UW-Madison Badger Ballistics
2022 Midwest High-Powered Rocketry Competition

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Abstract:

In this competition, UW-Madison AIAA was tasked with building one team rocket and seven accompanying rockets to be launched, each with unique design aspects. To design the rockets, OpenRocket simulations were used as well as SolidWorks. The rockets differed in a multitude of ways including number of fins and parachutes, motor size, and material. The fin numbers ranged from three to six fins and the team rocket featured dual deploy parachutes versus single deployment in the other seven rockets. The rockets featured two motor brands Cesaroni and Aerotech, with H, I & J level motors. Additionally, there were five rockets made from cardboard, two from fiberglass, and one made of polystyrene. These different design aspects were input into OpenRocket to simulate the expected performance of each rocket. On launch day each rocket was equipped with altimeters that were able to collect the flight data, which was then compared to the simulation to analyze how well the rockets performed compared to their expected performance. Based on the diversity of rockets and the execution of the team on launch day, the team finished second overall in the competition.

Introduction

For the 2022 Midwest High Powered Rocket Launch, the UW–Madison team was tasked with making eight rockets with a consistent theme while maintaining as much diversity between the rockets as possible. The one constant was that all teams competing had to build the same Binder Design Excel kit as a team, this rocket was called the core rocket. Since the team had eight rockets, a theme of the planets was chosen. The rockets exemplified diversity through having different engine manufacturers and engine size. Three of the rockets were designed, built and tested as a team, the other five were done individually. The core rocket featured a dual deploy ejection system, while the other seven had single deployment. The general rocket dimensions were also varied amongst the eight rockets. All of the diversity for the rockets can be seen in Table 1. In the engine row, A stands for Aerotech and C stands for Cesaroni. These are two popular solid rocket motor manufacturers. The team expected the rockets to perform very similarly, the only difference that was expected and eventually encountered was in the

The UW-Madison Badger Ballistics team would like to thank the Wisconsin Space Grant Consortium (WSGC), Wisconsin Engineering Student Council (WESC) and Department of Engineering Physics at UW – Madison for their generosity in supporting our engineering endeavors throughout this competition.

preparation of the motors on launch. One example where this was seen was that the Cesaroni motors required a casing around them to allow for the motor to be reusable, while the Aerotech motors did not have this feature. In Table 1 below, CP and CG stand for center of pressure and center of gravity, respectively, both are measured from the tip of the rocket.

Table 1: Rocket Armada Diversity

	Core Rocket	**Rocket 2**	**Rocket 3**	**Rocket 4**	**Rocket 5**	**Rocket 6**	**Rocket 7**	**Rocket 8**
Theme	Earth	Jupiter	Saturn	Uranus	Venus	Mars	Mercury	Neptune
Engine	C-H225	C-J760	A-J450	A-H45	A-I140	A-H115	A-H195	C-H125
Team or Ind.	Team	Ind.	Ind.	Team	Ind.	Ind.	Ind.	Team
Deploy	Dual	Single	Single	Single	Single	Single	Single	Single
Engine Size	38mm	54mm	54mm	38mm	38mm	29mm	29mm	38mm
Material	Card-board	Kraft Paper	Fiber-glass	Card-board	Card-board	Poly-styrene	Card-board	Fiber-glass
Nose Cone Type	Ogive	Parabolic	Ogive	Ogive	Ogive	Ogive	Ogive	Haack series
Number of Fins	3	6	4	4	3	3	4	3
RMS or DMS	RMS	RMS	RMS	DMS	DMS	DMS	DMS	RMS
Diameter	3.0”	4.0”	4.0”	3.0”	2.6”	2.6”	3.0”	2.6”
Length	52.53”	82”	62”	56.25”	57”	54”	45.3”	58”
CP	41.07”	67.3”	48.3”	43.35”	43.92”	41.01”	33.67”	46.87”
CG	31.21”	56.3”	40.2”	38.39”	39.24”	35.34”	29.77”	37.13”
Stability	3.29	2.75	2.01	1.65	1.83	2.18	1.27	3.7

