PAPER

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# High powered rocketry: design, construction, and launching experience and analysis

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**Abstract**

In this study, the nuts and bolts of designing and building a high powered rocket have been presented. A computer simulation program called RockSim was used to design the rocket. Simulation results are consistent with time variations of altitude, velocity, and acceleration obtained in the actual flight. The actual drag coefficient was determined by using altitude back-tracking method and found to be 0.825. Speed of the exhaust determined to be 2.5 km $s^{-1}$ by analyzing the thrust curve of the rocket. Acceleration in the coasting phase of the flight, represented by the second-degree polynomial of a small leading coefficient, have been found to approach '-*g*' asymptotically.

## 1. Introduction

High powered rocketry is a science that describes and predicts the motion of a rocket that uses a motor over a *G* impulse (>160 Ns) [1, 2]. In general, a single stage rocket encounters four different forces as it takes off [3]. The forces acting through the center of mass of the rocket are gravity and thrust forces, whereas drag and lift forces act through the center of pressure. Drag force arises from a number of effects, but acts opposite to the rocket motion. On the other hand, the lift force arises from air flow and acts on the surface of rocket perpendicular to the rocket motion. For vertical motion, the angle of attack is zero and hence the lift force [4]. The force of gravity changes as the mass of the system varies and the thrust force is seen by the rocket with its magnitude equal to the rate of change of momentum of the propellant mass: d(mu)/d*t*. Assuming propellant speed as constant, thrust force (*T*) is given by:

$$T = u\,(\mathrm{d}m/\mathrm{d}t) \tag{1}$$

where *u* is speed of the exhaust. Since gravity and drag forces act opposite to the motion of the rocket, the force of the rocket is given by:

$$F_{\text{rocket}} = u\,(\mathrm{d}m/\mathrm{d}t) - \mathrm{Mg} - (1/2)\,\rho v^2 A C_\mathrm{d} \tag{2}$$

where, *M* is the total mass of the rocket system at any instant, $\rho$ is mass density of air, *v* is speed of the rocket, *A* is cross sectional area of the rocket, $C_\mathrm{d}$ is drag coefficient given by [4]:

$$C_\mathrm{d} = \begin{cases} a + bMa^6 & \text{for } Ma < 1 \\ a + \frac{b}{Ma^2} & \text{for } Ma > 1 \end{cases} \tag{3}$$

where *a* and *b* are parameters which depend on the angle of attack; *Ma* is the Mach number, the ratio of speed of a rocket to that of sound i. e. $Ma = v/v_\mathrm{s}$. If $M_0$ is the initial total mass of the rocket system, then $M = M_0 - t\,\mathrm{d}m/\mathrm{d}t$. Assuming d*m*/d*t* as constant, equation (2) can be written as:

$$(M_0 - t\mathrm{d}m/\mathrm{d}t)\mathrm{d}v/\mathrm{d}t - v\mathrm{d}m/\mathrm{d}t + ({}^1/_2)\rho v^2 AC_\mathrm{d} - u\,(\mathrm{d}m/\mathrm{d}t) + (M_0 - t\mathrm{d}m/\mathrm{d}t)g = 0. \quad (4)$$

The purpose behind the building of this rocket was to compete in the First Nation Rocket Launch. The parameters of this competition were to construct a high powered, dual deployment (having two parachutes), single stage (having one engine) rocket and launch it to a certain height, and successfully recover in a flyable condition.

## 2. Materials

The construction of this rocket started with the 'Level 2' kit from Apogee Rockets [5]. It mainly consists of tubes made of G10 fiberglass with 4 inches (4″) in diameter. The nose cone is an ogive style that is 20″ long including the coupling shoulder. Connecting to this is a 20″ long main airframe tube that houses the main parachute. The main parachute is 48″ in diameter, made of nylon material. The e-bay, which is 9″ long and contains all the electronics, couples the main airframe tube to the aft airframe tube. The details of the e-bay will be covered later. The aft airframe tube is 31″ long which houses the drogue parachute and motor mount. The drogue chute is 18″ in diameter, made of nylon material as well. The rocket has four fins of a straight taper design and are mutually perpendicular. The fins connect through vertical slots, near the bottom of the aft airframe tube, to the motor mount.

The motor mount consists of a 12″ long tube, 54 mm in diameter, with a centering ring on both ends. An Aeropack 54 mm retaining ring, with a coupler, was used for converting it to a 38 mm engine retainer. The reasoning behind this was to meet the requirements of the rocket competition that we competed in.

The e-bay consists of a 3.9″ diameter tube with coupling ring of 4″ diameter that centers it between the main and aft airframe tubes. Two threaded rods run inside the length of the e-bay with washers and nuts on each side to hold them in place. A wooden sled rides on the rods, carrying the electronics of the rocket on its surface. The sled is held in place with nuts on each end. The electronics consist of a PerfectFlite StratoLoggerCF altimeter, connected to a 9 V battery with a rotary switch. A four pin connector comes off the altimeter and connects to wiring that is run within the e-bay. Two wires run through the bulkheads on both ends of the e-bay. These wires connect to terminal blocks that the ejection charge ignitors are hooked into. On each end of the e-bay are ejection canisters. These canisters are 0.5″ diameter PVC pipe caps mounted with bolts through the base.

