Using Black Powder for Parachute Deployment

Prepared for vNARCON-2025

Rev 1.2

Feb 23, 2025

Thomas B Fetter

NAR 15551

C Division

Summary

Black powder charges are the most common method of deploying parachutes in both model rocketry and high power rocketry, whether using motor deployment or electronic altimeter based deployment. When black powder is burned within the confined volume of the rocket body, it pressurizes the body, causing the rocket to separate and force the parachute out of the body tube. If shear pins are being used, then they will likely determine the force necessary to successfully separate the rocket and deploy the parachute.

Many of the available web based black powder calculators for predicting the required quantity of black powder can be traced back to the model used by a calculator on the Info Central web site. But based on flight experience, the amount of black powder recommended by these calculators does not guarantee a successful parachute deployment.

Pressure chamber testing and deployment fixture testing were used to quantify the pressure generated and the pressure required to deploy the parachute under different deployment conditions. Testing was done with different sizes and locations of the parachute, with both recovery blankets and pistons, and at sea level and high-altitude ambient pressures. The strength of shear pins was also tested. The test results showed that significantly more black powder is needed under most conditions to reliably deploy a parachute than the amount recommended by the black powder calculators.

A new model of the pressure generated by the combustion of black powder was developed that agrees closely with the pressure chamber and deployment tests and that can be used to create a more accurate black powder calculator. The new model gives better insight into the mechanism by which black powder works to create pressure and how the deployment configuration impacts the pressure generated.

Table of Contents

1 Objective and Approach

This project was started in July of 2020 after having several deployment failures where the parachute failed to completely exit the body of the rocket, or, in one case, the primary and backup charges went off, but the nosecone, with its shear pins, remained completely in place. Up until then, I had mostly used pistons to successfully deploy parachutes, but the more recent rockets that failed employed recovery blankets, or chute protectors, to protect the parachute from the hot gases. I had always used web based black powder calculators to determine the amount of black powder, bumping the recommendation up by a small safety margin, and I did the same for the newer rockets using recovery blankets.

Why did the rockets using recovery blankets experience recovery deployment failures? Does recovery blanket deployment require more black powder than piston deployment? Do the black powder calculators, in general, underestimate the amount of black powder needed to reliably deploy a parachute? Was there something wrong with my black powder? The objective of this project was to determine the cause of the deployment failures and better understand how black powder acts to create the pressure that deploys the parachute, and if necessary, develop new guidelines for calculating the quantity of black powder needed to ensure successful deployments.

This project started with several testable hypotheses based upon the initial questions above. During the course of the project, additional hypotheses were added based on results obtained along the way. In parallel, a theoretical model was developed to explain the test results and get a better understanding of the mechanism by which black powder combustion produces the pressure needed to deploy the parachute. Appendix 3 shows the final roadmap of the project.

2 Prior Work

The chemistry of black powder combustion and the equations that describe the reaction were determined by research that dates from the 1800's when black powder was used widely in military artillery and firearms. Black powder was largely replaced by smokeless powder in the late 1800's, so there has been less interest in black powder research since that time. Commercial production of black powder is very limited today. The largest uses are fireworks, black powder model rocket motors, and antique firearms. Nobel and Able[1] is one of the early sources that gives a very detailed and complete description of black powder combustion and discussion of black powder research. A

---

[1] (Noble & Abel, 1875)

good summary of black powder chemistry is provided in Ian von Maltitz's book[2] which is written for fireworks and antique firearms hobbyists. Malitz includes all of the black powder chemical reaction equations at are used in this paper. There are several papers including Sasse and Hussain & Ress[3] that describe using modern analytical equipment to analyze the combustion products of black powder, but they do not propose any additional chemical reaction equations for black powder.

The earliest calculator for calculating the size of the black powder charge for parachute deployment is likely the calculator on the Info Central website that first dates from 1996[4]. The Info Central page provides some information on the model used to calculate the pressure generated by the black powder. All other web based calculators appear to be based upon the original Info Central calculator and give similar results.

---

[2] (Maltitz, 2003)

[3] (Sasse, 1985); (Hussain & Rees, Combustion of Black Powder. Part 1: Thermo-Analytical Studies, 1990); (Hussain & Ress, Combustion of Black Powder. Part II: FTIR Emission Spectroscopic Studies, 1991);

[4] Current version of Info Central (Roth, McDonald, & Apke, Black Powder Sizing, 2020), Archived version of original Info Central page with the Black Powder calculator (Roth, McDonald, & Apke, Black Powder Sizing, 1996-2000)

3 The Chemical Equations for Black Powder Combustion

Traditional black powder is comprised of three substances, potassium nitrate, or salt peter, (KNO_3), sulfur (S), and carbon (C), which usually comes from charcoal. The traditional proportions, by weight, used in black powder manufacturing are 75% potassium nitrate, 10% sulfur, and 15% charcoal, which is known as the Waltham Abby formula[5]

A chemical reaction, such as burning black powder, is described by a chemical balance equation. The initial composition is described on the left side of the equation, and the post reaction composition is described on the right side of the equation. Each capital letter, or capital letter with a small letter following, indicates an atom from the periodic table. Each group of letters indicates a molecule, or substance. The numbers to the left of the molecule indicate the number of molecules of the substance, and the subscript after an atom indicates the number of atoms of that element in that molecule. The atoms on the right side of the equation may form different molecules than are on the left side, but the total number of atoms of each element on the left side of the equation must equal the total number of atoms of that element on the right side. Stoichiometry is the calculation of the molecular quantities needed to balance the chemical equation. The stoichiometric ratio is the ratio of the beginning molecular coefficient to the ending molecular coefficient for any pair of substances. For example, if two molecules of H_2 are combined with one molecule of O_2 , two molecules of H_2O are produced $\left(2H_2 + O_2 \rightarrow 2H_2O\right)$, the stoichiometric ratio of $O_2 : H_2O$ is *1:2* , and the stoichiometric ratio of $H_2 : H_2O$ is *1:1* .

There are four different equations for the black powder combustion reaction presented in Maltitz[6], all dating from the 1800's. These equations have the same number of atoms on each side of the equation for each element, so they are all balanced equations. The first equation is attributed to Chevreuil. This is also the first chemical equation listed on the Wikipedia page for gunpowder[7].

$$2KNO_3 + S + 3C \rightarrow K_2S + 3CO_2 + N_2 \tag{3-1}$$

The second equation is attributed to Debus. It also appears on the Wikipedia page.

$$10KNO_3 + 3S + 8C \rightarrow 2K_2CO_3 + 3K_2SO_4 + 6CO_2 + 5N \tag{3-2}$$

---

[5] (Maltitz, 2003, p. 73)

[6] (Maltitz, 2003, pp. 144-146)

[7] (Gunpowder, 2024)

The third equation is attributed to Berthelot.

$$16KNO_3 + 6S + 13C \rightarrow 2K_2CO_3 + 5K_2SO_4 + 11CO_2 + K_2S + 8N_2 \tag{3-3}$$

And the fourth equation is attributed to Kast.

$$74KNO_3 + 30S + 16C_6H_2O(charcoal) \rightarrow \begin{pmatrix} 56CO_2 + 14CO + 3CH_4 + 2H_2S + 4H_2 + 35N_2 \\ +19K_2CO_3 + 7K_2SO_4 + 2K_2S + 8K_2S_2O_3 \\ +2KCNS + (NH_4)_2CO_2 + C + S \end{pmatrix} \tag{3-4}$$

The more molecules of each substance starting on the left side of the equation, the more possible different molecules can be created after the reaction on the right side of a balanced equation.

Maltitz gives the mass percentages for the black powder constituents for each of the formulas above, but he does not show the derivation for those mass percentages, nor does he derive the pressure generated when the black powder is burned in a confined space, which is needed to calculate how much black powder is required to successfully deploy a parachute.

To determine the proportions by mass for a chemical equation, the mass of each molecule is first determined, and then that mass is divided by the total mass of all the molecules. The mass of the molecule is the sum of the masses of each element making up the molecule. The standard unit of measure for doing these calculations is the mole, which is $6.02 \cdot 10^{23}$ molecules of a substance. The mole is the basis for the molar mass, also called the molecular weight, of an element shown on the periodic table. One mole of a substance has a mass given by the molar mass for that element. Multiplying the molecular mass times the number of moles of a substance gives the total mass.

For the constituent elements of Chevreuil's equation (3-1), the element molar masses for potassium, sulfur, and oxygen, are shown in Table 3-1.

Element	$MolarMass = M_X$
K	39.1 gm/mol
S	32.06 gm/mol
O	16.0 gm/mol

Table 3-1 Molar masses of black powder constituent elements[8]

---

[8] (Periodic Table, 2024)

The the molar mass of the molecule potassium nitrate, is

$$M_{KNO_3} = M_K + M_N + M_0 \cdot 3 = 101.2\frac{gm}{mol} \tag{3-5}$$

The mass of one mole of Chevreuil's formula for black powder is the sum of the molar masses of the constituent parts divided by the total number of moles

$$M_{BP} = \frac{2mol \cdot M_{KNO_3} + 1mol \cdot M_S + 3mol \cdot M_C}{2mol + 1mol + 3mol} = 45.082\frac{gm}{mol} \tag{3-6}$$

The mass fractions are then calculated for each of the components of black powder for Chevreuil's equation by ratioing the mass of each component to the total mass of the black powder

$$\begin{aligned} m\%_{KNO_3} &= \frac{2mol \cdot M_{KNO_3}}{2mol \cdot M_{KNO_3} + 1mol \cdot M_S + 3mol \cdot M_C} = 74.8\% \\ m\%_S &= \frac{1mol \cdot M_S}{2mol \cdot M_{KNO_3} + 1mol \cdot M_S + 3mol \cdot M_C} = 11.9\% \\ m\%_C &= \frac{3mol \cdot M_C}{2mol \cdot M_{KNO_3} + 1mol \cdot M_S + 3mol \cdot M_C} = 13.3\% \end{aligned} \tag{3-7}$$

The molar mass for the combustion products for Chevreuil's equation is

$$M_{BPcp} = \frac{1mol \cdot M_{K_2S} + 1mol \cdot M_{N_2} + 3mol \cdot M_{CO_2}}{1mol + 1mol + 3mol} = 54.098\frac{gm}{mol} \tag{3-8}$$

Note that the total mass must be the same on both sides of a chemical equation, but the number of moles, and hence the molar mass, does not need to be the same as the individual atoms combine in different ways on each side of the equation.

