

# OPTIMIZATION OF AMMONIUM NITRATE SOLID ROCKET FUEL

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by

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# OPTIMIZATION OF AMMONIUM NITRATE SOLID ROCKET FUEL

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Brigham Young University - Idaho 2013

The purpose of this ongoing research is to optimize an ammonium nitrate based rocket fuel with a goal of future use as a sub-orbital rocket propellant. Ammonium nitrate based fuel was chosen based on certain qualities, not the least of which being that it is a lesser understood rocket fuel allowing for original research opportunities. Ammonium nitrate fuels are non-toxic because the exhaust fumes are naturally occurring gases, mostly water vapor. An ideal rocket fuel burns all of the reactants very quickly and at high temperatures (1500 - 3500 Kelvin), releasing a lot of energy in a very short time. In theory, the greatest energy output during combustion would provide peak performance, for that reason theoretical products were considered in balancing the chemical equation in order to make predictions for maximum enthalpy outputs. These theoretical calculations were compared with experimental data acquired with student designed and built lab equipment, such as a bomb calorimeter. Varying proportions of the reactants were tested and compared to isolate the peak energy output while minimizing solid waste to ensure that all of the reactants were consumed during combustion. The optimized rocket fuel will be tested in future research with a student built linear burn rate measuring device (strand burner). Research to follow in the near future includes accumulation of burn rate measurements which will be used to calculate solid rocket motor dimensions.

This document is dedicated to all Brigham Young University - Idaho undergraduate students, and to everyone who thinks that rocket science is the most difficult field of all.

## ACKNOWLEDGEMENTS

Special thanks go to David Oliphant and Schyler Porter, the team that got this research started, to Russell Daines for teaching me what a technical paper is supposed to be, but mostly to my wife who has been patient with my 'second lover' - physics.

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# CHAPTER 1

## INTRODUCTION

### 1.1 Purpose

The purpose of this ongoing research is to optimize an ammonium nitrate based rocket fuel with a goal of future use as a sub-orbital rocket propellant. Rocket fuel is a mix of multiple chemical components that simultaneously combust in an explosive reaction which is used to propel a rocket, where an explosive reaction is taken to be an exothermic reaction that emits large amounts of energy very quickly, hundreds of kilojoules per second. Multiple components are necessary to initiate combustion, which will consume as much of the reactants as possible, as quickly as possible [5] [4] [11] [10]. More of these reactants must be produced simultaneously in order for the process to be sustained over time. One of these essential components is oxygen, a gas, which is quickly consumed during ignition. This makes it necessary to include an oxidizer in any rocket fuel which produces more oxygen for the explosive reaction as it combusts.

### 1.2 Why Ammonium Nitrate

Ammonium nitrate based fuel was chosen based on certain qualities, one of which being that it produces oxygen during combustion, allowing the fuel to continue burning. Ammonium nitrate fumes are all naturally occurring gases, mostly water vapor, that are non-toxic and will not harm the environment or leave traceable pollutants. These fumes are transparent, making it a valuable

fuel for military suppliers because the transparency decreases visibility. Ammonium nitrate is commonly used worldwide for many purposes, mostly fertilizer, making it readily available in multiple forms at reasonable prices [6]. Sounding rockets, or rockets designed for the conducting of experiments, are often required to reach very specific altitudes. It is easier to make fine-tuning adjustments to ammonium nitrate based fuels in order to reach those required altitudes because it has a relatively limited range of burn rates. Another valuable quality is that it is a lesser understood rocket fuel with little publicized credible research, allowing for many original research opportunities.

### **1.3 Current Research**

Though ammonium nitrate has been studied extensively for its uses in other fields (fertilizers, cold-packs, fuel enhancer, etc.), research to date of ammonium nitrate with aluminum as ingredients in solid rocket fuels is either unpublished or for exclusive audiences only. One amateur rocket enthusiast, Richard Nakka, has posted extensive non-accredited research on the subject of ammonium nitrate solid rocket fuel with aluminum as an additive [14], while accredited research simply states that aluminum functions suitably as a catalyst, but magnesium is more effective [15] [3]. This absence of information allows for original research that can be built upon with more and more original work.

