Designing Cluster Rockets for Altitude

Research and Development Report

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Abstract

This Research and Development report focuses on designing a cluster rocket for maximum altitude, particularly one that meets the requirements of the NAR B Cluster Altitude competition requirements. The author looked at several aspects of the design for optimization including, drag, weight, motor ignition, and motor retention. The majority of the work done for this report were simulations using the OpenRocket system simulator and two fluid flow simulation tools. The research showed that there was not a single simple change that would make a step function difference in performance, but rather a combination of several small changes that together improved overall performance. It was found that due to the high relative thrust of the B cluster rocket, it was more beneficial to trade some weight to optimize the drag of the rocket, and that changes to the planform drag far outweighed the benefits of highly polishing the surface. The cross cluster configuration resulted in the smallest frontal area. Simulation showed that pods with a swept aerodynamic cowling significantly reduced drag over pods terminated with individual nosecones. The author also chose to sacrifice some weight to ensure that motors would not eject from the cluster. Finally the author investigated different methods of ignition to ensure all motors would light nearly simultaneously. Testing showed that Rocketflite ClusterFire pyrogen coated Estes Solar Starters resulted in the longest igniter burn time by 24%. Results of actual launches correlated well with the results of the simulations run using the same conditions. The result of the research resulted in enough improvement over existing designs to exceed NAR records in two cluster categories.

CAUTION

This project describes activities that use potentially hazardous materials including black powder granules, pyrogen dips, and acetone. Such activities should be performed with caution and with appropriate supervision. Follow manufacturer's recommendations. Safety procedures should be followed including wearing safety gear and eye protection. Good ventilation should be provided when using acetone or similar liquids.

Table of Contents

Introduction

In 2018 the B cluster event was chosen for competition at NARAM 60. This event has not been frequently held, so a large amount of information does not exist for the design of 5-B cluster rockets.

This Research and Development report will cover a design methodology used to develop a 5-B cluster rocket that performed well at the NARAM 60 competition and the lessons learned in that development process. This report does not focus on a single aspect of the design, but rather the key areas that the author believes contributed to an optimized altitude design.

The majority of the technical work done in this report was done using simulation tools that are available free for use to individuals. Links to those tools are included in the appendix to this report.

Objective

The objective of the research described in this document was to find optimal solutions for various aspects of cluster rocket design.

The areas investigated are:

- Motor configuration
- Aerodynamic design
- Drag vs. Weight
- Motor Retention and Venting
- Ignition

Summary of Previous Research

In 1997 Dan Wolf published an article in Sport Rocketry's May/June issue on Cluster rocket design. Mr. Wolf showed two different cluster configurations for a 6-C cluster and concluded that the tightly packed pentagon shaped cluster would provide superior performance. He also pointed out that the cluster of this many motors would require fins with large surface area to stabilize the rocket.

The following year Wally Etzel published an article in Sport Rocketry's January/February issue on his preferred configuration for a 6-C cluster model. Mr. Etzel utilized a 3 and 3 configuration where he integrated the fins on the rocket into the pods and formed pod fairings that tapered from the center body to the top of each pod. This is similar to the final pod/fin construction that I will describe below.

The Pod Bay Doors team published a series of reports on cluster ignition for NARAMs 49-51 from 2007-2009. The results of their work concluded that the Quest Q2 and Q2G2 igniters performed better than the Estes igniters. Unfortunately neither the Quest Q2 or Q2G2 igniters are available for purchase now, so I investigated improving the available Estes product.

Chris Flannigan presented a report on development of ignitors for cluster ignition last year at NARAM-60. His ignitor work was much more comprehensive than the work that was done here during the same time frame. Mr. Flannigan concluded that the existing commercial ignitors were inadequate for his task of cluster ignition and thus designed his own ignitors. Where Mr. Flannigan designed and built his own ignitors, the focus of that portion of this research paper was to simply augment the existing Estes Starters to provide a reasonably robust ignition source for the cluster.

Equipment and Facilities

The equipment and facilities used for this report were:

- Lenovo Thinkstation Computer
    - OpenRocket Simulation Software
    - PTC CREO 3D Modeling Software
    - Flow Illustrator (Web based flow tool)
    - SIM FLOW Computational Fluid Dynamic Software
- XYZ Davinci 1.0A 3D printer
- Estes Pro Series launch controller
- Whip clip
- Motorola Moto G4 (for video recording)

Research Approach

This research done for this report was divided up into four sections.

Cluster configuration, aerodynamic design of motor pods, motor retention and porting, and motor ignition. The data and results for each of these topics will be presented in the respective research section. The rocket performance was driven by the balance of mass and drag. The factors studied that impact the rocket performance due to drag were the cluster configuration and aerodynamic design of the motor pods. The configuration, motor pod design and retention means effected the overall mass of the rocket. The aspects of the study that impacted reliability of the rocket were the motor retention and venting, and the igniter study. The Cluster configuration, and motor pod aerodynamic studies were conducted using numerical modeling on a PC, whereas the motor ignition portion was physical testing of the prototype igniters. The results of each section of study were fed into the total system simulation to predict the altitude and stability performance of the entire 5-B cluster rocket.

Cluster Configuration

The drag of the rocket was determined by two of the aspects of this study, the frontal area and the coefficient of drag. The first step in the design of the cluster rocket was to determine which cluster configuration would provide the least frontal drag. The reduction of frontal drag is important as it is the main altitude robbing aspect of the design, apart from gravity. The drag that the rocket experiences in defined by the following equation.

$$F_{drag}=Cd*\rho*A*0.5*V^2$$

The frontal area that a rocket presents to the fluid flow is directly proportional to the drag force produced as the rocket moves through the fluid. Conversely, any reduction to the frontal area of the rocket will result in a proportional reduction in drag force experienced by the rocket. Since the motor selections for a B motor are limited and air starts are not allowed in cluster competition, there is no way to spread out the force imparted by the motors over time. The thrust you get is what it is, and the best one can do is to reduce the factors available to limit the drag force acting on the rocket. The air density is the same for all of the competitors on a given day, so, what we have left are the frontal area and the coefficient of drag.