Doing the same calculations to determine the mass percentage of the combustion products gives

$$m\%_{K_2S} = \frac{1mol \cdot M_{K_2S}}{1mol \cdot M_{K_2S} + 1mol \cdot M_{N_2} + 3mol \cdot M_{CO_2}} = 40.8\%$$

$$m\%_{N_2} = \frac{1mol \cdot M_{N_2}}{1mol \cdot M_{K_2S} + 1mol \cdot M_{N_2} + 3mol \cdot M_{CO_2}} = 10.4\% \tag{3-9}$$

$$m\%_{CO_2} = \frac{3mol \cdot M_{CO_2}}{1mol \cdot M_{K_2S} + 1mol \cdot M_{N_2} + 3mol \cdot M_{CO_2}} = 48.8\%$$

Table 3-2 shows a summary of the mass percentage composition for the Chevreuil equation (3-1) as well as the other three black powder equations (3-2), (3-3), and (3-4) shown above. Also shown are two measurements, one by Nobel & Able[9], and the other by Burnsen & Schischkoff[10] of both the mass composition of the black powder and the resulting mass composition of the reaction products. The last two columns show the composition listed in the Goex safety sheet[11] and the traditional Waltham Abby black powder formula[12]

---

[9] (Davis, The Chemistry of Powder and Explosives, 1941, pp. 42-43), (Noble & Abel, 1875)

[10] (Maltitz, 2003, pp. 143 Table 12-1)

[11] (Wendt, 2018)

[12] (Maltitz, 2003, p. 73)

Formula	Name	State	Appearance	Nobel & Able	Bunsen & Schischkoff	Chevreuil	Debus	Berthelot	Kast	Goex	Traditional
				Meas	Meas	Model	Model	Model	Model		
Black Powder Components											
KNO3	Potassium nitrate	solid		74.4%	79.0%	74.8%	84.0%	82.2%	75.6%	70-76%	75.0%
K2SO4	Potassium sulfate	solid		0.1%							
S	Sulfur	solid		10.1%	9.8%	11.9%	8.0%	9.8%	9.8%	9-20%	10.0%
C	Carbon	solid		12.4%	7.7%	13.3%	8.0%	8.0%		8-18%	15.0%
H	Hydrogen	gas		0.4%	0.4%						
O	Oxygen	gas		1.3%	3.1%						
Ash		solid		0.2%							
H2O		liquid		1.1%							
C6H2O	Charcoal	solid							14.6%		
Total				**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**		
Combustion Products											
K2CO3	Potassium carbonate	solid	white salt	34.1%	12.7%		23.0%	14.0%	26.5%		
K2SO4	Potassium sulfate	solid	white salt	8.4%	42.5%		43.4%	44.3%	12.3%		
K2S	Potassium sulfide	solid	colorless	8.1%	2.1%	41.0%		5.6%	2.2%		
K2S2O3	Potassium thiosulfate	solid	white salt		3.3%				15.4%		
KCNS	Potassium thiocyanate	solid	colorless	0.1%	0.3%				2.0%		
KNO3	Potasuum nitrate	solid	white salt	0.2%	3.7%				0.0%		
KNO2	Potassium Nitrite	solid	white salt								
(NH4)2CO3	Amonium carbonate	solid	white salt	0.0%	2.9%				1.0%		
C	Carbon	solid	black	0.0%	0.7%				0.1%		
S	Sulfur	solid	yellow	4.9%	0.1%				0.3%		
H2O	water	liquid	colorless	1.1%							
H2S2	Hydrogen disulfide	liquid							0.7%		
CO2	Carbon dioxide	gas	colorless	21.2%	20.2%	49.0%	22.0%	24.6%	24.9%		
N2	Nitrogen gas	gas	colorless	14.1%	10.0%	10.0%	11.7%	11.5%	10.0%		
CO	Carbon monoxide	gas	colorless	5.4%	0.9%				4.0%		
CH4	Methane	gas	colorless	0.2%					0.5%		
H2	Hydrogen gas	gas	colorless	0.9%	0.0%				0.1%		
H2S	Hydrogen sulfide	gas	colorless	1.1%	0.2%						
O	Oxygen	gas	colorless		0.1%						
solid				55.9%	68.4%	41.0%	66.4%	63.9%	59.8%		
liquid				1.1%	0.0%	0.0%	0.0%	0.0%	0.0%		
gas				43.0%	31.6%	59.0%	33.7%	36.1%	39.5%		
Total				**100%**	**100%**	**100%**	**100%**	**100%**	**100%**		

Table 3-2 Summary of the mass percentage of black powder and its combustion products for various models and measurements

Which chemical equation is the correct one to use? The measurements by Nobel and Able are among the most complete. They observed a wide range of results from their and other's experiments. They attributed the variations to different formulations of black powder and to the conditions under which the black powder was burned, where pressure had a significant impact depending on whether the black powder was burned in an open or confined space. Modern chemical analysis[13] of black powder combustion shows that there are a number of intermediate reactions that occur during the combustion process, and the temperature and pressure of the reaction affect the intermediate

---

[13] (Hussain & Rees, Combustion of Black Powder. Part 1: Thermo-Analytical Studies, 1990), (Hussain & Ress, Combustion of Black Powder. Part II: FTIR Emission Spectroscopic Studies, 1991)

and final combustion products, which will impact the final pressure created by the black powder combustion. So no one stoichiometric balanced chemical equation describes the combustion of black powder under all conditions. The Chevreuil and Kast equations are the closest match to the formulation given by Goex. The process for calculating the pressure will be shown here in detail using Chevreuil's equation because it is the simplest equation, but the final results using all four equations will be shown and compared to deployment measurements to see which one best matches the conditions when black powder is used for parachute deployment.

4 Pressure Generated by Black Powder Combustion

To determine the pressure generated when the black powder is burned in a confined space, the ideal gas equation is used

$$P = \frac{n \cdot R \cdot T}{V} \tag{4-1}$$

where P is the pressure, n is the number of moles of the gas, R is the universal gas constant, T is the absolute temperature of the gas, and V is the volume of the gas.

The value for n comes from the black powder combustion chemical equation. The three products of combustion for Chevreuil's equation are potassium sulfide (K_2S), molecular nitrogen (N_2), and carbon dioxide (CO_2). Of these, potassium sulfide is a solid, and nitrogen and carbon dioxide are both gases.

To determine the number of moles of gas generated by burning a certain mass of black powder, the molar mass of just the gaseous combustion products is needed. Equation (3-8) shows the molar mass of all the combustion products. The molar mass of the gaseous combustion products is the total mass of the starting black powder divided by the number of moles of gas produced. Since K_2S is a solid powder, it does not contribute to the number of moles of gas produced, hence the zero in the denominator for moles of potassium sulfide from equation (3-8) above.

$$M_{BPcpgas} = \frac{1mol \cdot M_{K_2S} + 1mol \cdot M_{N_2} + 3mol \cdot M_{CO_2}}{0mol + 1mol + 3mol} = 67.623 \frac{gm}{mol} \tag{4-2}$$

The number of moles of gas produced starting with 0.5 gm of black powder is the starting mass of the black powder divided by the molar mass of the combustion product gases

$$n_{BPcpgas} = \frac{m_{bp}}{M_{bpcpgas}} = 0.0074mol \tag{4-3}$$

The value of the universal gas constant, which describes the amount of energy needed to raise one mole of gas 1 degree Kelvin, is

$$R = 8.314 \frac{J}{K \cdot mol} \tag{4-4}$$

T in equation (4-1) is the temperature of the combustion gases for black powder. Sasse[14] gives the combustion gas temperature as $1549^\circ \pm 25^\circ C$, or $1797^\circ K - 1847^\circ K$, and the Info Central calculator uses $3307^\circ R$, or $1837^\circ K$, which falls within the range given by Sasse. This paper will use the Info Central calculator value to allow comparing results with the online calculators.

From equation (4-1), for a 4 inch diameter tube 12 inches long, the volume is $150.8 in^3$, the pressure increase created by 0.5 gm of black powder is

$$\Delta P = \frac{m_{BP} \cdot R \cdot T_C}{M_{BPcpgas} \cdot V} = 6.629 psi \tag{4-5}$$

and after the gas cools to a $70^\circ F$ ambient temperature, the pressure is

$$\Delta P = \frac{m_{BP} \cdot R \cdot T_{amb}}{M_{BPgas} \cdot V} = 1.062 psi \tag{4-6}$$

5 The BP Calculators

There are a number of black powder calculators available on the web that calculate how much black powder to use for a given parachute tube volume and a given number of shear pins of a specified size. These include calculators on Info Central[15], Rocketry Calculator[16], Insane Rocketry[17], HARA Rocketry[18], as well as a downloadable Excel

---

[14] (Sasse, 1985, p. 27)

[15] (Roth, McDonald, & Apke, Black Powder Sizing, 1996-2000)

[16] (BP Estimator, 2021)

[17] (Cook, 2015-2022)

[18] (How to Size Ejection Charge, n.d.)

calculator available from the author's web site[19]. Of these, the earliest appears to be the calculator on the Info Central Black Powder Sizing web page. Info Central shut down as an active site in 2009, but the content is still available on the Internet Archive[20]. The calculator appears on the archive site for the original page[21], but it is no longer active.

The Info Central web page shows the formula used in the calculator to calculate the black powder charge mass[22]

$$m_{BP} = \Delta P \cdot \frac{V}{R_{specific} \cdot T_C} \tag{5-1}$$

where m_{BP} is the mass of black powder, ΔP is the change in pressure, V is the volume, $R_{specific}$ is the gas specific gas constant, and T_C is the combustion temperature of the black powder gases.

The gas specific gas constant is defined as the universal gas constant divided by the molar mass of the specific gas

$$R_{specific} = \frac{R}{M} \tag{5-2}$$

where the ideal gas law using the universal gas constant and the gas specific gas constant is

$$P = \frac{n \cdot R \cdot T_C}{V} = \frac{\dfrac{m_{BP}}{M_{BPcpgas}} \cdot R \cdot T_C}{V} = \frac{m_{BP} \cdot R_{specific} \cdot T_C}{V} \tag{5-3}$$

So equation (5-1) is just the ideal gas law from equation (4-1) expressed in terms of the gas specific gas constant. This shows that the Info Central calculator uses the same method of calculating the change in pressure as shown in Section 4.

The value for gas specific gas constant, $R_{specific}$, is dependent on the chemical equation used for the black powder reaction since it is a function of the molar mass of the combustion gases. The value given on the Info Central site is

---

[19] (Fetter, 2015-2024)

[20] (Roth, McDonald, & Apke, Black Powder Sizing, 2020)

[21] (Roth, McDonald, & Apke, Black Powder Sizing, 1996-2000)

[22] The actual formula on the Info Central page is $W_p = dP \cdot V / (R \cdot T)$, but the variable names have been changed to be consistent with the nomenclature used in this paper

$$R_{specific} = 22.16 \cdot ft \cdot \frac{lbf}{lb} \cdot \frac{1}{{}^{\circ}R} = 0.119 \cdot \frac{J}{gm \cdot {}^{\circ}K} \tag{5-4}$$

from which the value of the molar mass of the black powder combustion products used by the calculator can be determined to be

$$M_{BPcpgas} = \frac{R}{R_{specific}} = 69.74 \cdot \frac{gm}{mol} \tag{5-5}$$

compared to a value of $67.623 \cdot gm/mol$ as calculated for Chevreuil's equation from Equation (4-2). The Info Central page does not say what chemical equation is used for the model, but the value given for the molar mass of the combustion gases, $M_{BPcpgas}$, is very close to the value calculated using Chevreuil's equation.