## 1.4 Necessity of Additives

Ammonium nitrate is a low-energy, hygroscopic chemical that will not burn unaided, thus necessitating the use of a catalyst, or additive [10] [7] [9] [4]. The most common and effective additive for ammonium nitrate based fuels is magnesium. This is because of magnesium's high burn temperature and also its reaction to water while burning. Magnesium was not used in this experiment for several reasons, one of them being that magnesium as an additive is highly researched and published, not allowing the opportunity to expand world knowledge. Magnesium was also rejected as the additive of choice because it would expand the limited range of burn rates, thereby making it more difficult to engineer formulas for very specific performances. The effects of other additives on ammonium nitrate have also been tested and studied, though not for propulsion purposes. For example, a range of chlorides were used to study their effect as a dampening agent to aid in accidental explosion prevention [10].

## 1.5 Why Aluminum

The simultaneous burning of ammonium nitrate and aluminum produces complementary reactions that help produce an effective sounding rocket fuel. Ammonium nitrate requires a threshold energy to initiate and sustain the decomposition process. If ammonium nitrate were to begin combustion alone, the products of decomposition would terminate the reaction. The presence of aluminum raises the temperature of the reaction so that the ammonium nitrate will continue to ignite. Oxygen is a product of ammonium nitrate decomposition, which aids the burn of aluminum while increasing the temperature [11] [4]. To-

gether, these ingredients produce an energy output large enough for use as a rocket propellant. The burn rate should be less than that of other metallic ingredients [15]. This is a beneficial characteristic of sounding rocket fuels because it helps make fine-tuning adjustments to motor performance in order to achieve specific outcomes, such as desired air speeds or a target altitude.

## **1.6 Why Sulfur**

Sulfur is an essential ingredient needed to sustain the burn of aluminum. Aluminum in its pure form readily burns and produces large amounts of energy. Pure aluminum is not readily accessible because it oxidizes rapidly, creating an aluminum oxide layer on the surface [3]. This layer must be burned through in order to ignite the pure aluminum beneath. Sulfur burns at a high enough temperature that burning a small amount is enough to accomplish this [14]. The specific enthalpy of sulfur is very low, three orders of magnitude less than that of ammonium nitrate, and its contribution to the overall energy produced from the rocket fuel is negligible.

## CHAPTER 2

### METHODS AND MATERIALS

#### 2.1 Optimization

To find the ideal solid rocket fuel formula, varying proportions of the reactants must be tested to isolate the one that produces the highest energy output. This energy output directly translates into thrust force when the fuel is used in a rocket motor. It is beyond the scope of this research to ensure that any formulas studied are, in fact, the best possible. With the time allotted to this research, a very good formula can be isolated, and if it is not the best possible it will establish a lower boundary to a range of performance levels in which the best possible formula would perform [8].

#### 2.2 Bomb Calorimeter

The common method for measuring energy output of combustion is by using a bomb calorimeter; a tool in which the formula is ignited and the heat dissipates through a stainless steel container into a small pool of water. The temperature change of the water is indicative of the energy produced by the reaction, as applied in the Specific Heat Capacity Equation:

$$Q = mc\Delta T \quad (2.1)$$

where  $Q$  is the energy produced,  $m$  is the mass of the medium through which

the energy passes,  $c$  is the specific heat of that medium, and  $\Delta T$  is the temperature change measured on the far side of the medium relative to the energy source. In this study two masses were measurable: the mass of the bomb, and the mass of the water. The bomb calorimeter used in this experiment is student-built and has many intricate parts. To account for these unmeasurable parts and unavoidable energy losses, the calorimeter must be calibrated. This is done by igniting a substance within that has a known energy output. The calibrating substance used here was Hornady® rifle powder with a known energy output of  $2 \text{ kJ/g}$ . Using this information we can find a dimensionless value that corrects calculations.

