PEAK OF FLIGHT

NEWSLETTER

ISSUE 455 | October 31st, 2017

IN THIS ISSUE

A Guide to Optimal Altitude: Part 1

www.ApogeeRockets.com/Rocket-Kits/Skill-Level-3-Model-Rocket-Kits/Midge

Apogee Components, Inc.
Your Source For Rocket Supplies That Will Take You To The "Peak-of-Flight"
3355 Fillmore Ridge Heights Colorado Springs, Colorado 80907-9024 USA
www.ApogeeRockets.com e-mail: orders@apogeerockets.com Phone: 719-535-9335 Fax: 719-534-9050

APOGEE COMPONENTS

PEAK OF FLIGHT

A Guide to Optimal Altitude: Part 1

This material copyrighted 2017, ARA Press. Reprinted by permission.

By Steve Ainsworth

Chapter 1: Introduction

The HPR hobby is now reaching for space. The next big step is to venture to high altitudes considered by NASA as space. Long burn motors, and perhaps staging, can reduce the aerodynamic stress experienced during the launch phase. What are the pitfalls of using long burn motors? What are the advantages? Is it possible to find the optimum motor thrust curve that will provide the highest altitude for the given total impulse? How to get to answer these questions is the subject of this book.

There are several books currently available that provide instruction for the beginner on rocketry fundamentals. The purpose of this newsletter is to provide instruction on the next level, or the fundamentals plus. There are also articles and books covering advanced topics in rocketry. This newsletter fits in between the fundamentals and advanced topics. What I hope you will find is some valuable equations and examples to allow you to get the most out of your propellant, that is to optimize the motor design.

Eventually it will be helpful to become familiar with the calculation of the Center of Gravity and the Center of Pressure from the "Handbook of Model Rocketry" by G. Harry Stine. It would also be helpful to become familiar with the linearized dynamic stability equations and constants discussed in detail in TR-201 "Fundamentals of Dynamic Stability" by Gordon K. Mandell. Both of these documents are available from the National Association of Rocketry (NAR).

A good overview of dynamic flight parameters such as Corrective Moment Coefficient, Damping Moment Coefficient, Natural Frequency and Damping Ratio is available from Tim Van Milligan's newsletters at www.apogeerockets.com. This newsletter will provide the formulas, but will not provide any details that are in the reference volumes.

The Ultimate Reference Source

David Ketchledge's 2009 book "Rocket Science" has possibly the best compilation of reference material included as appendices. You can get a downloadable copy from ARA Press.

Equation Notation

The equation notation convention used provides the chapter number where the equation first appears, and the equation number. Thus, Equation 3.2 would be the second new equation listed in chapter three.

4" diameter VTS rocket at El Dorado dry lake, NV

Chapter 2: What prevents vertical flight?

Anyone who has flown rockets for very long has learned by experience that wind at ground level causes the rocket to cock into the wind (like an old weathervane) as it leaves the launch rod. This "wind cocking" is a result of the crosswind hitting the rocket fins. The air pressure on the fins causes the rocket to point into the apparent wind, which is a combination of the wind caused by the rocket's vertical motion and any crosswind. The faster the rocket is traveling, the less effect the same crosswind has on the direction. Conversely, a slower rocket velocity as the rocket leaves the launcher allows the presence of a crosswind to have a much greater effect on the rocket attitude.

Amateur rockets are designed so that the center of pressure (CP) is aft of the center of gravity (CG). This is done so that the rocket is stable. All motion of a rocket is either displacement motion through the CG or rotation about the CG. When the CP is behind the CG, the air pressure forces acting on the fins (lift) due to an angle of attack of the fins with the apparent wind will tend to rotate the

Continued on page 3

About this Newsletter

You can subscribe to receive this e-zine FREE at the Apogee Components website **www.ApogeeComponents.com**, or by clicking the link here Newsletter Sign-Up

Newsletter Staff

Writer: Steve Ainsworth
Layout/Cover Artist: Chris Duran
Proofreader: Will Franks

This material copyrighted 2017, ARA Press. Reprinted by permission.

A Guide to Optimal Altitude: Part 1

Continued from page 2

rocket about its CG and keep the rocket pointed in the direction of travel through the air.