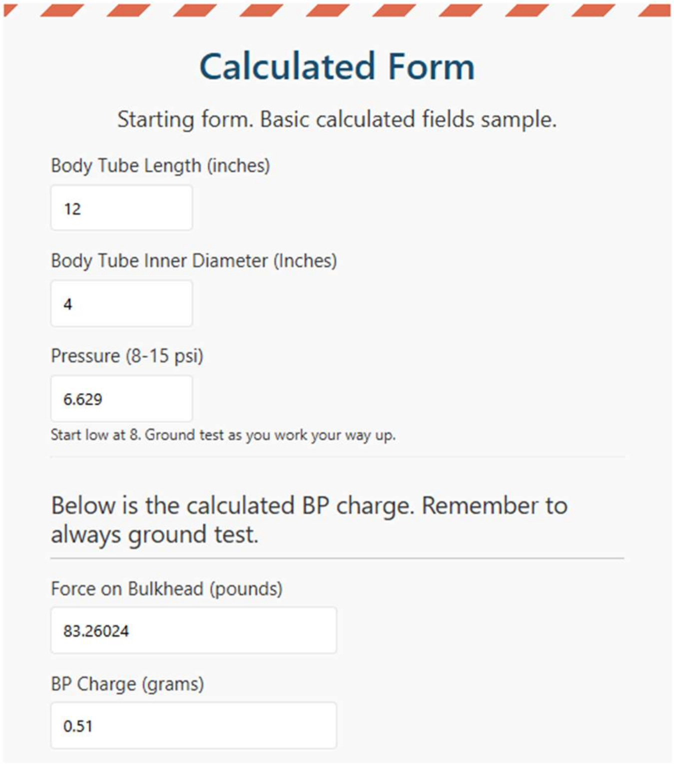
All the equations above have been shown without any unit conversion factors. The calculations used in this paper are done in a scientific and engineering modeling tool called Mathcad[23]. Mathcad knows about units. If all the parameters are entered with units, then Mathcad automatically uses the correct conversion factors so that the output of an equation has the correct numerical value in the units specified for that output. For example, if an equation contains a temperature parameter, the value can be entered with units of degrees Centigrade, Fahrenheit, Rankin, or Kelvin, and Mathcad will automatically convert to the native units of the specified units system (SI, USCS, CGS). If a tool like Mathcad is not used to do the calculations, such as an Excel spreadsheet, then it is necessary to explicitly pay attention to the units so that the units are consistent and the final output has the correct numerical value for the units specified. Appendix 1 shows the pressure calculation Equation (4-5) and the Info Central pressure equation with all of the explicit units conversion factors for the same example calculation shown in this section.

Since the Info Central calculator is no longer active, the Rocketry Calculator BP Estimator[24] was used to show, in Figure 5-1, that the online black powder calculators match the model from Section 4 using Chevreuil's equation. Entering a 12 in long, 4 in diameter tube, and using 6.629 psi as the pressure, results in 0.51 gm of black powder, which matches the value calculated by equation (4-5) for the same parameters. Note that both calculations use $3307^{\circ} R$ as the temperature of the black powder combustion gases.

---

[23] (Mathcad Home Page, 2024)

[24] (BP Estimator, 2021)



Calculated Form

Starting form. Basic calculated fields sample.

Body Tube Length (inches)

12

Body Tube Inner Diameter (Inches)

4

Pressure (8-15 psi)

6.629

Start low at 8. Ground test as you work your way up.

Below is the calculated BP charge. Remember to always ground test.

Force on Bulkhead (pounds)

83.26024

BP Charge (grams)

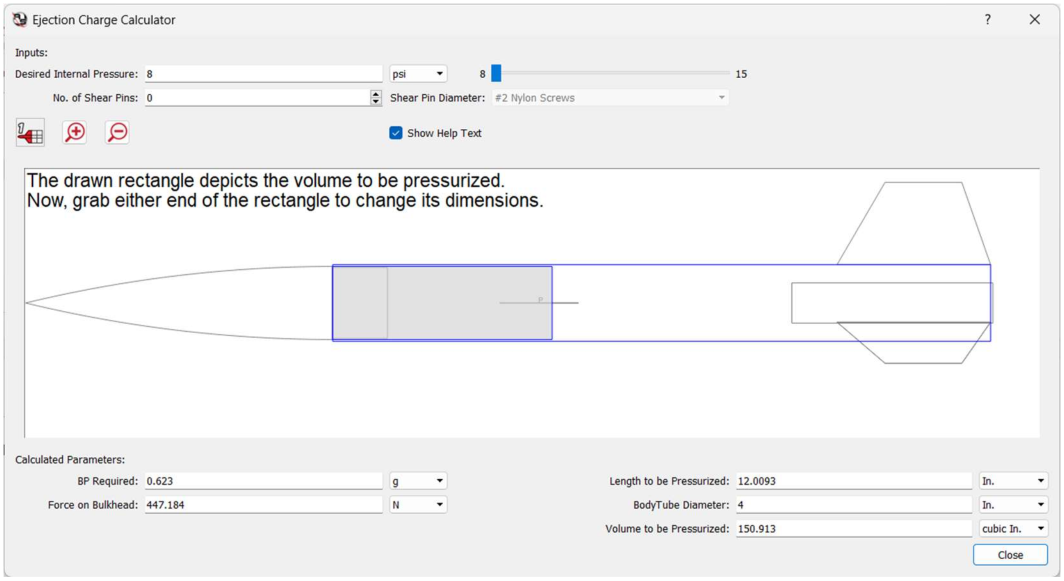
0.51

Figure 5-1 Result from the Rocketry Calculator BP Estimator

Version 11 of RockSim has also added a BP Calculator[25]. After a rocket design has been entered into RockSim, the Ejection Charge Calculator tool can be opened, the tube to be pressurized selected, and the length adjusted to correspond to the portion of the tube that is pressurized. Figure 5-2 shows the result for a 12 in section of 4 in diameter tube. The minimum pressure allowed in the tool is 8 psi, and the required black powder charge is 0.623 gm. Entering 0.623 gm into Equation (4-5) gives 8.26 psi, very close to the RockSim number, so it appears RockSim is using the same model as well.

---

[25] (RockSim, 2024)



Inputs:
Desired Internal Pressure: 8 psi
8 15
No. of Shear Pins: 0
Shear Pin Diameter: #2 Nylon Screws
☑ Show Help Text

The drawn rectangle depicts the volume to be pressurized.
Now, grab either end of the rectangle to change its dimensions.

Calculated Parameters:
BP Required: 0.623 g
Force on Bulkhead: 447.184 N
Length to be Pressurized: 12.0093 In.
BodyTube Diameter: 4 In.
Volume to be Pressurized: 150.913 cubic In.

Figure 5-2 Result from the RockSim Ejection Charge Calculator

6 Shear Pins

Shear pins are used to ensure the nosecone does not separate prematurely due to drag separation at motor burnout or the pressure differential between the parachute compartment and the external atmosphere on high altitude flights. If shear pins are not used, then only the force needed to overcome the friction of the nosecone in the body tube and the force needed to slide the parachute out the body tube must be produced by the black powder charge. But if shear pins are used, the black powder charge must create enough pressure to shear the pins, as well as overcome any frictional forces. The force required to shear the pins is usually much greater than the frictional force, which is why they are used. Some of the black powder calculators include the calculations needed to determine the charge size when using shear pins.

Shear pins are typically small nylon screws. For small to mid-sized rockets, they will typically be 2-56 English or M2 metric screws. Larger rockets will use 4-40 or 6-32 screws. Two to four screws are typically used, depending upon the retaining force required. Some black powder calculators will determine the number and size of screws needed to ensure the nosecone is not ejected by the pressure differential at maximum altitude, as well as the size of the black powder charge needed to shear those screws.

To calculate the force required to shear a screw, the shear strength of nylon is multiplied by the cross-sectional area at the minimum diameter of the screw. The minimum diameter, or minor diameter, is the diameter measured between the bottom of opposing threads.

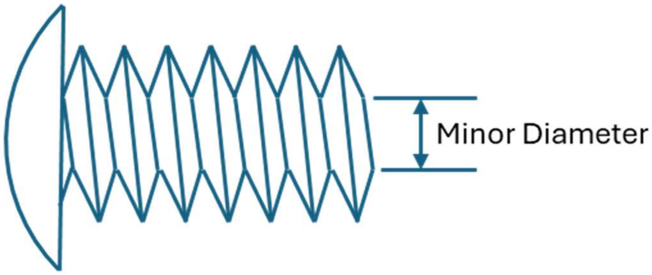


Figure 6-1 Minor diameter of a screw

The shear strength of Nylon is between 9600 and 10500 psi. The minimum diameter for a 2-56 screw is 0.0641 in, so the shear strength for a single 2-56 screw is

$$\pi \cdot r_{\min}{}^{2} \cdot ShearStrength = \pi \cdot \left(\frac{0.05942 \cdot in}{2}\right)^{2} \cdot 9600 \cdot psi = 26.62 \cdot lbf \tag{6-1}$$

The total force required to shear all the screws is the shear force per screw times the number of screws.

A summary of the minor diameters and shear strengths for commonly used screw sizes based on the parameters from Bob Feretich's web site[26] is shown in Table 6-1.

Nylon 6/6 Shear Strength (psi)			**Min**	**Max**
			9600	10500
Screw	**Diameters (in)**	**Areas (sq in)**	**Shear Strength (lbs)**	
Size	**Minor**	**Minor**	**Min**	**Max**
M2	0.05942	0.00277	26.62	29.12
2-56	0.0641	0.00323	30.98	33.88
4-40	0.0813	0.00519	49.84	54.51
M3	0.09396	0.00693	66.57	72.81
6-32	0.0997	0.00781	74.95	81.97

Table 6-1 Calculated shear force for various nylon screws from Feretich

---

[26] (Feretich, 2024)

Drake Damerau did extensive testing of rocketry related construction materials in a professional materials testing lab and summarized the results on his extensive rocketrymaterials.org web site[27] which is now only available through the Internet Archive. Table 6-2 shows the results from his nylon screw shear strength testing. The shear force for the M2 screw is very close the calculated value shown in Table 6-1. The data shows the force per screw drops with an increasing number of screws, but that amount is small.

#2 Nylon Screws				**#4 Nylon Screws**		
# of Pins	**Peak Load (lbs)**	**Peak Load (Each Pin)**		**# of Pins**	**Peak Load (lbs)**	**Peak Load (Each Pin)**
2	53.123	26.56		2	81.304	40.65
2	45.952	22.98		2	85.148	42.57
2	50.848	25.42		2	75.944	37.57
2	51.799	25.9		2	80.391	40.2
2	47.924	23.96		2	80.908	40.45
Avgs	***49.93***	***24.64***			***80.75***	***40.3***
3	62.637	20.88		3	119.273	39.76
3	60.569	20.19		3	110.999	37
3	64.395	21.47		3	99.969	33.32
3	62.413	20.8		3	113.554	37.85
3	68.76	22.92		3	116.208	38.73
3	66.643	22.21		3	121.121	40.37
				3	123.689	41.23
Avgs	***64.24***	***21.41***			***114.97***	***38.32***
4	86.699	21.67		4	143.405	35.85
4	86.855	21.71		4	152.368	38.09
4	78.771	19.69		4	142.026	35.51
4	84.269	21.07		4	160.489	40.12
4	85.617	21.4		4	153.302	38.33
4	90.402	22.6		4	154.766	38.69
				4	160.368	40.09
Avgs	***84.44***	***21.36***			***152.38***	***38.21***

Table 6-2 Measured shear forces for various nylon screws from Damerau

The black powder calculators appear to use these values for calculating the force needed from the black powder charge.

---

[27] (Damerau, 2002-2011)

7 Pressure Chamber Testing

To verify the model of Sections 3 and 4, a test chamber was built to measure the pressure generated by black powder combustion. The chamber contains the black powder combustion gases in a known volume and the resulting change in pressure is measured with an industrial electronic pressure sensor.