$$Q = \beta(m_w c_w + m_{ss} c_{ss}) \quad (2.2)$$

where  $\beta$  is the dimensionless correction coefficient,  $m_w$  is the mass of the water,  $c_w$  is the specific heat of water,  $m_{ss}$  is the mass of the bomb, and  $c_{ss}$  is the specific heat of stainless steel. After ten tests with the Hornady® rifle powder, the  $\beta$  value was averaged and the uncertainty taken to be the standard deviation of the ten test values. The values for the variables used in Equation 2.2 are given in Table 2.1.

### 2.3 Balancing the Chemical Equation

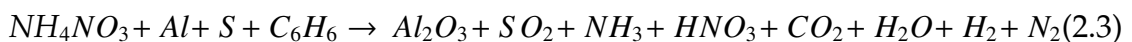
With the calorimeter ready to take measurements, it is only left to decide which formula to test. With only Richard Nakka's [14] unaccredited research to give any indication, we decided that his recipe was better than a shot in the dark. His recipe burned well but left a substantial amount of solid waste. If a formula

Variable Name	Variable	Value	Uncertainty
Beta	$\beta$	1.07	0.01
Mass of the Water	$m_w$	2.610 kg.	0.0005 kg.
Specific Heat of Water	$c_w$	4.1813 $\frac{kJ}{kg.K}$	-
Mass of the Bomb	$m_{ss}$	4.95 kg.	0.07 kg.
Specific Heat of Stainless Steel	$c_{ss}$	0.50 $\frac{kJ}{kg.K}$	-
Change in Temperature	$\Delta T$	To be measured	0.02 K

Table 2.1: Variables with Uncertainties

could be found that did not leave solid waste behind it would indicate that the fuel in its entirety was used to create gas products, being more effective than any fuel with leftover solid mass.

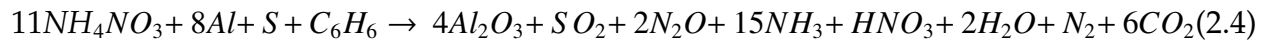
The initial formula was derived from the following unbalanced theoretical chemical equation:



which shows all of the known possible products. Knowing that ammonium nitrate produces more energy during combustion than any of the other reactants, the formula that produces the most energy will be made mostly of ammonium nitrate. Aluminum will be the ingredient with the second highest percent presence in the formula. Sulfur and binder contents will be minimal, maximizing the amounts of the other two ingredients. These parameters were used in a multi-dimensional equation with multiple unknown relationships, thereby having an



infinite number of solutions. Through trial and error several possible solutions were found and the most probable was selected to be the starting formula for experimentation.



This equation is not taken to be the hypothesized ideal formula, but a starting point for experimentation that will be adjusted throughout research until the energy produced reaches a peak amount.

## 2.4 Uncertainty

### 2.4.1 The Need for Uncertainty

The uncertainty of measurement is always an essential component for communicating data values. At times those uncertainties are of such a nature that the collected data may be rendered useless. In a theoretical calculation to predict energy outputs of specific formula combustion, it is impossible to consistently produce predictions that exactly match values measured experimentally. It is, however, possible to come within a margin of error of those values. In these situations it is shown by the overlapping of uncertainties that the calculated data coincides with the measured data, demonstrating that the equation governing the predictions is an accurate reflection of reality.

## 2.4.2 Potential Faults in Uncertainties

The overall uncertainty of any calculated prediction is a combination of uncertainties in measurements of the parameters that determine the output of the predicting equation. When there are few parameters that can be measured with relative accuracy, the overall uncertainty will give a reasonable margin of error, in that the uncertainty contributes to understanding of results. However, if there are too many parameters that cannot be measured accurately enough, the overall uncertainty becomes so large that large faults in the predicting equation cannot be observed because the erroneous outputs will lie within the margin of error, suggesting that the equation is accurate enough.