Stated differently, when the rocket encounters a crosswind, the wind pressure pushes the fins with the wind, cocking the forward end of the rocket into the wind. The flight direction thus varies from vertical and results in lower apogee. Wind cocking can also occur at higher altitudes when the rocket passes through a crosswind also known as wind shear. The more stable a rocket is, the greater the effect of wind cocking. Wind cocking is often the first cause of gravity turning.

Gravity Turning

I first heard the term Gravity Turning at a Tripoli Vegas launch in Southern Nevada around 1996. The term was used by the announcer to describe the fate of an "old" long burn F motor flown in a small rocket. The rocket left the pad and followed a graceful arc up, over and down. It was still under thrust as it impacted the dry lake bed. Ouch. I do not recall for certain, but the announcer was possibly Tom Blazanin TRA #003. These original members know their stuff.

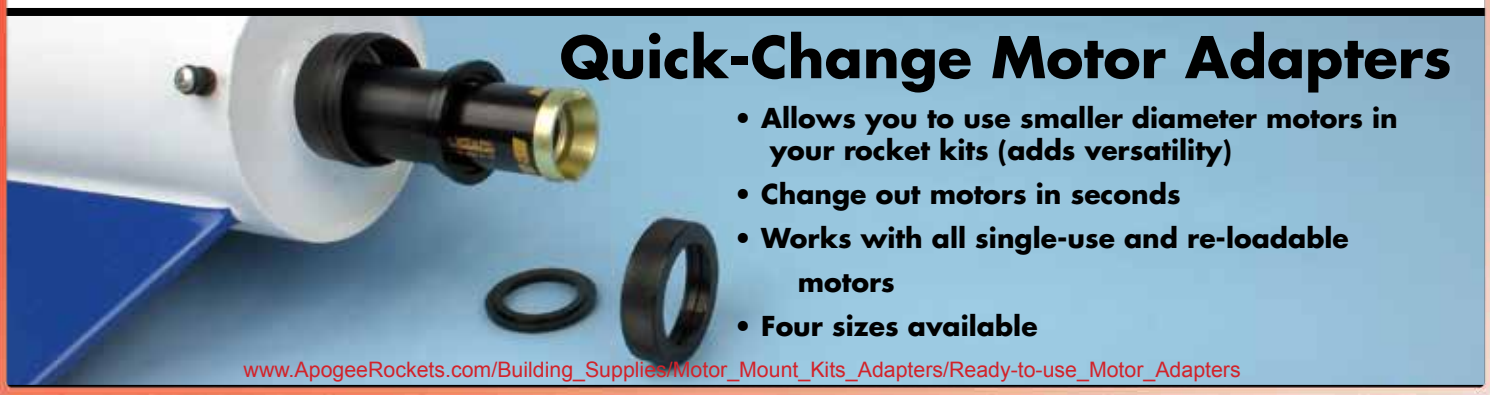
The memory of that flight has been with me ever since. In fact, it was one of the key events that inspired my interest in Vertical Trajectory Systems (VTS), to prevent the arc of death for all long burn rockets.

Tim Gubbins' rocket at Black Rock, NV (photo Bill Kositzky)NV

More recently, while flying my 2.5" diameter roll-controlled rocket, I experienced it once again. The flight used a G64 reload. I had assembled the motor at a previous launch but was not able to fly due to wind conditions. The G64 remained assembled for several weeks until the next launch.

Following motor ignition, the aft O-ring failed and burned through, damaging one side of the casing and causing an off-axis second jet. This reduced the forward thrust, caused the rocket to wobble, and likely increased the burntime as the motor was not up to nominal pressure. The rocket proceeded to follow an arc as it performed a textbook gravity turn and impacted just before the chute deployed.

Continued on page 4



This material copyrighted 2017, ARA Press. Reprinted by permission.

A Guide to Optimal Altitude: Part 1

Continued from page 3

Doing The Math

So, what is this Gravity Turning? Figure 2-1 provides a vector diagram of what is going on between the motor thrust and gravity. As shown, any rocket that is being pushed by its motor is also being pulled down by gravity. The vector diagram uses the length of a vector (the arrow length) to indicate magnitude (the size of the force), and the direction of the vector to indicate the direction of the force. If the motor provides 5 g's then its vector is 5 times longer than the gravity vector. Using this notation, you can do vector addition by simply placing the tip of one vector at the tail of the other. The result of the addition is a new vector that has a length and direction such that it completes the triangle. Thus in **Figure 2-1** vector Tt is motor thrust, vector g is gravity, and vector Tr is the result of adding Tt+g.

