Development of a Laboratory Experiment to Simulate Upper-Stage Rocket Explosions

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Development of a Laboratory Experiment to Simulate Upper-Stage Rocket Explosions

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This report is a summary of the senior project entitled Development of a Laboratory Experiment to Simulate Upper-Stage Explosions. The goal of the experiment was to recreate a NASA experiment which used aluminum soft drink cans to approximate the shape of an Ariane third stage rocket. The cans were placed in a vacuum chamber and fired upon with a projectile from a light gas gun. The resulting debris was collected and analyzed allowing several conclusions to be made regarding the behavior or rocket breakups and the formation of space debris. In lieu of a light gas gun, energy drink cans, fitted with a one-way valve from a bicycle inner tube and filled with a hydrogen and oxygen mixture, are detonated with an Estes model rocket motor igniter. The cans were successfully detonated and aluminum debris was formed in a manner consistent with the predictions of the original experiment. This report describes in detail the preliminary experiments and testing leading to the development of the final apparatus and procedure implemented in the Aerospace Engineering Department's Spacecraft Environment Laboratory.

Nomenclature

H	=	Hydrogen gas
n	=	Number of mols
O	=	Oxygen gas
p	=	Pressure
R	=	Universal gas constant
T	=	Temperature
v	=	Volume

I. Introduction

In the Spring of 2010 the Aerospace Engineering Department's Spacecraft Environment Laboratory class attempted to recreate a NASA experiment simulating the explosion and resulting debris formation of an Ariane upper-stage rocket. The experiment did not produce the desired results. The purpose of this senior project is to re-design the experiment into a viable experiment that accurately represents realistic debris formation from a rocket explosion.

The experiment is modeled after a series of tests conducted by the Hypervelocity Research Laboratory at the NASA Johnson Space Center. The experiments, conducted in the late 1980's, used aluminum soft drink cans to represent upper stage rocket bodies. The aluminum cans were compared to the Ariane upper third stage rocket body.[1] The comparisons were determined to be valid because both the can and the rocket are aluminum cylinders with similar length to diameter ratios and similar radius to thickness ratios.[1] During the experiment, the cans were emptied and either allowed to vent or sealed with air at atmospheric pressure. Both were placed inside a vacuum chamber and shot with a projectile from a light gas gun. The projectile impacted the cans with velocities between 6.5 km/s and 7.0 km/s. The debris formed from the vented of gas remained intact with debris exiting opposite the point of impact.[1] For the vented can, the majority of the mass remained in one piece with the debris representing less than 3% of the initial mass.[1] The cans that were pressurized catastrophically deformed into a few large pieces with very minor fragmentation.[1] It was also determined that for the case of an internal explosion, debris formation will occur in a more normalized and even distribution from all sides of the can.[1]

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Due to the fact that the Aerospace Engineering department does not possess a light gas gun nor a vacuum chamber large enough to serve as a firing range this experiment is limited to the case of internal explosion. Originally the cans were simply filled with a hydrogen and oxygen mixture and ignited with an Estes model rocket motor igniter. This produced little more than a small popping sound, paint chips and burnt aluminum. It was decided that in order to achieve more violent combustion and the formation of debris the cans would need to be sealed and the proper stoichiometric ratio would need to be determined. After several failed attempts where various cans were filled with a hydrogen and oxygen mixture and then sealed it was decided that the cans would not only need to be sealed but also pressurized with the proper volatile mixture. This led to the development of the final apparatus which consisted of a energy drink can with a removable lid. A one-way valve from a bicycle inner tube was inserted through the cap and the entire can was sealed with epoxy. The can was filled with a proper mixture of hydrogen and oxygen and the can was successfully detonated producing debris consistent with that predicted by the NASA experiment.

II. Determining the Stoichiometric Mixture Ratio

This experiment focuses on the case of internal combustion. To create the explosion the cans are filled with a hydrogen and oxygen mixture. The optimum mixture rate, which provides complete combustion of the fuel and oxidizer, is given by the equation

$$2H_2 + O_2 \rightarrow 2H_2O \tag{1}$$

where H_2 is hydrogen gas, O_2 is oxygen gas and H_2O is water vapor.[2] In order to produce this mixture inside the can, it should be filled with twice the number of mols of hydrogen as oxygen. The relative pressures required can be found by utilizing the ideal gas equation

$$pv = nRT \tag{2}$$

where p is pressure, v is volume, n is the number of mols, R is the universal gas constant, and T is temperature.[2] Holding volume and temperature constant it can be seen that to obtain the two to one hydrogen to oxygen ratio, the relative pressure inside the can from hydrogen must be twice the relative pressure increase from the oxygen.[2]

III. Initial Testing

Four different series of tests were performed before the desired results were seen and the final apparatus was decided upon. Each series of tests took the results from the previous tests and expanded and improved upon them.