## 2.4.3 Approximated Uncertainty

The  $\chi^2$  method of calculating uncertainty is a widely used and trusted method. It can be fairly involved and require many intermediate calculations. There is a simplified approximation of the  $\chi^2$  method that only involves one calculation, though at the cost of losing useful insight given by the results of intermediate calculations. This equation may be correctly used for calculating the uncertainties of values from equations involving only simple mathematical operators, i.e. addition, subtraction, multiplication and division. Equation 2.5 will be used to calculate the uncertainty of the output of Equation 2.2, which only uses simple mathematical operators, thereby qualifying use of Equation 2.5

$$u_{net} = (u_w^2 + u_{ss}^2 + u_\beta^2 + u_T^2)^{1/2} \quad (2.5)$$

where  $u_w$  is the uncertainty of the measured mass of the distilled water,  $u_{ss}$  is the uncertainty of the measured mass of the stainless steel bomb,  $u_\beta$  is the uncertainty of the  $\beta$  coefficient,  $u_T$  is the uncertainty of the measured temperature change, and  $u_{net}$  is the net uncertainty of the calculated energy output. Applying this equation to the uncertainties of the values given in Table 2.1, we find that the overall uncertainty of each calculated energy output is  $\pm 0.07$  kJ, or 70 J.

## CHAPTER 3

### RESULTS AND DISCUSSION

#### **3.1 Data Acquisition**

There were unforeseen constraints on time caused by complications with nearly every aspect of the experiment, which limited the amount of experimentation which could be done. Within this limited time frame, fourteen successful tests were conducted, with the term successful meaning that information was gained by the results, or lack thereof. With a larger time frame, the conclusion of this experiment could be more supported with additional evidence of any or all claims, or disproved with contradictory evidence.

#### **3.2 Evacuating the Bomb**

Conditions within the bomb were designed to simulate those that would be found within the motor of a rocket so that experimental results would reflect the performance of the fuel within a rocket motor. Initially, the bomb was evacuated so that the fuel would only burn with reactants that it produces itself during combustion. Of the test conducted with an evacuated bomb, tests 1 and 5 did not ignite, and those that did ignite took approximately 20 seconds to do so [See Table 3.1 on page 13]. Tests conducted without evacuating the bomb all ignited within 10 seconds. After consideration of the setup, it was concluded that evacuating the bomb did not simulate ignition conditions because a rocket motor would be open to the atmosphere, providing oxygen and other chemicals

that assist ignition.

### 3.3 Judgement Call

It was difficult to distinguish exactly which formula produced the best results with the data collected for the various tests conducted, largely due to the similarity of results. The best results were seen in fuels #6 and #7, where average energy outputs were 6.73 kJ and 6.57 kJ, respectively. These fuels both had the same amount of sulfur in their formula, but the difference was in the ratio of ammonium nitrate to aluminum, where fuel #6 had 0.265 grams of aluminum per gram of ammonium nitrate and fuel #7 had .249 grams [See Table 3.1 on page 13]. When these tests are magnified to larger scales and full sized fuel cells are burning, the slight differences seen here may or may not be magnified. In either case, fuel #6 produces more energy, though the margin of difference at full scale is unknown.

