Probabilistic Risk Assessment of Using Water Rockets for Educating Students In K-12 Classrooms Using a LIFTOFF Case Study

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Probabilistic Risk Assessment of Using Water Rockets for Educating Students in K-12 Classrooms Using a LIFTOFF Case Study

by

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Date
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Dedication

This report is dedicated to Alabama students and educators in the K-12 system, so that they may benefit from the testing done on their behalf to determine how to best educate young students when using exciting STEM projects.

This report is also dedicated to Joey Tittle, Jimmie Harding, and Joseph Burns, our LIFTOFF 2 team, so that they may benefit from this testing and project as a small building block of their career. The team worked long hours trying to get a reliable LIFTOFF project to demonstrate for students, and the work in our report would not be possible or practical if it were not for the members of our team.
Developing K-12 student interest in science, technology, engineering, and math (STEM) is a critical interest for Alabama. Simple but captivating technologies – like water rockets – are useful tools for engaging students in the classroom. Prior to implementing these tools, it is important to understand the risks and safety concerns associated with their use. This project will use engineering risk assessment techniques to analyze the LIFTOFF case study, assessing its risks and suggesting risk management and mitigation strategies for the use of water rockets for educating K-12 students.

Two primary risks involved in launching water rockets include launch pad failure and launch bottle failure. Launch pad failure includes inadvertent overturning and premature launch of the water rocket. Launch bottle failure includes over-pressurizing and bursting the water rocket, while still on the launch pad. To ensure the safety of students and teachers, testing must be done to obtain accurate data on minimum safe distances from the launch pad to mitigate risk.

Launch pad failure was tested by launching water rockets and determining the water rocket impact and damage from acceleration data. Launch bottle failure was tested at maximum pressure limits by pressurizing 2-liter bottles until failure.

It was determined that the safety precautions taken at the Elementary schools were more than enough to keep the students and teachers safe. The results show that if a person was standing next to the launch pad and it were to fail and strike them, it would roughly feel like a 61 pound weight resting on them for only a split second. It is unlikely that this amount of force could hurt someone unless it struck them in the face or other critical region; additionally, the amount of impact force decreases the farther away they are from the launch pad. It was also found that if a
water rocket were to explode on the test stand, it is highly unlikely for any shrapnel to exceed a 20 foot radius. From two runs there was twelve shrapnel pieces found, and only one exceeded the 20 foot radius and it only did it by less than 2 feet. Therefore, the 20 foot recommendation given was a very good estimate of the minimum distance people should be away from a water rocket that is under pressure. Hands-on engineering projects are important for K-12 students, but safety must be paramount.
Introduction

This report used the LIFTOFF 2 system single stage design as a case study for the risk assessment. The system design components used in single stage configuration are shown in Figure 1 below.

![Figure 1: LIFTOFF 2 Single Stage Configuration](image)

The ground station design was developed to allow remote, high pressurization of the rocket using an air compressor, pressure regulator, and water pump valve. The water rocket "launch vehicle" was built with a nose cone which housed avionics, camera attachment pointed from the nose towards the pad, a fin / nozzle attachment, and reinforcement for the bottle. The peak acceleration of the water rocket on liftoff was often very high; this level of acceleration was significant in comparison to the harm that it could cause if the water rocket hit a child on liftoff.
This type of kit has enormous potential for outreach to children, especially in less improved school districts such as those found in rural Alabama. This project was used to outreach to a large number of students, as shown in Figure 2.

Figure 2: Collage of STEM Outreach Potential

Because of this outreach potential, it is even more important to ensure the safety of the students that are intended to benefit from the kit.