The rocket will move in the direction of the resultant vector Tr. If the flight is perfectly vertical, then the gravity vector simply subtracts from the motor thrust vector. The resultant Tr vector is still straight up. But if the flight path is just slightly off vertical, the resultant vector Tr is even more off vertical, and the rocket will actually travel a bit sideways. The air then strikes the rocket fins at an angle causing the rocket to rotate away from vertical more.

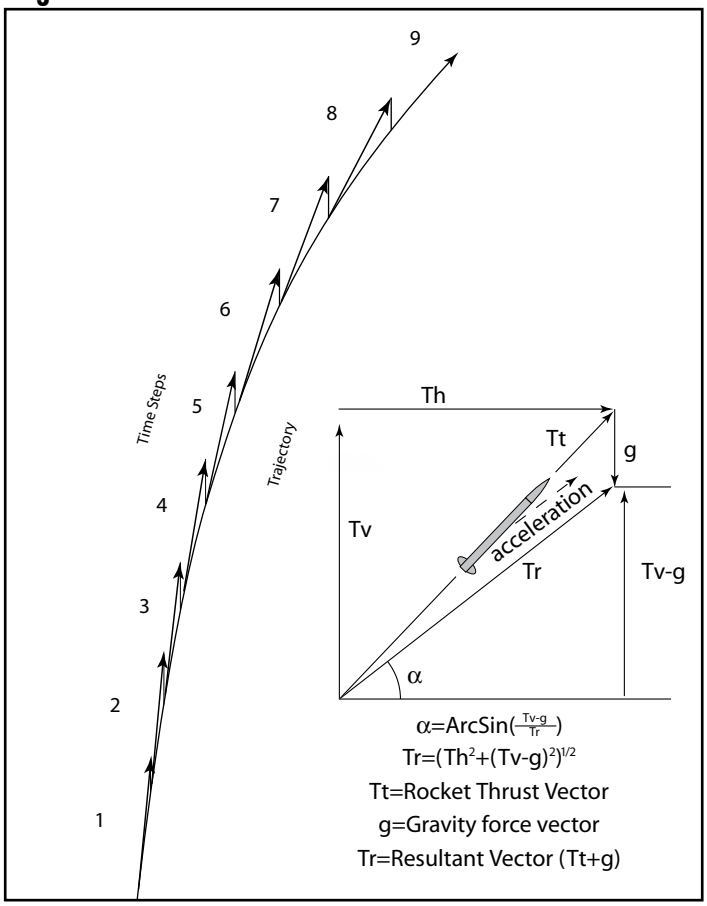
The Rocket Science

The turning part of Gravity Turning is caused by the air striking the rocket fins at an angle due to the sideways motion, thus pivoting the rocket "into the wind" causing it to rotate away from vertical. Gravity Turning pivots the flight path away from vertical at an increasing rate throughout the engine burn time. The longer the burn, the more off vertical the flight path at motor burnout and the more the thrust of the motor is used to add horizontal velocity to the flight as opposed to vertical velocity. This horizontal velocity robs the rocket of altitude and can shred the recovery system.

Simulations

What is the actual effect of this Gravity Turning on the flight path of a high powered rocket? In order to determine the magnitude of the effect, I ran many flight simulations using RockSim v7 for the same rocket with the same 40,000 Ns total impulse engine but with burn times varying from 5 seconds to 80 seconds, and with a launch angle varying generally from zero to five degrees off vertical.

Figure 2-1



Continued on page 5

Join Tripoli.org
Mention Apogee Components

A Guide to Optimal Altitude: Part 1

This material copyrighted 2017, ARA Press. Reprinted by permission.

Continued from page 4

Convention

For this paper, a perfectly vertical launch has a zero degree launch angle. The launch angle is thus measured from the vertical. **Figure 2-2** provides a comparison between a given non-zero launch angle with no wind and a zero degree launch angle with a given non-zero wind. As you can see, for this rocket, a 15 mph breeze at ground level is worse than a 5 degree launch angle. When wind and other factors are added into the actual launch angle, the result is the effective launch angle. This effective launch angle is what is called the launch angle for this paper.