### 3.4 The Optimized Formula

The initial balanced chemical formula had a calculated enthalpy change of 6.4 kJ. There may be multiple reactions occurring simultaneously; however, the intermediate reactions can be ignored as per Hess' law which states that "the enthalpy change accompanying a chemical change is independent of the route by which the chemical change occurs" [12]. The best performing fuel was not the initial formula and produced an average enthalpy change of approximately 6.73 kJ, exceeding expectations, though not so much as to give reason to doubt the

Test	Composition	Results
Test 1 Fuel #1 Evacuated	7.7358 g. NH <sub>4</sub> NO <sub>3</sub> 0.7448 g. Al 0.4425 g. S	Did not ignite
Test 2 Fuel #2 Evacuated	7.2900 g. NH <sub>4</sub> NO <sub>3</sub> 1.7000 g. Al 0.2000 g. S	7.66 kJ/g Solid product remains Ignition $\approx$ 23 sec.
Test 3 Fuel #3 Not Evacuated	7.4984 g. NH <sub>4</sub> NO <sub>3</sub> 1.7890 g. Al 0.2657 g. S	6.54 kJ/g Minimal solid product remains Ignition $\approx$ 10 sec.
Test 4 Fuel #4 Not Evacuated	7.4984 g. NH <sub>4</sub> NO <sub>3</sub> 1.5890 g. Al 0.2657 g. S	6.13 kJ/g Incomplete Burn Ignition $\approx$ 11 sec.
Test 5 Fuel #5 Evacuated	7.3984 g. NH <sub>4</sub> NO <sub>3</sub> 1.8890 g. Al 0.2657 g. S	Did not ignite

Table 3.1: Experimental Results

Test	Composition	Results
Test 6 Fuel #5 Not Evacuated	7.3984 g. NH <sub>4</sub> NO <sub>3</sub> 1.8890 g. Al 0.2657 g. S	6.46 kJ/g Minimal solid product remains Ignition $\approx$ 6 sec.
Test 7 Fuel #6 Not Evacuated	7.4984 g. NH <sub>4</sub> NO <sub>3</sub> 1.9890 g. Al 0.0657 g. S	7.20 kJ/g No solid product remains Ignition < 5 sec.
Test 8 Fuel #6 Not Evacuated	7.4984 g. NH <sub>4</sub> NO <sub>3</sub> 1.9890 g. Al 0.0657 g. S	6.75 kJ/g No solid product remains Ignition < 3 sec.
Test 9 Fuel #6 Not Evacuated	7.4984 g. NH <sub>4</sub> NO <sub>3</sub> 1.9890 g. Al 0.0657 g. S	6.48 kJ/g No solid product remains Ignition < 5 sec.
Test 10 Fuel #6 Not Evacuated	7.4984 g. NH <sub>4</sub> NO <sub>3</sub> 1.9890 g. Al 0.0657 g. S	6.48 kJ/g No solid product remains Ignition < 5 sec.

Table 3.2: Experimental Results(Continued)

Test	Composition	Results
Test 11 Fuel #7 Not Evacuated	7.5984 g. NH <sub>4</sub> NO <sub>3</sub> 1.8890 g. Al 0.0657 g. S	6.81 kJ/g No solid product remains Ignition $\approx$ 5 sec.
Test 12 Fuel #7 Not Evacuated	7.5984 g. NH <sub>4</sub> NO <sub>3</sub> 1.8890 g. Al 0.0657 g. S	6.50 kJ/g No solid product remains Ignition $\approx$ 5 sec.
Test 13 Fuel #7 Not Evacuated	7.5984 g. NH <sub>4</sub> NO <sub>3</sub> 1.8890 g. Al 0.0657 g. S	6.41 kJ/g No solid product remains 5 sec. < Ignition < 10 sec.
Test 14 Fuel #8 Not Evacuated	7.4984 g. NH <sub>4</sub> NO <sub>3</sub> 1.9890 g. Al 0. g. S	Did not ignite

Table 3.3: Experimental Results (Continued)

credibility of the data.