The test chamber was constructed from a section of PVC pipe with an internal diameter of 4 inches and an internal length of 12 inches for a volume of 150.8 inches, the same dimensions as used in the pressure calculations in the previous sections. The PVC pipe has a specified working pressure of 220 psi (4” Schedule 40 pipe), far greater than the maximum expected pressure generated by the black powder. The pressure sensor is a Honeywell PX3 Series 100 psi full scale Heavy Duty Pressure Transducer. It is mounted at the end of a brass pipe which is filled with brass wool to protect the sensor from the heat and particles of combustion. There is a pipe fitting with a valve to relieve the pressure after the test is complete. This port can also be used to pressure test the chamber, as well as evacuate the chamber for high altitude deployment testing. The wires to fire the black powder e-match pass through the top cover via binding posts.

The pressure sensor has an analog voltage output and is recorded by an Arduino based data logger that was designed and built for this purpose[28]. The e-match is fired from a button on the logger. The pressure data is plotted to a display on the logger real time and logged to a micro-SD card so the data can be pulled into an Excel spreadsheet for analysis and to generate the presentation graphs.

---

[28] See Appendix 1 for the complete schematic of the data logger

Figure 7-1 Black powder test chamber

For all the pressure chamber tests, the black powder is contained in standard 2 cc centrifuge vials, commonly used in rocketry, with the e-match leads passing through a hole in the bottom and with just enough shredded parachute wadding to hold the black powder in place against the e-match.

Figure 7-2 Black Powder charge canister

The first test was to verify the pressure chamber could hold pressure for the maximum duration of a black powder test. For this test, the chamber is pressurized from a compressor, and then the valve on the chamber is closed. Figure 7-3 shows the pressure test result. The pressure overshoots its final value as the chamber is pressurized and the valve is closed. But once the chamber pressure settles, the chamber loses very little pressure. At 30 seconds, the chamber pressure is 17.44 psi, at 120 seconds, 17.26 psi, and at 300 seconds, 17.14 psi, a loss of only 0.3 psi. Most of the tests are much shorter in duration.

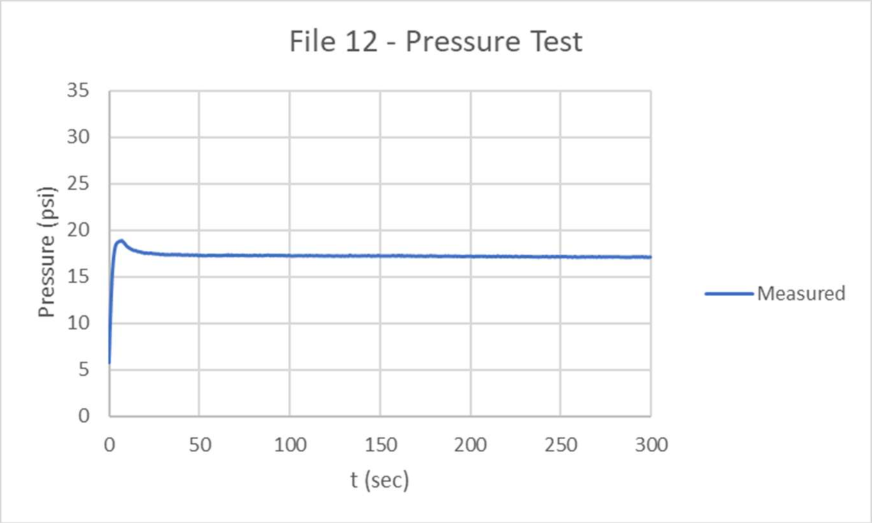


Figure 7-3 Leakage test of pressure chamber

All the black powder tests and actual rocket flights for this paper were done using Goex FFFF black powder. The FFFF powder has the smallest granular size and burns the fastest of all the available powder sizes. It is the same powder that is supplied by the rocket motor manufacturers for use in ejection charges.

Figure 7-4 shows a test of 0.5 grams of black powder[29]. The red trace is the pressure predicted by the Chevreuil black powder equation (4-5), 6.629 psi, and the blue trace is the actual measurement. The initial value, 25.26 psi, shows that the model significantly underpredicts the pressure generated by the black powder. The pressure then decreases as the gases cool. The final value of the pressure, 1.2 psi, is reached at about 60 seconds. This agrees very closely with the value the ambient pressure equation (4-6) predicts, 1.06 psi.

---

[29] The specific weight for Goex FFFF black powder is very close to 1, so 1 cm^3 weighs very close to 1 gram. The black powder was actually measured by volume using calibrated powder measuring scoops

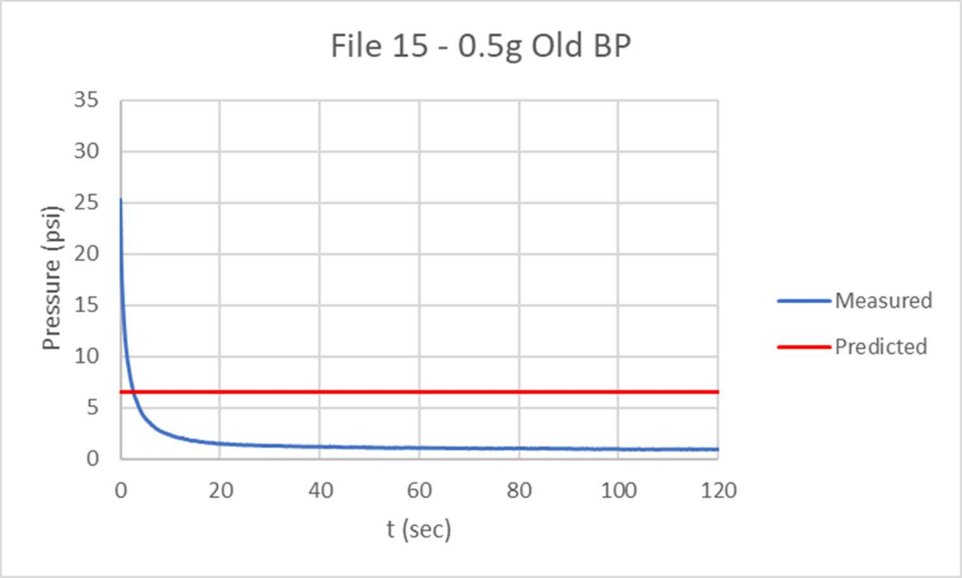
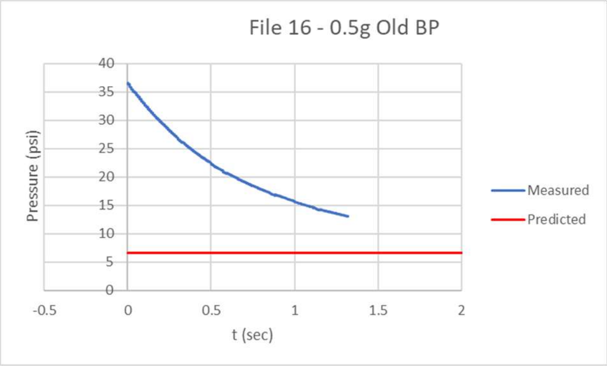
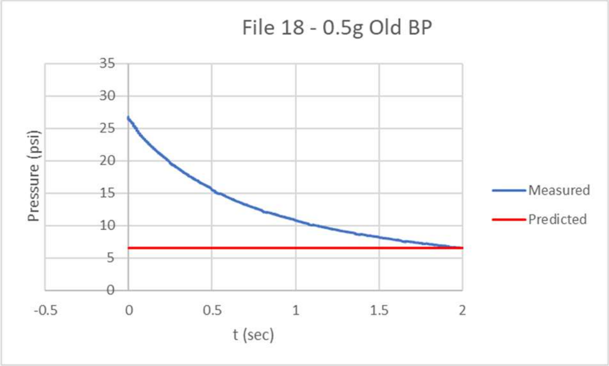
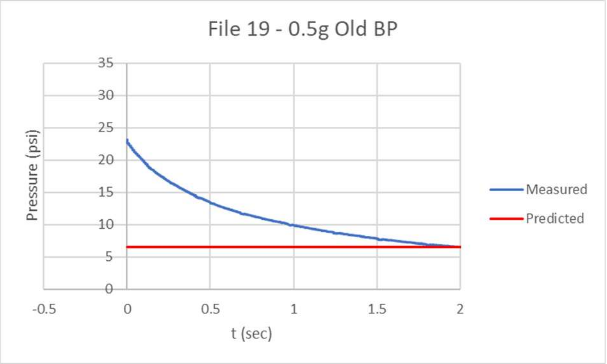


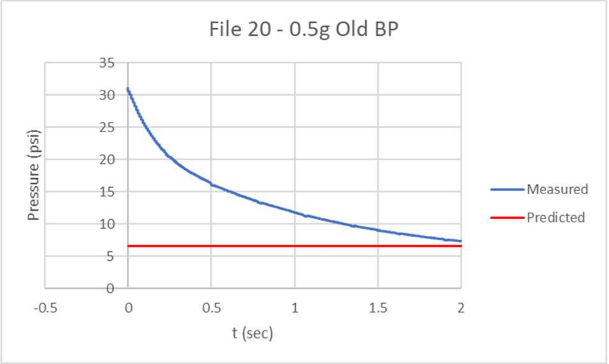
Figure 7-4 0.5 gram black powder – initial pressure: 25.26 psi, final pressure: 1.2 psi

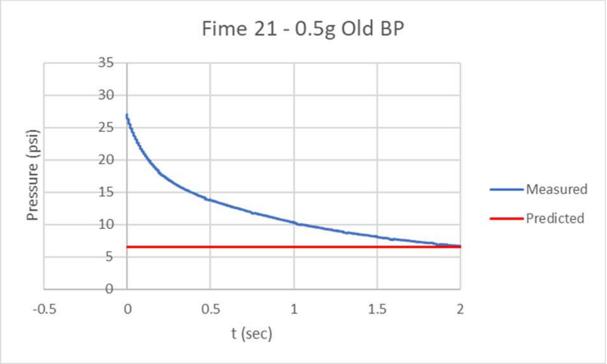
Figure 7-5 shows the test results from a series of 7 tests of 0.5 grams of black powder, along with the mean and standard deviation for the seven initial pressure values. The mean is 28.5 psi and the standard deviation is 4 psi, or 14% of the mean value.

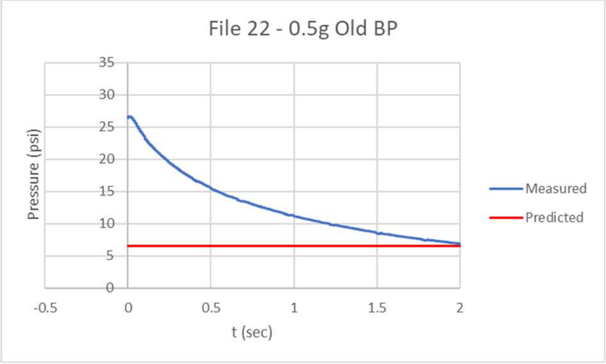


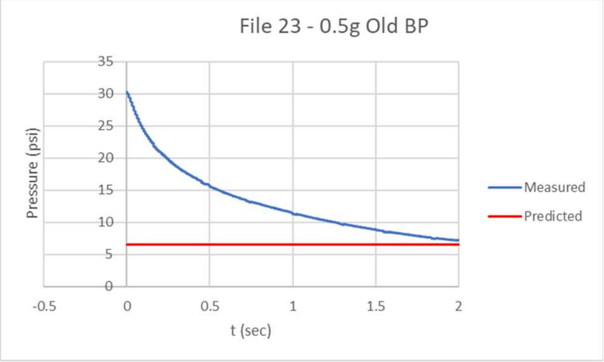












	Initial Pressure
FILE_16	36.64
FILE_18	26.78
FILE_19	23.14
FILE_20	31.15
FILE_21	27.05
FILE_22	26.34
FILE_23	30.24
Mean	**28.49**
Std Dev	**4.04 (14%)**

Figure 7-5 Mean and standard deviation for seven 0.5 gram tests

Figure 7-6 and Figure 7-7 show test results for 0.5 grams of 20 year old and new black powder. The initial values are 31.86 psi for the old black powder and 34 psi for the new black powder. The difference in initial pressure for the tests of the old and new powder fall well within the standard deviation shown in Figure 7-5, so there is no significant difference between the pressure generated by the old and new black powder.

