]
volume_ox	Volume of the oxidizer of each stage [m^3]
volume_fuel	Volume of the fuel of each stage [m^3]
stages	Number of stages
tank_material	Material of each stage
L_skirt	Length of each interstage skirt [m]
Length_stage	Length of each stage [m]
L_cone	Length of the nose cone [m]
LITVC_V	Volume of the LITVC for each stage [m^3]
press_vol	Volume of pressurant for each stage [m^3]

Output Section:

Description of output.

Variable Name	**Description**
COST_stage	Total cost per stage [USD]
Tot_Cost	Total cost of the launch vehicle {USD]

User's Guide for *tank_cost.m*

Written by David Childers
Revision 2.0 - 6 March 2008

Description:
Calculates the cost of each tank needed for each of the 3 stages based on information provided by ATK

Input Section:

The call line of the function is:

Tank_Cst=tank_cost(stages,tank_material,diameter,volume_ox,volume_fuel,LITVC_V,
press_vol)

All of the variables that are passed into the function are described below:

Variable Name	**Description**
diameter	Diameter of stages [m]
volume_ox	Volume of the oxidizer of each stage [m3]
volume_fuel	Volume of the fuel of each stage [m3]
stages	Number of stages
tank_material	Material of each stage
LITVC_V	Volume of the LITVC for each stage [m3]
press_vol	Volume of pressurant for each stage [m3]

Output Section:

Description of output.

Variable Name	**Description**
Tank_Cst	Tank cost for each stage [USD]

User's Guide for *welding.m*

Written by David Childers
Revision 2.0 - 6 March 2008

Description:
Finds welding cost for each stage based on the amount of time needed for a given material being used.

Assumptions:

Approximately $150/hr for labor, insurance, equipment, etc.

Input Section:

The call line of the function is:
Weld_Cst=welding(stages,tank_material,diameter,L_skirt,L_cone)

All of the variables that are passed into the function are described below:

Variable Name	**Description**
stages	Number of stages
tank_material	Material of each stage
L_skirt	Length of each interstage skirt [m]
L_cone	Length of the nose cone [m]

Output Section:

Description of output.

Variable Name	**Description**
Weld_Cst	total welding cost/stage [USD]

User's Guide for *Engine_Cost.m*

Written by Stephen Bluestone
Written 19 February 2008

Description:

The purpose of this code is to simply calculate the cost of the engines that we will be using on our rockets. Inputs of several engine specifications and performance criteria are sent to the code where a series of equations determines a cost for each engine. Output from this code will be essential in determining the lowest cost launch vehicle.

Assumptions:

- A main assumption associated with this code is that all costs associated with the manufacturing, transportation, and purchase of the engine can be rolled into a single value.

Important Notes:

Equations used to estimate the cost of the engines were found in 1965 making their accuracy somewhat questionable. Unfortunately this was the only resource that provided cost estimation in a manner suitable for our team. An inflation factor is added to the code to adjust the cost of the engines from 1965 dollars to 2007 dollars. Additional inflation may be required to adjust for 2008 dollars.

All parameters are in the form of arrays.

Input Section:

The function call line appears as:

[C1]=Engine_Cost(Mass_en,F_vac,mdot,fuel_type)

All of the variables that are passed into the function are described below:

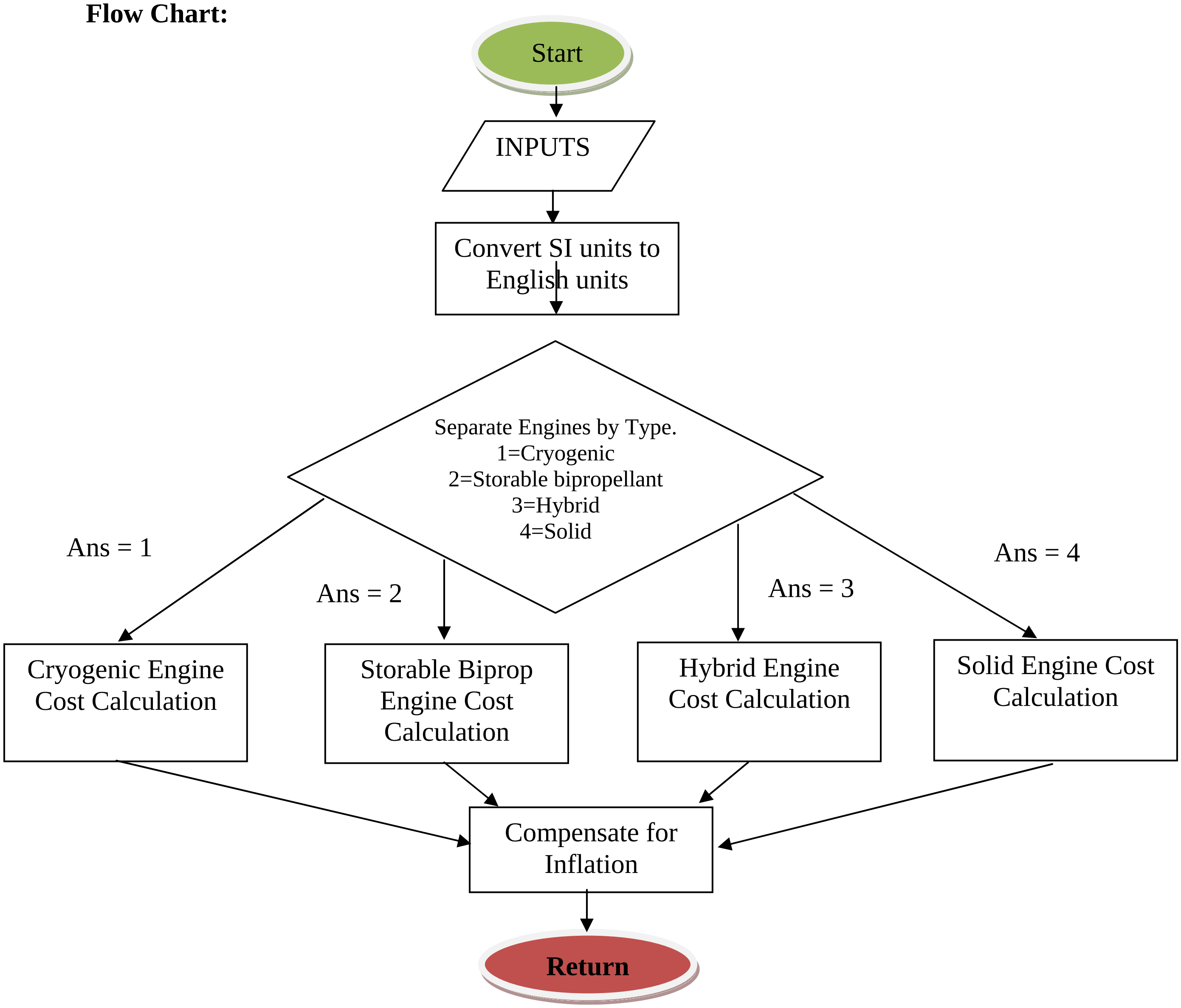
Variable Name	Description
Mass_en	Mass of the Engine (vector) [kg]
F_vac	Vacuum Thrust (vector) [N]
Mdot	Mass Flow Rate of Propellant (vector) [kg/s]
fuel_type	Type of Propellant being used, i.e hybrid, solid (vector) [-]

Output Section:

Only one variable comes out of the code and is described below:

Variable Name	Description
C1	Engine Cost (vector) [$ 2007]

Flow Chart:



Authors: David Childers, Stephen Bluestone, and William Yeong Liang Ling

User's Guide for *Aircraft_Cost_Modifier.m*

William Yeong Liang Ling

Revision 1.0 - 3/16/2008

Description:

This code inputs the gross lift off weight of the launch vehicle in order to determine if the White Knight aircraft is capable of carrying it and if so, to calculate the costs required.

Assumptions:

We assume that 24 hours of simulation before the launch is required and that the actual launch will require the plane for 56 hours. The cost per hour for crew hire and White Knight rental is $5030 per hour.

Input Section:

The call line of the function is:

Cost_Modifier = Aircraft_Cost_Modifier(GLOW)

All of the variables that are passed into the function are described below:

Variable Name	Description
GLOW	Gross lift off weight of the launch vehicle [kg]

Output Section:

If the gross lift off weight is greater than the White Knight's maximum payload, the user is notified. If not, a cost is provided.