Design & Expected Performance

The general design of the rockets was completed in a simulation software program called OpenRocket. General section dimensions were first determined in this program and then subsequent mechanical designs were completed in Solidworks for some of the rockets. The red dot in the OpenRocket figures indicates the center of pressure and the blue dot indicates the center of gravity when fully loaded. Each of the rockets had similar requirements for their avionics bays, so each used a similar design for the avionics bay. The avionics bays featured two threaded rods, which acted as guides for a 3D printed sled, that held a MissileWorks RRC3 Sport Altimeter and JollyLogic Altimeter2. The JollyLogic Altimeter2 was used to collect flight data and the MissileWorks RRC3 Sport Altimeter was used to produce rocket separation as well as be a second source of flight data. It will become clear in each of the following sections that these rockets met and exceeded the competition parameters.

Rocket 1 (Core Rocket) – Earth. As specified by the competition, the core rocket was the Binder Design Excel Dual Deploy Kit, which flew on the Cesaroni 38mm 2-grain H225 White Thunder motor. The core rocket was the main rocket that the entire team worked on and the rocket everyone was most familiar with, so it was decided to make Planet Earth the theme for this rocket. As shown in Figure 1, the painting of this rocket went along with the Earth theme.

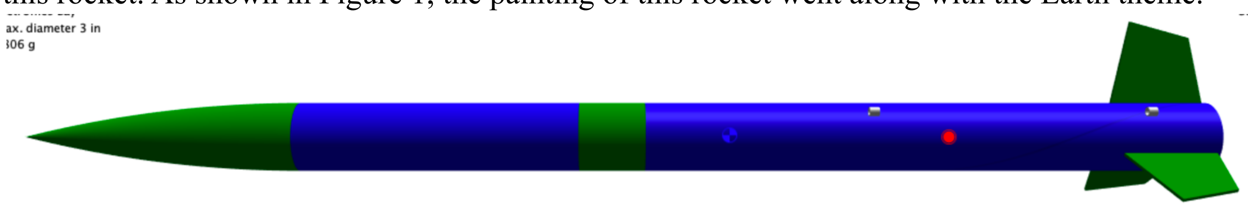


Figure 1: Core Rocket Finished OpenRocket Design

As seen in Figure 1, the core rocket was a total length of 52.41", had a diameter of 3.0", had a center of pressure that was 41.07" from the tip and a center of gravity that was 31.21" from the tip. The overall stability of the core rocket, based on the center of pressure, center of gravity and diameter was 3.29 cal, which ensured that if there were to be a disturbance to the rocket, it would be able to correct and still fly straight. The total weight of the rocket, including the motor, was 99 oz.

After finalizing all the components in the core rocket, simulations were able to be performed. In order to get an accurate simulation, it was ensured that each component was the correct weight, had the correct paint finish and the launch was simulated as if the rocket was actually launching from North Branch, Minnesota. The simulations predicted the rocket would reach an apogee of 1236', have a peak velocity of 284 ft/sec, peak acceleration of 264 ft/sec^2, landing speed of 23.5 ft/sec, time to apogee of 9.13 sec and a total flight time of 52.2 sec.

Rocket 2 – Jupiter. The Jupiter Rocket was built from scratch by ordering parts from trustworthy vendors. The Jupiter Rocket flew with a Cesaroni - P54-3G White Thunder (J760) motor. Figure 2 below shows a rough 3D rendering of the completed rocket. The center of gravity was 56.3" from the tip of the nose cone and the center of pressure was 67.3" from the tip. The stability of the rocket was 2.75 cal.

Figure 2: Jupiter Rocket Finished OpenRocket Design

The Jupiter Rocket had a 3D printed parabolic nose cone made from PLA. The Jupiter rocket also had a unique six finned design. These additional fore fins added diversity within the fleet and stability to the rocket.