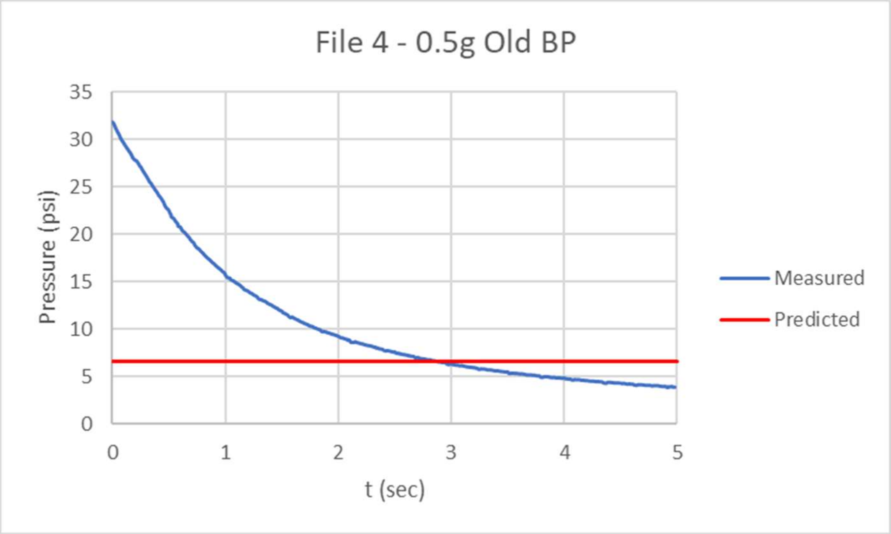


Figure 7-6 0.5 gram old black powder

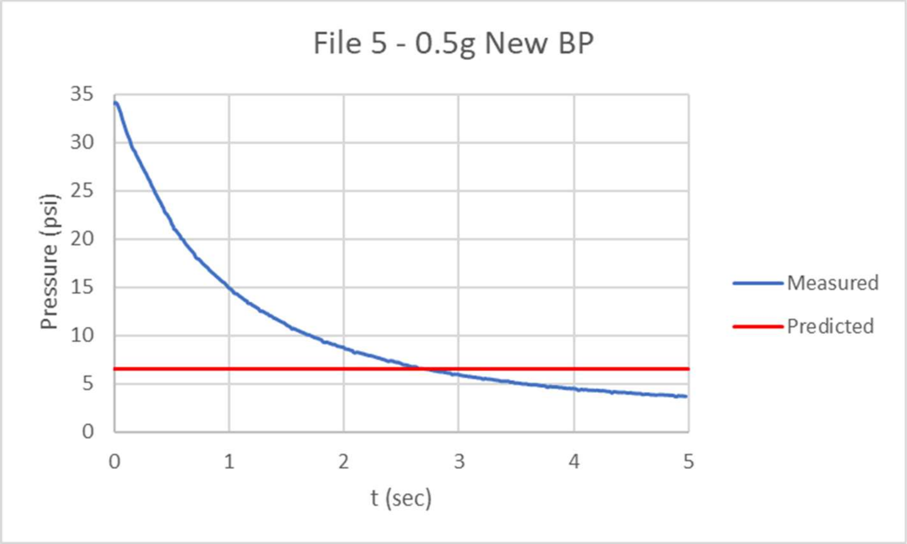


Figure 7-7 0.5 gram new black powder

The large difference in pressure between the model and measurements was very surprising. To verify that the pressure gauge was accurately reading the chamber pressure, a mechanical pressure sensor was attached to the test chamber, and the same 0.5 gm of black powder was used for a test. Figure 7-8 shows a frame from a video taken during the test, showing 28 psi for the peak reading. This agrees very closely with the peak values from the electronic sensor, verifying the electronic sensor is reading correctly. The electronic sensor, which is specified for accuracy, is likely the more accurate of the two sensors.

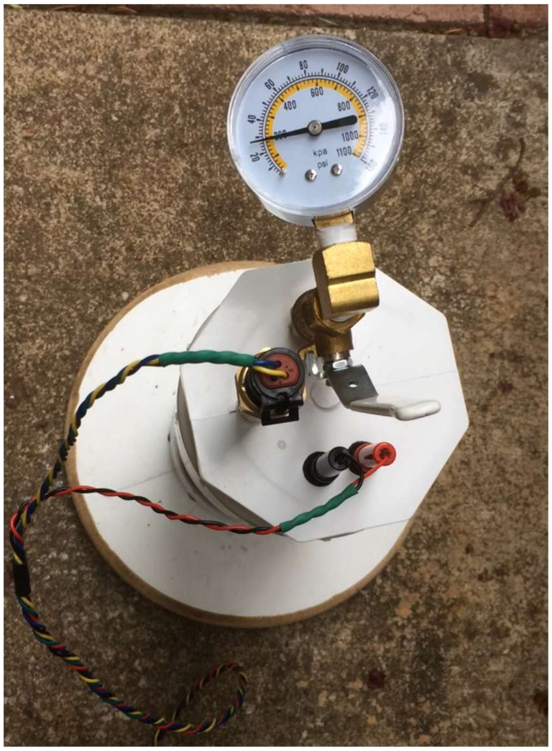


Figure 7-8 Mechanical pressure gauge at peak reading for 0.5 gm of black powder

The large standard deviation in the pressure generated shows one of the reasons why black powder is no longer used in commercial and military applications. This variability supports the results found by Noble & Abel. The large variation in pressure must be taken into account when determining the quantity of black powder needed to reliably deploy a parachute.

These tests show that the model described in Section 4 , which predicted 6.629 psi for 0.5 gm of black powder in the test chamber volume, significantly underpredicts the initial pressure of black powder combustion, but it accurately predicts the final ambient pressure. That means the model accurately predicts the number of moles of gas produced by the combustion, but something is missing from the model to account for the higher initial pressure.

8 Enhanced Black Powder Combustion Model

The pressure calculation of Section 4 assumes that it is only the gas generated by the black powder, at the temperature of combustion of the black powder, that increases the ambient pressure of the closed volume that contains the gas. In the model, the air that is already in the chamber sets the ambient pressure but does not contribute in any way to the increase in pressure. But black powder combustion generates more energy than is needed to raise the solid and gaseous combustion products to the temperature of combustion. That energy must go somewhere. Initially, it must either go to heating the gas in the chamber, or go to heating the walls of the chamber, or both. Any energy absorbed by the air in the chamber will raise its temperature, which increases the pressure in the chamber. This increase in temperature and pressure due to the radiated energy must be added to the model. The assumption will be made that all the energy initially goes to heating the air in the chamber, after which that energy is re-radiated to the chamber walls over a longer time, as seen in the measurements as the drop in pressure, as the gases lose their energy and cool. This assumption will be verified by comparing the pressure obtained from the model to the measurement results.

The derivation of this model will be a worked example for the test conditions used so far in this paper, 0.5 gm of black powder contained in a $150.8in^3$ volume. First, starting with Chevreuil's equation

$$2KNO_3 + S + 3C \rightarrow K_2S + 3CO_2 + N_2 \tag{8-1}$$

and summarizing the equations from Section 4 that will be used in this model, the molar mass of black powder is

$$M_{BP} = \frac{2mol \cdot M_{KNO_3} + 1mol \cdot M_S + 3mol \cdot M_C}{2mol + 1mol + 3mol} = 45.082\frac{gm}{mol} \tag{8-2}$$

the molar mass of the black powder combustion products is

$$M_{BPcp} = \frac{1mol \cdot M_{K_2S} + 1mol \cdot M_{N_2} + 3mol \cdot M_{CO_2}}{1mol + 1mol + 3mol} = 54.098\frac{gm}{mol} \tag{8-3}$$

and the molar mass of the gaseous combustion products alone is

$$M_{BPcpgas} = \frac{1mol \cdot M_{K_2S} + 1mol \cdot M_{N_2} + 3mol \cdot M_{CO_2}}{0mol + 1mol + 3mol} = 67.623\frac{gm}{mol} \tag{8-4}$$

The number of moles in 0.5 gm of black powder is

$$n_{BP} = \frac{m_{BP}}{M_{BP}} = 0.0111 mol \tag{8-5}$$

the number of moles of combustion products is

$$n_{BPcp} = \frac{m_{BP}}{M_{BPcp}} = 0.0092 mol \tag{8-6}$$

the number of moles of the individual combustion products is

$$\begin{aligned} n_{BPcpN2} &= n_{BPcp} \cdot \frac{1}{5} = 0.0018 \cdot mol \\ n_{BPcpCO2} &= n_{BPcp} \cdot \frac{3}{5} = 0.0055 \cdot mol \\ n_{BPcpK2S} &= n_{BPcp} \cdot \frac{1}{5} = 0.0018 \cdot mol \end{aligned} \tag{8-7}$$

and the number of moles of the total combustion product gases is

$$n_{BPcpgas} = \frac{m_{BP}}{M_{BPcpgas}} = 0.0074 mol \tag{8-8}$$

Then, the mass of each of the components of the black powder combustion products is

$$\begin{aligned} m_{BPcpN2} &= n_{BPcpN2} \cdot M_{N2} = 0.052 \cdot gm \\ m_{BPcpCO2} &= n_{BPcpCO2} \cdot M_{CO2} = 0.244 \cdot gm \\ m_{BPcpK2S} &= n_{BPcpK2S} \cdot M_{K2S} = 0.0204 \cdot gm \end{aligned} \tag{8-9}$$

When atoms are combined in a chemical reaction to form a molecule, a certain amount of energy is generally released. Conversely, when that molecule is disassembled in a chemical reaction into its constituent atoms in the process of forming a different molecule, that same amount of energy must be absorbed. In a chemical reaction that involves reassembling a number of molecules into a different set of molecules, if there is a net excess of energy, the reaction is exothermic, and if external energy is required to complete the reaction, the reaction is endothermic. The combustion of black powder is exothermic, so net energy is released.

The delta enthalpy (ΔH) is the net energy in joules per mole released when the atoms are assembled into a molecule. A negative ΔH indicates energy is released in creating the molecule. For a chemical equation, if the sum of the delta enthalpies for each of the starting molecules times the number of moles of that molecule is subtracted from the same for the ending products, the result is net energy absorbed or released by that chemical reaction. A negative net value indicates energy is released and the reaction is exothermic, and a net positive value indicates energy is absorbed and the equation is endothermic.

Table 8-1 shows the ΔH values for the starting and ending products of Chevreuil’s equation.

