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The Quarter Pounder

A Vehicle to Launch Quarter Pound Payloads to Low Earth Orbit
QP_SYS_001 V 2.0

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Introduction

Attainment of orbit by amateur rocketry enthusiasts is seen as the ultimate goal by many. It represents a capability to explore beyond the confines of Earth's atmosphere and possibly beyond to such places as the Moon, asteroids or other planets. It brings the hope that space exploration and development will become available to the common man.

This is, however, a very difficult goal to accomplish and is beyond the skills of many amateurs. It requires the development of sophisticated rockets as well as sophisticated launch and support infrastructure.

The first difficulty in attaining orbit by amateurs is the very requirements needed to attain orbit. Attaining roughly 17,500 MPH velocity horizontal to the Earth at an altitude of over 100 miles is not easy. It was only about five years ago that the Civilian Space Exploration Team was the first amateur group to reach the altitude of space after nearly a decade of development. Attaining that altitude is only the first part to attaining orbit.

Another difficulty arises due to the complexity of the vehicles required to attain the altitudes and reach the horizontal velocities. The Rocket Equation governs the limits of rocket capability. It specifies the physics that all vehicles attempting to reach orbit must attain. Because of the realities that it imposes on them, orbital vehicles are exclusively multistage vehicles. Amateur orbital vehicles will also be multistage vehicles.

The legal regime governing orbital launch vehicles is yet another difficulty. International laws and treaties impose special requirements due to the danger of harming non-involved individuals and property around the world.

Despite these difficulties, it is the intent to pursue this worthy goal using resources available to amateur rocketry enthusiasts. This paper describes the conceptual design of an amateur launch vehicle capable of placing a quarter-pound payload into orbit.

Requirements

Orbital Altitudes

It is not possible to attain orbit in the atmosphere. By convention, space starts at 100 kilometers or 62.14 miles. The atmosphere, however, does not suddenly stop at that altitude, but gets progressively thinner. Lower orbits have shorter lifetimes whereas higher orbits have longer lifetimes. To maintain orbits lasting more than one day generally requires an altitude of 100 miles or better.

Orbital Velocities

The equation governing the speed required to maintain a circular orbit about Earth is:

$$V = \sqrt{\frac{\mu}{r}}$$

where:

V = velocity in feet per second

μ = Earth's gravitational constant (1.4076540×10^{16} ft³-sec⁻²)

r = radius of orbit from Earth's center in feet

and since the Earth's radius is 3959 miles or 20,903,520 feet, the following table lists several different orbital altitudes and the tangential velocity required:

Orbital Altitude (miles)	Orbital Radius (feet)	Velocity (feet per second)
100	21431520	25628
150	21695520	25472
200	21959520	25318
250	22223520	25168

Therefore, to attain an orbit at 150 miles altitude requires a tangential velocity of 25472 feet per second (or 17367 miles per hour).

Summary

To attain orbit requires that the rocket's payload reach an appropriate altitude and acquire a tangential velocity near 25500 feet per second.

System Description

The following is the description of the vehicular system chosen to meet the orbital requirements for delivering a quarter-pound payload to a circular orbit of 125 miles altitude.

Design Strategies

The following design strategies were chosen as the basis of the design of the Quarter-Pounder vehicle.

High Mass Fraction Vehicle

Relatively high vehicle mass is selected to allow simpler construction techniques. In general, the first stage has a propellant mass fraction of 71.4% or a structural mass fraction of 28.6%. This means that the propellant makes up less than 71.4% of the total lift-off mass and means that the vehicle is relatively heavy as far as modern rockets go.

Four Stages with Duplicated 2nd and 3rd Stages

Rather than try to create a multistage vehicle which is highly optimized for weight, the design chosen is one that uses multiple non-optimized components. Although the first stage is a unique vehicle design, stages 2 through 6 are all identical in construction and capability. Therefore, only two different vehicles must be developed although multiple copies of the upper stage design are used.