Once again, after finalizing all the components in the core rocket, simulations were able to be performed. The simulations predicted the rocket would reach an apogee of 4528’, have a peak velocity of 1188 ft/sec, peak acceleration of 1069 ft/sec^2, landing speed of 20 ft/sec, time to apogee of 13.1 sec and a total flight time of 233 sec.

Rocket 3 – Saturn. The Saturn Rocket was built primarily from scratch with parts ordered from trustworthy and reliable suppliers. The Saturn Rocket flew on an Aerotech 54mm J450DM-14A Dark Matter Motor. Figure 3 below shows a rough 3D rendering of the completed rocket. The red dot indicates the center of pressure and the blue the center of gravity when fully loaded and assembled. The center of gravity was 40.2” from the tip of the nose cone and the center of pressure was 48.3” from the tip. The stability of the rocket was estimated to be around 2.01 cal.

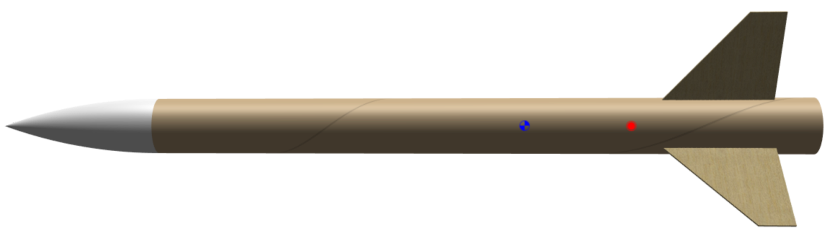


Figure 3: Saturn Rocket Finished OpenRocket Design

The Saturn Rocket’s airframe was made from fiberglass, the fins from wood (birch), and the nose cone from PLA. For this rocket the simulations predicted the rocket would reach an apogee of 4500’, have a peak velocity of 542 ft/sec, peak acceleration of 196 ft/sec^2, landing speed of 19.8 ft/sec, time to apogee of 16.6 sec and a total flight time of 238 sec.

Rocket 4 – Uranus. The Uranus Rocket was a team built rocket that was built from scratch. Figure 4 presents an image of the finished OpenRocket design of this rocket.

Figure 4: Uranus Rocket Finished OpenRocket Design

The center of gravity was measured to be 38.389 inches from the tip of the nose cone, and the center of pressure was calculated, in the same manner, to be 43.347 inches from the tip of the nose cone. Based on simulation, the apogee was 2700 ft with a max velocity of 377 feet per second and a max peak acceleration of 146 feet per second squared. The landing speed was 23.2 feet per second with a total flight time of 129 seconds taking 6.53 seconds to get to apogee.

Rocket 5 – Venus. Rocket 5, named "Venus" after the second planet in the solar system, was a scratch-built rocket designed and simulated in the OpenRocket design program. It featured a 57 inch long, 2.6 inch diameter body with inverted fins, and was primarily made from cardboard and wood materials. The center of gravity and center of pressure were located 39.24 inches and 43.92 inches, respectively, behind the tip of the nose cone. This implies that the center of pressure was located 4.68 inches behind the center of gravity, which corresponds to a stability of 1.83 caliber. Figure 5 below shows the finished OpenRocket design.