The determination of the most efficient cluster configuration is then a simple matter of determining which configuration will have the least effective area. For this study, 4 cluster configurations were considered; a fully shrouded cluster, a pentagonal arrangement, a cross arrangement, and a trapezoidal arrangement. The pentagonal arrangement is the tightest packed configuration. In other words, the radius from the center of the cluster to its outermost edge is the smallest of the three cluster configurations. Since the pentagonal configuration is the tightest packed configuration, the shrouded configuration consists of the pentagonal configuration with a thin tube placed around the cluster touching the outer edges of the cluster. An issue with a five motor cluster, is that the tightest packed arrangement does not have a motor at the center, so a body tube has to be mounted over the center of the cluster. The same case follows for the trapezoidal cluster. The profiles of the three exposed clusters are shown in Figure 1. It is apparent that while the cross configuration can use, the center motor as the rockets body tube, this is not possible with the pentagon and trapezoid configurations. Figure 1 shows the additional area taken up by a BT 20 tube mounted above the cluster as the body tube.

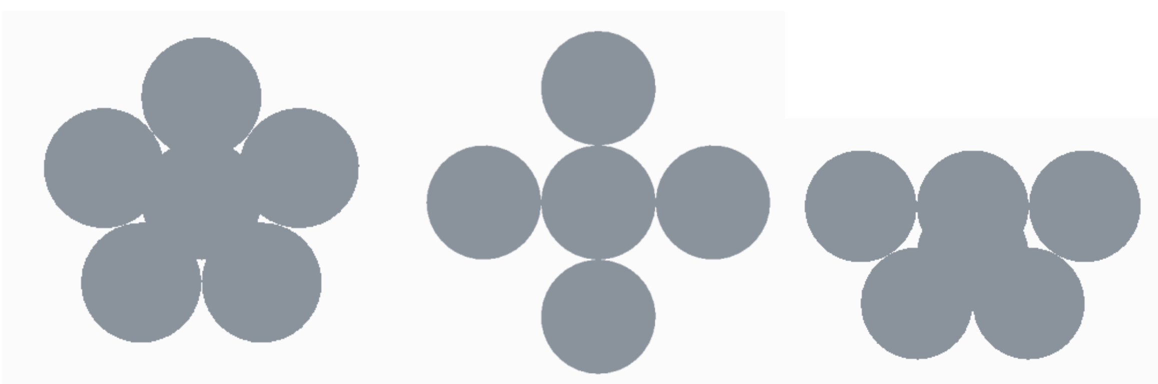


Figure 1

Table 1 shows the frontal area calculations for each of the four cluster configurations. These calculations are based on using a standard T-20 tube size for the motor tube, and vellum for the shroud tube.

Configuration	Frontal Area (mm^2)
Fully Shrouded	1099
Pentagon	838
Cross	737
Trapezoid	752

Table 1

The fully shrouded design has the largest frontal area, followed by the pentagonal, then trapezoidal, and finally the cross arrangement. The cross configuration area is 33% smaller than the fully shrouded configuration, 12% smaller that the pentagon configuration, and 2% smaller than the trapezoid configuration. Based on this information, the cross configuration of a central T-20 body tube with four external pods at intervals of 90 degrees was chosen for the 5-B cluster design.

Aerodynamic Design of Motor Pods

Once the frontal area portion of the drag equation was locked in, the next step was to work on optimizing the coefficient of drag of the rocket. The components of the rocket that would drive the over-all Cd of the rocket are the nose cone, transition from center body tube to pods, and fins. There are numerous studies that have delved into the effect of nosecone shape and fin shape on drag. Since this is so well documented, an elliptical nosecone, and elliptical-airfoil fins were chosen for the design. Since it was decided early on that the model would use a 3D printed nose cone and fins, the design was not locked in to existing parts and aspect ratios for the nose cone. The aspect ratio vs. weight of the nosecone could be optimized in OpenRocket and then custom made for the model. In order to effectively optimize the aerodynamic design of the body tube to pod transition, the maximum velocity of the rocket has to be predicted. This was accomplished using OpenRocket. Since the author did not know that a beta version of OpenRocket existed which supported pods, two models were created to simulate the performance of the rocket. The first design used a single tube equivalent of the motor cluster that had the same cross-sectional area as the motor cluster. This was used for initial velocity estimations, length to weight optimization of the shroud, and rocket stability calculations. The second model utilized the tube fin feature in OpenRocket along with a fudge factor for drag which will be covered later in this report, and was just used to estimate altitude of the competed design but not stability.

The initial direction of this design was to create the most efficient transition from the body tube to the pods, and the comparison to the other popular construction method of ogive nosecone terminated pods was performed post NARAM 60. The two pod designs that were considered are shown below in Figure 2. These two pod designs will be referred to as swept aerodynamic and ogive designs.

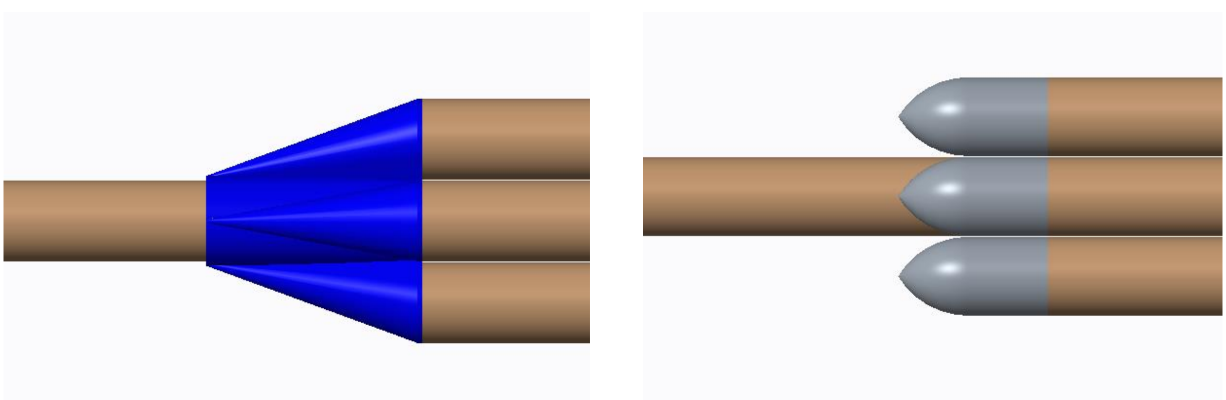


Figure 2

The rocket was modeled in the first method with a transition between the body tube and the equivalent cluster tube, and the mass values were over-ridden to actual part values to estimate the maximum velocity and time varying velocity of the rocket. Using this method and the optimization function in

OpenRocket, the optimal transition length vs weight was determined to achieve a maximum altitude. The length of this transition and the velocity information was then used to perform Computational Fluid Dynamic simulation of the rocket structure. (In the end the mass of the optimal printed transition was almost identical to that of four 18mm balsa ogive nosecones.)