### 3.5 Uncertainty of the Chemical Reaction

We can only know that the desired energy output lies within a certain range because it cannot be certain that the optimal formula was found. It can be certain that the energy we calculated is possible; therefore we can set it as a lower extremity to the range of possible optimal energies. To find the higher extreme, the chemical equation can be manipulated without balance so that the percentage of high energy output chemicals is maximized and the others minimized. There is no chemical arrangement that would create higher energies. To do this, ten grams of ammonium nitrate were mathematically 'burned' to 'create' ten grams of aluminum oxide ( $\text{Al}_2\text{O}_3$ ). This resulted in an enthalpy change of approximately 27 kJ, which may be set as the maximum limit.

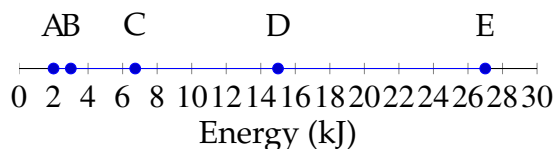


Figure 3.1: A scale of energies. Point A is the energy content of the Hornady® rifle powder [1]. Point B is the energy content of traditional black powder [2]. Point C is the energy content of Fuel#6 as found in experimentation. Point D is the energy content of TNT [13]. Point E is the energy content of the maximum limit as mathematically predicted.

## CHAPTER 4

### CONCLUSION

Results of this study were limited by the quality of measurements and time constraints which resulted in a broad understanding of the relationship between the formula composition and energy performance. More precise measurements would decrease the margin of error of the measured values, allowing for comparisons with theoretical values. Comparing theoretical values would be used to derive the mathematical equation that represents the physics of the tests. More time would allow for more tests to produce more data points which would be used to quantify the relationship between the formula composition and energy production. These relationships can be combined into a multidimensional equation with an overall maximum. This maximum represents the optimum rocket fuel formula.

Rocket fuel #6 produces the most energy observed within the range of this experiment, though it cannot be concluded that the best recipe has been isolated. For now it can only be said that the recipe isolated above is the best found yet, and if there is better, the range where the energy production would lie is between 6.73 kJ and approximately 27 kJ. Knowing this will help future searches for better performing fuels by eliminating any formula that does not produce energies within this range.

## CHAPTER 5

### FUTURE WORK

#### 5.1 Improvements

More about the relationship between energy output and the formula composition would be revealed if certain improvements were made to the methods of this experiment. Continued research should start with any formula already tested and followed by making slight changes to the amount of only one ingredient. For example, Fuel #6 uses 2.9992 g. ammonium nitrate, 0.7953 g. aluminum, 0.0262 g. sulfur, and the rest of the ten gram sample is made up of binder. While maintaining the same amounts of ammonium nitrate, sulfur and binder, increase the amount of aluminum by small increments until the weight percent composition has changed by ten percent. Then do this again, but decrease the amount of aluminum by the same sized increments until the weight percent composition has changed by ten percent. This process would be repeated by changing the weight percent composition of only one ingredient at a time while holding the other three constant at the amounts detailed in Fuel #6. The results of these experiments could then be plotted with weight percent composition of the changing ingredient compared with the overall energy output per gram. A theoretical prediction based upon the experimental data in Table 3.1 is represented in Figure 5.1 on page 20. These plots would demonstrate a five-dimensional relationship between formula composition and energy production. Finding a global maximum to this relationship would isolate the best performing formula.

## 5.2 Expected Trends

Test #14 showed that sulfur is an essential ingredient, though other tests showed that the fuel operates best with less than 5 % sulfur. The specific enthalpy of binding agent suggests that it does not contribute to the energy production of the fuel, though it is also an essential ingredient needed to bind the fuel in its solid form. Using less binder allows for the use of more energy productive ingredients. Aluminum is required in large amounts because it raises the temperature of the burn so that the ammonium nitrate will sustain decomposition. However, using too much aluminum will limit the amount of ammonium nitrate contributing to the energy production. Ammonium nitrate is the key ingredient which produces the most energy by combustion, therefore maximizing the amount of ammonium nitrate would theoretically maximize the energy production. These expected trends are shown in Figure 5.1 Finding the formulation of additives that will be used completely to aid the reaction and not hinder it is key to optimizing the rocket fuel formula.