.

Molecule	State	$deltaEnthalpy = \Delta H_X$
KNO_3	solid	-494600 J/mol
K_2S	solid	-376560 J/mol
CO_2	gas	-393500 J/mol
S	solid	0 J/mol
C	solid	0 J/mol
N_2	gas	191.61 J/mol

Table 8-1 Delta enthalpies for the components of Chevreuil’s equation found on the NIST Chemistry WebBook[30]

To simplify later equations, a single value for the enthalpy of black powder for Chevreuil’s equation (8-1) can be calculated

$$\Delta H_{BP} = \frac{1}{6 \cdot mol} \cdot \left(\begin{array}{l} \left(1 \cdot mol \cdot \Delta H_{K_2S} + 1 \cdot mol \cdot \Delta H_{N_2} + 3 \cdot mol \cdot \Delta H_{CO_2}\right) \\ -\left(2 \cdot mol \cdot \Delta H_{KNO_3} + 1 \cdot mol \cdot \Delta H_S + 3 \cdot mol \cdot \Delta H_C\right) \end{array} \right) = -94611 \cdot \frac{J}{mol} \tag{8-10}$$

For Chevreuil’s equation, the total energy generated by the combustion of 0.5 gm of black powder is

$$Q_{bpc} = n_{BP} \cdot \Delta H_{BP} = \frac{m_{BP}}{M_{BP}} \cdot \Delta H_{BP} = -1049 \cdot J \tag{8-11}$$

Assume that the exothermic energy calculated by equation (8-11) goes to heating the air in the test chamber. The combustion product gases, that are initially at the temperature of combustion, T_C, also give up some of their energy to the air as the air and combustion gases mix and come to an equilibrium temperature.

From the ideal gas equation, the number of moles of air in the test chamber is

$$n_{air} = \frac{P_{atm} \cdot V}{R \cdot T_{amb}} = 0.1024 \cdot mol \tag{8-12}$$

---

[30] (NIST, 2023)

The composition of air by volume is 78% molecular nitrogen (N_2), 21% molecular oxygen (O_2), 0.9% argon (Ar), and 0.04% carbon dioxide (CO_2)[31]. Table 8-2 shows the composition and molar mass for each of the components of air.

Molecule	Air composition by volume	$MolarMass = M_X$
N_2	78%	28.2 gm/mol
O_2	21%	32 gm/mol
Ar	0.9%	39.9 gm/mol
CO_2	0.04%	44.01 gm/mol

Table 8-2 Molar mass for gases in air and black powder combustion products[32]

The molar mass of air is the molar mass of each component times the fraction of that gas in air

$$M_{air} = 78 \cdot M_{N2} + 21 \cdot M_{O2} + .009 \cdot M_{Ar} + .001 \cdot M_{CO2} = 29.119 \cdot \frac{gm}{mol} \tag{8-13}$$

The mass of each of the gases of the air in the chamber is

$$\begin{aligned} m_{airN2} &= .78 \cdot n_{air} \cdot M_{N2} = 2.252 \cdot gm \\ m_{airO2} &= .21 \cdot n_{air} \cdot M_{O2} = 0.688 \cdot gm \\ m_{airAr} &= .009 \cdot n_{air} \cdot M_{Ar} = 0.037 \cdot gm \\ m_{airCO2} &= .001 \cdot n_{air} \cdot M_{CO2} = 0.0052 \cdot gm \end{aligned} \tag{8-14}$$

and the total mass of the air in the chamber is

$$m_{air} = m_{airN2} + m_{airO2} + m_{airAr} + m_{airCO2} = n_{air} \cdot M_{air} = 2.096 \cdot gm \tag{8-15}$$

To determine the change in temperature of the air and combustion product gases, the specific heat is used. For gases, there are two values of specific heat, one where the gas is held a constant pressure, c_p, and one where the gas

---

[31] (Air - Composition and Molecular Weight, 2024)

[32] (Air - Composition and Molecular Weight, 2024)

is held at constant volume, c_v. In the test chamber, the gases are held at constant volume, so c_v is used. The values for c_v are assumed to be constant, although the specific heat for constant volume does vary some over temperature. Including the change with temperature makes the model far more complicated. The fixed value approach is a close approximation that matches the measurement results closely enough. The specific heat of solids is denoted by c_p. Table 8-3 shows the specific heat for the components of air and black powder combustion at a temperature of $300^\circ K$.

Molecule	$SpecificHeat = c_V$
N_2	743 J/(kg·K)
O_2	659 J/(kg·K)
Ar	312 J/(kg·K)
CO_2	655 J/(kg·K)
K_2S	c_p = 74.67 J/(kg·K)

Table 8-3 Specific heat for the components of air and black powder combustion[33]

To simplify later equations, a single value for the specific heat of air and the combustion products of Chevreuil's equation is calculated. The value is the mass weighted average of the specific heat of the individual components.

For air

$$c_{vair} = \frac{c_{vN2} \cdot m_{airN2} + c_{vO2} \cdot m_{airO2} + c_{vAr} \cdot m_{airAr} + c_{vCO2} \cdot m_{airCO2}}{m_{airN2} + m_{airO2} + m_{airAr} + m_{airCO2}} = 718.167 \cdot \frac{J}{kg \cdot K} \tag{8-16}$$

and for the black powder combustion products

$$c_{vBPcp} = \frac{c_{vN2} \cdot m_{BPcpN2} + c_{vCO2} \cdot m_{BPcpCO2} + c_{pK2S} \cdot m_{BPcpK2s}}{m_{BPcpN2} + m_{BPcpCO2} + m_{BPcpK2s}} = 673.231 \cdot \frac{J}{kg \cdot K} \tag{8-17}$$

The energy required to raise the temperature of the black powder combustion products from the ambient temperature up to the temperature of combustion can then be determined from the mass of the black powder and specific heat of the black powder combustion products

---

[33] (Gases - Specific Heats and Individuel Gas Constants, 2024)

$$Q_{BPcp} = \left(T_C - T_{amb}\right) \cdot c_{vBPcp} \cdot m_{BP} = 519.385 \cdot J \tag{8-18}$$

The excess energy from the black powder combustion is the total change in enthalpy minus the energy needed to raise the black powder combustion products up to the temperature of combustion

$$Q_{BPexcess} = -Q_{BPc} - Q_{BPcp} = 529.95 \cdot J \tag{8-19}$$

Assuming all the excess energy is absorbed by the air, the temperature of the air can be calculated from the specific heat and mass of the air

$$T_{air} = \frac{Q_{BPexcess}}{c_{vair} \cdot m_{air}} + T_{amb} = 541.82^{\circ} K \tag{8-20}$$

Immediately after the reaction, assume that the combustion product gases and the air have not yet mixed, and each occupies its own volume at its own temperature as if a sliding wall exists within the test chamber with the air on one side and the black powder combustion product gases on the other side, as shown in Step 1 in Figure 8-1.

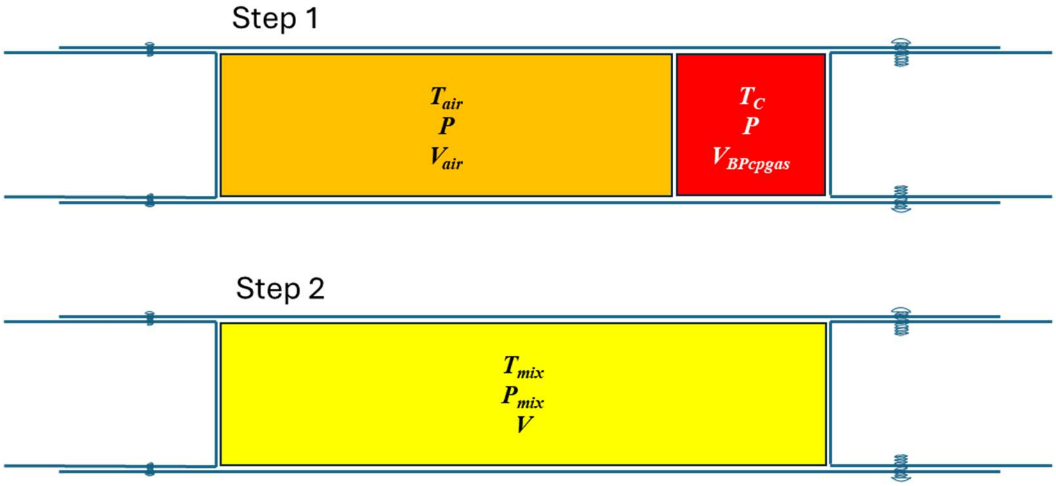


Figure 8-1 Steps for calculating the pressure in the test chamber

The pressure on each side of the wall must be the same, so, from the ideal gas equation

$$\frac{n_{air} \cdot R \cdot T_{air}}{V_{air}} = \frac{n_{BPcpgas} \cdot R \cdot T_C}{V - V_{air}} \tag{8-21}$$

and solving for the volumes

$$V_{air} = V \cdot \frac{n_{air} \cdot T_{air}}{n_{BPcpgas} \cdot T_C + n_{air} \cdot T_{air}} = 121.129 \cdot in^3$$
$$V_{BPcpgas} = V - V_{air} = 29.667 \cdot in^3 \tag{8-22}$$

The pressure can then be calculated from either the air or the combustion gases

$$P = \frac{n_{air} \cdot R \cdot T_{air}}{V_{air}} - P_{atm} = \frac{n_{BPcpgas} \cdot R \cdot T_C}{V - V_{air}} - P_{atm} = 18.996 \cdot psi \tag{8-23}$$

As the gases intermix, they exchange energy and come to an equilibrium temperature. Equating the energy before and after the gases mix

$$c_{vair} \cdot m_{air} \cdot T_{mix} + c_{vBPcp} \cdot m_{BPcp} \cdot T_{mix} = c_{vair} \cdot m_{air} \cdot T_{air} + c_{vBPcp} \cdot m_{BPcp} \cdot T_C \tag{8-24}$$

Note this heat transfer equation includes the solid Potassium Sulfide (K_2S) combustion product. Black powder burns with a white smoke, but the gases produced by black powder combustion are clear. The white appearance is due to fine solid Potassium Sulfide combustion product particles that are mixed in with the gases[34], so it is assumed that they transfer their heat along with the gaseous particles to the air. Solving Equation (8-24) for the temperature at equilibrium gives

$$T_{mix} = \frac{c_{vair} \cdot m_{air} \cdot T_{air} + c_{vBPcp} \cdot m_{BPcp} \cdot T_C}{c_{vair} \cdot m_{air} + c_{vBPcp} \cdot m_{BPcp}} = 717.83^\circ K \tag{8-25}$$

Another approach to solving the equilibrium temperature is to look at the final temperature when all the products are directly raised from the ambient temperature to the equilibrium temperature by the total change in enthalpy energy from equation (8-11).

$$T_{mix} = \frac{-Q_{BPc} + c_{vair} \cdot m_{air} \cdot T_{amb} + c_{vBPcp} \cdot m_{BPcp} \cdot T_{amb}}{c_{vair} \cdot m_{air} + c_{vBPcp} \cdot m_{BPcp}} = 717.83^\circ K \tag{8-26}$$

This method gives the same result as equation (8-25) and does not require knowing the temperature of combustion of black powder, which says the equilibrium temperature is only dependent on the total energy produced by the

---

[34] (Davis, The Chemistry of Powder and Explosives, 1941)

reaction and is independent of the combustion temperature. The combustion temperature is difficult to measure accurately, so this is a good outcome.

