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ASSESSMENT AND APPLICATIONS OF THE CONVERSION OF CHEMICAL ENERGY TO MECHANICAL ENERGY USING MODEL ROCKET ENGINES

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Abstract

To provide the first-year engineering students with a hands-on experience in an engineering application using both chemistry and physics, this team project uses a set of chemical and physical energy concepts and MS Excel based analysis. The main objective of the project is to calculate how much of the potential maximum possible chemical energy is converted into propulsion when using model rocket engines with solid fuel. The secondary objective is to determine the effects of increasing conversion rates on the performance of a model rocket. The solid fuel or propellant used in common model rocket engines is black powder. Compared to composite and hybrid engines, engines with black powder are cheaper and easier to ignite. Affordability of this propellant has made it possible to test fire many engines of different sizes. In addition, solid model rocket engines provide a good analogy to solid rocket boosters used in some of today's launch vehicles. Rockets are momentum engines; thus, it is unusual to consider them in terms of energy, but energy is felt by observers even in model rocket launches. Total impulse is the measure of momentum imparted to the vehicle and depends on several processes including the chemical energy of the propellant and the useful kinetic energy of the exhaust. The project centers around calculation of the total energy released by the combustion of the reactants in model rocket engines of various types (A through F). The propulsion energy is a small fraction of the total energy released during combustion where a significant part of the total is lost heat. Many students enjoyed this activity as they learned how to code several sets of chemical balance and physical energy equations using MS Excel. Each team wrote a detailed technical report that explains the overall project. They used field pictures and the graphs to illustrate various parts of the project. They also included an essay on alternative propulsion means to explore the outer Solar system and beyond. An anonymous learning survey was developed, implemented, and analyzed to assess the educational effect of this project. The survey results and anecdotal evidence show this was a good and a challenging learning experience that was also too demanding for some of the students.

Introduction

Experiential learning is a well-documented [8, 9, and 17] and a well recognized part of Kolb's experiential learning cycle/spiral [5, 10, and 12] that is used as a powerfull pedagogical strategy in many engineering programs. Project-based learning (PBL) pedagogy is well accepted in education. It is also emphasized as one of the high priority education methods/pedagogies required in early engineering education. Model rocketry can be viewed as miniature astronautics, technological recreation, and an educational tool. A model rocket is a combined miniature version of a real launch vehicle [27 and 28]. A model rocket is a very convenient metaphor to illustrate many important engineering concepts and principles in a fun and exciting way. Once a model rocket leaves the launcher, it is a free body in air. Model rockets have been used as student projects for decades. Many publications [1, 2, 4, 7, 13, 15, 18, 20, 21, 23, 24, and 25] report engineering projects in the same general area. Mathematical and physical aspects of model rocketry are reported in references 3, 6, 14, 16, 19, and 31. This paper describes a successfull implementation of PBL in an introduction class using the conversion of chemical energy into propulsion as its focus instead of the flight based focus found in earlier publications. Hence, this paper is the first its kind in model rocket literature. The practical experience described in this paper is realization centered.

Curricular Context

ENGN 110 is an introduction to engineering and technology course designed to "introduce a variety of engineering and technology disciplines" through a series of engineering projects. The course emphasizes teamwork, design, testing, communication and presentation skills, as well as discovery, creativity, and innovation. This is a one-semester, 2 credit-hour course required for all engineering and engineering technology programs at the university. The described practical chemistry and physics related engineering experience presents one of the major modules (team project) in this course.

Educational Goals, Activities, and Outcomes

Educational goals of this project include increased excitement for engineering resulting in increased retention, motivational preparation for further studies in engineering, and gaining an insight into what engineers do. The practical experience consists of several exciting and "explosive" activities. There are several project learning outcomes that stem from project educational goals that are reinforced/implemented through project activities. The project learning outcomes include 1) development of teamwork skills, 2) increased appreciation for current and future coursework in physics and chemistry, 3) an early understanding of the role of experimental and analytical approaches to engineering problem solving, 4) development of written communication skills through writing technical team reports, 5) development of MS Excel programming skills directly applicable to a real-life like project and 6) increased appreciation for engineering by experiencing a real life like hands-on engineering project from start to finish. These outcomes are closely related to ABET-EAC Criterion 3, 1-7 student learning outcomes, specifically outcome 1 - an ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics, outcome 3 - an ability to communicate effectively with a range of audiences, outcome 5 – an ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives, and outcome 6 – an ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions.

This project also sought to dispel the following popular misconception for the potential rocket scientists in the class: a rocket needs to push against something to work! Before the space programs, many believed that rockets might not work in space, but they do even better than in air. Rockets work because of Newton's third Law that all forces come in pairs: exert a force in one direction and automatically there is an equal and opposite force. Another way to look at it is that momentum (mass x velocity) is always conserved when the net force is zero. Before a model rocket is ignited, it has zero momentum. When it is ignited, hot gases are expelled to the rear of the rocket having some total momentum (a vector in one direction). To maintain zero net momentum, the rocket has an equal momentum magnitude but in the opposite direction through the force called thrust. The rocket shoots out a lot of hot gases and some combustion particles. The mass of everything expelled is not much but they move very fast. The rearward momentum is large, and it is necessary to add up all the individual masses times their different speeds to get the total. Since momentum is always conserved when the net force is zero, an equal momentum in the opposite direction must occur. This forward momentum is made up of a large rocket mass times a slower average speed than the average exhaust speed. Therefore, the total forward and rearward moments cancel each other out. The final speed of the rocket is found by dividing the total momentum for the exhaust or the opposite rocket momentum by the mass of the rocket. This simple explanation ignores gravity and air resistance. In this project, many model rockets were launched, and the students clearly observed that expelled gases push against something (the launch pad) only during the brief ignition and lift-off moment. In Figure 12, model rocket ZE-1's flight trajectory shows the rocket thrusting without having to push against anything for up to 53 meters.

Energy Source for Propulsion for Model Rocket Engines

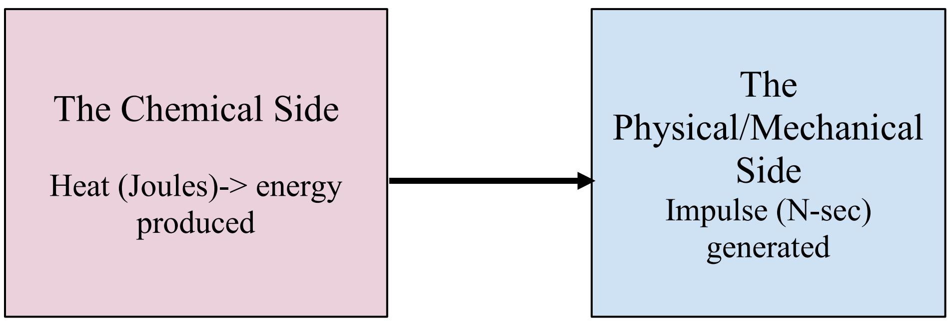

Figure 1. The main idea of the team project

Figure 1 illustrates the main idea of the project. Black powder is ignited to generate heat. In turn, some of the heat is converted into a fundamental propulsion input of impulse through conservation of momentum. Impulse is an implied input and it is defined as the area under the burn time and thrust curve as explained in Sarper et al. [26]. How does the conversion in Figure 1 occur? The project centers around this question. Figure 2 shows 40% to 70% of the available chemical energy is converted into propulsion in actual chemical rockets. This project seeks to teach students how to assess the conversion rate for black powder-based model rocket engines in a fun and exciting way using experimentation, chemistry, physics, and MS Excel programming. Obviously, today's space bound rockets use chemical means other than black powder.