Miscellaneous hardware included in the kit were: a 25-foot piece of 9/16″ wide nylon shock cord, eyebolts, washers, nuts, standard size rail buttons, two 12″ square Nomex parachute protectors, removable plastic rivets, threaded rods for the e-bay, and the wooden components of the e-bay sled.

Some of the components that were not included in the kit were: altimeter, 9 V battery, rotary switch, wires, ejection charge canisters, terminal blocks for the ejection charge ignitors, sheer pins, 54 mm engine retaining ring, 54–38 mm adapter, epoxies, wood filler, glues, and paints.

## 3. Methods

The construction started with the motor mount. The centering rings were sanded so that they fit nicely over the motor mount tube, inside the aft airframe tube. The motor mount tube was also sanded where the centering rings would sit. Sanding is necessary wherever the fiberglass parts are epoxied. The position of these rings was determined by the fin slots, so that the fins could be inserted and sit between the centering rings. The centering rings were then connected to the motor mount by using liquid epoxy.

The centering rings had to be sanded flat on one edge, allowing them to slide past the backside of the lower rail button. A ¼″ hole was drilled into the upper centering ring for an eyebolt. This eyebolt was installed with a washer and nut. Epoxy was used to cover the bolt threads and nut. This ensured that it would be permanently installed. The shock cord attaches to this eyebolt. The motor mount was then prepared for the installation of the motor retaining ring. The end of the tube was sanded where this ring would sit until the retaining ring fit snugly. Liquid epoxy was used to secure the engine retainer.

The next part to be worked on was the e-bay. To begin, the bulkheads on each end needed to be constructed from two different diameter disks.

One of these disks is smaller as to fit inside the e-bay tube, while the other has the same diameter as that of outer surface of the e-bay to prevent the bulkheads from falling into the e-bay. One side of each disk was sanded and liquid epoxy was used to combine the disks. Clamps were used to ensure that the disks were closely fixed to each other.

Once the epoxy was cured on the e-bay bulkheads, a ¼″ hole was drilled on each bulkhead at the center. These provided a place to install the eyebolts for the shock cord. The eyebolts were installed with a nut then epoxy was applied over the threads to ensure a permanent installation. Two more ¼″ holes were symmetrically drilled into each bulkhead, along its diagonal, on either side of the center hole such that the holes on the two bulkheads are aligned. This is where the threaded rods insert to house the electronics sled. The sled consisted of four pieces of balsa wood that fit perfectly together to form a platform on two legs with holes for the threaded rods. Liquid epoxy was used to hold them all together.

In order to install the coupling ring, a 3″ wide middle section of the surface of the e-bay and inner surface of coupling ring, approximately 2″ wide, were sanded around the circumference. The coupling ring acts as a spacer between the main and aft airframe tubes. Liquid epoxy was used to secure this ring on the outer surface of the e-bay. After all the epoxy was cured, the components of the e-bay were test fitted to ensure correct positioning. This included inserting the threaded rods through both bulkheads with the electronics sled installed.

Coming back to the aft airframe tube: two more holes, separated by 20″, were drilled in line with each other vertically down the tube, the bottom one being a few inches from the base. These are meant for the rail button posts to be inserted into. As the rocket ascends, atmospheric pressure decreases but pressure inside the rocket still remains high. Therefore, an additional 7/16″ hole was drilled between the rail button holes to allow pressure equalization.

The motor mount was test fitted into the aft airframe tube to determine the location of the centering rings inside the tube. These were marked and the motor mount was removed. Hand sanding followed on the inner surface of the aft airframe tube where the centering rings would lay. The outer surface of the rings was also sanded along with the outer surface of the motor mount where the fins would attach. Epoxy was applied to the furthest centering ring location first, then the motor mount was inserted halfway into the rocket. This allowed epoxy to be spread on the location of the second centering ring without smearing it all off. The motor mount was fully inserted, positioned, and allowed time to cure.

Preparation of the installation of the fins follow. The fins were sanded all over to rough up the surface. The fins were installed one at a time. The bottom of each fin would get coated in liquid epoxy before being inserted into its slot in the airframe. Liquid epoxy would also be applied where the fin touched the slot in the airframe for extra support. Aligning by eye and holding the fin straight for several minutes, the epoxy was allowed to partially cure to remain in the correct position. The same procedure was repeated for all the fins and finally allowed to cure completely. Once cured, epoxy putty was mixed up for the fin fillets. Rolling the putty first into a ball, then stringing it out into sections as long as the width of the fins before laying it on the airframe. The putty was then pushed into where the fins meet the airframe tube. This putty was then worked into a rough shape of the fillets. Wetting a finger and running it down the length of the fillets helped shape them into a smoother form. The putty was allowed time to cure.

Sand paper was wrapped onto a ½″ wooden dowel. This provided the perfect shape to fit into the fillets and smooth them out evenly. Both sides of each fin needed to be meticulously sanded as smooth as possible. After this sanding the fillets were still in a rough form, but much more even than before. Wood filler paste was then watered down into a paintable viscosity. A small paintbrush was then used to cover the fin fillets with this paste, making sure to coat farther up the fins and down the airframe. This was allowed time to dry. The ½″ wooden dowel was again used briefly to help sand the fillets smooth. Then a sanding block was used to hand sand the edges of the fillets. Most of the wood filler was sanded off, but just enough was left to provide a smoother transition for the fillets. The use of wood filler here is to just give the fillets more aesthetic appeal. In other words, it does not provide any structural support.