Figure 5: Venus Rocket Finished OpenRocket Design

The inverted fin design can be seen clearly in Figure 5, and was part of an ongoing experiment to see if a sharp angle of attack for the leading edge of a rocket fin can help reduce drag from both friction and the vortices created by the flow of fluid over a fin. Each fin was set at an angle of 59.1°. The idea was that by creating an abrupt disturbance as the fin passes through the fluid, a "protective" layer of disturbed air pushes the stagnant air out of the way before it comes into contact with the fin itself, creating a reverse teardrop shape flow instead of the usual "normally-oriented" teardrop shape of fluid flow over a standard-shaped fin. The two possible benefits of this were: less air impacting the leading edges of the rocket fins, which would result in lower frictional forces from the air to fin contact, and a smoother, reverse teardrop shaped flow over the fin, which would hopefully reduce the size and severity of the vortices created by the absence of a fin passing through the fluid. Venus flew on an Aero I140W-14A White Lighting motor, which produces a little over 175 Newtons of thrust and burns for about 2.5 seconds. From this data, OpenRocket simulated that Venus should hit appogee around 3600 feet after 13.5 seconds with a maximum velocity and acceleration over that time of 660 ft/s and 419 ft/sec^2 respectively.

Rocket 6 – Mars. The general design of this kit rocket - the Arreauxbee-Hi - was created in the rocket simulation program OpenRocket. The dimensions and material selections for the rocket were selected based on the kit descriptions. In Figure 6 below, the finished OpenRocket model of the rocket is shown; the red dot represents the center of pressure located 41.013 [in] from the tip and the blue dot represents the center of gravity located 35.34 [in] from the tip. The stability of the rocket was 2.18 cal.

Figure 6: Mars Rocket Finished OpenRocket Design

For this rocket the simulations predicted the rocket would reach an apogee of 2498', have a peak velocity of 599 ft/sec, peak acceleration of 460 ft/sec^2, landing speed of 18.7 ft/sec, time to apogee of 11.2 sec and a total flight time of 144 sec.

Rocket 7 – Mercury. The general design of this kit rocket, the Forte rocket, was created in the rocket simulation program OpenRocket. Figure 7 below shows the finished OpenRocket model. The red dot represents the center of pressure located 33.669 in. from the tip of the nose cone and the blue dot represents the center of gravity located 29.772 in. from the tip of the nose cone. The center of pressure was 3.949 inches behind the center of gravity, resulting in a stability of 1.27 cal.

Figure 7: Mercury Rocket Finished OpenRocket Design

For this rocket the simulations predicted the rocket would reach an apogee of 2575', have a peak velocity of 624 ft/sec, peak acceleration of 714 ft/sec^2, landing speed of 23.5 ft/sec, time to apogee of 11.2 sec and a total flight time of 120 sec.

Rocket 8 – Neptune. Rocket 8 was built from the kit Darkstar 2.6-38mm. The CG was 37.128" and the CP was 46.868", resulting in a stability of 3.7 cal. Figure 8 below shows the finished OpenRocket design for this rocket.

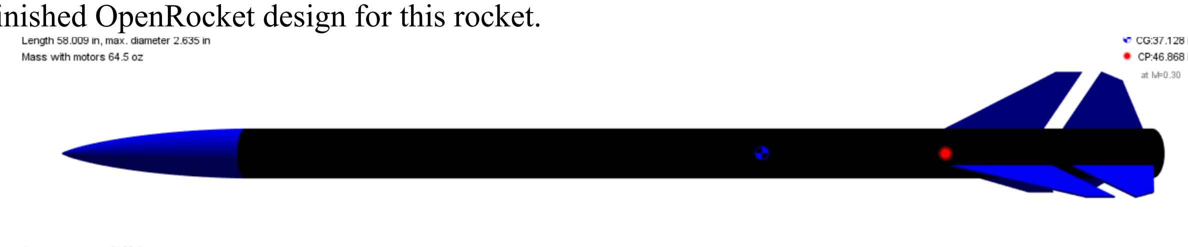


Figure 8: Neptune Rocket Finished OpenRocket Design

For this rocket the simulations predicted the rocket would reach an apogee of 2136', have a peak velocity of 406 ft/sec, peak acceleration of 244 ft/sec^2, landing speed of 23.8 ft/sec, time to apogee of 11.8 sec and a total flight time of 99.6 sec.