Slower, Longer and Higher

Figures 2-3 & 2-4 show the maximum altitude for burn times of 5, 10, 20 and 40 seconds with a 0 and 5 degree launch angle. As you can see, the maximum altitude for a rocket with a 5 second burn decreases very little as the launch angle increases. However, the same rocket with a 40 second burn can reach an altitude over 12% greater if a vertical flight is achieved. If the launch angle is off vertical, the flight altitude drops drastically for the 40 second burn scenario. In fact it drops from 12% greater to 10% lower than the 5 second burn flight for a launch angle of just 5 degrees. This is due to Gravity Turning. If you used an 80 second burn and achieved a vertical flight, you could reach 100,000 feet with the same total impulse! Cool! What we need is a very long burn and a very vertical flight. If you can fly straight, the long burn motor is the best.

Straight Up

Why would a flight go off vertical in the first place? One problem is a launch rail that is not vertical. Assuming that the launch is accomplished in near zero ground level wind conditions, it is critical that the rocket leave the rail as close to vertical as can be accomplished. The launch system should be leveled using a level placed on both the rocket and the rail.

A less controllable problem is wind and wind cocking discussed earlier. Wind at ground level can affect the flight path the most as the rocket is traveling its slowest at that point. With a low launch rail exit velocity a small breeze can be a large percentage of the total velocity and easily cause a 5 degree off vertical launch angle. Keep in mind that ground level wind effects the flight path from the start allowing gravity turning more time to take a greater toll on the altitude.

For high altitude flights, winds at altitude can be much stronger that the ground level breezes and can deflect the flight path considerably. You would not want the motor of a static fin guided rocket still running as you pass through the jet stream unless the rocket is going very fast.

Figure 2-2

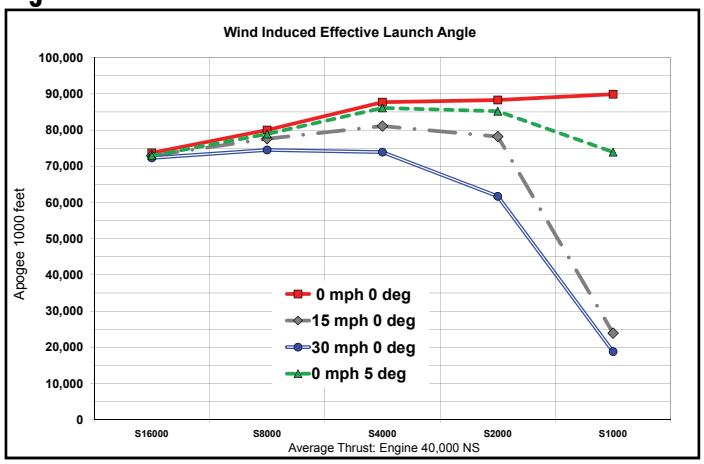


Figure 2-3

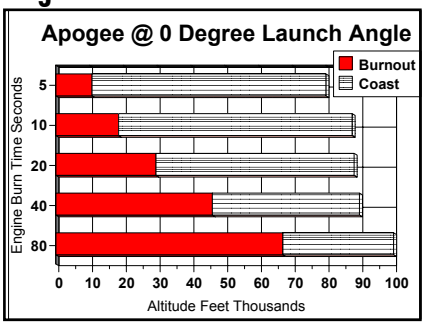
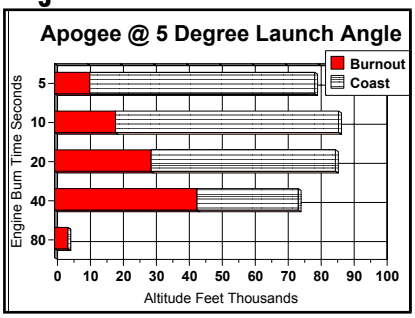


Figure 2-4



Continued on page 6

A Guide to Optimal Altitude: Part 1

This material copyrighted 2017, ARA Press. Reprinted by permission.