Epoxy putty was again mixed up. It was again rolled into a ball and then strung out into a long cord. This was used on the bottom of the rocket where the centering ring meets the inner surface of the aft airframe tube. Pushing it around and then smoothing with a wet finger sets it into place. The putty provides extra support for the motor mount. This was allowed time to cure.

Moving to the nose cone, it was prepared for the installation of the bulkhead. A ¼″ hole was drilled in the middle of the bulkhead and an eyebolt was installed with a nut. Epoxy putty was used to secure the nut on the eyebolt permanently. Since the bulkhead fits freely within the nose cone, a little shelf had to be made. Epoxy putty was mixed up, rolled into a ball, and strung out. This was then placed into the inner circumference of the nose cone and pushed into place. The bulkhead was immediately pushed into this putty. Liquid epoxy was then mixed up and applied on the top of the bulkhead where it meets the inner wall, further increasing the structural support. Since the nose cone was cast from fiberglass, there was a seam where the resin protruded. This seam was removed using the blade of the X-ACTO knife to scrape away any protruding material leaving a smooth finish.

Going back to the e-bay again: wires were measured out and installed inside. A pair of wires runs to both sides of the e-bay for the ejection charge ignitors. Clips were used to hold the wires in place and a simple four-pin connector was soldered on the wire leads. Holes were drilled into both bulkheads for the wires to pass through. Liquid epoxy sealed the wires in the holes. Terminal blocks and ejection charge canisters were next laid out for their positions on the e-bay bulkheads and marked. A small area was sanded for each of the components to be installed. For each of the two ejection canisters, a small hole had to be drilled for the bolt that runs through the bottom. Nuts securing the ejection canisters were installed. Liquid epoxy was then used to secure the terminal blocks, the ejection canisters, and the threads of the bolts. The wires were cut to length and installed into one side of the terminal blocks.

The electronics were next laid out on the e-bay sled and their positions marked. The battery already had a predetermined location based on the sled design. One side of the 9 V battery rests on a protruding piece of wood to prevent it from moving. A bolt was used on the other side of the battery as a stop. A strip of Velcro was used to strap down the battery on its sides. This Velcro was epoxied onto the sled on the opposite side. The altimeter was then positioned at the end of the sled. Small holes were drilled into the sled marking each corner of the altimeter. Plastic posts were then epoxied into these holes to slightly raise the altimeter up off the sled. These posts also acted as a sheering point in case of a hard landing, preventing damage to the altimeter. The location of the rotary switch was also determined. It sat on the edge of the sled, so it could be accessed from a hole in the coupling ring of the e-bay. Epoxy putty was used to create a housing for the switch to be installed into. Two holes were drilled through the sled, pushing epoxy putty through, to make supports for this housing. The switch was then wired into the circuit. A ¼″ hole drilled into the coupling ring had two purposes:

a. It is the access for the power up switch for the electronics; a simple flathead screwdriver could be used to ‘arm’ the rocket on the launch pad
b. It is the vent for pressure equalization. This ensured that the altimeter would be receiving correct altitude readings throughout the flight.

The rocket was then put together and taped on all the connections to avoid movement of the airframes. Three vertical guiding lines, equispaced at an angle of 120 degrees along the circumference, were drawn on the rocket surface along its length. Two holes, a sheer pin and a plastic rivet hole, were drilled on each guiding line. The three sheer pins hold the nose cone in place until the main parachute is deployed and the three plastic rivets keep the e-bay secured to the main airframe tube. A 2-56 Tap & Drill set was used to create threaded holes for the sheer pins that connect through the main airframe to the nose cone. These were placed about an inch from the bottom of the shoulder of the nose cone on the guiding lines. Sheer pins were temporarily installed to hold the nose cone in and test the threads. The pins were then removed. Three more 5/32″ holes were drilled an inch above the bottom of the main airframe tube on the guiding lines. These holes go through the main airframe and into the e-bay allowing for the installation of removable plastic rivets that hold the e-bay in place during the flight. These were test fitted and then removed.

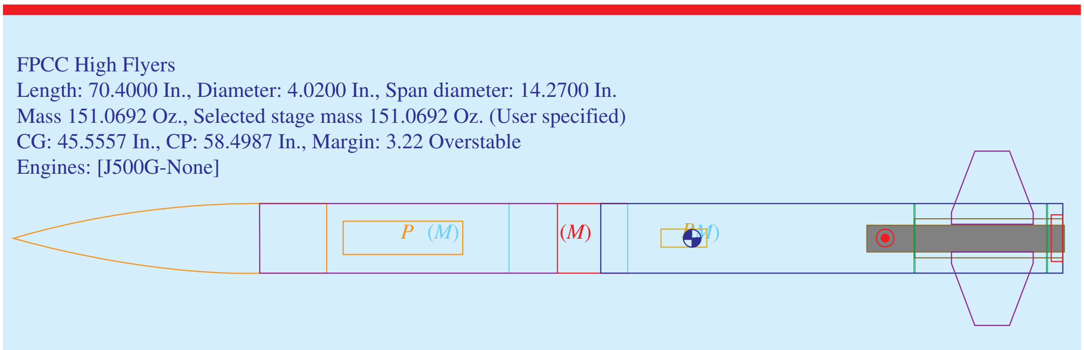

FPCC High Flyers
Length: 70.4000 In., Diameter: 4.0200 In., Span diameter: 14.2700 In.
Mass 151.0692 Oz., Selected stage mass 151.0692 Oz. (User specified)
CG: 45.5557 In., CP: 58.4987 In., Margin: 3.22 Overstable
Engines: [J500G-None]

**Figure 1.** The 2D profile of the Rocket, ‘FPCC High Flyers’, designed using RockSim.

Another 7/16″ hole was drilled into the main airframe, 3″ from the top, on one of the guiding lines for pressure equalization.