Flight Performance Data

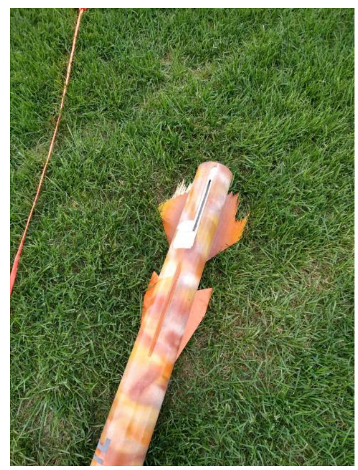
For the UW-Madison team, the overall competition day for the rockets was a success. Out of the eight total rockets that were launched, six were completely successful flights. In this context, a successful flight is one where there were no catastrophic motor failures, the rocket flew with stability, reached apogee, there was an ejection event, the parachute was ejected and the parachute opened up. The two that were not considered to be successful flights only had one of these categories not met, and this paper will go into further detail about each flight that was not successful in their respective section. Table 2 presents the expected and actual flight data for all of the rockets.

Table 2: Expected Flight Data Compared to Actual Flight Data

		Mass [oz]	**Motor**	**Max Altitude [ft]**	**Peak Velocity [ft/sec]**	**Peak Acc. [ft/sec2]**	**Landing Speed [ft/sec]**	**Time to Apogee [sec]**	**Flight Time [sec]**
Core Rocket	Exp.	94.9	H225	1325	297	277	23	9.37	55.4
	Act.	98	H225	1325	282	229	16	8.95	60.1
Rocket 2	Exp.	96	J760	4528	1188	1069	20	13.1	233
	Act.	138	J760	4005	1048	782	18	13.05	203.4
Rocket 3	Exp.	160	J450	4500	542	196	19.8	16.6	238
	Act.	165	J450	3571	620	-	20	13.85	180.3
Rocket 4	Exp.	47.1	H45	2700	377	136	23.2	6.53	129
	Act.	51	H45	1849	262.5	86.94	22	7.1	96.7
Rocket 5	Exp.	41.09	I140	3609	663	419	19.2	13.6	197
	Act.	49	I140	2893	545.6	454	22	10.2	136.5
Rocket 6	Exp.	35.1	H115	2316	509	379	22.2	11.3	115
	Act.	39.3	H115	2034	453.2	402.5	49.9	9.3	52
Rocket 7	Exp.	39.1	H195	2575	624	714	23.5	11.2	120
	Act.	42	H195	2155	491.3	515.2	26.4	9.3	92.7
Rocket 8	Exp.	65.7	H100	2260	400	176	23.7	12.3	107
	Act.	56.8	H100	1869	462	437.9	36.7	9.2	60.5

Rocket 1 (Core Rocket) – Earth. The flight of the core rocket followed closely to how it was expected to go. The rocket flew straight up, demonstrating that the simulations were correct in predicting that this would be a stable rocket. Shortly after apogee, the drogue parachute was ejected from the ejection charge, which was set off by the MissileWorks RRC3. The main parachute was then ejected at approximately 700 ft, once again from the ejection charge set off by the RRC3. Afterwards, the rocket landed down on the ground at a speed of approximately 16 ft/sec. Once the team reached the rocket and was able to assess the state of the rocket, it was found in a flyable condition and did not suffer any major damages. This rocket reached an apogee of 1325', had a peak velocity of 282 ft/sec, peak acceleration of 229 ft/sec^2, landing speed of 16 ft/sec, time to apogee of 8.95 sec and a total flight time of 60.1 sec. It was found that this rocket was slightly heavier than expected. It is believed that this additional mass that the rocket had caused the peak velocity and peak acceleration to be lower than what was simulated. The landing speed of the rocket was less than what was simulated and it is believed that this may have been due to not correctly modeling the parachutes in the rocket.