Continued from page 5

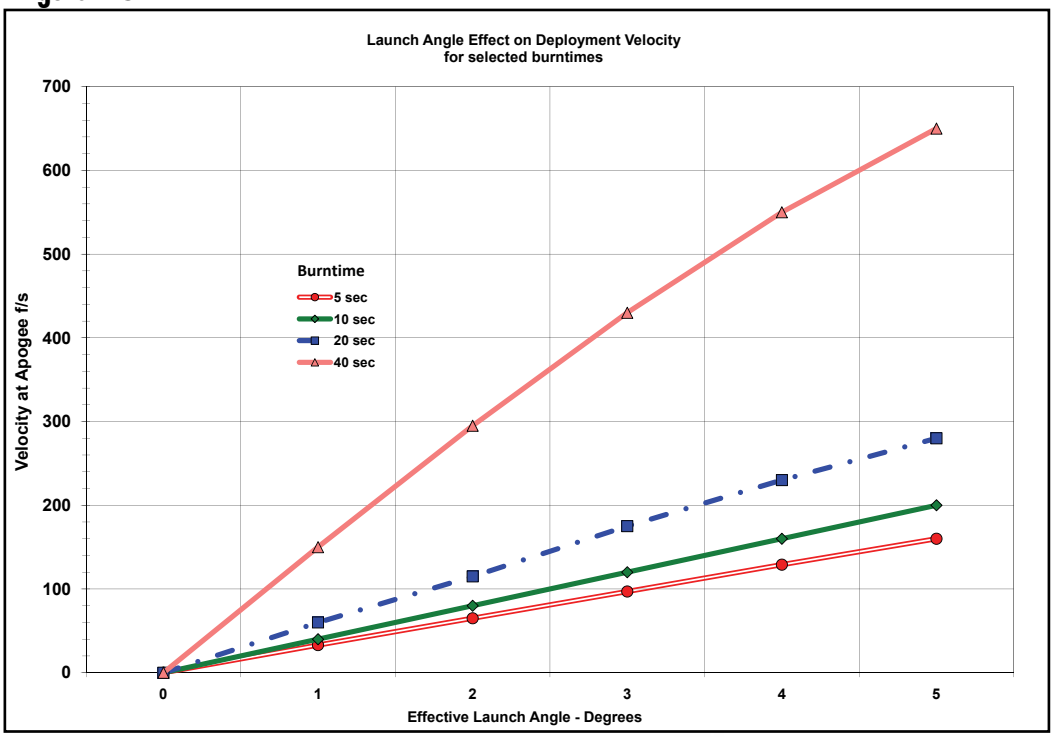
Off axis forces such as those resulting from asymmetric drag, off-axis thrust from the motor, motor miss-alignment and fin misalignment contribute to a flight path with an increasing deviation from vertical. These are impossible to eliminate completely.

The Coast to Apogee

The force situation changes greatly at motor burnout. The resultant force is now slowing the vertical and horizontal components of velocity and gravity turning is on the decrease.

Figure 2-3 and **2-4** show a comparison of the altitude gained during motor burn, altitude gain during coast, and apogee altitudes for several motor burn times and launch angles. For the vertical launch, the 80 second burn motor gets you above 100,000 feet. But for a 5 degree launch angle, the 80 second burn altitude drops to below 5,000 feet.

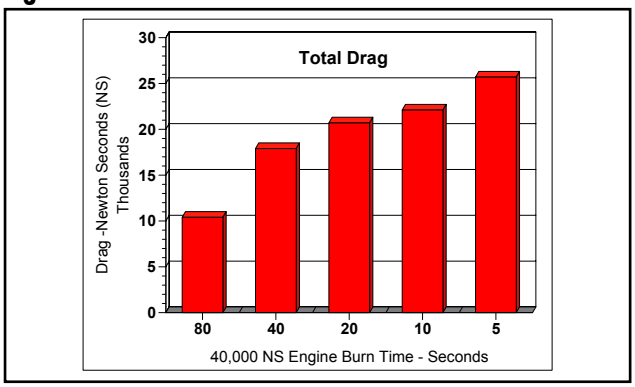
Figure 2-5



Deployment Velocity

Figure 2-5 demonstrates the launch angle effect on the rockets velocity at apogee. When deployment occurs at apogee, you can see that a long burn motor combined with a non-zero launch angle is a deadly combination. The 40 second burn motor with a 5 degree launch angle yields a deployment velocity over 600 feet per second! If you use a long burn motor, you must have a vertical flight.