A. The First Series of Tests

The first series of tests for the project was performed on Tuesday, November 2nd. Several large Rockstar energy drink can were used to represent the rocket body. The large Rockstar can was decided upon because it can be easily sealed as it possesses a resalable cap. The H_2 and O_2 tanks were connected to two hoses from an oxy-acetylene torch. Two short copper pipes were inserted into the ends of each hose. The copper pipes could then be easily inserted into the can. An Estes brand model rocket motor igniter was placed inside the can to ignite the mixture. A volumetric flow meter was not available so the two to one hydrogen to oxygen flow rate was approximated by adjusting the pressures of hydrogen and oxygen to the two to one ratio. The inside of the can was filled with the H_2 and O_2 mixture and the can was immediately sealed. The thread was lined with Teflon tape to increase the effectiveness of the seal. This was necessary because the wires connecting the igniter to the power supply interfered with the seal. A containment box was constructed out of a cardboard shoebox and Styrofoam. The hope was that the box would contain the blast and the aluminum fragments would imbed themselves in the Styrofoam allowing them to be easily collected.

The first test produced exciting, but misleading results. When the igniter was activated there was a loud bang, and the containment box flew apart. Upon examining the blast area, it was discovered that the cap had popped off of the can and acted like a rocket, blasting through the container. No metal deformation occurred.

For the second test a large c-clamp was found and used to hold the cap on the can hopefully forcing the explosion out the sides. The test was prepared in the same manner as test 1 with the addition of the c-clamp. There was a faulty connection in the ignition system, preventing ignition. Tape was placed around the connection to prevent faulty connections. The test was prepared again in the same manner as before. The system was detonated and there was a small pop. Examining the can revealed that the can was hot, almost too hot to handle with bare hands. Tests 3 and 4 were repeated in this same manner and yielded the same results. It was determined that an explosion did occur, causing the pop and the increase in heat however the explosion did not create a great enough pressure increase to rupture the can.

While the first series of tests did not produce the desired results, it allowed for several improvements to be made and confirmed that a sealed can could be used for this experiment allowing the explosion to be completely separated from the gas supply.

B. The Second Series of Tests

For the second series of tests, the results from the first series of tests were examined and several different approaches were decided upon. Since the flow of the hydrogen/oxygen gasses could not be controlled precisely, the flow rates were adjusted based on pressure so that the hydrogen flow was roughly twice that of the oxygen flow. However the flow rates were higher than expected and it was believed that the higher flow rate of hydrogen displaced the oxygen causing too rich of a mixture inside the chamber. To determine whether or not this was occurring, the flow rates were reduced and equalized so that the mass flow rate of the hydrogen was approximately equal to that of the oxygen. Latex gloves were placed over the ends of each pipe, if they inflated at roughly the same rate, the mass flow rates were considered to be equal. The ignition source was prepared and Rockstar energy drink can was filled with the mixture, after the flow was allowed to fill the can for several seconds, the pipes were pulled out and the can was sealed. The can did not burst as a result of the explosion. As in the first series of tests, a "pop" was heard followed by the sounds of creaking metal. It was discovered that despite the increase in heat, the decrease in the total number of mols of gas produced a decrease in pressure preventing the can from exploding.

For the second, third, and fourth tests, large Fosters "oil-drum" beer cans were used. It was speculated that the larger volume combined with the shorter, stouter shape of the can would cause a more concentrated explosion causing the can to rupture. For the second test the Fosters can was prepared with the igniter the can was filled with the hydrogen/oxygen mixture roughly adjusted to the two to one ratio. The can was allowed to fill for approximately 30 seconds and it was capped. Unlike the energy drink cans used in the first test, the Foster's can does not have a threaded top. A cap was improvised by epoxying a bolt to the inside of a washer. This created a solid disk, which was then covered with epoxy to aid in the formation of a tight seal. This cap was placed on the can and then held down with a large c-clamp. The mixture was ignited and a loud pop was heard. Upon examining the can it was seen that the expanding gas escaped through the side of the cap where the igniter wires protruded from the cap showing that there was not a tight enough seal around the wires. The fourth test was prepared in the same manner except the wires were flattened and separated to minimize their interference in the forming of a tight seal. Once the can was filled and capped, the epoxy was allowed to settle for a few minutes. The c-clamp was again placed over the cap and the igniter was fired. Unfortunately there was no explosion. This was possibly due to a faulty igniter or the possibility that during the time allowed for the epoxy to dry the chemical reaction slowly occurred reducing the explosive mixture to inert water vapor.