This first pass optimization was compared to the shrouded design in OpenRocket. One nice feature of OpenRocket is that in addition to the normally simulated characteristics like velocity, acceleration, altitude, and dynamic stability, one can also plot the total drag force on the rocket vs time. Running these two models in OpenRocket showed that the shrouded cluster design would experience a drag force at its maximum velocity of 6.2N while the open cluster estimation only experienced a maximum drag force of 4.5N. Adding in a conservative amount to account for the added skin friction drag produced a drag on the open cluster rocket of 4.85N. The effect of the fully shrouded design is the equivalent of adding 138g of extra mass to the rocket at peak velocity, and results in a 20% decrease in peak altitude. Another byproduct of this simulation was to change the surface texture of the parts that were to be printed. The simulations showed that the skin friction drag due to surface imperfections was negligible compared to the cross section and shape optimizations. That is not to say that a highly polished surface would not have improved the results somewhat. The simulations showed that the surface finish on the parts in question would have changed the apogee height a few feet, which was small compared to the tens to hundreds of feet achievable through shape optimization.

These numbers are based on the approximations used to model the rocket in open rocket. In order to see the true effect of a particular design on drag, more advanced tools were required. Two different tools were used to simulate the fluid flow around the rocket and the drag force imparted on the airframe by drag.

The first tool used gave a quick estimate of the flow around a 2D structure. This is a web based tool called Flow Illustrator. Flow illustrator is a simple tool that makes quite a few assumptions and should be used with caution. In order to use flow illustrator, the user creates a 2D image of the cross section of interest. The size of this image is limited and important. Flow Illustrator uses the following relationship in its calculations: $Re=U^* L /v$

Where Re is the Reynolds number, U is the velocity far upstream from the object, L is the distance in physical space from the top to bottom of the picture, and v is the kinematic velocity of the fluid. U is the velocity of the rocket in this case, as our frame of reference is with the rocket not fixed on the ground. This tool was used purely to identify points where the air flow around the rocket would split or stagnate resulting in increased drag. No numerical data was taken from these visualizations, they were only used to get a design in the right ballpark quickly before using more accurate and time consuming CFD tools. Different design approaches could each be run in the Flow Illustrator tool in a few minutes compared to hours in the full blown CFD tool.

Once a design was identified as a good candidate a more advanced CFD tool was used to more accurately simulate the flow and drag on the rocket. The tools used for this purpose was Sim Flow.

Sim Flow is a full Computational Fluid Dynamic package that can simulate steady state as well as transient flow around an object, including accurate simulation of turbulence and the force imparted on the structure subjected to the flow. In order to do this however, the user has to define a 2-dimensional or 3-dimentional mesh of the fluid around the object, define the appropriate boundary conditions, run the simulation, and then post process the data. Fortunately all of these things can be done in Sim Flow after the import of the 3D structure of the object. The 3D geometry was created in PTC CREO. Individual parts were created for each component, and the rocket was virtually built up in an assembly file. The assembled geometry was then exported for use in Sim Flow. Sim Flow is a GUI and post-processing tool utilizing the OpenFOAM solver family. For each of the two designs being simulated, steady state and transient models were run. The data simulated and analyzed for these cases was flow velocity, pressure magnitude, flow vectors, and drag force exerted on structure.

The solver used for the steady state simulations was the simpleFoam solver, and the RANS k-w SST model for turbulence. RANS stands for Reynolds-averaged Navier–Stokes equations. RANS Computes Reynolds stresses though Reynolds decomposition: where an instantaneous quantity is decomposed into its time-averaged and fluctuating quantities. The k-ω SST model is a two-equation eddy-viscosity model, usable all the way down to the wall through the viscous sub-layer. This model exhibits good behavior in adverse pressure gradients and separating flow, which is ideal for the cases being studied here. (For those unfamiliar with CFD, the k factor is turbulent kinetic energy which determines the energy in the turbulence. ω is the specific dissipation, which determines the scale of the turbulence. The SST designation stands for shear stress transport. The SST formulation switches to a k-ε behavior in the free-stream and avoids the k-ω problem of exaggerated sensitivity to the inlet free-stream turbulence.) Figure 3 shows the meshes used for the steady state simulations.

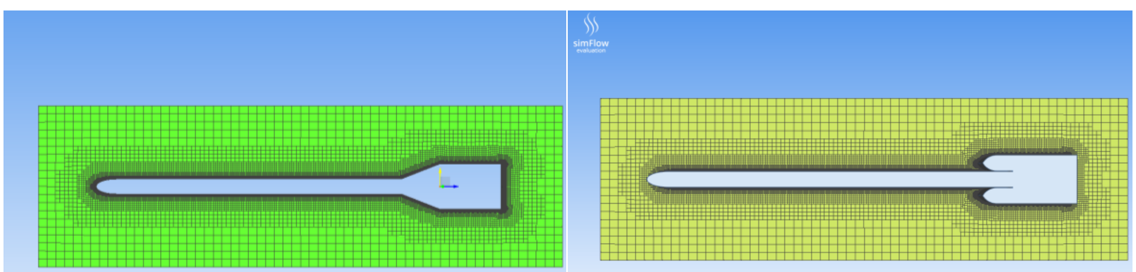


Figure 3

Figure 4 and 5 show representations of the fluid velocity results for the steady state simulations at the maximum velocity derived from the OpenRocket model. Notice the region of stalled air in front of the ogive nose cone terminated pods. What this means is when the flow achieves a steady state, a volume of air is being dragged along with the rocket. There is a positive and negative aspect to this. The positive behavior is that the flow around this region has become more streamlined. The negative aspect is that the mass of air actually acts like added rocket weight.