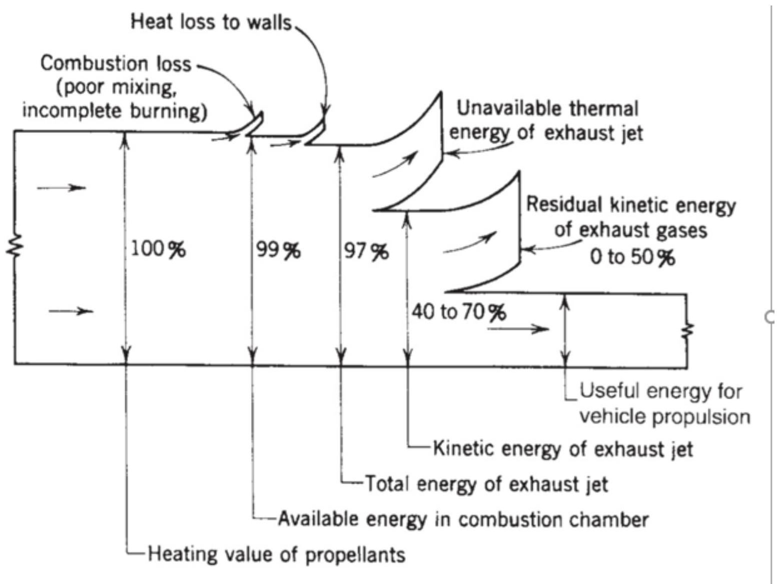

Figure 2. Typical energy distribution of a chemical rocket [29]

Figure 3 lists the names and the proportions of the reactants of black powder fuel manufactured by the Estes Corporation located in Penrose, CO. The manufacturing process remains essentially the same as the one developed by Mr. Estes in the 1960s. The first author has visited the plant several times.

3 Composition/information on ingredients

· **Chemical characterization: Mixtures**

· **Components:**			
7757-79-1	Potassium nitrate	Ox. Sol. 2, H272	60-80%
7704-34-9	Sulfur	Skin Irrit. 2, H315	10-20%
16291-96-6	charcoal	Flam. Sol. 1, H228	10-20%

· **Additional information:** For the wording of the listed Hazard Statements, refer to section 16.

Figure 3. Black Powder Composition of Engines [30]

Figure 4 shows the cross section of a typical engine with black powder as its fuel. Fuel grain or black powder usually represents about half of the mass of an engine. Delay and ejection charges are also made of black powder.

Figure 4. Components of an Estes Model Rocket Engine [11]

Motor vs. Engine

Is the propulsive unit an engine or a motor? Both terms are used by the manufactures and the users for decades interchangeably. Reference 11 provides a good clarification for this historical confusion: “To be technically correct, nearly all amateur rockets from the smallest to the largest use motors. According to the American Heritage Dictionary, a motor is "something, such as a machine or an engine that produces or imparts motion" and an engine is "A machine that converts energy into mechanical force or motion." A machine is "A device consisting of fixed and moving parts that modifies mechanical energy and transmits it in a more useful form." ……. A solid propellant rocket motor has no mechanical moving parts. The only thing moving is the igniter as it is ejected out the nozzle and the gas and propellant particles resulting from combustion of the propellant. There are no moving parts like there is in your car engine”. This paper uses the term ”engine” although it appears that the term “motor” is the correct one.

Practical Experience: Static Engine Testing

Figure 5 and Equation 1 show the reactants and the products of black powder reaction or explosion. Samples shown were obtained from the Chemistry department, but no actual mixing of the reactants was performed. The reactants in Figure 5 are in a compressed format as a fuel grain in Figure 4. Before any rockets were launched, many engines of different sizes were static fired as shown in Figure 6. The students were able to see and/or feel the products (especially the gases) of reaction in Figure 5 after most of the firings.

Figure 5. The black powder reaction

In Figure 6, an F engine is seen when thrusting (left) and ejecting (right)

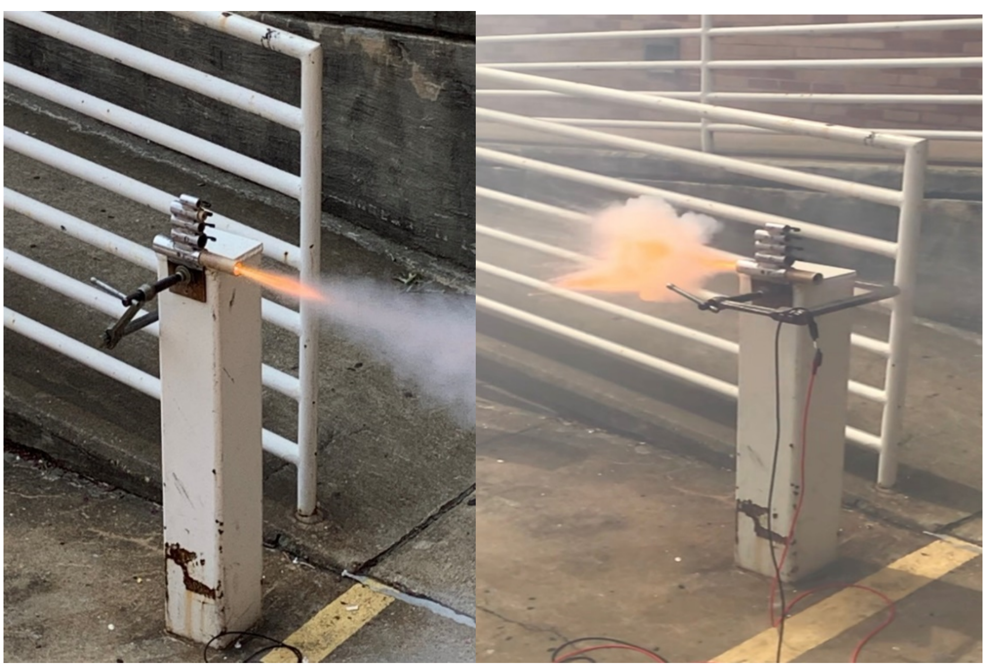

Figure 6. Static engine testing

Figure 7 shows the activities involved before and after static engine testing. For each engine, the difference in mass value was calculated by recording pre and post firing masses. The difference includes the fuel as well as the other consumables except the tube shown in Figure 4. Hence, published fuel mass values were used in the calculations shown later.

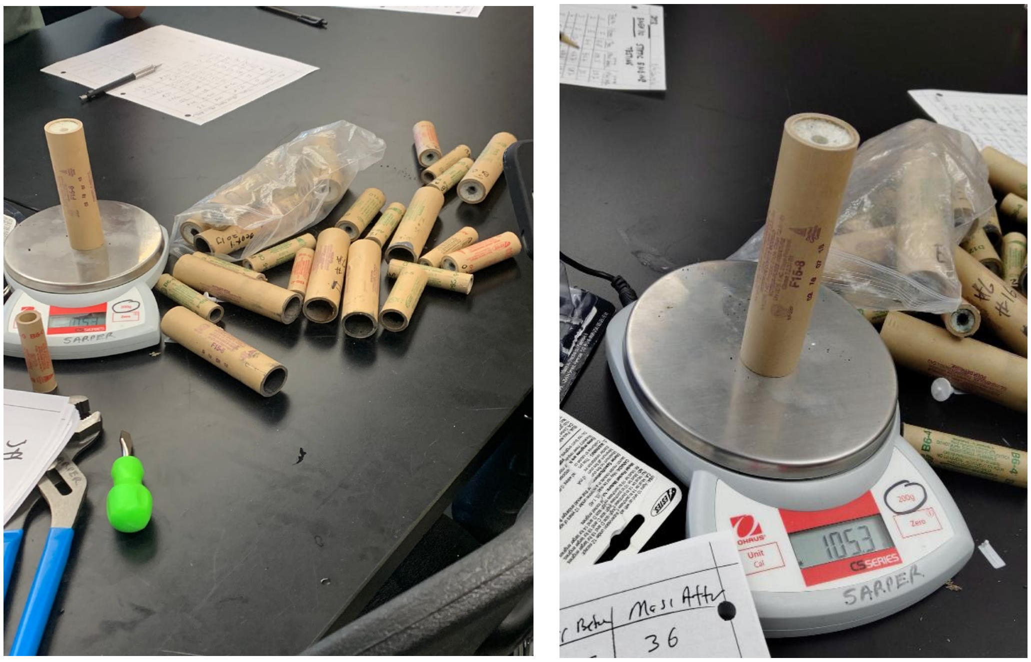

Figure 7. Sample of engines used for testing and launching

Each student turned in an early MS Excel homework using the data from about 50 firings of various engine types. They calculated the net change in mass of each engine and compared the change with published fuel only mass to estimate the percent of the change that represents the fuel mass. It was also observed that idential engines varied somewhat in overall mass and the net change in mass.

Practical Experience: Model Rocket Launches

Two types of model rockets were used: the large rocket (B&D model) powered by a D12-5 engine and small rocket (Skytrax model) powered by a B6-4 engine. Each rocket can also be powered by other engines that have higher or lower impulse ratings.   Figure 8 shows some of the large rockets during the launch mass recording process. Figure 10 shows a large (left) rocket and a small (right) rocket during the lift-off stage.   Each rocket was fitted by an altimeter to collect flight data. Figure 9 shows the altimeter and its insertion under the nose cone of the large rocket. The large rocket does not have a dedicated payload section and the altimeter was hung under the nose cone. In Figure 10 (right), altimeter can be seen inside the payload section of the small rocket.