Variable Name	Description
Cost_Modifier	The cost required to utilize the White Knight [$]

User's Guide for *Balloon_Cost_Modifier.m*

William Yeong Liang Ling

Revision 1.0 - 3/16/2008

Description:

This code determines the volume of lifting gas required to lift the launch vehicle and the gondola. From the volume, the maximum diameter of a spherical balloon is calculated. Using the ideal gas equation, the volume of the gas at standard sea level is determined in order to determine the cost of the lifting gas. This is added to the cost of the gondola and the balloon to output the total cost of the balloon assisted launch.

Assumptions:

- We assumed that the barometric formula accurately models the pressure, density and temperature of the atmosphere.
- The balloon costs are obtained from a best fit curve through commercial figures obtained from Aerostar.
- A spherical design was assumed for the balloon.

Important Notes:

There is a range of altitude depending on the GLOM of the vehicle which we have termed the constant regime. This arises because the amount of lifting gas required decreases until a certain altitude before increasing again. However, in order to provide a positive buoyancy force at ground level, it is required that the amount of lifting gas be greater than the amount in this constant regime. The code automatically determines whether the maximum altitude of 30km lies within the constant regime of the specified gross lift off weight and to select the correct corresponding costs.

Input Section:

The call line of the function is:

Cost_Modifier = Balloon_Cost_Modifier(GLOW)

All of the variables that are passed into the function are described below:

Variable Name	Description
GLOW	Gross lift off weight of the launch vehicle [kg]

Output Section:

The code outputs a single variable: *Cost_Modifier*.

Variable Name	Description
Cost_Modifier	The cost required to utilize a balloon launch platform [$]

User's Guide for *Cost_Modifier_Init.m*

William Yeong Liang Ling
Revision 1.0 - 3/16/2008

Description:
Initializes all cost modifier codes and outputs the total cost modifier.

Assumptions:

All assumptions are as per the individual cost modifier codes.

Input Section:

The call line of the function is:

Cost_Modifier = Cost_Modifier_Init(launch_type, GLOW, stages, propellant_type, Length_stage)

All of the variables that are passed into the function are described below:

Variable Name	Description
launch_type	Type of launch, 1: Ground launch, 2: Balloon launch, 3: Aircraft launch
GLOW	Gross lift off weight of the vehicle [kg]
stages	Number of stages on the launch vehicle [#]
propellant_type	Type of propellant in each stage, [#, #, #] 1: Cryogenic, 2: Storable, 3: Hybrid, 4: Solid, 0: n/a
Length_stage	Length of each stage, [m,m,m]

Output Section:

The code outputs a single variable: *Cost_Modifier*.

Variable Name	Description
Cost_Modifier	The total cost modifier associated with our launch [$]

User's Guide for *Ground_Cost_Modifier.m*

William Yeong Liang Ling

Revision 1.0 - 3/16/2008

Description:

This code determines the ground costs required to launch a vehicle depending on the fuel types.

Assumptions:

- Transportation of fuel to the launch site is neglected and it is assumed that all fuels are ready at hand and only labor is required.
- There is no scaling of the number of personnel required with the rocket size. It is assumed that the rocket will be large enough to require said personnel to maintain and small enough not to require an army of maintenance crew.
- Our analysis is based on a full time 2 week period.
- We did not account for the possible labor and additional costs required to clean up possible toxic fuels from discarded spent stages.
- The baseline is assume to be a total of 7 personnel, one from each section of our multidisciplinary team and our project manager, with a fixed hourly rate of $75 per hour working a 40 hour week for two weeks.
- Two specialists are assumed to be required for cryogenic propellants.
- One fuel technician is assumed to be required for storable propellants.
- One fuel technician is assumed to be required for hybrid propellants.
- Four explosive technicians are assumed to be required for solid propellants.
- The tubing costs for the rocket is scaled with the length of each stage.

Input Section:

The call line of the function is:

Ground_Cost_Mod = Ground_Cost_Modifier(stages, propellant_type, Length_stage)

All of the variables that are passed into the function are described below:

Variable Name	Description
stages	Number of stages [#]
propellant_type	Type of propellant in each stage, [#, #, #] 1: Cryogenic, 2: Storable, 3: Hybrid, 4: Solid, 0: n/a
Length_stage	Length of each stage, [m,m,m]

Output Section:

The code outputs a single variable: *Ground_Cost_Mod*.