## 5.3 Complimentary Research

Research to follow in the near future includes accumulation of burn rate measurements which will be used to calculate solid rocket motor dimensions. The dynamics of gas flow exhausting from a burning solid fuel rocket motor require precise dimensions of the motor housing and exhaust nozzle. Parameters that define these dimensions include enthalpy output, burn rate, and pressure changes created by the burning fuel. The first of these we have from the aforementioned study, the second will come from current research underway, and

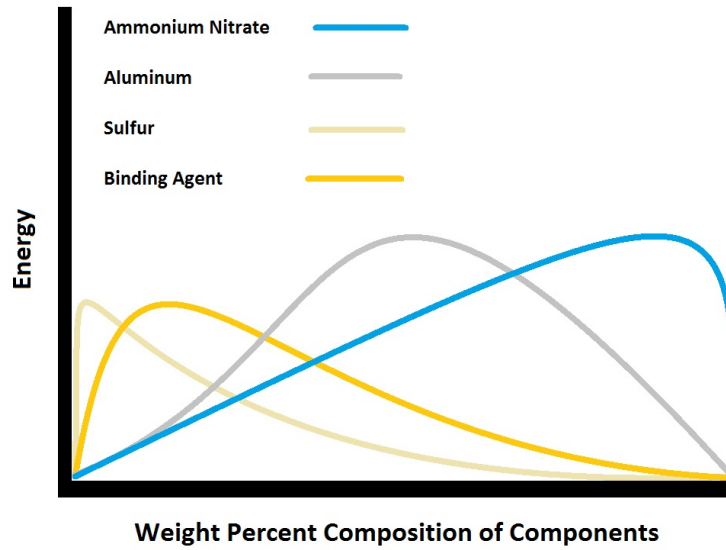


Figure 5.1: An overlay plot of theoretically expected energy outputs vs. percent weight composition of each ingredient.

the third will soon follow. Once all of this data has been collected, preparations are ready to begin designing a sounding rocket.

## BIBLIOGRAPHY

- [1] Will Omera of Hornady®. Personal Communication, 2013.
- [2] www.chuckhawks.com Chuck Hawks. *Chuck Hawks*. 2013.
- [3] Stefania Cagnina et. al. *Chemical Engineering Transactions*. AIDIC Servizi S.R.L., 2013.
- [4] Thomas Hager. *The Alchemy of Air*. Harmony Books, New York, 2008.
- [5] Aaron John Ihde. *The development of modern chemistry*. Courier Dover Publications, 1984.
- [6] Werner L Nelson John L Havlin, Samuel L Tisdale. *Soil Fertility and Fertilizers: An Introduction to Nutrient Management*. Prentice Hall, 2004.
- [7] Dan Herbeck Lou Michel. *American Terrorist*. Regan Books, 2001.
- [8] David Oliphant. Personal Communication, 2013.
- [9] Fire Prevention and Texas Engineering Bureau of Texas, Dallas. *Texas City, Texas, Disaster, April 16, 17, 1947*. The National Board of Fire Underwriters, New York, New York, 1947.
- [10] Anton I. Levshenkov Valery P. Sinditskii\*, Viacheslav Yu. Egorshv and Valery V. Serushkin. *Ammonium Nitrate: Combustion Mechanism and the Role of Additives*. Propellants, Explosives, Pyrotechnics, 2005.
- [11] www.ammoniumnitrate.org. *Ammonium Nitrate*. 2013.
- [12] www.chemguide.co.uk. 2013.
- [13] www.madsci.org. *Mad Sci Network*. 2013.
- [14] Richard Nakka; www.nakka rocketry.net. *Richard Nakka's Experimental Rocketry Web Site*. 2013.
- [15] www.wickmanspacecraft.com. *Wickman Spacecraft & Propulsion Company*. 2012.