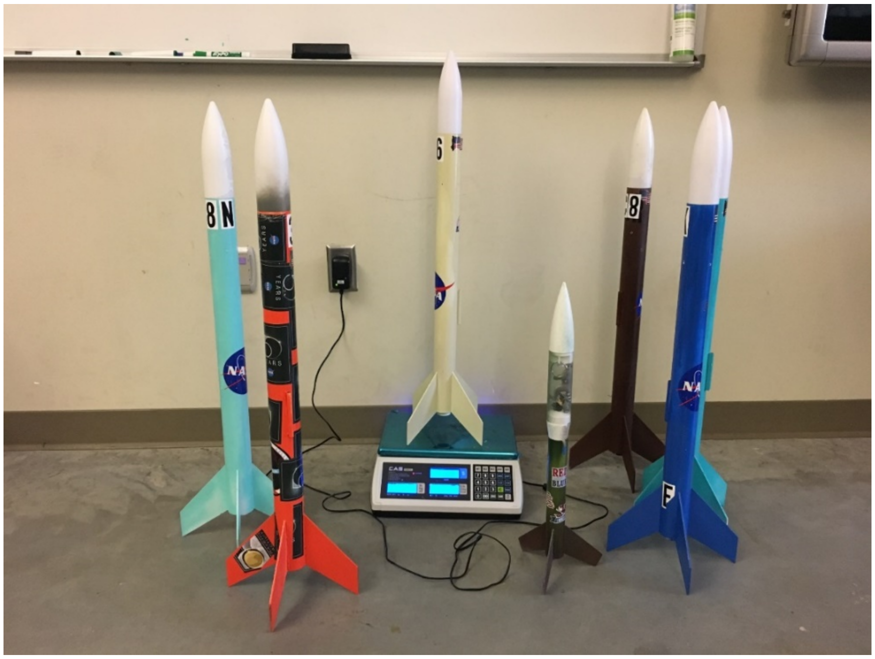

Figure 8. Some of the large (B&D) rockets and a Falcon 9 rocket (not used)