Variable Name	Description
Ground_Cost_Mod	The ground cost required to launch our vehicle [$]

A.10.0 Before AAE 450, I wish I had known…

After all was said and done, the design team reflected back on the knowledge gained. Below is a collection of advice, quotes, and fun hints to help future design teams.

"…how to speak with people in industry."

"…'A little inaccuracy sometimes saves a ton of explanation.' – Hector Hugh Munro"

"…proofread carefully to see if you any words out."

"…Eating fast food several days in a row can do such bad things. ☹

"…that I would have the busiest semester of my life, but would feel the most accomplished at the end. I am going to miss the smart and motivated people I got to work on this project with."

"…ANYTHING AT ALL about avionics! Taking a course in power systems would have been a real help!"

"…don't sell back your books, because you will need them for 450."

"…get to know your professors, because they will be much needed for helping with 450."

"…that ARMS 2106 didn't have a Laz-e-Boy to get those few hours of sleep."

"…how to lick my elbow."

"…what spin torque, ballistic coefficient, and steering laws were."

"…there are no things called weekends when taking senior design."

"…ARMS 2106 would be my new home. I would've brought a pillow."

"…that tasks change rapidly."

"…how important it is to communicate clearly with others."

"…it is important to make tables and plots with sharply contrasting colors."

"…how to program MATLAB to use multiple cores."

"…that I was not on the mailing list for the first six weeks."

"…the words to 'Don't Stop Believing'."

Compiled by: Nicole Wilcox

"…AAE 450 would be so much work before convincing Prof. Williams to let me enroll."

"…how much you could love and hate MATLAB at the same time."

"…to take a light schedule when I took senior design. It's very time consuming."

"…that the work-load required in AAE 450 is twice or three times as much as a normal undergraduate course in AAE."

"…taking AAE 539 before senior design would make things much easier."

"…computers tend to die before deadlines."

"…don't call people to ask about state or industry secrets, you may get a knock on your door."

"…sleep is second priority."

"… you will be printing … A LOT."

"…the design of the telecommunications system uses a cluster of antennaes instead of just one, and it should have been modeled as an omni-directional signal instead of a directional one."

"…a scientific method of determining gain matrices for controllers."

"…to take more grad level courses before taking senior design so I could help with more in depth topics."

"…many, if not most aerospace companies will not give you price estimates without a big wallet, a security clearance, or at least a small country."

"…taking 18 credit hours the semester I was taking senior design was suicide."

"…there were so many cool aeros before my last semester."

"…just how difficult communication can be for a group this large. Lines of communication need to be set up quickly and used frequently."

"…to keep all my old books and class notes from previous classes."

"…how little sleep I would get this semester so I could have stocked up more over Christmas break."

"…how much time I would spend in Armstrong 2106 so I could have got a cot installed in the back corner."

"…3D Fluent does not play well with others."

Compiled by: Nicole Wilcox

"…CFD is harder to do accurately in a short time than just making your own aerodynamic solver."

"…how to use Simulink (because it's easier to use a program when you've actually been taught how to use it)."

"…methods of quick and effective research."

"…'the mark of an educated individual is to demand no more precision from a subject than the subject itself allows.' – Aristotle"

"'pleasure in job puts perfection in work.' – Aristotle"

"…how to play blues guitar."

"...there is actually an Astronautics Structures Manual on how to do this."

"…how important it is to establish good relationships with multiple professors within the AAE department."

"…making connections with professors pays off big time!"

"…DO RESEARCH."

"…Stadium Bar and Grill is only a minute walk from Armstrong!"

"…not to be afraid to ask questions. Each team member needs to understand the process AND the final product."

"…not to forget to relax. Happy people are more productive."

"…to always solicit the help of professors. They are not going to tell you how to do something, but they can help you get off on the right foot."

"…I should have kept all my textbooks, because they might be worth more in knowledge than in dollars."

"…how much of the design process is educated guesswork."

"…that having a very specific coding standard can save a million headaches when working with a group of people with various backgrounds."

"…always assume the other person doesn't completely understand you, because 9 times out of 10 you are not on the same page."

"…make senior design fun from the start. You will be spending a lot of time with these people better make the most of it!"

"…that all the smart people in the world write their own CFD programs."

"…that I would never have enough room on my roger.ecn.purdue.edu account for all of my schoolwork."

"…that all of my fellow astro majors are awesome and I should have started hanging out with them earlier."

"…Stadium Bar and Grill is just minutes from Armstrong."