In order to prepare the rocket for painting, every hole was taped over on the inner surface of the tubes. The rocket was positioned so all the holes lined up correctly as the paint pattern would also act as alignment marks. The entire outer surface of the rocket was sanded rough and washed clean with isopropyl alcohol. The rail buttons were removed and the posts were taped over. To begin painting, two coats of gray primer were sprayed on. Between each coat of primer, very fine sand paper was used to wet sand the entire outer surface. This was followed by three coats of a white base paint. Half of the rocket was taped off and two more coats of maroon were sprayed onto the exposed surface of the rocket. This created a half and half paint job that runs the length of the rocket. Letter stencils were created and used to paint the words on the white portion of the rocket. It spells out ‘High Flyers’ on the top and ‘FPCC’ near the bottom.

After the paint was dry, all the masking tape was removed and the rocket was ready for final assembly. The rail buttons were reinstalled. Epoxy putty was applied to the inside of the post of the top rail button to make sure that the inner surface of the airframe tube was completely smooth.

The 25′ piece of nylon shock cord was cut into two sections. One measured 10′ and the other 15′. The longer piece was used for the drogue parachute because it provided a few extra moments for the rocket to slow down before the parachute deployment. A slip knot was used to ensure that a force tugging on the shock cord would only tighten it more. A loop was created about 1/3 of the way down the shock cord near the aft airframe tube. This provided a place to install the drogue parachute. Protective Nomex was positioned near the parachute to protect it from the hot ejection gases. A similar loop and Nomex setup was used on the main parachute. The loop was located about 1/3 of the length of the rope from the nose cone.

The parachutes were rolled up, wrapped in the Nomex cloth, and loaded into the airframes. The rocket was then assembled for a final test fitting. After the airframes were positioned correctly, the sheer pins were installed and the plastic rivets were popped into place. The altimeter was tested by turning it on with a flathead screwdriver and listening for the beeping tone. This completed the construction of the rocket. A brief video of our experience can be watched in the YouTube [6].

## 4. Results and discussion

### 4.1. Simulation detail

To design a high powered rocket of desired weight, length, and diameter; check the stability; and predict speed, altitude and flight duration with a specific motor under different weather conditions, a computer simulation program called RockSim was used. The rocket was built with the simulator to the same specification as the actual rocket, whose 2D RockSim profile is shown in figure 1. The mass (without motor), length and diameter of the rocket were 128 Oz, 70.4 inches and 4.02 inches respectively. The mass of each object was measured and put into RockSim. The center of gravity (CG) was calculated and then verified by balancing the rocket on a ruler. The

**Table 1.** Center of pressure values as calculated using RockSim.

| Method | Center of pressure (Inches) | Static margin | Remark |
|---|---|---|---|
| RockSim method | 58.50 | 3.22 | Overstable |
| Barrowman method | 56.84 | 2.81 | Overstable |
| Cardboard Cut-out Method | 65.67 | 5.00 | Overstable |

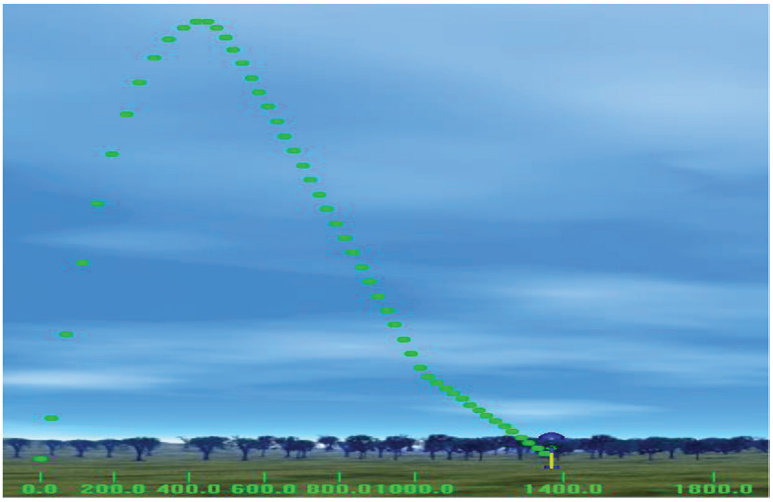


**Figure 2.** Trajectory of the rocket predicted by RockSim simulation.

CG of the rocket measured from the tip of the nose cone with and without motor of mass 23.1 Oz were: 45.56 and 42.25 inches respectively.