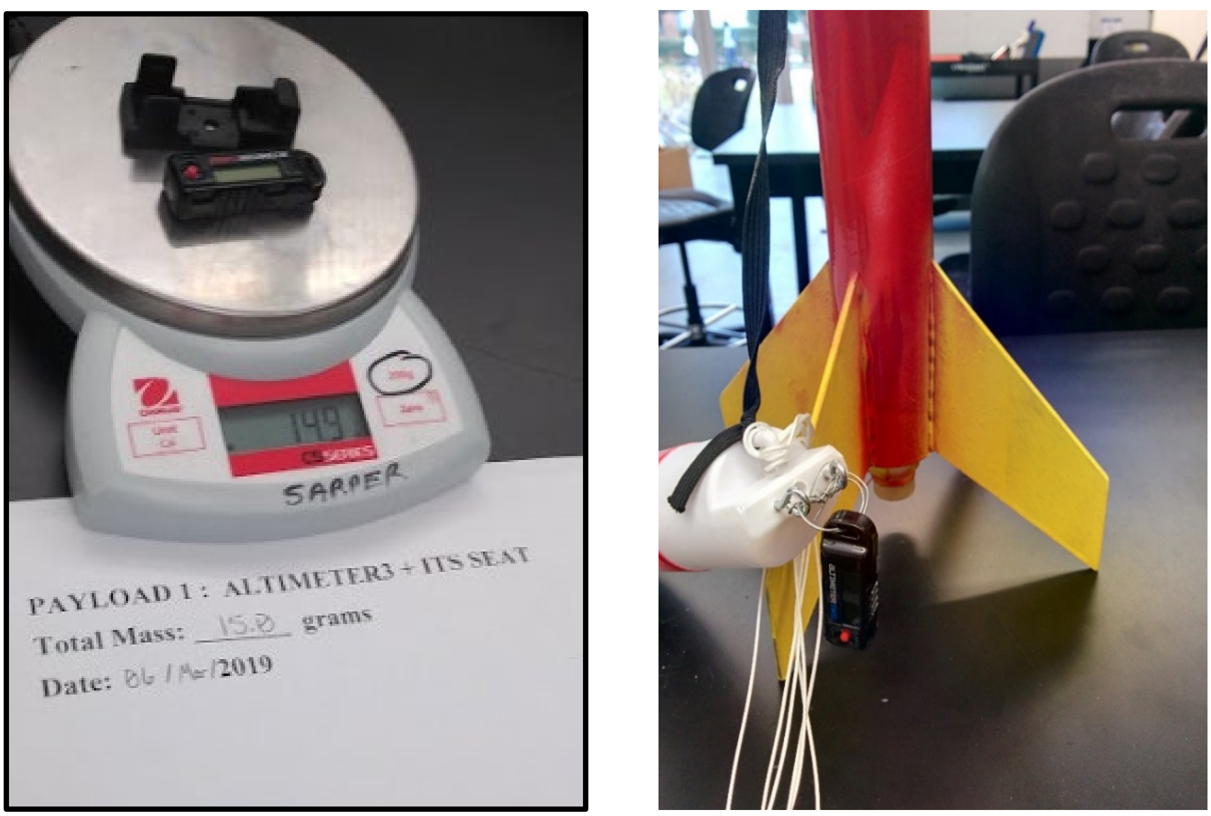

Figure 9. The onboard altimeter used on both rocket types

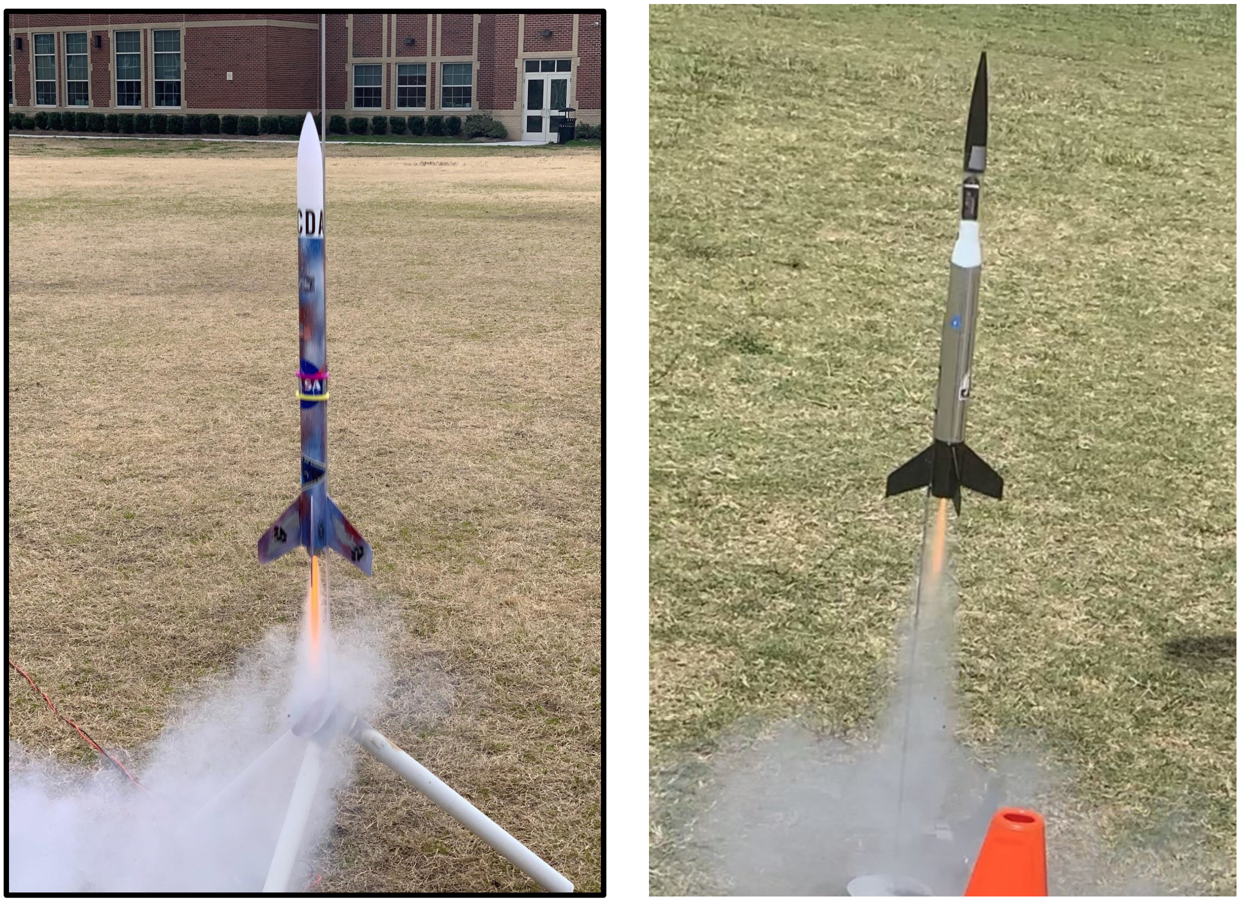

Figure 10. Lift-off of large (B&D) and small (Skytrax) rockets

Dozen of rockets of both sizes were launched (Figure 11) in order to get some "perfect" flights. A "perfect" flight is the case when flight data reported by an on-board altimeter matches or nearly matches with the theoretical flight performance values as calculated using "rocket science" equations. This is indeed a rare event that helps instill the fact that analytical methods are useful and students will be able to predict a system's behavior using the knowledge gained during the STEM studies. Many things can and do go wrong not just with the model, but with real-life rocket launches. The students were able to observe many launches with bad outcomes due to many forseen (high winds, nearby trees) and unforseen (sudden wind gust after the launch) problems. Two "perfect" flight data sets were used in this project: large rocket with the serial number ZE-1 and the small rocket Skytrax-3. This paper only uses the ZE-1 data for illustrations. Figure 12 shows downloaded flight profile of this rocket with a launch mass of 226 grams including a 45.50 gram D12-5 engine with an estimated 21 grams of black powder fuel. Figure 13 shows how an on-line rocket science tool [22] can be used to predict the ideal performance of this rocket using all known input values shown. The students made extensive use of this on-line tool to classify each launch as "perfect", marginal, or poor.

Figure 11. Model rockets ascending (small & large)

As seen in Figure 12, rocket ZE-1 achieved an apogee of 134.70 m. vs. a predicted apogee of 134.90 m. in Figure 13. At the burn-out point, the maximum actual speed of 197.50 kph (54.87 m/s) matches with the predicted maximum speed of 54.85 m/s in Figure 13. The rocket reached the apogee after 5.10 – 1.50 = 3.60 s of coasting while the predicted duration is 4.00 s of coasting. Predicted (44.17) and actual (53.10) burn-out altitudes do not match well, however. The flight of rocket ZE-1 is still a “perfect” flight as the apogee match is the top priority. In Figure 13, published average impulse value of 16.84 N-s was used, but the actual impulse can vary from 16 to 18. There is no way to know the actual impulse value unless a destructive test described in Sarper et al. [26] is carried out. The nominal thrust or burn-time for a D12-5 engine is 1.65 s, but rocket ZE-1 experienced an unusually short (1.50 s) burn-time. Unlike the unknown actual impulse, the actual burn-time can be entered in Figure 13.

In Figure 12, propellant is consumed at the burnout point and no thrust force is available to push the rocket which continues to ascend while losing speed (negative acceleration). At the apogee, the velocity is 0 before the descent begins. A parachute is successfully ejected in 85% of the flights. In this case, delay time for ejection was 5.05 s after the burnout time of 1.50 s or at time = 6.55 s on the x axis. The delay fuel (a simple timer) in Figure 4 starts burning as soon as the main fuel is consumed at the burnout. Ejection charge explodes out to eject the parachute after this time-out. For engine D12-5, average thrust is 12 Newtons and the average delay is 5 seconds. The total flight time is about 33 seconds. Ejection happens before the apogee in about 20% of the launches. Such flights are never “perfect”. Failed ejection is a serious concern even for small rockets because rockets then act like a ballistic missile and crash with a high terminal velocity.