Lofted Ascent Trajectory

A lofted ascent trajectory, where the first stage vehicle ascends vertically during its entire flight, was selected. Although non-optimal for attaining orbit, it provides a number of benefits for amateurs. First, it minimizes the locations that the first stage might fall either after burn-out or during a failure. Second, it ensures that the first stage flight is visible and no radar tracking is necessary.

Performance Allocations

The following table lists the various performance allocations for each of the stages. The table has six columns. The first column from the left is the parameter being detailed. The second column is the particular performance allocations for stage 4, the third column is performance allocations for stage 3, the fourth column is performance allocations for stage 2, the fifth column details performance allocations for stage 1 and the sixth column details the units for each parameter.

Each row lists parameters for each of the stages. There is a color coding to delineate between user-entered values and those calculated by the spreadsheet that generated this table. Light Blue values are user-entered values. Light Orange fields are calculated

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values. The oxidizer row lists the chosen oxidizer for each stage. The Fuel row lists the chosen fuel for each stage.

	STAGE 4	STAGE 3	STAGE 2	STAGE 1	
Oxidizer	Lox	Lox	Lox	Lox	
Fuel	Propane	Propane	Propane	Kerosene	
Payload	0.250	13.25	54.16	96.08	lbs
OF Ratio	2.200	2.200	2.200	2.200	
Oxidizer Density	71.230	71.230	71.230	71.230	lbs/cuft
Fuel Density	36.330	36.330	36.330	50.150	lbs/cuft
Avg Density	60.324	60.324	60.324	64.643	lbs/cuft
Propellant Isp	310	310	310	250	Seconds
Desired DeltaV	14016.90	9369.45	4325.90	7541.54	FPS
Body:Fuel Mass	0.30000	0.24000	0.24000	0.400000	
Payload Ratio	0.019	0.324	1.292	0.174	
Structural Coef	0.231	0.194	0.194	0.286	
Propellant Ratio	0.769	0.806	0.806	0.714	
Mf/Me Ratio	4.077	2.558	1.543	2.554	
Propellant Mass	10.000	32.988	33.812	394.465	lbs
Oxidizer Mass	6.875	22.679	23.246	271.195	lbs
Fuel Mass	3.125	10.309	10.566	123.270	lbs
Oxidizer Volume	0.097	0.318	0.326	3.807	cuft
Fuel Volume	0.086	0.284	0.291	2.458	cuft
MT	3.000	7.917	8.115	157.786	lbs
Me	3.250	21.168	62.270	253.868	lbs
Mf	13.251	54.156	96.082	648.334	lbs
Stage Impulse	3100.126	10226.276	10481.674	98616.322	lb-sec
Cum delta V	14016.900	23386.350	27712.250	35253.790	

Payload Row - The payload is the allocated payload in pounds for each stage. The payload is for stage 4 is listed as light blue because that is the user-entered payload value. The light orange payloads for each other stage is calculated based on the values of the previous upper stage. It is presumed that each stage contains the weight of whatever devices are necessary to carry and release its payload.

OF Ratio - The OF Ratio row is the propellant Oxidizer to Fuel Ratio.

Oxidizer Density – This is the likely density of the oxidizer in pounds per cubic foot.

Fuel Density – This is the likely density of the fuel in pounds per cubic foot.

Avg Density – This is the average density of the propellants in pounds per cubic foot. This calculation computes the weighted average of the combined oxidizer and fuel considering the OF Ratio.

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Propellant Isp – This is the Specific Impulse of the propellants in seconds expected for reasonable combustion characteristics (which have not been detailed here).

Desired Delta V – This is the user-specified value for the desired change in velocity (in feet per second) that each stage contributes. This is a key variable used in the rocket equation to calculate the stage masses.

Body:Fuel Mass – This user input is a ratio relating the mass of the body to the mass of the fuel. This input parameter is a rough indicator of the technical sophistication of the rocket stage construction. Obviously, higher body:fuel ratios indicate “heavier” rockets while lower body:fuel ratios indicate “lighter” rockets.