It is important to note here that the distributed mass of the rocket acts through CG of the rocket and similarly the aerodynamics forces acting on the rocket parts can be assumed to act through CG, a physical quantity dependent on shape of the rocket. In general, finding CP is a mathematically involving process. Therefore, several methods are adopted to determine CP in practice: (a) Cardboard Cut-out Method [7] (b) Swing Test [8] and (c) RockSim Software [5]. In our project, we used RockSim to calculate the CP. Current version of RockSim software has three methods for determining CP namely: RockSim Method, which utilizes 'rocksim stability equations'; Barrowman Method, which utilizes Barrowman stability equations [9]; and cardboard cutout method. The RockSim Method essentially is the Barrowman method which tries to 'remove as many assumptions as possible' from the original Barrowman equations [10]. Center of pressure as calculated from the nose, are listed in the table 1. For predicting flight characteristics, RockSim provides two methods for the simulations: (a) Fourth Order Runge–Kuta and (b) Explicit Euler (RASP style) methods. We applied the fourth order Runge–Kuta method in our simulation. The trajectory of the rocket, as a result of RockSim simulation, is shown in figure 2, while the simulation properties are listed in table 2.

In order to make sure that a rocket fly in predictable and safe manner, it is important to check the stability of the rocket. For a rocket to be stable, CG should lie nearer to the nose cone and CG-CP separation should lie between one and two body tube diameter or 'caliber' of the rocket [7]. If the rocket is unstable, the rocket either will not fly or fly erratically [11]—some ways to make it stable are: (a) add weight to the nose or payload section of the rocket (b) make the rocket longer (c) add more fins or choose their size bigger (d) move the fins toward the rear [12]. In our case, the rocket was overstable as indicated by static margin in table 1. Static margin is a dimensionless quantity, defined as relative separation of CP and CG with respect to body tube diameter. An overstable rocket might gradually arc into the wind, if the launch condition is windy; it might even go

**Table 2.** Simulation properties of the rocket and the launch site parameters.

| Parameter | Value |
|---|---|
| Drogue parachute deployment | Apogee |
| Main parachute deployment (ft) | 700 and 500 |
| Launch guide length (inch) | 72 |
| Launch angle (degree) | 10 |
| Launch site location from sea level (ft) | 445 |
| Relative humidity (%) | 60 |
| Temperature (°F) | 68.76 |
| Barometric pressure (bar) | 1.013 |
| Latitude (degrees) | 42.575 |
| Wind conditions (Mph) | 8–14 |
| Wind starts at altitude (ft) | 10 |
| Cloud coverage | Sunny |

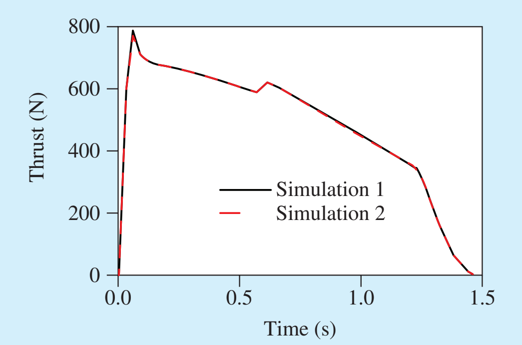


**Figure 3.** The thrust produced during the motor burnout, as calculated by RockSim.

horizontal at worst. To minimize this problem, we can choose a motor with higher thrust level or use a longer launch rod.

### *4.2. Thrust force*

As shown by equation (1), the thrust of a rocket can be written as the product of mass flow rate and exhaust speed, both of which rely on engine characteristics and setting of the motor throttle [13]. The motor we chose for our rocket flights was the J500G from Aerotech, which had a total weight of 23.1 Oz. Ammonium perchlorate composite propellant (APCP) contained in the motor is a solid-fuel, along with the oxidizer, and had the total weight of 12.8 Oz. The *J* is the impulse of the motor. A *J* impulse is classified as having the thrust in the range: 640–1280 Ns. The 500 is the average thrust of the motor. The *G* means that the propellant burns green. This motor had no ejection delay and was chosen to meet the specifications of the competition that we competed in for our two launches.

Figure 3 shows the time variation of thrust during the motor burnout in two simulations performed in RockSim. The two simulations were performed with exactly same parameters except one change: main parachute deployment altitude of 700 ft (simulation 1) was replaced by 500 ft (simulation 2). These two simulations were performed to match the corresponding change in flight event, as indicated in the altimeter, during the rocket launchings: launch 1 and launch 2 respectively. As expected, the two thrust curves perfectly match to each other. The total impulse, motor burnout time, peak thrust and average thrust, calculated in the two simulations, are listed in table 3. The two simulation values of each physical property are in excellent agreement to each other and to the standard value.

### *4.3. Kinematic analysis*

High-Powered Rocket Competition was held in Richard Bong State Recreation Area, Kansasville, Wisconsin on 22 April 2017. We successfully launched and recovered the same rocket twice. For both the flights, the altimeter was programmed to deploy the first ejection charge at apogee. The drogue parachutes were, hence, deployed at respective apogee of 2268 and 2381 ft, at 11.75 and 11.8 s after the launch respectively. The main parachutes were, however, deployed at two different heights of 700 and 500 ft, at 46.75 and 46.8 s after the launch respectively, as shown in table 4.