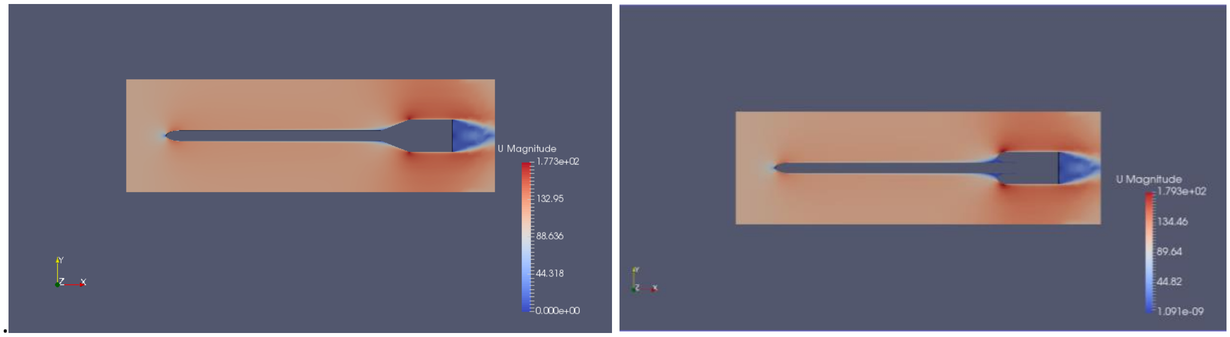


Figure 4

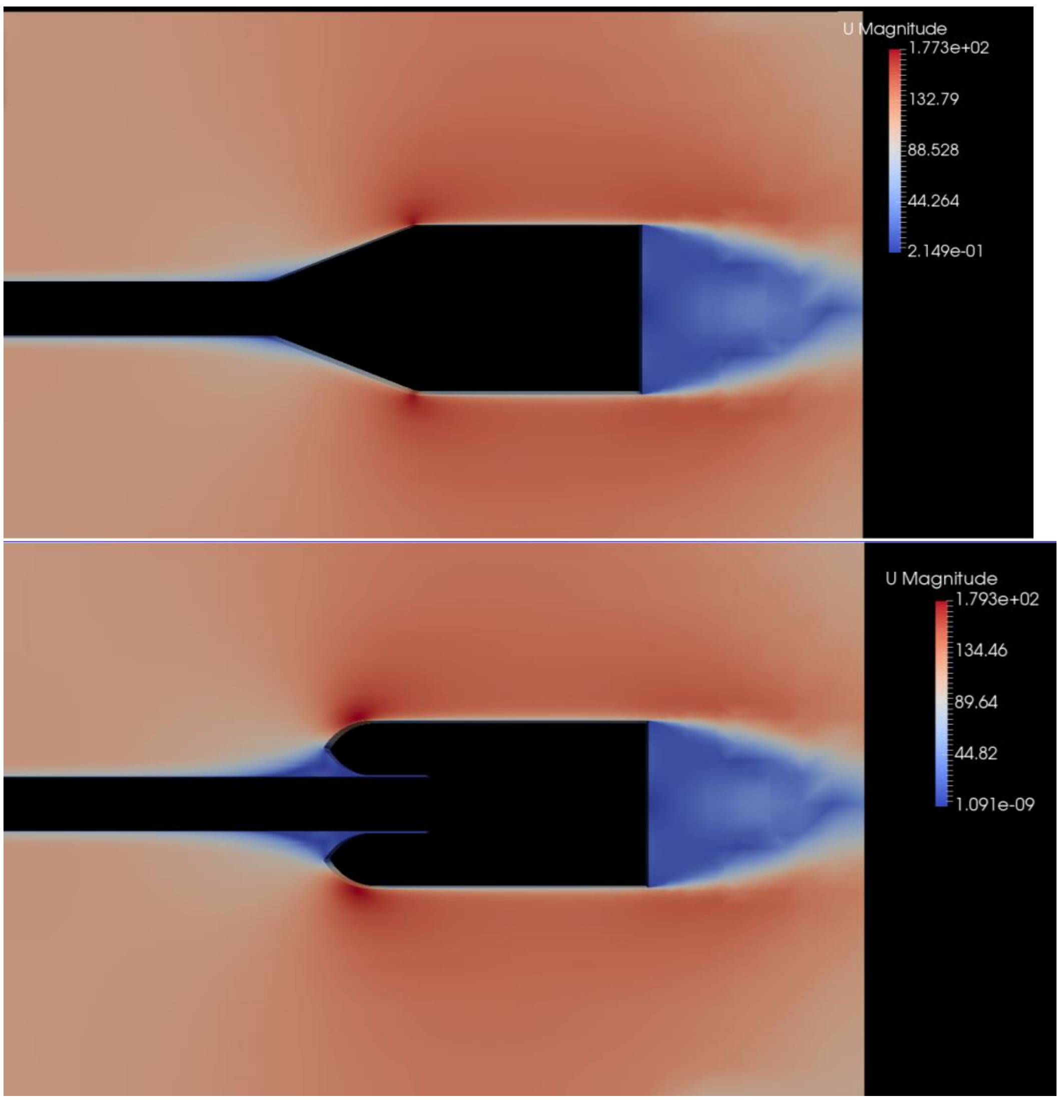
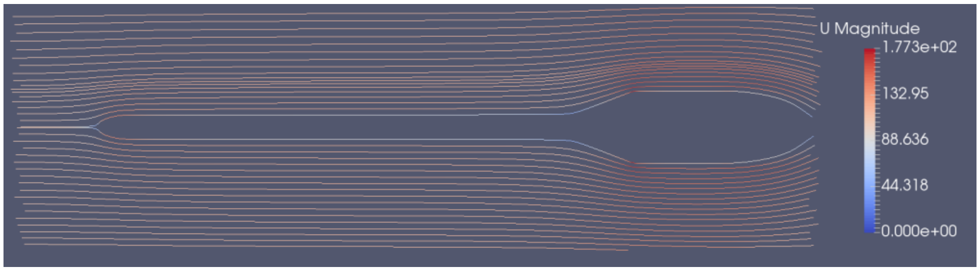


Figure 5

Figures 6-8 depict the flow lines for each simulation as well as the velocity vector plots which better help to show the actual movement of the air in the steady state for these two models.