Payload Ratio – This is the commonly used rocket Payload Ratio that is calculated as the payload mass divided by the sum of the empty mass of the rocket and the mass of the propellant. This is a useful metric for identifying the sophistication of the rocket payload carrying capability.

Structural Coef – This is the commonly used Structural Coefficient that is calculated as the mass of the empty rocket divided by the sum of the mass of the empty rocket and the mass of the propellant. Like the Body:Fuel Mass ratio number above, it’s a useful indicator of the sophistication of the construction of the rocket stage.

Propellant Ratio – This is the commonly used Propellant Ratio that is calculated as the mass of the propellant divided by the sum of the mass of the empty rocket and the mass of the propellant. This is the converse of the Structural Coefficient and is useful in the same way.

Mf/Me Ratio – This is the commonly used Mass Ratio that is calculated as the sum of the payload mass, the propellant mass and the empty vehicle mass divided by the sum of the propellant mass and the empty vehicle mass. Again, this is a useful indication of the performance of the vehicle.

Propellant Mass – This is the mass of the propellant in pounds calculated using the user-input values and the rocket equation. This is the total mass which includes the sum of the oxidizer mass and the fuel mass necessary to bring the vehicle to the earlier-specified delta V.

Oxidizer Mass – This is the mass of the oxidizer in pounds calculated from the total propellant mass and the specified OF Ratio.

Fuel Mass – This is the mass of the fuel in pounds calculated from the total propellant mass and the specified OF Ratio.

Oxidizer Volume – This is the volume of the oxidizer in cubic feet calculated from its mass and the specified oxidizer density.

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Fuel Volume – This is the volume of the fuel calculated in cubic feet from its mass and the specified fuel density.

MT – This is the empty weight in pounds of the stage without payload or propellant.

Me – This is the weight in pounds of the empty stage and the payload (no propellant).

Mf – This is the weight in pounds of the empty stage, the payload and the propellant.

Stage Impulse – This is the impulse for this stage in lb-sec.

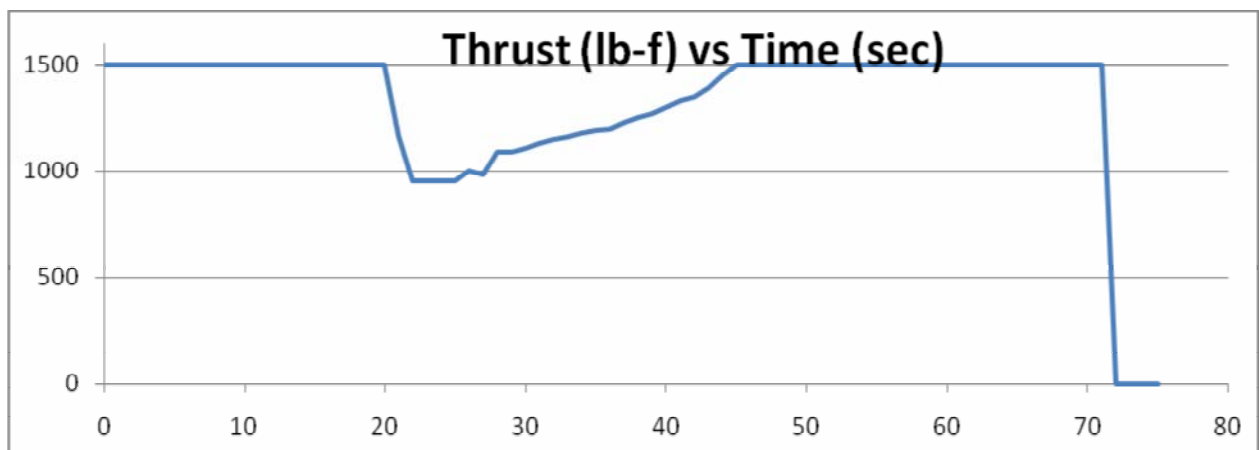
Cumulative Delta V – This is the cumulative sum of delta V (in feet per second) from the upper stage down down to the first stage.