The equilibrium pressure can then be calculated from the ideal gas law using the equilibrium temperature of the mix of gases

$$P_{mix} = \frac{\left(n_{BPcpgas} + n_{air}\right) \cdot R \cdot T_{mix}}{V} - P_{atm} = 23.75 \cdot psi \tag{8-27}$$

Note that the pressure of the gases, after they come to a common temperature, is higher than the initial pressure when the gases are at different temperatures. The measurements show that the mix must happen very rapidly because there is not an increase in the pressure in the measurements within the response time of the pressure sensor.

The final pressure when the gases have cooled to ambient is

$$P_{amb} = \frac{\left(n_{BPcpgas} + n_{air}\right) \cdot R \cdot T_{amb}}{V} - P_{atm} = 1.062 \cdot psi \tag{8-28}$$

This result for the initial pressure is still lower than the measurements shown in Figure 7-5, 28.49 psi average, but it is much closer than the model used by the BP calculators that do not include the effects of the exothermic energy, which show the pressure is 6.629 psi in equation (4-5). This also validates the assumption that all the exothermic energy must initially be absorbed by the air. The calculation of the final pressure at ambient temperature, from Equation (8-28), which is due just to the additional moles of the combustion product gases, is no different than the calculation based on the original model.

Table 8-4 shows the pressure results for each of the different black powder chemical equations described in Section 3 using the same process used above for Chevreuil's equation. The values for the enthalpy and specific heat for all the products of combustion needed to evaluate the equations are given in Appendix 5. The values for Potassium Thiosulfate, Potassium Thiocyanate, Ammonium Carbonate, and Charcoal are estimates, as these values have not been found in any available sources. These are only used for calculating the initial pressure of Kasat's equation, so that value is shown in red to indicate it is an estimate.

	BP Calc Model Pressure	Enhanced Model Pressure	Ambient Temp Pressure
Chamber Measurement	28.49 psi		1.2 psi
Chevreuil's Equation	6.63 psi	23.75 psi	1.062 psi
Debus's Equation	4.10 psi	35.23 psi	0.656 psi
Berthelot's Equation	4.33 psi	23.45 psi	0.693 psi
Kast's Equation	4.76 psi	32.30 psi	0.762 psi

Table 8-4 Pressures calculated by each of the equations and models for 0.5 gm of black powder in the volume of the test chamber

Which equation most accurately describes the black powder reaction in the test chamber? Table 8-4 shows that Chevreuil's equation comes closest to predicting the final pressure. This is due just to the number of moles of gas produced by the black powder. Chevreuil's and Berthelot's equations both underpredict the initial value, and Debus's and Kast's (estimate) equations both over predict the initial value. From Table 3-2, Chevreuil's and Kast's equations are the closest fit to the proportions of the initial ingredients for the black powder formulation used by Goex, assuming that all of the initial ingredients are consumed by the reaction. The two measurements in Table 3-2, one by Nobel & Able[35], and the other by Burnsen & Schischkoff[36] show a variety of components produced by the black powder combustion that exceeds any of the four combustion equations. So it is difficult to identify any one of these equations as best describing black powder combustion, and the actual reaction could be a mix of these equations. But since Chevreuil's equation most accurately models the final pressure and is close for the initial pressure (under predicting the initial pressure is better than over predicting the pressure), as well as being the simplest equation, this is the equation that will be used for the black powder calculator model presented in this paper.

The chamber measurements show that the gases cool to the ambient temperature within 20-40 seconds. The heat of the gases is re-radiated and absorbed by the PVC test chamber walls. The specific heat and specific gravity of PVC are given in Table 8-5.

Specific Heat = c_{pPVC}	Specific Gravity = SG_{PVC}
1047 J/(K·kg)	1.4 gm/cm^3

Table 8-5 Specific heat and specific gravity of PVC pipe

---

[35] (Davis, The Chemistry of Powder and Explosives, 1941, pp. 42-43), Nobel & Able dates from 1875

[36] (Maltitz, 2003, pp. 143 Table 12-1)

For a wall thickness of 0.2 in, the volume of the PVC pipe for the test chamber is

$$V_{PVC} = \left(\pi \cdot \left((2.2 \cdot in)^2 - (2 \cdot in)^2\right) \cdot 12 \cdot in\right) + \left(2 \cdot \pi \cdot (2 \cdot in)^2 \cdot 0.2 \cdot in\right) = 36.69 \cdot in^3 \tag{8-29}$$

The energy lost by the gases when they cool to ambient is

$$Q_{loss} = \left(c_{vair} \cdot m_{air} + c_{vBPcp} \cdot m_{BP}\right) \cdot \left(T_{mix} - T_{amb}\right) = 1049 \cdot J \tag{8-30}$$

and the temperature of the test chamber pipe once the heat has been absorbed is

$$T_{PVC} = \frac{Q_{loss}}{c_{pPVC} \cdot SG_{PVC} \cdot V_{PVC}} + T_{amb} = 72.144^{\circ} F \tag{8-31}$$

where the ambient temperature is $T_{amb} = 70^{\circ} F$. The final increase in the temperature of the test chamber is only $2.1^{\circ} F$ because the specific heat and mass of the PVC is much greater than the specific heat and mass of the gases. This is not a surprise because there is little noticeable increase in the temperature of the test chamber after a black powder test. The inner layer of the test chamber would absorb the energy first, and then that heat would diffuse through the thickness of the PVC. If it is assumed that all the energy is first absorbed by the inner $0.001 \cdot in$ of the PVC, then the inner surface temperature would be $114.6^{\circ} F$, still not very hot compared to the initial temperature of the gases.

9 Deployment Testing

The pressure chamber testing showed that the pressure generated by black powder combustion is significantly greater than the pressure predicted by the black powder calculators which do not include the heating of the air due to the exothermic energy of combustion. And shear strength tests by Damerau show that the nylon screws shear at a force close to the value calculated using the shear strength of nylon. Something other than a lack of pressure or the strength of the shear pins must be the cause of the parachute deployment failures seen by the author.

As Noble and Able observed, the black powder reaction is dependent upon the conditions under which the black powder is burned. They found burning in a confined space produces different results than burning in an open space. Does burning the black powder in a pressure chamber where the pressure reaches 30 psi represent the environment in a rocket where the rocket will likely separate below that pressure? Up to the point where the nosecone separates, the black powder reacts within a confined volume just like the pressure chamber. Once the pressure needed to separate the rocket is reached and the pressure of the reaction environment drops, the course of the remainder of the reaction no longer matters. So, the pressure chamber test should reflect the deployment environment, but a test fixture that more closely resembles the actual rocket parachute deployment is needed to verify this.

The deployment test fixture consists of a length of tube with a removable coupler tube on each end. Each coupler tube is sealed with a bulkhead. The rear coupler tube is secured to the body tube with metal bolts and has a small hole in the bulkhead for feeding the charge canister wires through and remains fixed during the test. The front coupler tube is secured to the body tube using the shear pins and is ejected by the charge during the test. Since the shear pins represent the greatest force the black powder must overcome, they must be included in the fixture. The forward coupler/bulkhead is tethered to the rear coupler/bulkhead with a shock cord and has a roll of soft foam taped to the front to help cushion it on landing. The same 2 cc centrifuge vial charge canisters used for the pressure chamber tests were used for the deployment fixture tests. There are three deployment test fixtures of different sizes. The smallest test fixture has the same parachute section dimensions as a rocket called TR-1. The medium sized test fixture matches a rocket called VTS-1. Both TR-1 and VTS-1 use a Nomex chute protector to protect the parachute, and both had deployment failures during one of their flights. The largest test fixture does not match any particular rocket, but was included to test a larger variety of rocket sizes.

Figure 9-1 shows a drawing and picture of the components of the large test fixture. The other two test fixtures look very similar.

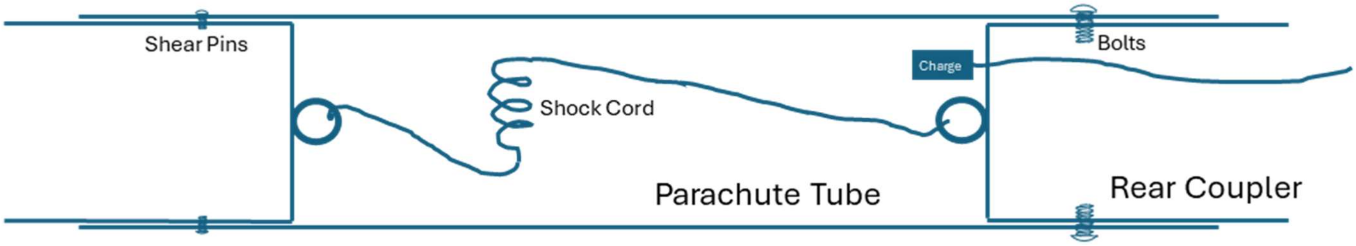


Figure 9-1 The large deployment test fixture

Table 9-1 shows the dimensions of the three test fixtures used for the deployment tests as well as the dimensions of the pressure test chamber for comparison. It also shows the forces required to shear the number of shear pins being used and the amount of black powder needed to generate that force as predicted by both the BP calculator and the enhanced model.

	Size	Volume	# 2-56 Shear Pins	Force Required	BP Calc Charge	Enhanced Model Charge
Test Chamber	4” dia c 12” len	150.8 in^3				
Large	3.9” dia x 10” len	119.5 in^3	6	185.9 lbf	0.93 gm	0.253 gm
TR-1	2.15” dia x 9” len”	32.7 in^3	2	61.9 lbf	0.279 gm	0.076 gm
VTS-1	3” dia x 15” len	106.0 in^3	2	61.9 lbf	0.465 gm	0.124 gm

Table 9-1 Dimensions of the three deployment test fixtures, the force required to shear the shear pins, and the required black powder charge predicted by the BP Calculator and enhanced models

It would be interesting to measure the pressure in the deployment fixture to determine the pressure it takes to shear the pins. Unfortunately, the step response time for the sensor is 2 ms, and the plug is ejected by the black powder combustion in less time than that, so the pressure sensor is too slow to measure the pressure build up before the pressure is released. Therefore, the test process consists of starting with a small quantity of black powder and increasing the amount until the forward plug (nosecone) deploys energetically. The pressure chamber must be used to measure the pressure profile generated by the black powder, and the deployment fixture is used to verify the amount of black powder needed to shear the pins and deploy the plug and validate the results from the pressure chamber tests.

The first set of tests used the large deployment test fixture to verify the amount of black powder required to shear the shear pins and eject the nosecone. Because the enhanced model shows the black powder produces so much pressure, six 2-56 shear pins were used so that the amount of black powder required was large enough to be easily measurable. The smallest powder measuring scoop is 0.3 gm. Filling it half full, which is not hard to gauge, means the smallest measurable amount of black powder would be 0.15 gm. For the large test fixture, the enhanced model predicts 0.19 gm of black powder is required to create the 185.9 lbf needed to shear the six 2-56 nylon screws.

Table 9-2 shows the test results. The first test using 0.15 gm of black powder failed to deploy. The second test using 0.3 gm deployed very energetically. An energetic deployment is defined as a deployment where the nosecone rapidly reaches the max travel allowed by the shock cord and snaps back down to the ground. The two black powder quantities from the tests bracket the 0.19 gm predicted by the enhanced model which is well below the 0.93 gm predicted by the BP calculators. Figure 9-2 shows a frame from a video of the test just after deployment.