Rocket 2 – Jupiter. The main issue with this rocket was the amount of thrust the motor provided. The amount of force exerted on the rear MDF fins was more than the allowable which causes them to flutter and ultimately shear. A photo of the sheared fins can be seen in Figure 9 to the right. The fin material was simply too weak for the amount of thrust provided by the engine. One of the fins was actually separated from the body of the rocket. However, the rocket still flew to almost 4000 feet and deployed its parachute successfully 1 second after apogee. Something that was not expected was upon impact, the nose cone sheared perfectly along the top of the body tube in two pieces. This rocket reached an apogee of 4005', had a peak velocity of 1048 ft/sec, peak acceleration of 782 ft/sec^2, landing speed of 18 ft/sec, time to apogee of 13.05 sec and a total flight time of 203.4 sec. The mass was heavier than anticipated, which was likely due to having more weight in the AV bay and nose cone than initially expected. The max altitude was likely short due to the destruction of the fins upon its ascent.



Rocket 3 – Saturn. The Saturn Rocket was successfully launched in an attempt for a Level 2 Tripoli Certification. The rocket had a successful launch off the pad, flew with stability, reached apogee and then deployed the main parachute shortly thereafter. After it was safe to do so, the rocket was recovered in a flyable condition with little to no damage. Unfortunately there was an error with the JollyLogic Altimeter, so it was not possible to get data from that, leading to some data being missing. This rocket reached an apogee of 3571', had a peak velocity of 620 ft/sec, landing speed of 20 ft/sec, time to apogee of 13.85 sec and a total flight time of 180.3 sec. This rocket performed closely to what was expected, but had slight variations in some of the parameters. The actual mass of this rocket was higher than what was modeled, this is likely due to additional epoxy being applied that was not accounted for in the model. The rocket being heavier than expected most likely caused the rocket to not fly as high as what was expected. The peak velocity for the actual flight was slightly higher than expected and could be attributed to variances in the motor impulse. The flight time was significantly shorter than what was expected, this could have partially been attributed to the additional mass causing it to fall slightly faster than expected. Another possible explanation for this could be that there may have been some wind gusts that pushed the rocket down at certain points faster than normal.

Rocket 4 – Uranus. This rocket had a successful launch. The rocket flew straight into the air then deployed the parachute at 1849 ft. The rocket then landed at a velocity of 22 ft/sec. After landing, the rocket was in good condition and flyable. This rocket had a peak acceleration of 86.94 ft/sec^2, landing speed of 22 ft/sec, time to apogee of 7.1 sec and total flight time of 96.7 sec. The expected max altitude was much higher than the actual altitude this perhaps could be caused by a difference in mass of the expected vs the actual rocket which also affects all the other variables.

Rocket 5 – Venus. The venus rocket flew successfully for a level 1 certification attempt. The venus rocket soared to a maximum altitude of 2893 feet, ejection occurred at 2886 feet, which eventually led to a landing speed of 22 ft/s. Once the signal was given for an all clear at the launch site, the rocket was successfully recovered and inspected, where it was determined to have sustained little to no damage and that Venus could immediately perform another flight. Once back at the staging area, data was collected from both the MissileWorks RRC3 and JollyLogic 2 altimeters. This rocket had a peak velocity of 545.6 ft/sec, peak acceleration of 454 ft/sec^2, time to apogee of 10.2 sec and a total flight time of 136.5 sec. The only true anomaly during the flight was that the maximum altitude was lower than simulations showed, which could have been due to additional mass from epoxy being on the rocket that was not accounted for.

Rocket 6 – Mars. The mars rocket had an unsuccessful launch due to a tangled parachute that did not open once it was deployed. The rocket fell much faster than expected due to the failed opening. The rocket was then recovered; despite landing at a much higher speed than anticipated, none of the rocket's components were damaged and it was in flyable condition. This rocket reached an apogee of 2034', had a peak velocity of 453.2 ft/sec, peak acceleration of 402.5 ft/sec^2, landing speed of 49.9 ft/sec, time to apogee of 9.3 sec and a total flight time of 52 sec. The faster landing speed and the much shorter flight time was due to the failed opening of the parachute, as the rocket had nothing substantially slowing its fall.