To determine the actual drag coefficient, we used the altitude back-tracking method which involved: overriding $C_d$ in the '$C_d$ override' table of the RockSim, running simulation ten times with a fixed value of $C_d$, and take the average value of altitudes given by the simulations. If the altitude thus predicted matches actual altitude from altimeter, the value of $C_d$ used in the simulation is the back-tracked value of drag coefficient. Figures 4 and 5 show the summary of different simulation properties, in tabular form, calculated in the back-track procedure for the two launches. The actual drag coefficient for first and second flights were, thus, determined to be 0.87 and 0.78 respectively. Thus, average value of the actual

**Table 3.** Peak and average thrust in two simulations.

| | Total impulse (Ns) | Burn time (s) | Peak thrust (N) | Average thrust (N) |
|---|---|---|---|---|
| Simulation 1 | 724.063 | 1.47 | 787.823 | 492.5599 |
| Simulation 2 | 723.266 | 1.4575 | 786.246 | 496.2372 |
| Standard [14] | 722.664 | 1.45 | 787.971 | 498.389 |

drag coefficient is 0.825, given that the motor produced a total of 723 Ns impulse during the burnout.

With the back-tracked value of drag coefficient determined, we analyze how altitude, velocity and acceleration varies with time in a rocketry motion. Figure 6 shows the time variation of altitude of the two flights, launch 1 and launch 2, and their comparison with RockSim prediction, simulation 1 and simulation 2, respectively. The altimeter readings have a little bit of discrepancies because, for instance, the launch rail altitude above the sea level changes from 445 ft in the first launch to 469 ft in the second launch. It is seen from actual flight altitude graph that the drogue parachute is deployed at a location indicated by letter $D$ and main parachute is deployed at a location indicated by letter $M$. Figure 7 shows the time variation of velocity of the two flights, launch 1 and launch 2, and their comparison with RockSim prediction, simulation 1 and simulation 2, respectively. The maximum velocity of the first flight was 426 ft s$^{-1}$ at 1.9 s of its motion while the maximum value of velocity for the second flight was 499 ft s$^{-1}$ at 1.75 s of its motion as shown in table 5. Figure 8 shows the time variation of acceleration of the two flights, launch 1 and launch 2, and their comparison with RockSim prediction, simulation 1 and simulation 2, respectively. The maximum acceleration of the first flight was 19 g at 1.2 s of its motion while the maximum value of acceleration for the second flight was 31 g at 1.3 s of its motion as shown in table 5. Figure 9 compares the time variations of altitude, velocity and acceleration in actual flights and simulations from 0 to 80 s. Three vertical lines at 1.8, 11.8 and 46.8 s represent motor burnout, drogue and main parachute deployments respectively. It is seen from the table 5 that the burnout occurs at 1.9 and 1.75 s for the two flights, when the rocket attains respective altitudes of 360 and 331 ft.

**Table 4.** Flight events of the rocket.

| Flight events | Launch 1 | Launch 2 |
|---|---|---|
| Main setting (ft) | 700 | 500 |
| Apogee (ft) | 2268 | 2381 |
| Drogue deployment time (s) | 11.75 | 11.8 |
| Main deployment time (s) | 46.75 | 46.8 |

After the motor burns out, the velocity starts decreasing and becomes minimum at apogee. This phase is called the coasting phase. Basically, the rocket falls at a constant speed to the ground after the coasting phase i.e. after the point indicated by $D$ in the figures 6–9. Simulation results, as seen in figures 6–9, are qualitatively consistent with the actual flight data in the entire time range for all the variations studied. Figure 10 shows the time variation of acceleration of the two flights, in the time range from 2 to 11 s, in the coasting phase. The acceleration was found to approach '-$g$' in asymptotic form (equation (5)) and shown by dotted lines (figure 10).

$$y = 0.687 - 66.601 \times 0.936^{x} \text{ (for launch 1)} \tag{5a}$$

which is equivalent to the second-degree polynomial:

$$y = -0.095\,x^2 + 4.1\,x - 65 \tag{5a$'$}$$

$$y = 1111.119 - 1177.353 \times 0.997^{x} \text{ (for launch 2)} \tag{5b}$$

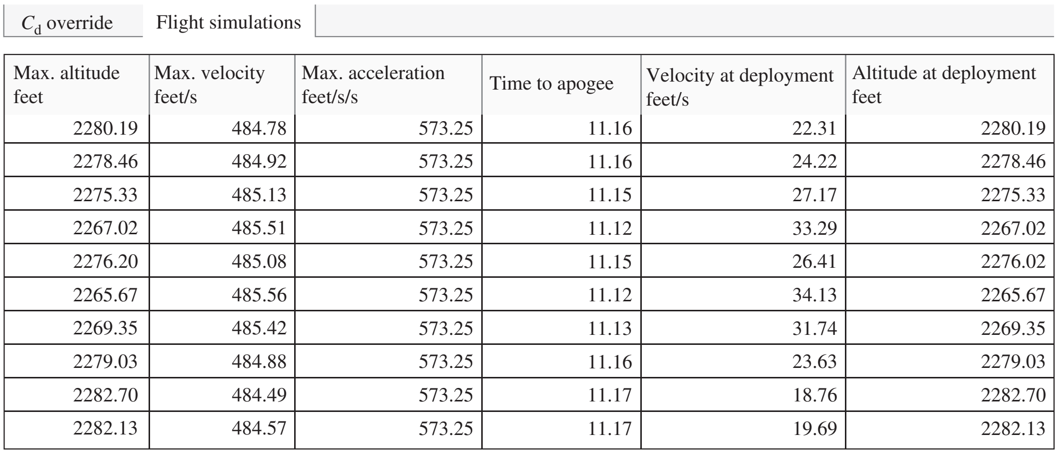
which is equivalent to the second-degree polynomial:

$$y = -0.0052\,x^2 + 3.5\,x - 66. \tag{5b$'$}$$

To study speed of the exhaust, we use the thrust curve of the rocket and equation (6):