The two risks investigated, launch pad failure and launch bottle failure, were the enveloping failure scenarios. The maximum impact that the water rocket could deliver to a child would be with the child at zero range on liftoff. This case is more extreme than the secondary failure scenario of the water rocket nosediving from apogee and hitting a child. This is because air resistance reduces impact on descent. Secondarily, the water bottle bursting due to overpressure poses a risk of sending a shard of plastic towards a child, which could cause laceration to the child. These risks were investigated, and the results are presented in following sections of this project report.
Test Procedure

Launch Pad Failure

For the first risk investigation, the launch pad was tested by using the water rocket data from previous launches at schools and previous practice launches. Using this velocity and basic physical equations, the impact force was calculated and the raw data can be found in Table 1. The launch pad was set up normal as it was either during a presentation for the school or a practice test for the schools. Inside the nose cone was a Jolly Logic Altimeter Three to measure the maximum velocity, which is the velocity at liftoff. The amount of fuel, fuel types, and amount of pressure varied throughout the launches, because raw data was used to make it as realistic as possible. Once the velocity was measured, the force of impact was calculated using Equation 3.

Before Equation 3 could be used, it had to be solved using Newton's Second Law, which can be found according to the equation

\[ F = ma \]  

(1)

where \( F \) is the force (N), \( m \) is the mass (kg), and \( a \) is the acceleration.

Next, the acceleration can be broken down into its velocity and time components, which can be found by

\[ a = \frac{v}{t} \]  

(2)

where \( a \) is the acceleration (\( \frac{m}{s^2} \)), \( v \) is the velocity (\( \frac{m}{s} \)), and \( t \) is the time during impact, which was estimated to be about 0.1 seconds.
Finally, the impact force was calculated by substituting Equation 2 into Equation 1, where it can be found according to the equation,

\[ F = \frac{mv}{t} \]  

(3)

where \( F \) is the force, \( m \) is the mass, \( v \) is velocity, and \( t \) is time.

Using Equation 3, the impact force was calculated for all the runs, and the data can be found in Table 1.

<table>
<thead>
<tr>
<th>( v ) (m/s)</th>
<th>30.5</th>
<th>23.2</th>
<th>29.3</th>
<th>21.9</th>
<th>23.8</th>
<th>24.7</th>
<th>10.3</th>
<th>32.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>( F ) (N)</td>
<td>338.3</td>
<td>257.1</td>
<td>324.8</td>
<td>243.6</td>
<td>263.9</td>
<td>274.0</td>
<td>114.1</td>
<td>362.2</td>
</tr>
</tbody>
</table>

Launch Bottle Failure

To determine a safe distance for students to be standing during launch, a 2-liter bottle was put onto the test stand and the pressure was increased until it exploded. The experiment was executed twice with both bottles spray painted a bright pink color so it would be easier to find. The goal was to increase the pressure until the bottles bursted and measure the distances the shrapnel reached. Therefore, a safe distance away to be standing could be determined. There was no water added to the 2-liter bottles, because adding water reduces the amount of potential force in the water rocket. Therefore, leaving the rocket empty would be worse case scenario when it fails. So if the water rocket is presented at schools were to fail, it wouldn't fail as nearly as bad.

The experiment was set up by putting the spray painted 2-liter bottle onto the launch pad. It was attached to an air hose, that was attached to an air regulator, that was attached to a CO2
compressed air tank. The experiment started when the valve on the CO2 tank was turned on completely, and the pressure regulator knob was turned to increase the pressure entering the 2-liter bottle. The pressure was increased until the 2-liter bottles burst. The distance for the shrapnel was then recorded. Figure 3 shows the test stand setup for the experiment.

Figure 3: Launch Pad Setup for Bottle Failure
Results

Launch Pad Failure Results

After finding the average impact force from all the launches, the result was 272.3 N, which is equivalent to 61.2 lbf. That is equivalent of feeling a 61.2 pound weight on top of you, but only for an instant. Therefore, it is unlikely that if the water rocket hit a person it would do serious damage. However, it could bruise someone, especially a small child, and could do more damage if it were to strike someone in the face. Luckily this is worse case scenario, where the person would have to be right next to the launch to experience this much amount of force. More likely is that everybody would be at least 20 feet away from the launch pad, and the impact force would be much smaller.