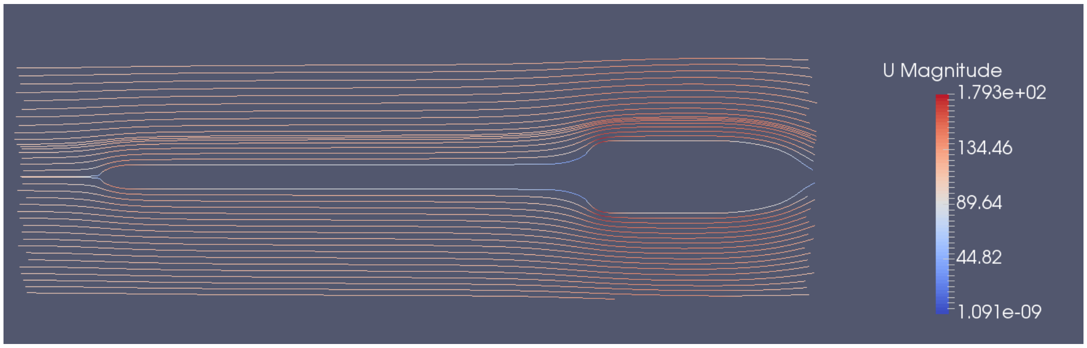
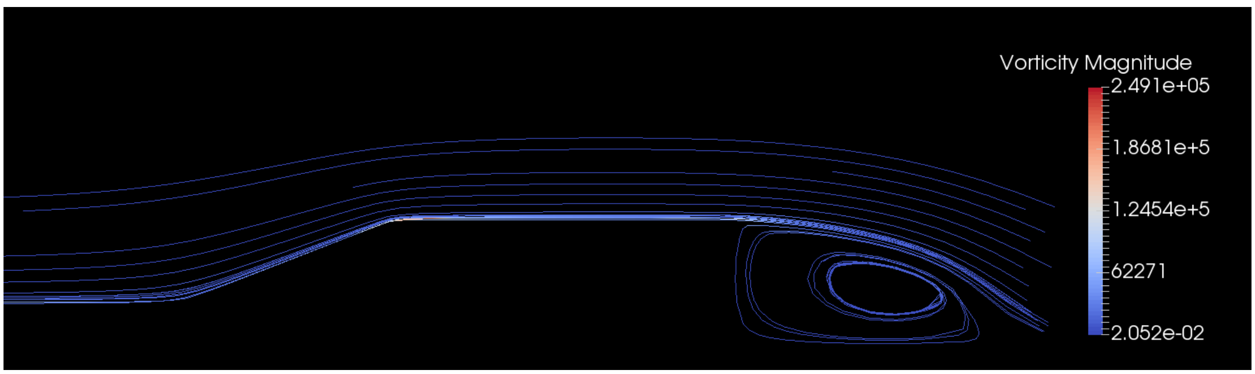