Rocket 7 – Mercury. The mercury rocket launched successfully for a level 1 certification attempt and the rocket landed successfully with no broken parts. This rocket reached an apogee of 2155', had a peak velocity of 491.3 ft/sec, peak acceleration of 515.2 ft/sec^2, landing speed of 26.4 ft/sec, time to apogee of 9.3 sec and a total flight time of 92.7 sec. Once again, the apogee and a few other statistics for this launch were lower than expected, which likely was due to additional mass from epoxy, which was not accounted for.

Rocket 8 – Neptune. The launch for the neptune rocket was successful and the rocket was retrieved in a flyable condition. This rocket reached an apogee of 1869', had a peak velocity of 462 ft/sec, peak acceleration of 437.9 ft/sec^2, landing speed of 36.7 ft/sec, time to apogee of 9.2 sec and a total flight time of 60.5 sec. Unlike the majority of the other rockets, the actual mass of this rocket was less than the expected mass of the rocket.

Safety

To ensure that the flights were safe and able to be recovered, several precautions were taken. First, it was ensured that all rockets had a stability margin between 1 and 5 cal fully loaded to guarantee a stable flight. To safely recover the rockets, it was ensured that all rockets had a landing speed that was less than 24 ft/sec so that when the rocket hit the ground they would not break. Also, for rockets that will go above 3,000 ft, tracking systems were installed, which helped locate the rocket after the launch.

To build the rockets, multiple building techniques were used. For structurally and thermally critical components, RocketPoxy was used to join parts together. For parts that were not structurally important, WestSystems Epoxy was used. For any parts that needed to be put together and reopened again, nuts and bolts, screws and shear pins were used. Since epoxy can cause negative health effects, measures were taken to keep the team safe. When working with epoxy, the team was required to wear personal protective equipment that consisted of gloves, safety glasses, a mask, appropriate clothing and closed-toed shoes. Anytime the team was working with epoxy, it took place in a well ventilated area and a sink and eyewash station were nearby in the case that there was a direct contact of epoxy to skin or eyes. While working with the engines, extreme caution was taken to ensure that the team stays safe, nearby observers stay safe and that there is no accidental ignition. To achieve this, the motors were never transported with the igniters installed and the igniters were not installed until on the launch pad.

Discussion

The team found that for motor thrust, if someone is going for a certification flight, it may be best to use a lower thrust motor, because this will put less stress on the rocket and the rocket will be less likely to break. Only Cesaroni reloadable motors and Aerotech disposable motors were used because the team had heard from mentors that these were easier to use. This was exactly what was found when working with each of these respective motors. For the materials, cardboard, fiberglass and wood were used. It was found that although the fiberglass was much stronger, it was much more difficult to work with because it is stronger and the safety hazards associated with it. For future projects, cardboard and wood will likely be used, unless a high thrust and high impulse rocket is being flown. It was found that when team building a rocket, it was much easier to bounce ideas off the fellow team members rather than having to think it all through individually. It was found that the team built rockets are preferable, especially if the rocket is more complex. Although it was found that the single deploy rockets were much less complicated, the team found a preference for dual deploy rockets due to the fact that they lead to a much easier recovery. A preference between three fins and four fins was not found, the only main differences between those that was found were in construction time and helping stabilize the rocket. Four fin rockets take longer to construct, but are more stable typically. It was found that the inverted fin and the dual fin designs were successful and could be options to use in the future. The nose cones varied by changing the material and geometries, a preference for material, but not for geometry was found. The nose cones were made out of plastic and fiberglass. One of the plastic nose cones was 3D printed, which proved to be a weak nose cone and broke upon impact, therefore this is not a design that will be used moving forward. The regular plastic nose cones worked well, but if a larger rocket were to be made, the fiberglass nose cones will be required because they can withstand higher thrusts and impulses better.