The fourth test was prepared with the Foster's can in a similar manner as in test number four. The alligator clips connecting the wires to the igniter inside the can were covered with tape to prevent a short from occurring. The wires are laid flat across the opening and the cap was placed. The epoxy was not allowed to settle for a significant amount of time to prevent the reaction from occurring prematurely. When the system is ignited, a loud pop was heard, followed by the sound of the metal contracting. Examining the can revealed no fragmentation. This confirmed that the explosion does not produce enough of a pressure increase to cause the can to burst. After the initial explosion, the can cools and decreases in pressure causing the can to compress.

The fifth and final test for the day utilized a Rockstar energy can prepared a few days before. A hole was drilled in the top of the can and a one-way Presta valve from a bicycle inner tube was inserted into the hole. Epoxy was generously applied to the cap to seal the opening where the valve was inserted. An igniter was placed into the can and the cap was placed on and sealed with epoxy. During the test the can was filled with oxygen by holding the valve against the oxygen hose and then vented. This was repeated three or four times to purge the residual atmospheric gasses form the inside of the can. The can was then pressurized with hydrogen and then with oxygen one last time. There was a small leak near the cap however the test was continued. The wires protruding from the can were immediately connected to the ignition source and the mixture was ignited. There was a significantly louder sound and smoke was immediately visible. Upon examining the can, a hole near the was found. This is likely where the leak was; however this is the first test that significantly ruptured the can.

C. The Third Series of Tests

It was decided that the pressurized can was the most likely to produce the desired explosion. As a result, the third series of tests expanded on the pressurized can test from the previous series of tests. Two test cans were constructed from Rockstar energy drink cans in a manner similar to the can in the previous test. Unlike in the previous test, where the cap was sealed around the wires, two small holes were drilled in the cap and the wires were inserted through the top of the cap. Quest brand model rocket motor igniters were used instead of the Estes igniters. An air chuck from an air compressor hose used to inflate tires was connected to the hoses from the hydrogen and oxygen tanks. The fitting is for a Schrader valve so a Schrader to Presta adapter also had to be used. The fitting was also threaded with the standard right handed thread. The hydrogen fuel hose has a left handed thread. The fitting had to be attached to the hydrogen hose with duct tape.

The cans were pressurized with a two to one hydrogen oxygen mixture, however no ignition occurred for either can. Upon examining the igniters closely it was decided that the Quest igniters were unable to produce enough heat under pressure to ignite the mixture.

D. The Fourth Series of Tests

The fourth and final series of tests expanded on the pressurized cans used in the third series of tests. Comparing the Estes igniters to the Quest igniters revealed that the Estes igniters create more heat and essentially glow red hot to ignite the motor while the Quest igniters heat up a small filament and rely on a black powder to ignite the motor. It was hoped that the Estes igniters would generate enough heat to ignite the pressurized mixture. Four Rockstar energy drink cans were prepared, each with a Presta valve and two Estes igniters. A redundant igniter was added and each of the igniters were soldered together in order to decrease the likelihood of a faulty connection. As in the previous tests, the cap was epoxied shut. The four cans and redundant igniters would allow for up to eight different pressures to be tested if necessary.

The first can was pressurized and vented several times with hydrogen gas. This removed any remaining nitrogen and oxygen from the can. The can was pressurized to approximately 30 psia (15 psig) with hydrogen gas and to 45 psia (30 psig) with the remaining oxygen gas. The igniters were connected to the power supply and the can was placed into the cardboard and Styrofoam container. The igniter was activated and after several seconds a very loud explosion occurred. The can blew apart into several fragments destroying the containment box along with it.

For the second test the pressures of each gas were lowered significantly. The can was filled and vented several times with hydrogen gas and left at a final pressure of 14.7 psia (0 psig) and then filled to approximately 22 psia (7 psig) with oxygen gas. Another Styrofoam container was used to attempt to contain the explosion. This can mixture successfully ignited and fragmented the can into several large pieces again destroying the Styrofoam container.