Figure 6



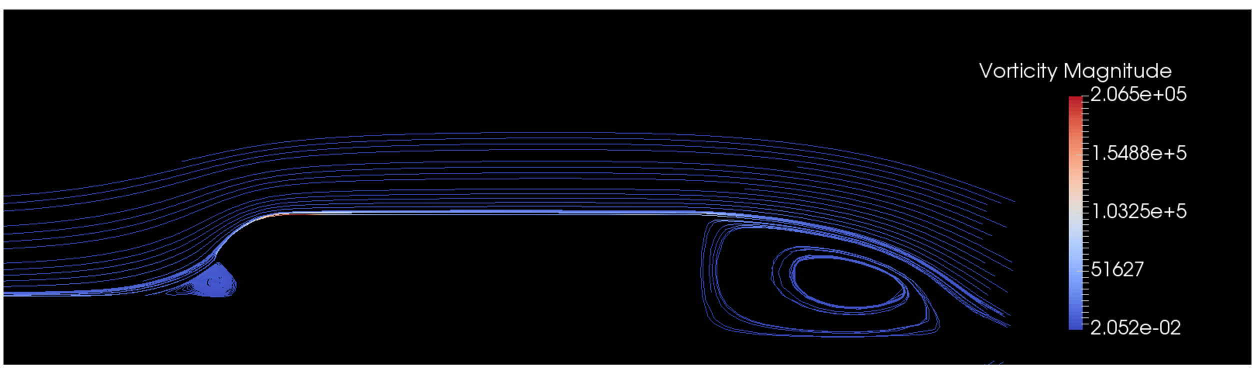


Figure 7

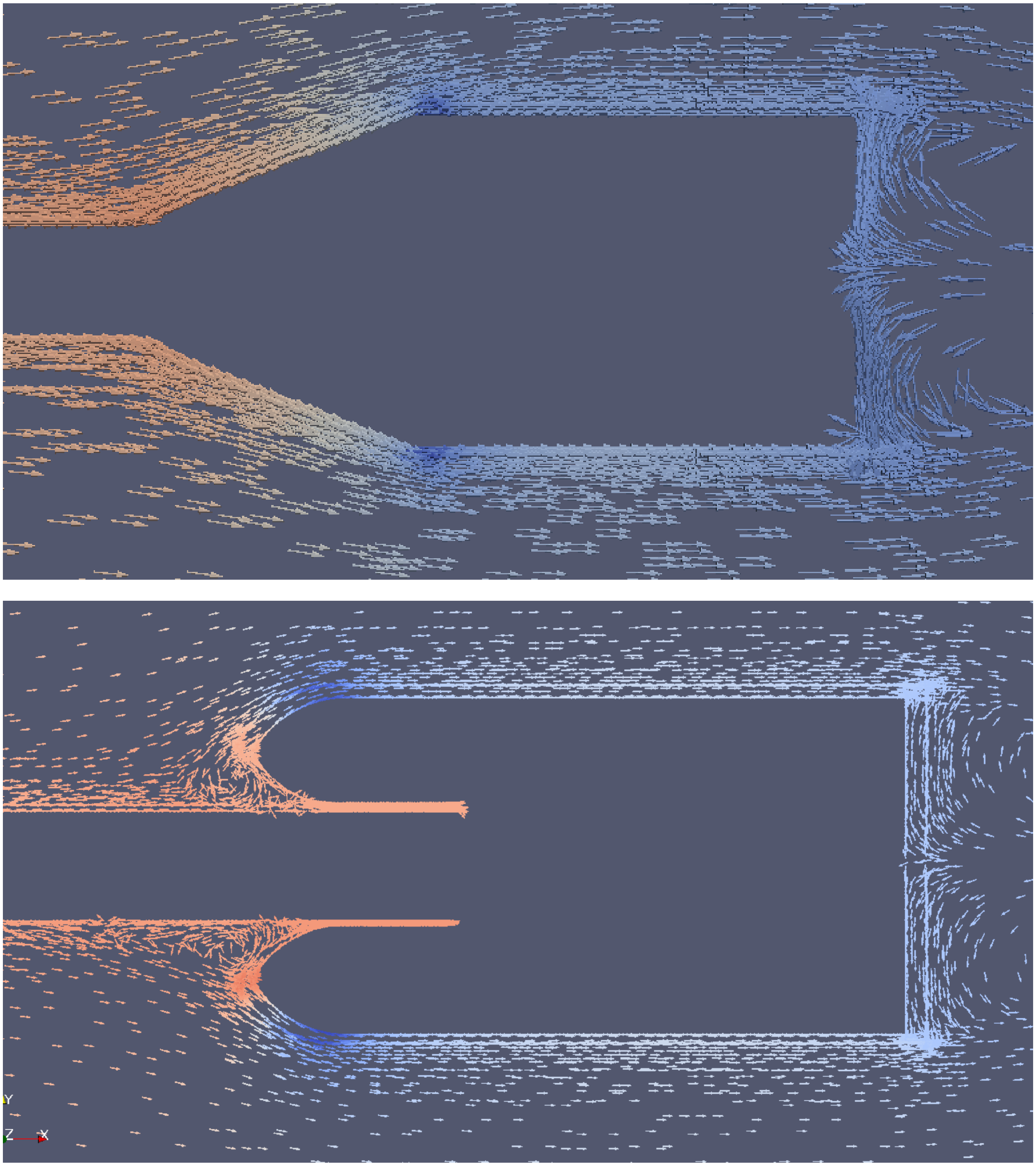


Figure 8

Looking at the two simulations, the end results do not look very different between the two designs in the steady state and this is bore out in the drag force experienced by each of the structures. The total drag force measurement for each model for both the steady state and the peak velocity of the transient simulation are shown in Table 2.

	Steady State Force (N)	Transient Force (N)
Swept Aerodynamic	2.95	2.26
Ogive	3.08	4.27

Table 2

In the steady state, the drag of the two designs is nearly identical, only differing by 4.2%. Unfortunately, with the short burn of model rocket motors, the rocket is never really in a steady state condition, with the velocity either ramping up or down. Therefore to truly see the effect of a given design for a 5-B cluster, transient analysis of the fluid flow is required. Figure 9 shows the fluid velocity magnitude colormap for each model at the maximum velocity time step. It can clearly be seen, that when the ogive design is not settled into a steady state condition, the area of turbulence in front of the pod nose cones is significantly larger than that of the swept aerodynamic design. This results in a higher drag for the Ogive design. At the peak velocity time step, the Ogive design has a drag force of 4.27N where the swept aerodynamic design has a drag force of only 2.26N