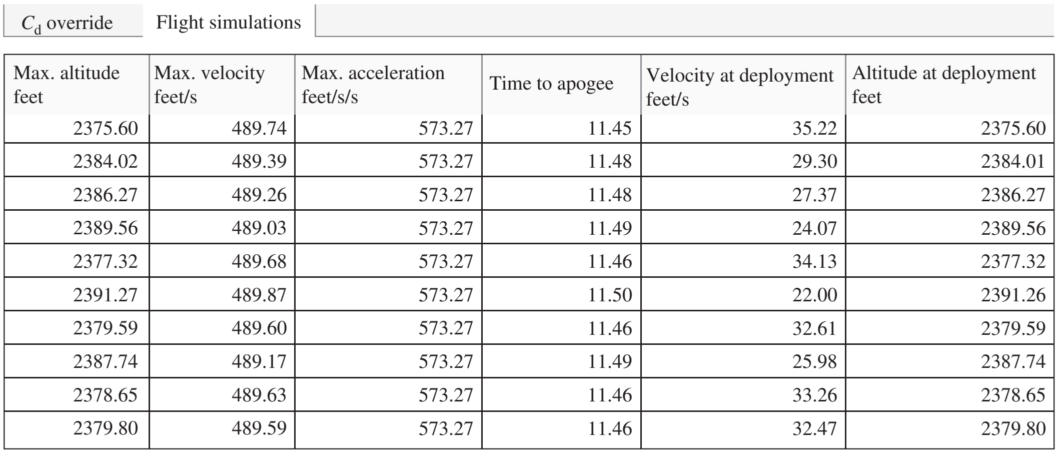
$$T = u\,(\mathrm{d}m/\mathrm{d}t)\,. \tag{6}$$

We know that APCP contained in the motor had the total weight of 12.8 Oz and burnout time of the propellant for two launches were 1.9 and 1.75 s respectively. Given that the motor produced a total impulse of 723 Ns, $(\mathrm{d}m/\mathrm{d}t)_1$ and $(\mathrm{d}m/\mathrm{d}t)_2$ were found to be 0.191 kg s$^{-1}$ and 0.207 kg s$^{-1}$ for the two launches i.e 0.2 kg s$^{-1}$ in average. Since the average thrust



| Max. altitude feet | Max. velocity feet/s | Max. acceleration feet/s/s | Time to apogee | Velocity at deployment feet/s | Altitude at deployment feet |
|---|---|---|---|---|---|
| 2280.19 | 484.78 | 573.25 | 11.16 | 22.31 | 2280.19 |
| 2278.46 | 484.92 | 573.25 | 11.16 | 24.22 | 2278.46 |
| 2275.33 | 485.13 | 573.25 | 11.15 | 27.17 | 2275.33 |
| 2267.02 | 485.51 | 573.25 | 11.12 | 33.29 | 2267.02 |
| 2276.20 | 485.08 | 573.25 | 11.15 | 26.41 | 2276.02 |
| 2265.67 | 485.56 | 573.25 | 11.12 | 34.13 | 2265.67 |
| 2269.35 | 485.42 | 573.25 | 11.13 | 31.74 | 2269.35 |
| 2279.03 | 484.88 | 573.25 | 11.16 | 23.63 | 2279.03 |
| 2282.70 | 484.49 | 573.25 | 11.17 | 18.76 | 2282.70 |
| 2282.13 | 484.57 | 573.25 | 11.17 | 19.69 | 2282.13 |

**Figure 4.** $C_d$ determination for first flight: $C_d = 0.87$; actual altitude = 2268 ft.



| Max. altitude feet | Max. velocity feet/s | Max. acceleration feet/s/s | Time to apogee | Velocity at deployment feet/s | Altitude at deployment feet |
|---|---|---|---|---|---|
| 2375.60 | 489.74 | 573.27 | 11.45 | 35.22 | 2375.60 |
| 2384.02 | 489.39 | 573.27 | 11.48 | 29.30 | 2384.01 |
| 2386.27 | 489.26 | 573.27 | 11.48 | 27.37 | 2386.27 |
| 2389.56 | 489.03 | 573.27 | 11.49 | 24.07 | 2389.56 |
| 2377.32 | 489.68 | 573.27 | 11.46 | 34.13 | 2377.32 |
| 2391.27 | 489.87 | 573.27 | 11.50 | 22.00 | 2391.26 |
| 2379.59 | 489.60 | 573.27 | 11.46 | 32.61 | 2379.59 |
| 2387.74 | 489.17 | 573.27 | 11.49 | 25.98 | 2387.74 |
| 2378.65 | 489.63 | 573.27 | 11.46 | 33.26 | 2378.65 |
| 2379.80 | 489.59 | 573.27 | 11.46 | 32.47 | 2379.80 |