Bottle Failure Results

The first bottle used in the experiment had two fins attached to it, and it exploded at about 140 psi. The shrapnel that resulted from the experiment was a large chunk of the plastic bottle that can be seen in Figure 4, two fins, and numerous small plastic pieces that were similar in size to the piece that can be seen in Figure 5. The results of the first run of the experiment for the 2-liter bottle failure can be found in Table 2.
Figure 4: Large Shrapnel from Run 1

Figure 5: Small Shrapnel from Run 1

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Table 2: 1st Bottle Failure Results

<table>
<thead>
<tr>
<th>Shrapnel</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fin 1</td>
<td>3ft 4in</td>
</tr>
<tr>
<td>Fin 2</td>
<td>7ft 10in</td>
</tr>
<tr>
<td>Large Bottle</td>
<td>15ft 5in</td>
</tr>
<tr>
<td>Small Piece 1</td>
<td>18ft 3in</td>
</tr>
<tr>
<td>Small Piece 2</td>
<td>21ft 5in</td>
</tr>
<tr>
<td>Small Piece 3</td>
<td>11ft 7in</td>
</tr>
<tr>
<td>Small Piece 4</td>
<td>11ft 5in</td>
</tr>
</tbody>
</table>

Nearly all of the shrapnel was found within 20 feet, except a small piece that was found at 21ft 5 in.

The second bottle in the experiment had no fins attached to it, and it failed when it reached about 160 psi. Similar to the first bottle, the shrapnel that resulted from the explosion was a large chunk of the 2-liter bottle and multiple small fragments. The results of the second bottle can be found in Table 3.

Table 3: 2nd Bottle Failure Results

<table>
<thead>
<tr>
<th>Large Bottle</th>
<th>6ft 11in</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small Piece 1</td>
<td>7ft 0in</td>
</tr>
<tr>
<td>Small Piece 2</td>
<td>13ft 4in</td>
</tr>
<tr>
<td>Small Piece 3</td>
<td>4ft 1in</td>
</tr>
<tr>
<td>Small Piece 4</td>
<td>4ft 7in</td>
</tr>
</tbody>
</table>

All of the shrapnel was found within 20 feet of the launch pad.
Conclusion

Overall, it was found that if a water rocket were to fail from either the launch pad tipping over or the bottle were to burst before launch, it was more than likely nobody would seriously get harmed as long as they were a minimum 20 feet away. The results from the launch pad fail shows that the average impact force from previous launches was 61.2 lb. This is equivalent to a 61.2 pound object resting on a person at rest for a given instant. Therefore, that amount of weight is not likely to do serious damage unless it were to strike a small child or hit a person in the face. Also, the data that was measured was worst case scenario; the person would have to be standing right next to the launch pad for this situation to occur. Since it is required for student to be standing at least 20 feet away in risk mitigation planning, the chances of a child being harmed by shrapnel or impact are very small.

During the bottle failure experiment, both bottles ended up created a large piece of shrapnel in addition to many small pieces. All but one piece of shrapnel stayed within the recommended 20 foot radius. The piece that passed the recommended 20 foot distance was a relatively small piece and exceeded the radius by less than 2 feet. Therefore, the 20 foot minimum requirement was a very good estimate for safety reasons. However, only the shrapnel that was found was measured. So, there could have been more pieces farther than 20 feet that were not located. Overall, the experiments were found to prove that the presentations at the schools were done very safely. Every classroom stood much farther than 20 feet away, and therefore that reduced the risk of getting harm to almost zero. In the future, if students stood at 25 feet, the probability of injury during the LIFTOFF launch is effectively 0.
The impact of this research project is that students, teachers, and UAH personnel can safely enjoy the LIFTOFF project and use the project for learning more about STEM without fear of injury to a child. Operators of the LIFTOFF project should be made aware of pressurization concerns, and understanding of the risks in the event of over pressurization or a misguided launch. In the future, a small first aid kit should be made available for launch pad operators in the event that a failure occurs. It is important that safety protocols are followed, and that the minimum distance requirement is followed. As long as these procedures are not ignored, no child will be hurt, and the project can be safely used to promote interest in STEM.
Acknowledgements

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Thanks to Joey Tittle and Joseph Burns for design support provided as members of the LIFTOFF 2 team.

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