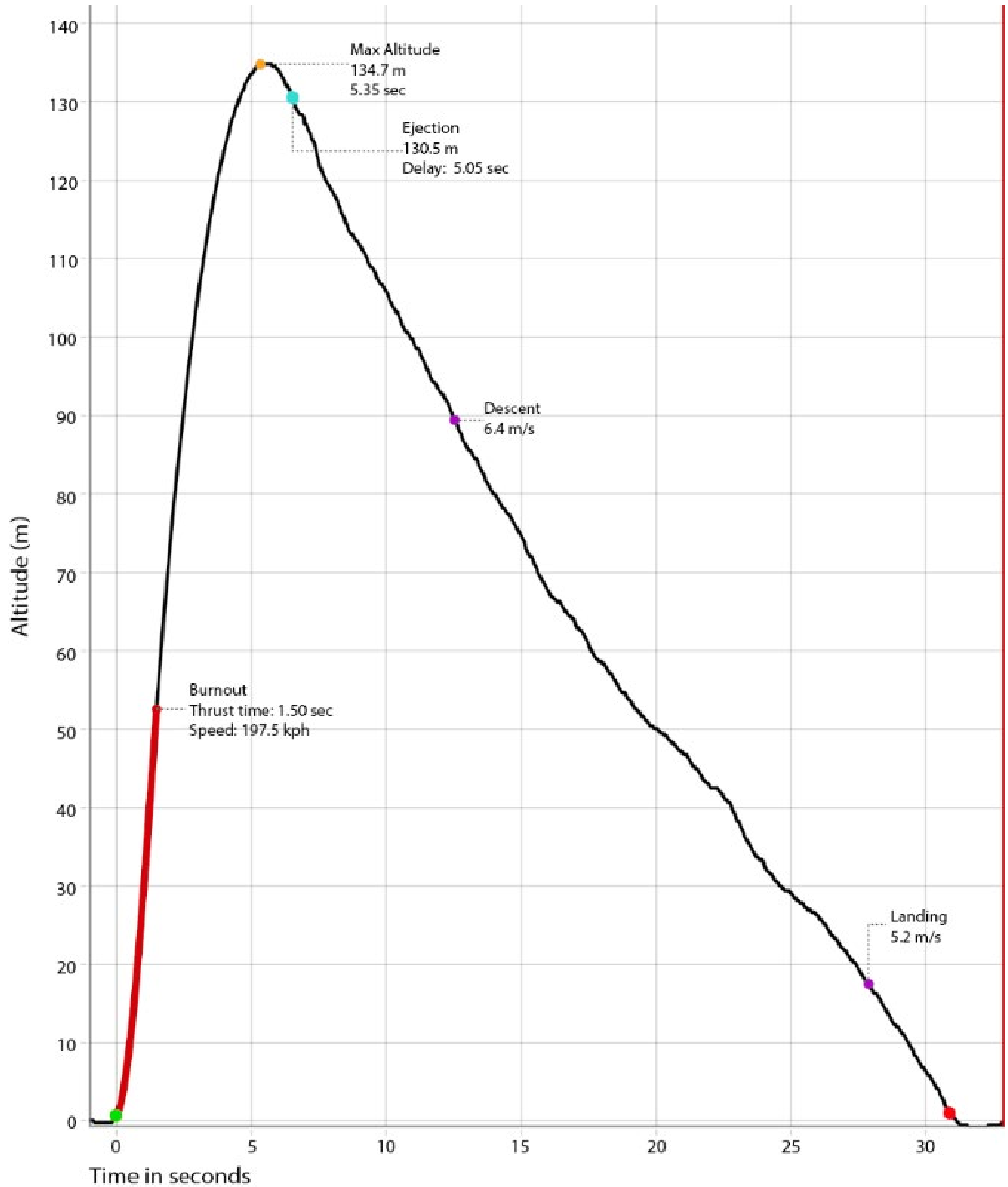

Figure 12. Flight profile of large rocket ZE-1

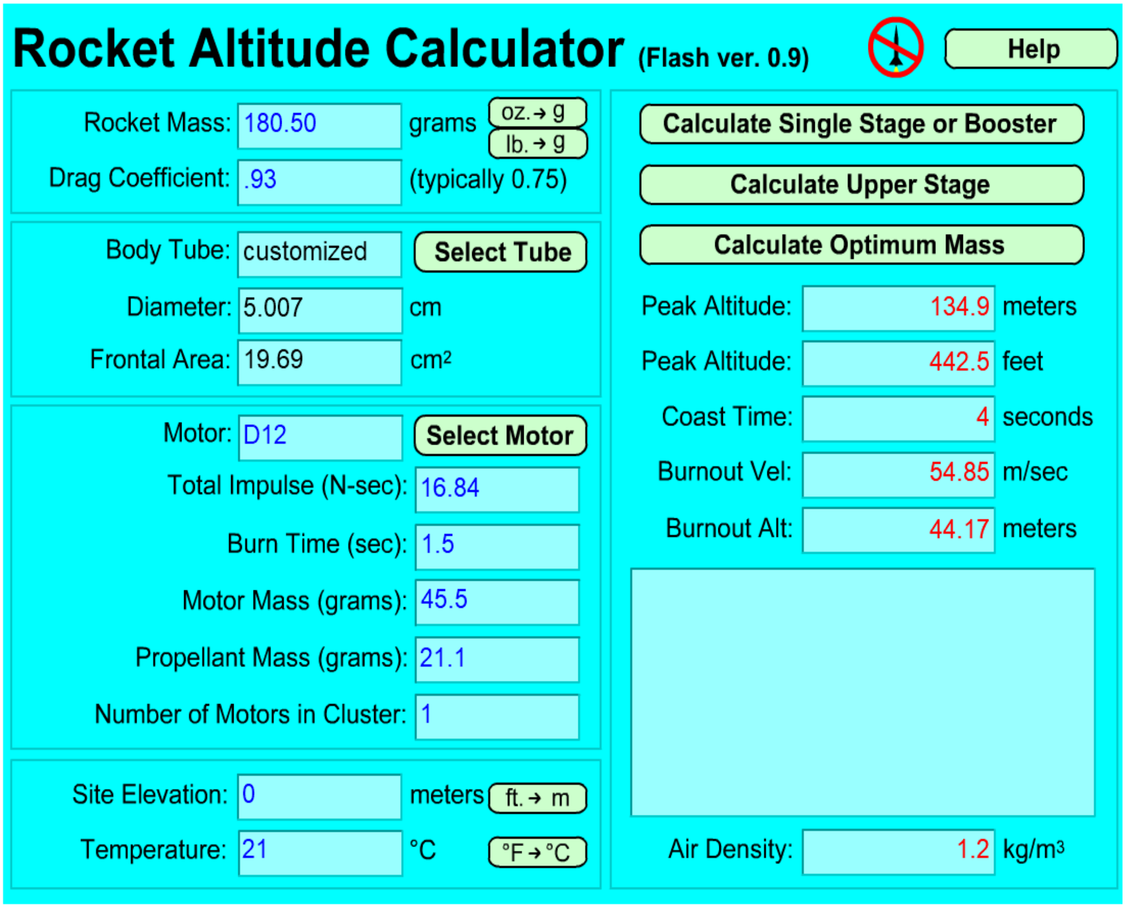

Figure 13. Prediction of performance of the large rocket ZE-1 [22]

The Variables and the Equations

Table 1 shows the variables using the metric system. V_f refers to the exhaust velocity of the gases and the particles expelled, not the velocity of the rocket. Equation 1 is the fundamental black powder reaction in Figure 5. Equations 2 and 7 and 3 and 6 are the same.

Table 1. Definition of the Variables

V_f	Final Velocity (m/s)
m_p	Propellant Mass (kg)
E_p	Energy of Model Rocket (J)
E_f	Efficiency (%)
$E_{p(new)}$	New Energy of Model Rocket (J)
$E_{f(new)}$	New Efficiency Value (%)
E_c	Chemical Energy value (J)
I	Impulse (N-sec)
I_{new}	New Impulse value (N-sec)
I_{base}	Base Impulse value (N-sec)
ΔI%	Percent Change in Impulse (%)

$$10KNO_3+3S+8C->2K_2CO_3+3K_2SO_4+6CO_2+5N_2 \tag{1}$$

$$V_f=\frac{I}{m_p} \tag{2}$$

$$E_p=\frac{1}{2}m_pV_f{}^2 \tag{3}$$

$$E_f=\frac{E_p}{E_c} \tag{4}$$

$$E_{p(new)}=-E_{f(new)}*E_c*1000 \tag{5}$$

$$V_f=(\frac{2E_p}{m_p})^{\frac{1}{2}} \tag{6}$$

$$I=V_f*m_p \tag{7}$$

$$\Delta I\%=\frac{I_{new}-I_{base}}{I_{base}} \tag{8}$$

Calculation of the conversion efficiency of chemical energy to mechanical energy

The heat of reaction (also known as enthalpy of reaction) is the change in the enthalpy of a chemical reaction that occurs at a constant pressure. It is a thermodynamic unit of measurement useful for calculating the amount of energy per mole either released or produced in a reaction. Many students seemed to be well informed of these concepts. When a process occurs at constant pressure, the heat involved (either released or absorbed) is equal to the change in enthalpy. For KNO_3, for example, the value of 494.50 kJ is published. Figure 14 shows the MS Excel worksheet for energy calculations all teams developed for this project.

The spreadsheet in Figure 14 shows reaction of potassium nitrate, sulfur, and carbon to form potassium carbonate, potassium sulfate, carbon dioxide, and nitrogen. The lines below the reaction in the spreadsheet are molecular weight of each reactant and product; molar coefficients from the reaction equation; total grams of each reactant and product assuming the reaction is run at full scale (i.e. 10 moles of KNO_3, 3 moles of sulfur, etc.); total mass of reactants (which is also total mass of products); published values of the heat of formation of each reactant and product (note that elements in their most stable state have heat of formation = 0); Calculation of the molar coefficient times the heat of formation - these values are used to calculate the heat of reaction.

The heat of reaction is defined as sum of heats of formations for all products minus sum of heats of formation for all reactants, or [(products - reactants)]. Note that for any stable compound, the heat of formation is negative. So, for example, the delta H (formation) values should all be negative, like -494.50 kJ/mol for KNO3. Also note that heat of formation is defined as the energy change accompanying formation of one mole of any pure substance directly from its constituent elements, with all substances present in the reaction in their standard states. Because of this definition, the heat of formation for any element in its standard state is zero. A large negative heat of formation (for a compound) means the compound is relatively stable. As seen in Figure 14, the heats of formation of both potassium carbonate and potassium sulfate are much larger (and they are negative) than the heat of formation of potassium nitrate. But comparing different substances by their heats of formation is just a qualitative argument, because there are atoms present in KNO_3 that are not in K_2CO_3 and vice versa. So, it is not an accurate quantitative argument.

In Figure 14, the total mass of the reactants and the products is 1203 grams for the full reaction. Heat of formation per mole values are taken from the tables to calculate the total heat of formation for each compound on both sides. Then, the net heat energy is found via [(products - reactants)]: [(2300.40 + 4313.10 + 2361) - 4945] = -4029.50 kJ for the full reaction. The 4029.5 kJ value is the amount of heat released (the reaction is exothermic) when run at "full scale" (i.e. 10 moles of KNO_3, 3 moles S, etc.). Note that the negative values indicate that all the compounds (whether reactant or product) are formed exothermically from their elements. The minus sign tells that the heat is released. The term ("released") implies that the heat is given off and therefore the sign of delta H is understood to be negative. Since the amount of the propellant is only 21 g., the actual net heat energy is (21/1203)*(-4029.50) = -70.34 kJ after each D12-5 engine is ignited.

How is this net energy used? The exhaust velocity is 16.84/0.021 = 801.90 m/s (Eq. 2). This speed corresponds to a kinetic energy of $0.50*(0.021)*(801.90)^2 =$ 6752.04 J (Eq. 3) or 6.75 kJ. This means only 6.75 kJ of the available 70.34 kJ of chemical heat energy is used for propulsion. The conversion efficiency then is 6.75/70.34 = 9.60% for engine D12-5.