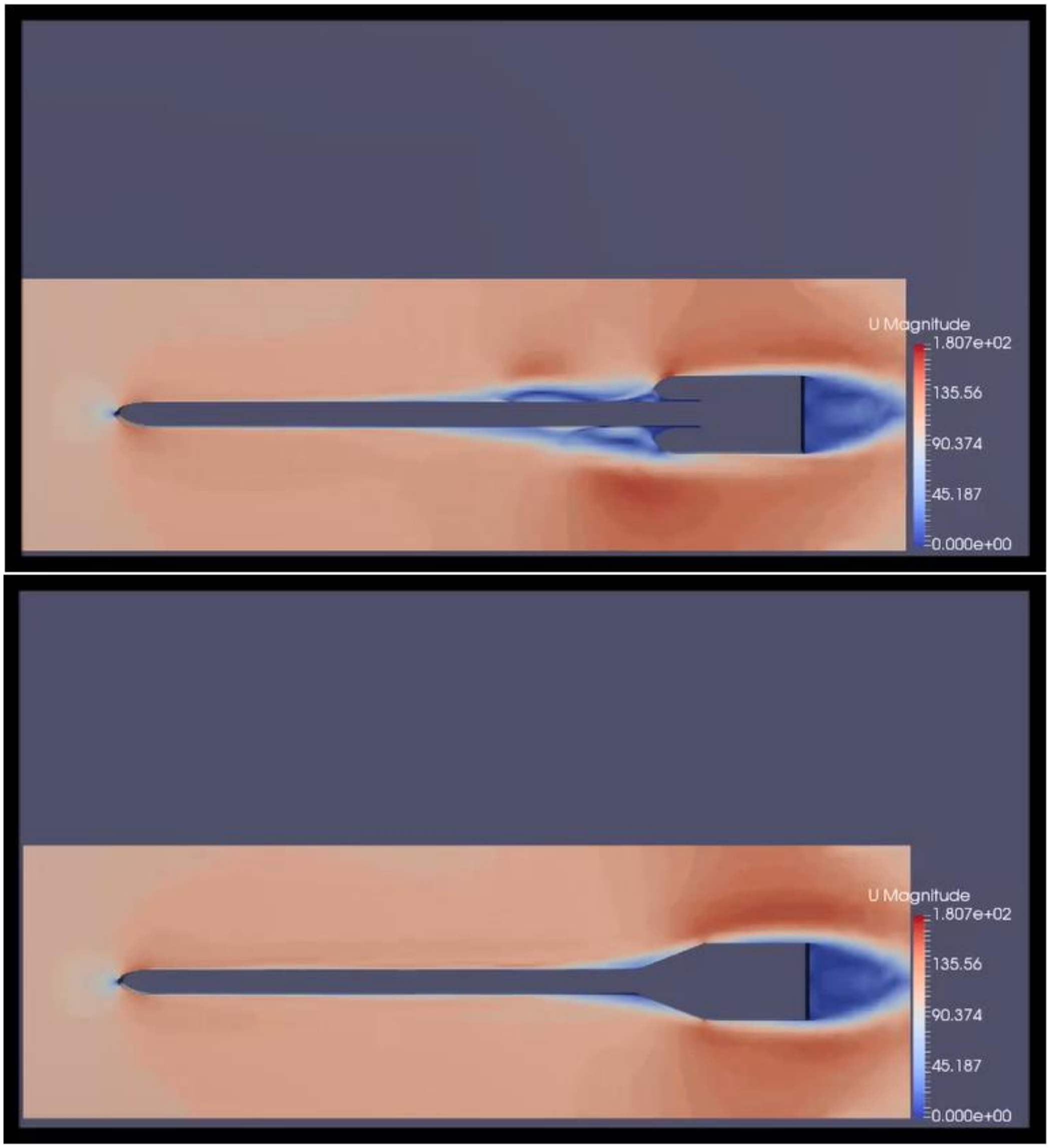


Figure 9

Now that more realistic drag values have been calculated, the second OpenRocket model using the tube fins is tweaked, until the drag profile predicted by OpenRocket matches that calculated in Sim Flow.

Using the altitude and temperature data for the actual launch site and date of NARAM 60 resulted in a predicted altitude of 536m.

The actual flight results from of this optimized design at NARAM 60 was an altitude of 543m. The simulated data matched the actual flight data to within 2%.

Motor Retention and Venting

During the 5-B cluster competition at NARAM-60, 22% of the competitors had at least one motor eject. In order to prevent this failure mode, a lightweight motor retainer was designed and printed. The motor retainer is shown in red in figure 10. The retainer provided retention around the entire center motor, and over an angle of roughly 60 degrees of each outboard motor. The retainer is attached to the body tube with two #4-40 screws treaded into a low drag mount between motor pods.

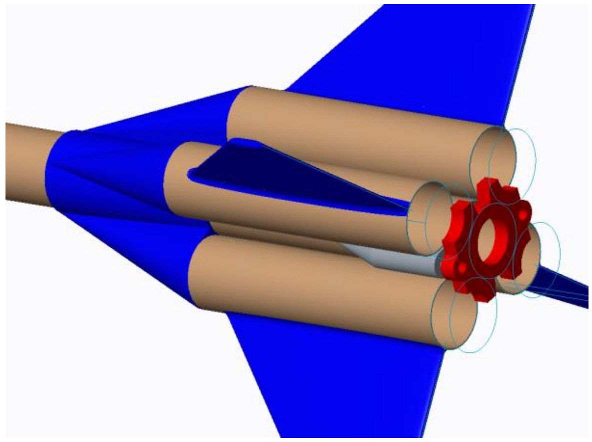


Figure 10

Traditionally venting of ejection gasses is normally done through a single hole in each pod radially oriented about the body tube. Observations of this type of ejection gas venting showed that rockets using this method would often jerk, or wiggle off axis momentarily when the pod motors ejected, or when a booster motor burned through. In order to avoid this altitude robbing phenomenon, each pod was designed with two vent holes oriented such that the axis between them was tangent to the body tube and perpendicular to the pod axis. This configuration can be seen in Figure 11. These symmetric vents allowed for the gasses to eject in opposite directions from each other resulting in zero net torque on the rocket. With this method it does not matter if all of the motors ejected at the same time or not as symmetry was not guaranteed with pairs of motors, but with each motor ejection.

Figure 11

Motor Ignition

As was stated earlier in this report, since the author did not poses quest igniters and did not want to manufacture home-made igniters, the goal of this portion of the research was to come up with a treatment for existing Estes Solar Starters that would more reliably light all of the motors in the cluster.

To this end, a small experiment was set up, with four groups of igniters tested simultaneously in parallel with the same launch controller. The first step in this process was to sort Estes igniters by resistance. Once enough igniters were identified with the identical resistance, they were coated with one of three different types of treatment. (One group was left unmodified as a control group.) The three different treatments chosen were two off the shelf pyrogen dips, and one homemade recipe. The two off-the-shelf pyrogen dips were RocketFlite's Clusterfire, and MagneLite treatments. These treatments were applied to the Estes Solar starters per the manufacturer's instructions. The third treatment involved brushing lacquer nail polish onto the solar starter tip, then dipping the tip into FFFF Black Powder while the lacquer nail polish was still wet. The off-the-shelf treatments provided very consistent results, whereas the nail polish/black powder resulted in igniters that varied more in diameter and thickness.

The test setup for the igniter comparison consisted of an Estes Pro Series launch controller, a four-motor-whip clip, and a phone to record videos of the ignition of the igniters. Burn duration timing was then extracted from the video files using video editing software. An image of one of the tests is shown in Figure 12, and the results of the testing is shown in table 3.