Figure 2-6



25,000 Newton Seconds of Drag

Why does a vertical flight with a long burn motor make the rocket go higher than a vertical flight with the same total impulse motor but with a short burn? The answer is drag. Short burn high impulse motors make fast rockets. Drag increases with the square of the velocity (this is approximate). **Figure 2-6** compares the total energy consumed by drag (given in Newton-seconds like a motor) for long and short burn 40,000 Ns motors. A short burn means a higher velocity. A higher velocity means much higher drag.

Drag is a force (newtons) just like the motor thrust is a force. The total drag for the flight of the 5 and 10 second burn motors is over 50% of the total impulse of the motor, whereas the total drag for the 80 second burn motor flight is 25% of the total impulse (newton-seconds) of the motor. The long burn motors use less of their total impulse on overcoming drag. This is not the complete story. The devil is in the details.

Continued on page 7

A Guide to Optimal Altitude: Part 1

This material copyrighted 2017, ARA Press. Reprinted by permission.

Continued from page 6

What To Do?

How can the wind and gravity turning problem be solved? An active Vertical Trajectory System (VTS) based on Gordon Mandell's linearized dynamic equations can react to correct small deviations from a vertical flight path (up to 12 degrees). This correction could eliminate gravity turning altogether and allow the effective use of longer burn motors. Note that a VTS system based on Mandell's equations will not be accurate for flight deflections in excess of 12 degrees, and thus could not be used to aim a rocket at a target, either on the ground or in the air.

Neutral Stability

Computer simulations suggest that designing a rocket with near neutral stability, that is a CP very near the CG, would render the rocket less susceptible to wind. Such a design would be pushed sideways by the wind but not rotated. A rocket that has near neutral stability would be much less affected by gravity turning because the air from the side motion would not rotate the rocket. This suggests designing high altitude rockets with a smaller stability margin. If you want to do this, you will want a very accurate computer simulation run to be certain that the rocket flies straight.

Spin

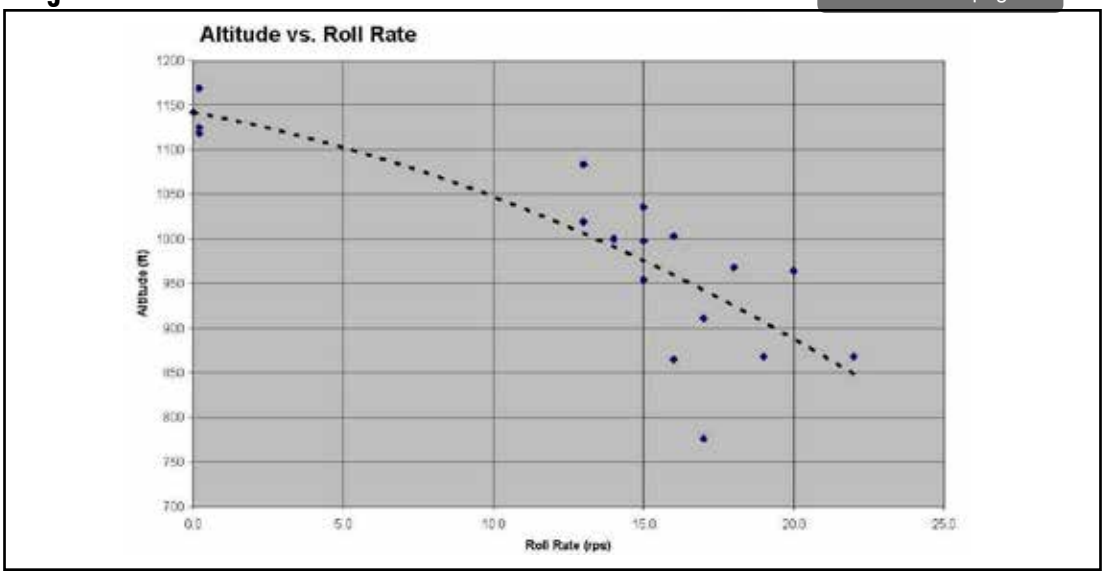
Another potential way around this problem could be spinning the rocket in order to average the off-axis forces over all directions and add gyroscopic forces to shift the effective CP. To achieve maximum altitude, you would want the rocket spinning at liftoff so as to not use the fins to force the spin and thus increase fin drag. One big drawback is it is difficult to analyze the flight of a spinning rocket. The Apogee newsletter #90 dated 2002 entitled "How to Stabilize Your Rocket Using Canted Fins" provides some info on this topic (https://www.apogeerockets.com/education/downloads/Newsletter90.pdf).