ANALYSIS OF THE EFFICIENCY OF THE CHEMICAL SIDE:

Combustion of black powder as model rocket engine propellant

				The Reactants:			The Products:				
		Equation 1		**10 KNO3**	**+ 3 S**	**+ 8 C —>**	**2 K2CO3**	**+ 3 K2SO4**	**+ 6 CO2**	**+ 5 N2**	
INPUTS		Equation :	Mass/mole (gr.)	101.10	32.00	12.00	138.20	174.20	44.00	28.00	grams/mol
Elements	Mass (gr.)	Input	Number of moles	10	3	8	2	3	6	5	moles
K	39.10	Equation*	Total Mass (gr.)	1011.00	96.00	96.00	276.40	522.60	264.00	140.00	grams
N	14.00	Equation*	Total mass of reactants & products			1203.00	1203.00				grams
O	16.00	Input	Heat of formation per mol (in Tables)	-494.50	0.00	0.00	-1150.20	-1437.70	-393.50	0.00	DHf (kJ/mol)
S	32.00	Equation*	Total Heat of Formation of Each Compound	-4945.00	0.00	0.00	-2300.40	-4313.10	-2361.00	0.00	DHf (kJ)
C	12.00	Equation*	Net heat energy [(products-reactants)]:				Per	1203.00	grams:	-4029.50	DHrxn (kJ)
		Equation*	Net heat energy (for the propellant mass):				Per	21.00	grams:	**-70.34**	**DHrxn (kJ)**
Engine	D12-5										

Mean Values of

Input	Impulse (I)	16.84	N-sec
Input	Burn-time (tb)	1.65	seconds
Input	Propellant Mass (m)	21.00	grams
Equation*	Propellant Mass (m)	0.021	kg.

* denotes an implied equation without an equation number in the paper

THE PHYSICAL SIDE:

Equation :	Exhaust Velocity (m/sec) :	801.90
Equation :	Propulsion Energy (Joules):	6752.04
Equation*	Propulsion Energy (kilo Joules):	6.75
Equation ·	Chemical to Physical Efficiency :	9.60%

Only 9.60% of the available 70.34 kJ of energy was used for propulsion.

Figure 14. Calculation of the efficiency of the conversion of chemical energy to mechanical energy for the D12-5 engine

Table 2 shows calculated efficiencies of all common engines tested in this project. The composite engines were not used, but they appear to have high conversion efficiencies comparable to chemical fuels used for real rockets as depicted in Figure 2. Note that burn-time is not used in efficiency calculations, but included here as it is a major input for other calculations.

Table 2. Conversion of chemical energy efficiency of common engines

Engine Type	Fuel Type	Impulse (N-s)	Propellant Mass (g)	Burn time (s)	Conversion Efficiency (%)
1/4A3T-3	Black Powder	0.63	0.83	0.25	8.46
1/2A3T-2,4	Black Powder	1.25	2.00	0.36	5.83
1/2A6-2	Black Powder	1.25	2.60	0.33	3.45
A3T-4	Black Powder	2.50	3.30	1.01	8.57
A8-0	Black Powder	2.15	3.84	0.53	4.68
A8-3,5	Black Powder	2.50	3.30	0.73	8.57
A10T-0	Black Powder	1.88	3.57	1.06	4.14
A10T-3,P	Black Powder	2.50	3.80	0.85	6.46
B4-2,4	Black Powder	4.29	6.00	1.03	7.63
B6-0	Black Powder	4.90	5.60	0.86	11.43
B6-2,4,6	Black Powder	4.33	5.60	0.86	8.92
C6-0,3,5,7	Black Powder	8.82	10.80	1.86	9.96
C11-0,7	Black Powder	8.80	12.00	0.81	8.03
D11-P	Black Powder	17.49	24.50	1.86	7.61
D12-0,3,5,7	Black Powder	16.84	21.10	1.65	9.60
E9-0	Black Powder	27.87	35.80	3.09	9.05
E12-0,4,6,8	Black Powder	27.24	35.90	2.44	8.59
E16-0,4,6,8	Black Powder	33.38	40.00	2.09	10.40
F15-0,4,6,8	Black Powder	49.61	60.00	3.45	10.21
E30-4,7	Composite	33.56	17.80	1.02	53.06
F26FJ-6	Composite	62.19	43.10	2.31	31.08
F50T-4,6	Composite	76.83	37.90	1.43	61.34

Flight performance predictions with improved theoretical conversion rates

This part of the project dealt with the question of "if we can improve the conversion rate of the available chemical energy to mechanical energy, what are the benefits of this?". As in most engineering systems, improvements can be made. There was a class discussion on how to make and implement improvements, but these were clearly beyond scope of this class. If heat losses can be reduced with better insulation, the conversion rates in Table 2 should improve. The main purpose of this part of the project was to teach students 1) it is possible to make predictions using analytical means only at first, 2) their STEM education will make it possible to do so without modifying a single engine, 3) actual changes in real practice would happen after much discussion and management approval, 4) cost of any improvement must be considered along with its benefit, 5) they should always consider adding a "what-if" analysis in their future technical reports as this is something most managers will appreciate even if they did not ask for it.

Figure 15 shows the application of the on-line rocket altitude calculator [22] if, somehow, a full conversion efficiency of 100% is achieved when launching rocket ZE-1. At 100 % conversion rate, the total chemical energy of 70.34 kJ or 70340 J is available for propulsion using equation 5. Using equation 6, $V_f = [(2*70340)/(0.021)]^{0.5} = 2588.26$ m/s which, using equation 7, correponds to I = 2588.6 * 0.021 = 54.35 N-s of impulse. Compared to the nominal impulse of 16.84 N-sec, this new theoretical impulse represents (Equation 8) an increase of (54.35 – 16.84)/16.84 or 222.76% over the value possible with the current 9.60% conversion efficiency. Figure 17 shows therotical impulse increases as a function of hypotetical energy conversion increases for D12-5 and B6-4 engines.

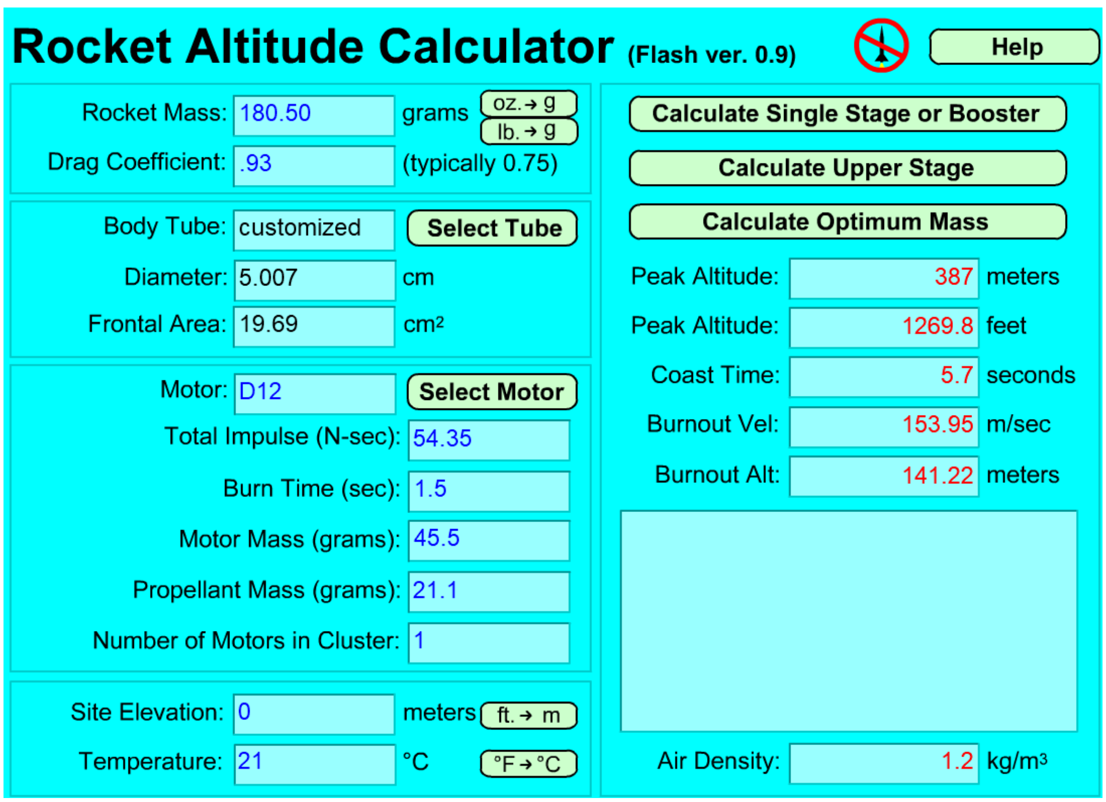

Figure 15. Prediction of performance of the large rocket ZE-1 at 100% conversion rate

Figure 16 shows application of equations 5 through 8 at increasing energy conversion rates for engine D12-5. The last four columns in Figure 16 are obtained using the rocket altitude calculator [22] by simply entering the corresponding impulse value. Figures 18, 19, and 20 show the potential improvements in flight performance as functions of increasing chemical energy conversion rates of both engine types. The students found this part of the project particulary interesting and exciting. There were class discussions on the concepts illustrated in Figures 18-20.