For the third test, the pressures were lowered even more. The can was pressurized and vented with hydrogen gas several times and then filled to 22 psia (7 psig) with oxygen. The can was then vented back to atmospheric pressure. It was assumed that the relative pressures of hydrogen and oxygen were 10 psia and 15 psia respectively. Upon igniting the mixture, a pop was heard and then the can contracted in on itself. This is a result of the nature of the chemical reaction. As in previous tests there was not a significant enough pressure increase to rupture the can and once the reaction was complete the mixture immediately began to cool.

It was decided that the lowest pressures able to produce the desired explosion were the pressures from the second test. The fourth test was conducted under the same conditions as the second test with the exception of the Styrofoam container. The container was determined to be futile as the explosions which ruptured the can destroyed the container. The can was successfully exploded and the debris was able to be collected from the test area despite the absence of the container.

IV. Final Apparatus and Procedure

The final apparatus and procedure used in the Spacecraft Environments laboratory was derived from the fourth series of tests. A list of materials needed to prepare and test the cans can be found in Appendix A. The cans were constructed by taking an empty Rockstar energy drink can and drilling a hole in the center of the cap. The hole is sized to match the one-way Presta or Schrader valve from a bicycle inner tube, because of the adapter, either type of valve can be used. The hole should be sized so that the valve fits tightly. Four small holes are then drilled in the top of the cap, these holes allow the ignition wires to be fed through the top of the cap.

Each can uses two Estes brand rocket motor igniters. Each igniter is prepared by soldering a wire approximately eight inches long to each end. The direction the electrical current travels though each igniter does not matter so in order to avoid confusion between igniters the first igniter should use one color wire for both of its connections and the redundant igniter should use another color wire for both of its connections.

Once the wires are soldered, the valve and the wires can be inserted. The valve should be inserted to that gas can flow into the can but not out once it is sealed. The wires should be inserted so that the igniter will be inside the can near the middle. It is important to make sure the igniters do not come into contact with each other or the inside of the can. Twisting all four wires together increases their rigidity and prevents them from moving. After the wires and valve are in place, a generous amount of epoxy must be applied to the inside of the cap. Care should be taken to cover each hole and the edges of the cap with epoxy as this will insure an airtight seal. After the cap is sufficiently epoxied, the cap should be placed on top of the can and tightened down with care taken to make sure the cap is tightened down around the threads. The can should then be allowed to sit upside down for a period of 24 hours. This allows the epoxy to fully harden and form its seal. The existence of an airtight seal can be verified using a bicycle pump. Each can was colored into five longitudinal strips with a permanent marker, this allows for the origin of each fragment to be compared to its final location after the explosion. Once the can has been constructed and the epoxy has been allowed to dry, the mass was taken. This will be used later to determine what percent of the can was collected after the explosion. Figures 1-3 all depict the test can described above. Figure 1 is a cutaway view schematic of the test can. Figure 2 is a photograph of a completed can fitted with a Schrader valve and Fig. 3 is a photograph showing the internal wiring of the can, the redundant Estes igniters can be seen.

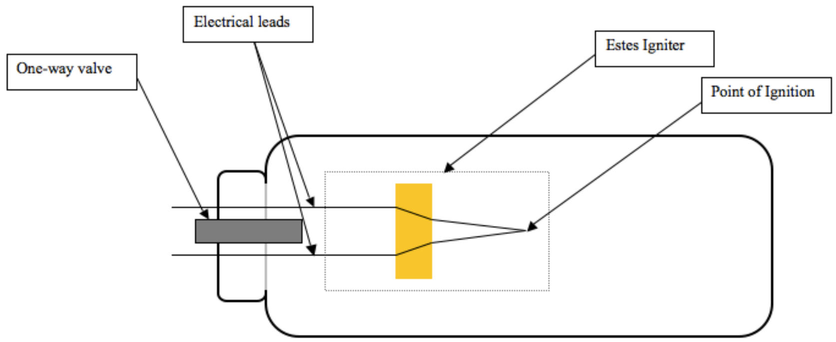

Figure 1. Schematic showing a cut away view of the can test apparatus. Note that the redundant igniter is not shown.

Figure 2. Photograph showing a completed test can.

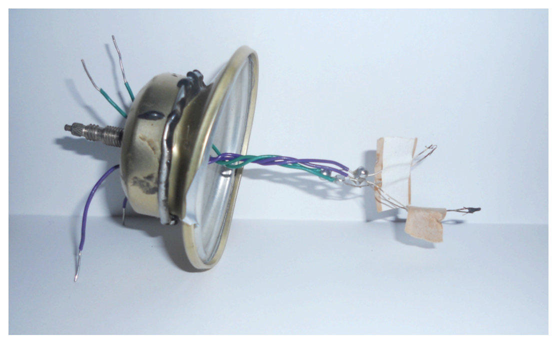

Figure 3. Photograph showing internal wiring of the test can.