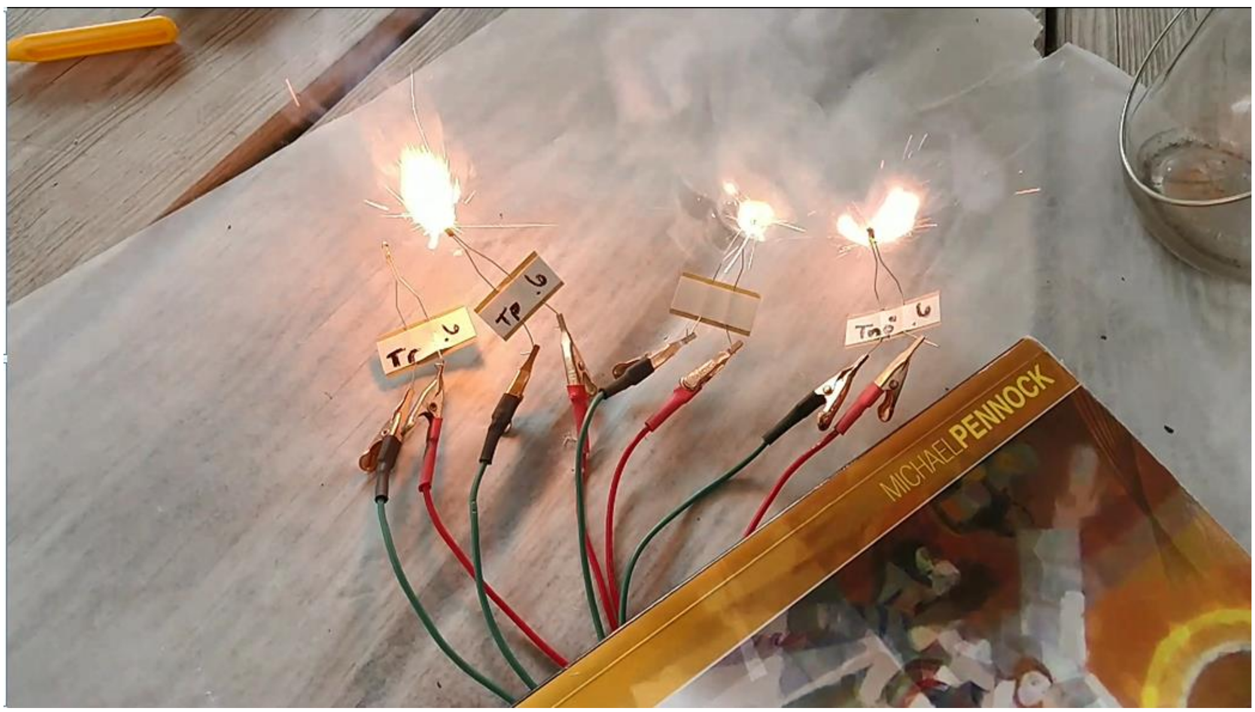


Figure 12

	Stock Estes	ClusterFire	MagneLite	Nail Polish/BP
Burn Duration (s)	Only glowed	.467	.375	.232

Table 3

As you can see from the data in table 3, the ClusterFire pyrogen had the longest burn time, followed by the MagneLite, then the nail polish/BP mixture. The untreated Estes Solar Starters never actually burned but only glowed in the testing. The ClusterFire burn duration exceeded the MagneLite by 24% and was twice as long as the nail polish/BP treatment. Figure 13 shows a great picture taken by Todd Schweim of all of the motors lighting on the pad at NARAM 60.

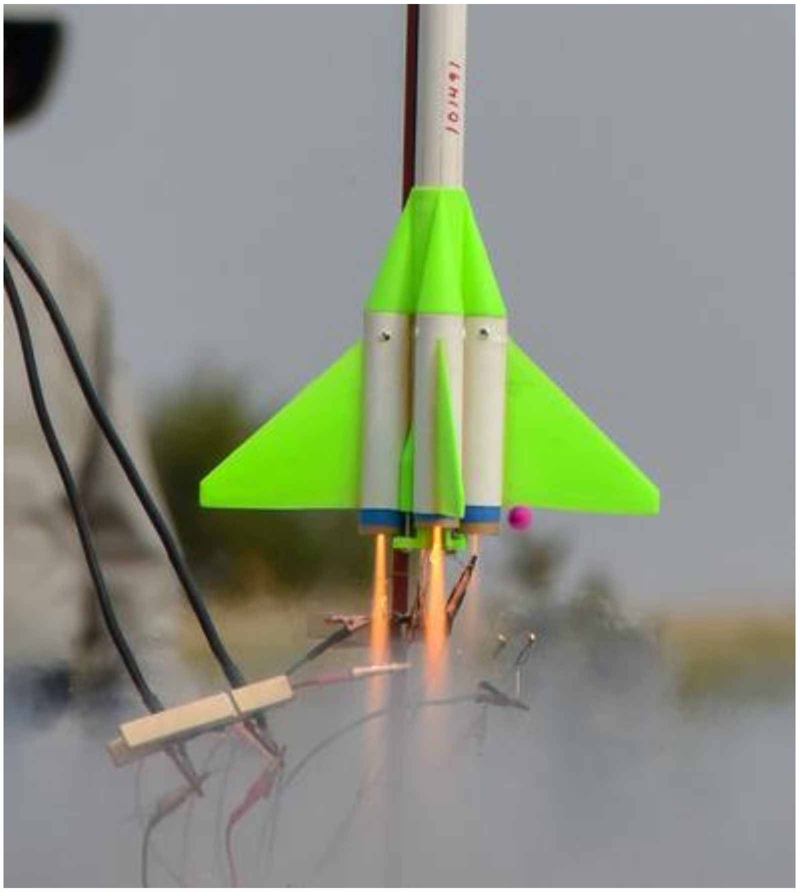


Figure 13

Conclusions

For each of the four areas studied in the report, an optimal or reliable solution was obtained. In the area of cluster configuration, the cross configuration with a single central motor with four outboard pods 90 degrees apart produced the smallest frontal area. Simulation in Open rocket and SimFlow resulted in a reduced coefficient of drag that reduced the peak drag force seen by the rocket by over 50% compared to the nearest competitive design. A motor retention method was devised that securely retained all five motors while minimizing weight, and a gas venting configuration was implemented that eliminated lateral thrust during pod motor burn-out or ejection. Testing showed that Rocketflite ClusterFire pyrogen coated Estes Solar Starters resulted in the longest igniter burn time by 24%. Results of actual launches correlated to within 2% to the results of the simulations run using the same conditions.

Project Cost

ClusterFire Pyrogen Dip	$42.95
Magnelite Pyrogen Dip	$38.95
Estes Solar starters	$13.16
3D Printer Filament	$22.95
T20-body tubes	$4.00
Engine block	$0.15
Parachute	$2.39
Total cost	$124.55

Further Work

Future planned work includes applying the same techniques to other cluster categories, a lightweight ejection means to open up longer delay times for small motor clusters, and further study into venting of ejection gasses to augment altitude.

References

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Appendix A - Software Used

- Open Rocket: http://openrocket.info/
- Flow Illustrator: http://www.flowillustrator.com/
- Sim Flow: https://sim-flow.com/