Engine	D12-5								
Impulse (I)	16.84								
Propellant Mass (m)	0.021			USING THE ON-LINE ROCKET MOTION CALCULATOR					
Equation *	Equation 5	Equation 6	Equation 7	Equation 8	For Rocket ZE1	Launch mass: 226 gr	with a 45.50 gr engine		
Conversion Efficiency	Propulsion Energy (J)	Exhaust Velocity (m/sec)	Impulse (N-sec)	Impulse Increase	Apogee (m)	Burnout Altitude (m)	Burnout Speed (m/sec)	Coast time (sec)	
9.60%	6752.04	801.90	16.84	0.00%	134.70	44.17	54.84	4.00	
15.00%	10551.06	1002.43	21.05	25.01%	176.10	56.60	68.98	4.40	
20.00%	14068.08	1157.50	24.31	44.34%	204.70	65.89	79.23	4.70	
25.00%	17585.10	1294.13	27.18	61.38%	227.90	73.86	87.81	4.90	
30.00%	21102.12	1417.65	29.77	76.79%	247.30	80.89	95.22	5.00	
35.00%	24619.14	1531.23	32.16	90.95%	264.20	87.24	101.81	5.10	
40.00%	28136.16	1636.96	34.38	104.13%	279.00	93.04	107.73	5.20	
45.00%	31653.18	1736.26	36.46	116.52%	292.20	98.38	113.11	5.30	
50.00%	35170.20	1830.18	38.43	128.23%	304.20	103.36	118.07	5.30	
55.00%	38687.22	1919.50	40.31	139.37%	315.30	108.05	122.68	5.40	
60.00%	42204.24	2004.86	42.10	150.01%	325.40	112.46	126.96	5.40	
65.00%	45721.26	2086.72	43.82	160.22%	334.80	116.64	130.99	5.50	
70.00%	49238.28	2165.49	45.48	170.04%	343.70	120.63	134.80	5.50	
75.00%	52755.30	2241.50	47.07	179.52%	351.90	124.41	138.80	5.50	
80.00%	56272.32	2315.01	48.62	188.69%	359.70	128.06	141.80	5.60	
85.00%	59789.34	2386.26	50.11	197.57%	367.10	131.53	145.04	5.60	
90.00%	63306.36	2455.44	51.56	206.20%	374.00	134.87	148.13	5.60	
95.00%	66823.38	2522.72	52.98	214.59%	380.70	138.12	151.11	5.60	
100.00%	70340.40	2588.26	54.35	222.76%	386.70	141.19	153.89	5.70	

Figure 16. Performance prediction of the large rocket ZE-1 at increasing conversion rates