Once the cans have been prepared and the epoxy has been allowed to sit, the final preparation and testing can begin. To begin filling the cans the oxy-acetylene hoses were attached to both the hydrogen and oxygen regulators and the air chucks. The hydrogen regulator was closed completely and the tank is slowly opened. Care was taken to make sure the area in front of the regulator was clear as a faulty regulator can cause harm. The regulator was slowly opened, once flow began the can was filled with the hydrogen gas. The can was then vented back to atmospheric pressure. This process was repeated several times to remove any trace gases from the can. The hydrogen tank and regulator was closed and the oxygen tank and regulators were opened in the same manner. The can was then filled with oxygen to approximately 7 psig (22 psia) creating the approximate two to one hydrogen oxygen mixture. The area was evacuated and the igniter was attached to the power supply. Once the area was secure and all individuals were wearing ear and eye protection the mixture was ignited. In several tests, the power supply had to be activated several times before ignition occurred. Once the can exploded the debris was collected with attention being paid to the final location of each fragment. The mass of each collected piece was collected for comparing to the original mass.

V. Discussion of Results and Possible Improvements

The final apparatus and procedure implemented in the laboratory experiment successfully created the desired explosion and aluminum fragmentation. The debris formed in large fragments and were propelled outward from the center of the can. This pattern is consistent with the predicted debris formation from an internal explosion.[1] Figure 2 is a photograph showing the debris collected from the first successful test. During the laboratory class the students were able build and explode the cans and collect the debris, measure the mass and calculate the cross sectional area of each fragment and draw conclusions about the behavior of debris formation.

While this experiment was a success there are several improvements which can be made. During the laboratory tests, several cans did not form an air tight seal because the one-way valves were faulty. The valves should be checked prior to construction to insure that the valves are in working order. Several cans also failed because the lids were not tightened down when the epoxy was applied. Preparing the cans further in advance and allowing a day to check the airtight seal and apply more epoxy if necessary would help prevent the test cans from failing.

Figure 2. This photograph shows the debris collected after the first successful test.

One concern with debris testing is that the testing environment affects the formation of the debris. This effects of the testing location and environment were clearly seen during these tests. The fragments created from the can near the ground were flattened by the explosion while the other fragments formed irregular shapes similar to those seen in Fig. 2. There were also several instances where the debris impacted an obstacle in the testing area causing it to change direction. Wind also affected the final location of the debris as several fragments were blown around before they could be collected. There are several possible solutions to mitigate these testing environment effects. Suspending the can prior to ignition, possible hanging it from the valve at the top of the can, would eliminate the flattening effects caused by the cans close proximity to the ground. A containment mechanism which could withstand the pressure change from the blast and allow the debris to imbed itself in the walls of the container would prevent any obstacles or wind from affecting the trajectories of the fragments. The container however would likely cause the debris to deform differently than if left in the open. A soft layer, possibly made out of aerogel, ballistics gel, or Styrofoam, backed by a solid casing capable of withstanding the blast could possible collect the debris and minimize the impact effects.

VI. Conclusion

This senior project successfully redesigned the particulate experiment for the Aerospace Engineering Department's Spacecraft Environments laboratory class. Through trial and error, the experiment was redesigned to simulate the explosion of an upper-stage Ariane rocket. The final apparatus, when filled with an explosive hydrogen and oxygen mixture and ignited, explodes and creates debris in a manner consistent with the predictions from the NASA Johnson Space Center Hypervelocity Research Laboratory.

Appendix

Appendix A

Table 1. This table contains complete list of equipment, tools, and materials needed for the construction and explosion of a single test can apparatus.

Materials for Preparation	Tools for Preparation	Materials for Testing	Equipment for Testing
Large Rockstar can with re-sealable lid	Drill	Alligator clips for repairs to power supply	Oxygen Tank and Regulator
Epoxy (Metal epoxy rated to 3200 psi)	Drill bits of various sizes	Duct tape	Hydrogen Tank and Regulator
Red and Black electrical wires	Soldering iron		Oxy-Acetylene hoses to connect to regulators
2 Estes Igniters	Wire Cutters		2 Air Chucks
Presta or Schrader valve	Wire Strippers		Presta/Schrader Adapter
Solder			Pressure Gauge
		Calipers	2 igniter power supplies
		Scale	Box or tray to collect debris

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