Lofted Trajectory Detailed Description

If we examine the performance allocation table above, we see that the vehicle has a takeoff weight of about 648 pounds. The upper stages, which are the payload for the first stage, weigh about 96 pounds. The flight trajectory of the first stage is known as a Lofted Trajectory; this means that its primary flight path is vertical with little or no horizontal velocity from the launch site.

What is not described in the performance allocation table, above, is the thrust of the various stages. This is a design decision to be made. However, currently, the assumption is that the first stage will have a takeoff thrust of 1500 pounds force.

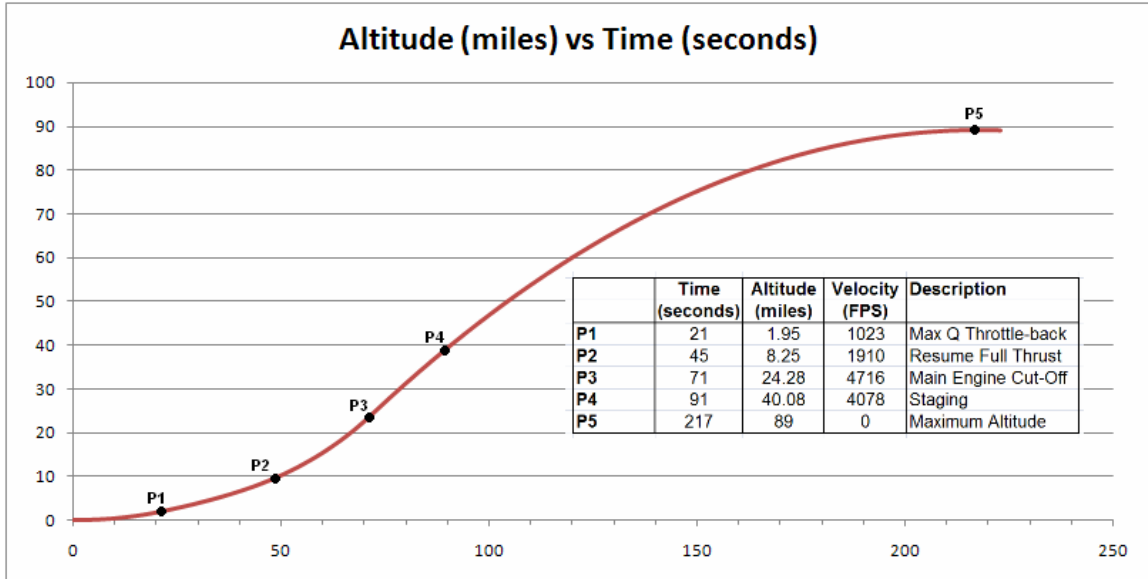
Based on the performance allocations described earlier, a notional vehicle aerodynamic profile, presumed 1500 #-f thrust for the first stage and simulations, the nature of that trajectory is described in the following images. The first image is a the thrust profile versus time.



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The chart shows that the first stage rocket starts out with a thrust of 1500 lb-f until about 21 seconds in flight when it drops to about 950 lb-f (63% of maximum). It then slowly increases until it is back to its 100% value of 1500 lb-f at about 45 seconds. The reason for the drop in thrust is to accommodate a maximum pressure due to air drag (known as “max Q”). As the thinner air density at higher altitudes is reached, the effects decrease. This thrust profile illustrates a requirement that the first stage motor must be able to throttle effectively down to about 60% of its maximum.

The second chart, below, shows the altitude versus time profile for the first stage.



This chart shows that the 1st stage launches at time 0, encounters Max Q and throttles down at 21 seconds (P1), resumes full thrust at about 45 seconds (P2), runs out of fuel and shuts down the engine at 71 seconds (P3), stages at 91 seconds (P4) and continues on a ballistic trajectory to a maximum altitude of 91 miles (P5).

Once the first staging event occurs, the second stage, carrying the other upper stages, has two major functions: increase the upward velocity sufficiently to attain the desired altitude and to impart as much horizontal velocity as is available in the correct direction. The result should be a trajectory like that detailed in the following figure.

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