In 2002, Evan Gates conducted experiments with spin stabilization, and the effect on the maximum altitude achieved. His report was titled "The Effects of Spin Stabilization in Amateur Rocketry". The very detailed report provided a chart showing Spin Rate vs. Apogee (**Figure 2-7**). He concludes that the added drag forces are proportional to the square of the spin rate, and lower the Apogee.

Using a fin ring in the place of standard fins would provide a fin system with little added drag due to the roll and could be used to place the CP at a design point. As the flight progressed there would be a shift forward in the CG as propellant was consumed adding to the stability margin. The result could be a rocket that is stable at launch due to spin, and stable at motor burnout due to shifted CG. And Rock Sim can analyze fin rings.

Continued on page 8

Figure 2-7



This material copyrighted 2017, ARA Press. Reprinted by permission.

A Guide to Optimal Altitude: Part 1

Continued from page 7

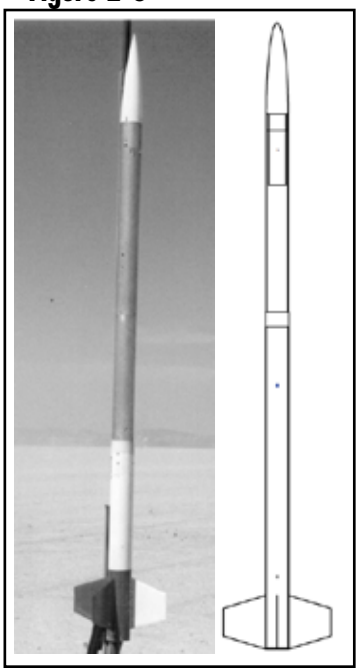
Combinations

A rocket made with neutral stability and provided with spin along its longitudinal axis could fly straight. However, any unbalanced forces could cause the rocket to nutate badly due to gyroscopic effects.

Data Source

The rocket design used for the figures and tables in this chapter is from the author's aluminum vtS cold-gas thruster rocket flown in 2002 (**Fig 2-8**). this is the same rocket analyzed in the vtS book (ArA press). The flight simulations were run using rockSim software.

Figure 2-8



How We Fly Today

The above phenomena are why amateur high altitude rockets typically use short burn motors. A short motor burn time (the shorter the better) minimizes the impact of gravity turning on apogee by applying the thrust very quickly, before the rocket has a chance to undergo much gravity turning. However, in order to get to a high altitude, we need to impart a lot of energy to the rocket. This requires a highly energetic motor that imparts its energy quickly. The result is a rocket that has very high acceleration and very high velocity at low altitude. As mentioned above, high velocity means more drag. Especially at low altitude in dense air.

We will discuss more on this topic in the upcoming Peak of Flight Newsletter "A Guide to Optimal Altitude: Part 2"

About The Author:

Steve Ainsworth is a Civil Engineer with a Master's degree in Physics from UNLV. He has published articles in both HPR and ER since he became a "Born Again Rocketeer" in 1994. Steve joined Tripoli Vegas in 1995 and began flying his "gizmo" rockets. In 1995, Las Vegas was the perfect setting for re-entering rocketry with Gary Rosenfield of Aerotech providing motor tutoring and Tom Blazinin (TRA # 003) as the local Prefect, coaching and signing for Steve's Level 1 and Level 2 flights. While on an extended engineering assignment in northern California, Steve had evening time to think about rocketry. He used that time to learn enough aerodynamics to develop a computational method for flight predictions based on Gordon Mandell's MIT Thesis articles.

Steve Ainsworth standing with his vtS cold gas thruster rocket in 2002.