**Figure 5.** $C_d$ determination for second flight: $C_d = 0.78$; actual altitude = 2381 ft.

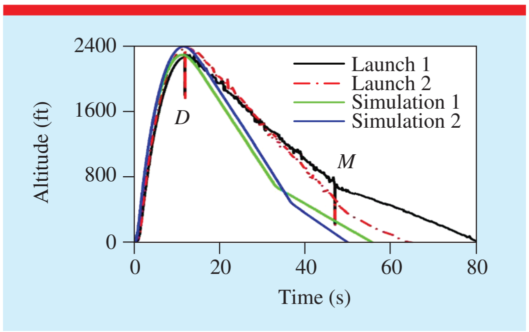


**Figure 6.** Variation of altitude with time in actual flights and simulations.

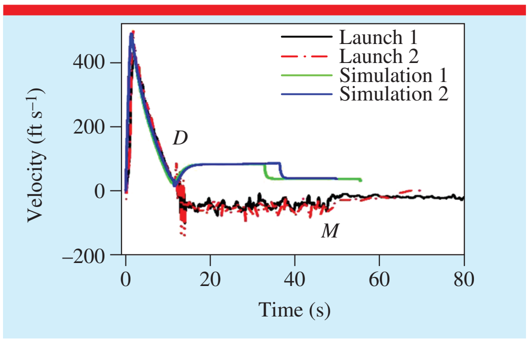


**Figure 7.** Variation of velocity with time in actual flights and simulations.

**Table 5.** Flight characteristics of the Rocket.

| Flight Characteristics | Launch 1 | Launch 2 |
|---|---|---|
| Apogee (ft) | 2268 | 2381 |
| Maximum velocity (ft $s^{-1}$) | 426 | 499 |
| Time for maximum velocity (s) | 1.9 | 1.75 |
| Maximum acceleration (ft $s^{-2}$) | 620 | 1000 |
| Time for maximum acceleration (s) | 1.2 | 1.3 |
| Maximum retardation (ft $s^{-2}$) | −760 | −1160 |
| Time for maximum acceleration (s) | 13.9 | 13.75 |
| Altitude at maximum velocity (ft) | 360 | 331 |
| Velocity at drogue deployment (ft $s^{-1}$) | 27 | 50 |
| Drogue deployment time (s) | 11.75 | 11.8 |
| Main deployment time (s) | 46.75 | 46.8 |
| Velocity at main deployment (ft $s^{-1}$) | −44 | −56 |

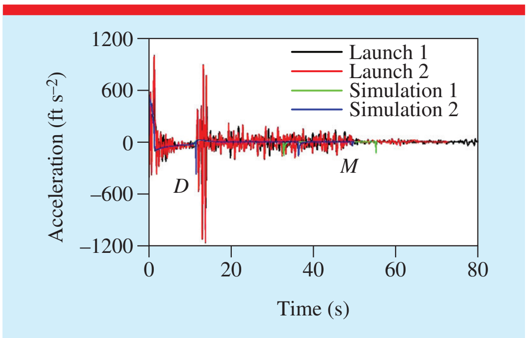


**Figure 8.** Variation of acceleration with time in actual flights and simulations.

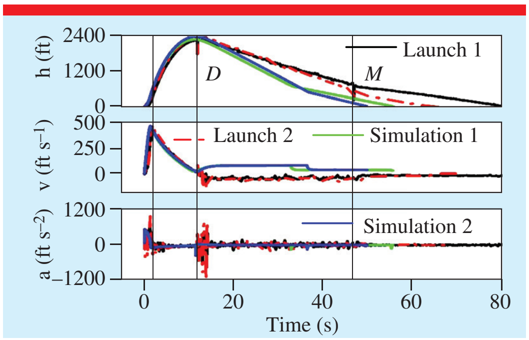


**Figure 9.** Time variations of altitude, velocity and acceleration in actual flights and simulations.

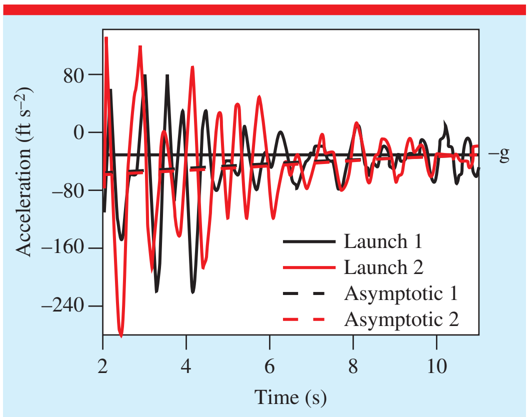


**Figure 10.** Variation of acceleration with time in actual flights in coasting phase.

was 498.389 Newton, the average speed of the exhaust was found to be 2491.94 m $s^{-1}$.

## 5. Conclusions

Design, construction, and launching experience of a high powered rocket have been presented in this study. Simulation results are compared with time variations of altitude, velocity and acceleration obtained in actual flight and are found to be consistent. Acceleration in the coasting phase have been found to approach '-*g*', in asymptotic form given by the second-degree polynomial of a small leading coefficient. To determine the actual drag coefficient, we used the altitude back-tracking method. The average value of the actual drag coefficient was found to be 0.825, given that the J500G motor from Aerotech produced a total of 723 Ns impulse during the burnout. In order to study the speed of the exhaust, we used the thrust curve of the rocket and the average speed of the exhaust was found to be 2.5 km $s^{-1}$.

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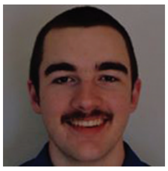

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