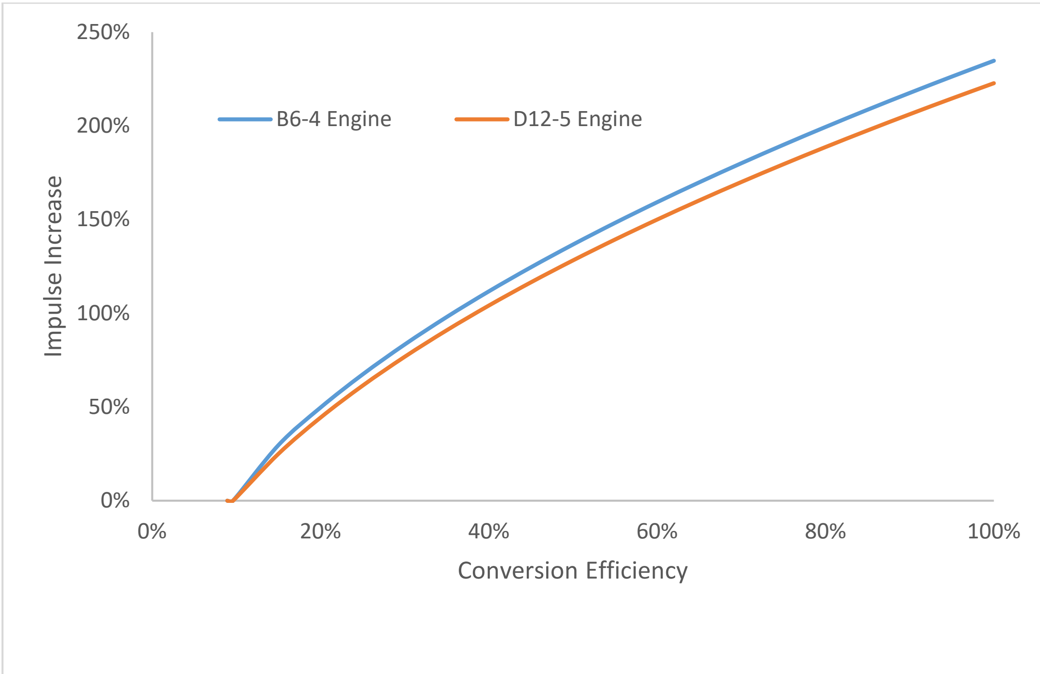

Figure 17. Impulse increase vs. chemical energy conversion efficiency rate

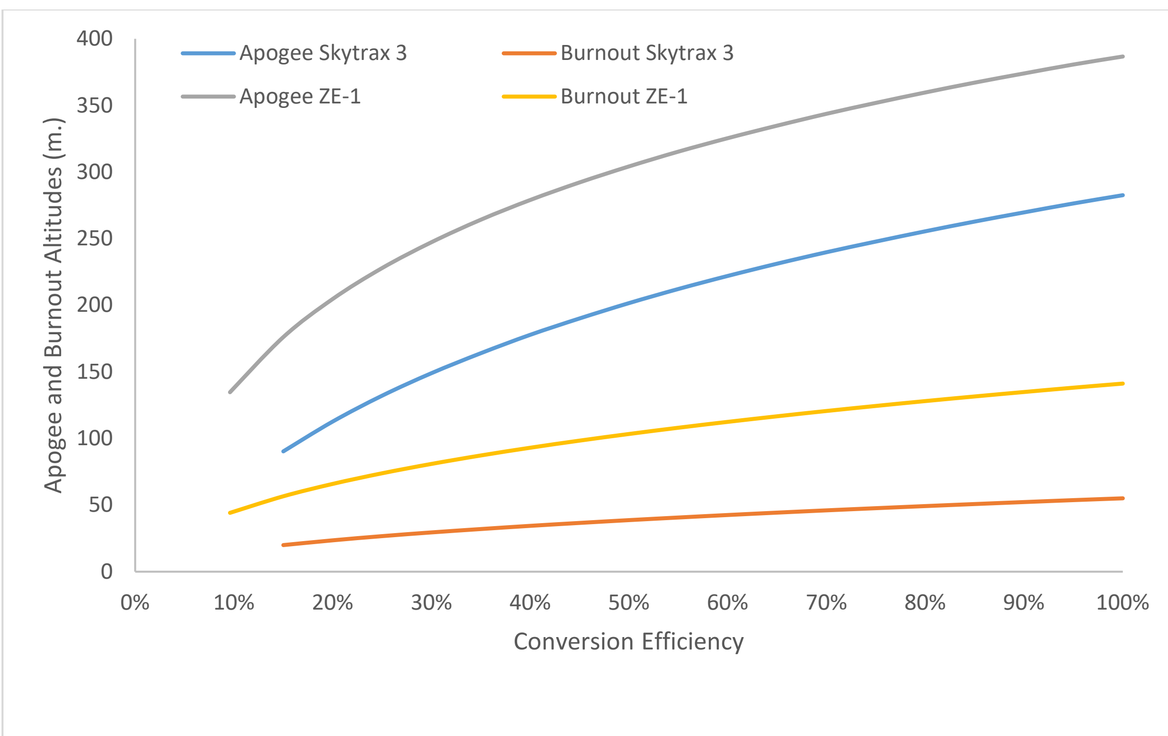

Figure 18. Altitude values vs. chemical energy conversion efficiency rate

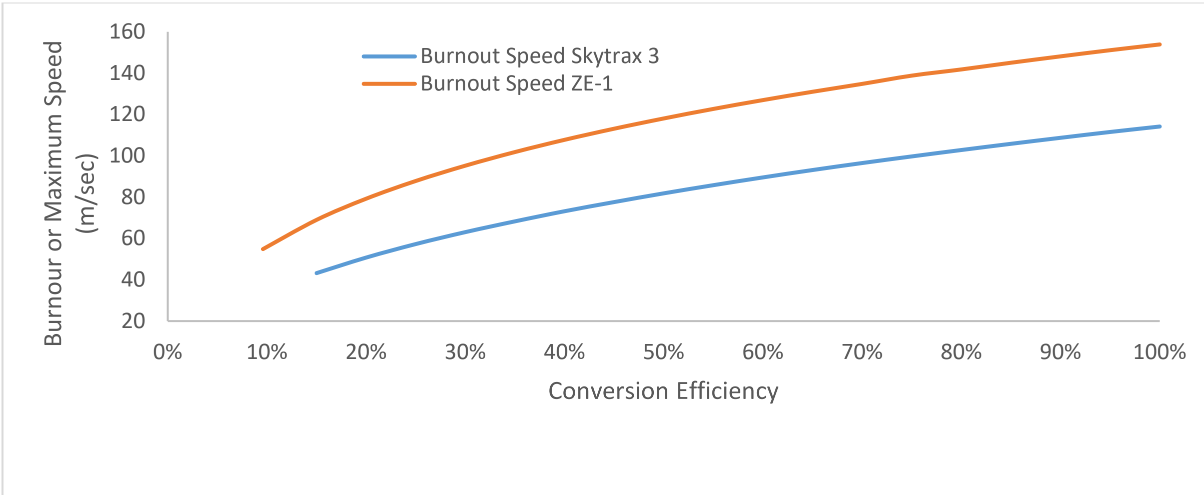

Figure 19. Burnout speed vs. chemical energy conversion efficiency rate

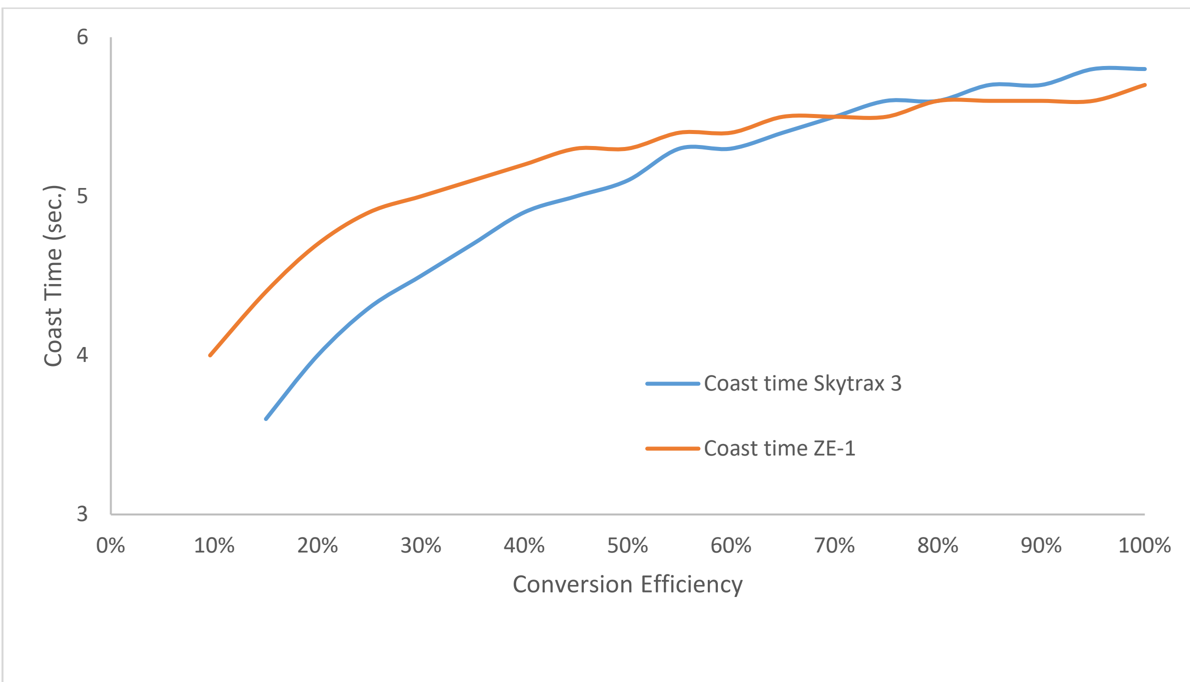

Figure 20. Coast time vs. chemical energy conversion efficiency rate

Essay on other propulsion methods

Each team also had to research other propulsion methods and write an English composition type essay. Students were encouraged to discuss the state-of-the-art proposed, and theorized propulsion methods such as liquid chemical propulsion, ionic propulsion, solar sails, and even warp drives.

Assessment and Evaluation of Course Educational Objectives

Students received a practical introduction to many engineering concepts they will encounter in their later studies. The instructor scheduled additional project help sessions on most Friday afternoons as the class time was not long enough due to other topics that were covered. Also, for most of the students, this was their first meaningful encounter with MS Excel. While most of the students rose to the challenge, a few of them found this project to be too difficult.

As mentioned earlier, there were several educational goals expected of this project: 1) development of teamwork skills, 2) increased appreciation for current and future coursework in physics and chemistry, 3) an early understanding of the role of experimental and analytical approaches to engineering problem solving, 4) development of written communication skills through writing technical team reports, 5) development of MS Excel programming skills applied to a real-life like project and 6) increased appreciation for engineering by experiencing a real life like hands-on engineering project from start to finish. These educational goals were either fully accomplished or it is too soon to tell as in the case of goal 6 that also seeks to improve retention.

An anonymous exit survey (shown in Figure 21) using a 5-point Likert scale was completed by 80 of the 95 students in 5 sections. The results are shown in red using mean and standard deviation format. Most of the freshmen felt this project was a good learning experience for all the goals above. 90 of the 95 students were freshmen in their first or second semester of study. Most of students (about half) planned to major in mechanical engineering. It appeared that there were big differences among the students with respect to their degree of college preparedness. It was evident that those who were less prepared academically were not able to contribute to the group effort as much. Those with strong high school chemistry and AP physics backgrounds enjoyed and understood this project much better than those with weaker backgrounds.

Please rate the following questions:

1. **Working with model rocket engines was (3.94/1.09).**
   1 = boring, 2 = somewhat boring, 3 = OK, 4 = somewhat exciting, 5 = very exciting
2. **From this project I learned (3.19/0.81) about chemical propulsion and its conversion into mechanical energy.**
   1 = nothing, 2 = little, 3 = something, 4 = much, 5 = very much
3. **By performing calculations using Excel I became (4.15/0.81) with coding in Excel.**
   1 = less proficient, 2 = somewhat less proficient, 3 = neither less nor more proficient, 4 = somewhat proficient, 5 = very proficient
4. **By performing calculations using the online model rocket calculator, I became (3.38/0.76) with rocket science.**
   1 = less proficient, 2 = somewhat less proficient, 3 = neither less nor more proficient, 4 = somewhat proficient, 5 = very proficient.
5. **Static engine testing and physical model rocket launches, and the calculations were (3.94/0.97) in gaining some understanding of rocket science.**
   1 = unhelpful, 2 = somewhat unhelpful, 3 = neither unhelpful nor helpful, 4 = helpful, 5 = very helpful.

Figure 21. Students' Opinion Survey and the Results (in Red)

Conclusions

This detailed project not only introduced the concepts of chemical and mechanical energy, but also provided a real life like calculations for the conversion of these two energies using black powder-based model rocket engines. Students learned and programmed many engineering and science topics they will study soon. Concepts of chemical balancing, Newton's laws, impulse, thrust, propulsion, and chemical heat of formation were studied analytically and experimentally in a fun, drawn out, challenging, and sometimes frustrating team environments. Students enjoyed conducting experiments with engines and rockets. For some, this project was too overwhelming while many of them enjoyed the challenges of this project and its many tasks including writing a major team technical report. A students' attitude assessment survey was designed, implemented, and analyzed. Overall, students felt this was a very exciting real life like worthwhile learning experience that taught them the usefulness and importance of chemistry, physics, and programming in engineering projects.

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