BP Charge	Deployment Result
0.15 gm	Failure to deploy
0.3 gm	Energetic deployment

Table 9-2 Test results for the large deployment fixture with six 2-56 shear pins

Figure 9-2 Energetic deployment for the large deployment fixture using 0.3 gm black powder from a frame of a video of the test

This result confirms that the pressure chamber is a valid test environment for making black powder deployment pressure measurements. This also confirms the enhanced model that was developed to explain the results seen from the pressure chamber testing. It also verifies the model of the force needed to shear the shear pins. But it does not explain the series of deployment failures from the author's actual flights that motivated this research project. There is still something different between the deployment fixture tests and actual rocket flights.

That one key missing part is the parachute. It was assumed that the parachute would reduce the volume of the test chamber by a very small amount, which would only increase the pressure created by a given amount of black powder, so testing without a parachute would give a worse-case answer for the quantity needed for deployment. But given the significant discrepancy between these test results and the results from actual flights, a parachute was added to the deployment fixture for the next set of tests.

The deployment failures occurred after starting to fly rockets that used Nomex chute protectors rather than the pistons that had been used reliably on prior flights. The rockets that saw failures had very tightly packed parachute compartments; the parachute filled the space available in the parachute tube. Both rocket configurations placed the black powder charge opposite the end of the nosecone and separation point, so the charge was behind the parachute, the same arrangement as the test fixture.

Figure 9-3 shows the TR-1 deployment test fixture with the parachute. A cotton t-shirt wrapped in a Nomex chute protector serves as a proxy for the parachute. After many tests, the parachute will eventually see damage from the hot gases. Using a cotton rag saves damaging a real parachute. The chute protector wrapped t-shirt nearly fills the space in the fixture as the parachute does in the actual rocket of the same size.

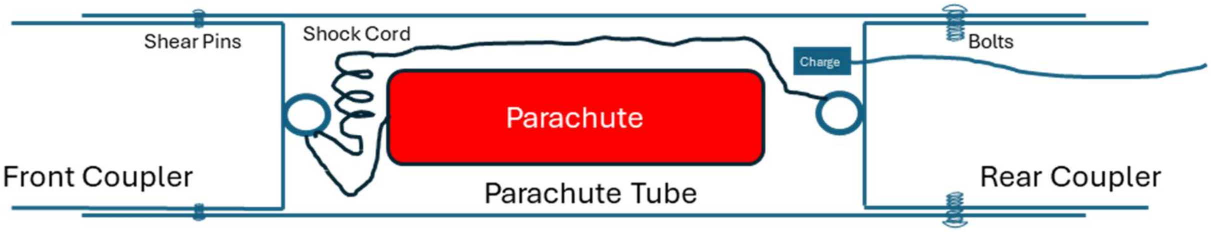


Figure 9-3 TR-1 and the deployment test fixture with parachute

Table 9-3 shows the results of the TR-1 deployment fixture tests. The black powder calculator model says 0.28 gm of black powder is required for two 2-56 shear pins. The enhanced model says only 0.056 gm is required. Starting without a parachute, 0.15 gm of black powder results in a very energetic deployment. But when the parachute is added, the 0.3 gm charge does not deploy the fixture. It takes 1.0 gm to get a deployment, and 1.3 gm to get an energetic deployment. This is significantly more black powder than either of the BP models predict.

BP Charge	Parachute	Deployment
0.15 gm	No	Very energetic
0.3 gm	No	Very energetic
0.3 gm	Yes	No
0.5 gm	Yes	No
0.7 gm	Yes	No
1.0 gm	Yes	Clean
1.3 gm	Yes	Very energetic

Table 9-3 Test results for the TR-1 deployment fixture with two 2-56 shear pins

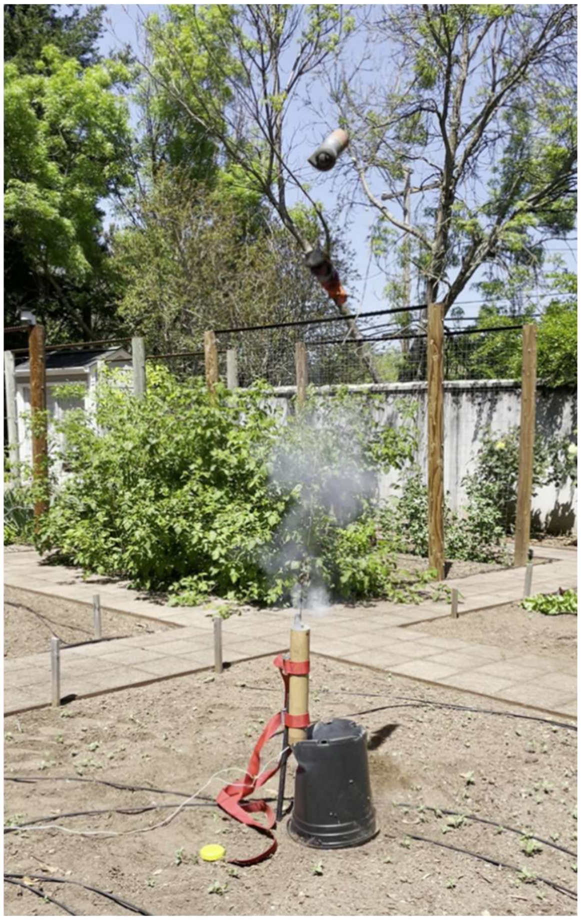


Figure 9-4 Energetic deployment of TR-1 fixture with 1.3 gm of black powder

The VTS-1 deployment fixture shows similar results. The VTS-1 deployment fixture matches the dimensions of a rocket that separates into two sections, each with its own 48" parachute. Both parachutes are in the same parachute bay, and both are deployed at apogee using a single black powder charge, although there is also a backup charge in the real rocket. In the rocket, there is no shock cord connecting the forward and rear sections, so both sections come down separately. But in the test fixture, the front section is tethered to the rear section for safety. Figure 9-5 shows the configuration of the VTS-1 deployment fixture with the two parachutes.

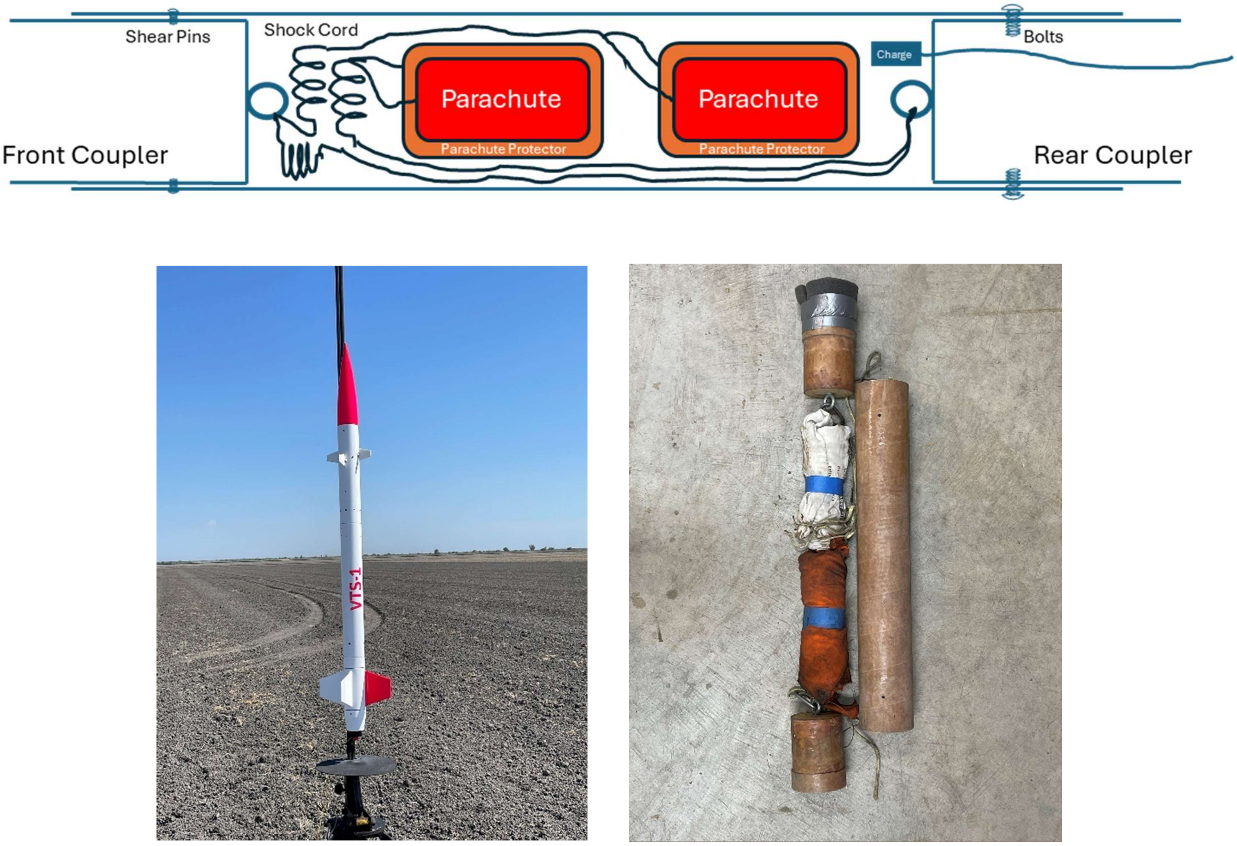


Figure 9-5 VTS-1 and the deployment test fixture with two parachutes

For this fixture, the BP Calculator model says 0.47 gm is required, and the enhanced model says 0.095 gm is required. VTS-1 had a parachute deployment failure where only one of the two parachutes completely exited the parachute bay when 1.0 gm of black powder was used. Table 9-4 shows the test results. It takes 1.6 gm of black powder to get a clean deployment of both parachutes and 1.9 gm to get an energetic deployment (note: the packing order of the parachutes has been changed from the failed flight where the forward section's parachute is now packed behind the rear section's parachute to ensure the momentum of the forward section pulls the rear section's parachute out of the tube). Figure 9-6 shows the energetic deployment of the VTS-1 fixture with 1.9 gm of black powder, where both parachutes have been cleanly ejected. These results confirm that the 1 gm of black powder used in the actual flight, where one parachute failed to deploy, was not adequate.

BP Charge	Parachute	Deployment
0.15 gm	No	Very energetic
1.0 gm	Two	No
1.2 gm	Two	1 of 2 chutes deploy
1.6 gm	Two	Both chutes deploy
1.9 gm	Two	Very Energetic

Table 9-4 Test results for the VTS-1 deployment fixture with two 2-56 shear pins

Figure 9-6 Energetic deployment of VTS-1 fixture with 1.9 gm of black powder showing both parachutes have cleanly deployed

So why does it take so much more black powder than either model predicts to deploy the system when a parachute is present? Looking at the ideal gas equation

$$P = \frac{n \cdot R \cdot T}{V} \tag{9-1}$$

n is the total number of molecules of air plus black powder combustion gases which does not change significantly, and V is the volume of the chamber, which gets insignificantly smaller, when adding the parachute (the parachute bundle is mostly air - if a parachute is folded flat and compressed, it takes up very little volume), leaving only the temperature of the gases as the parameter which must be different with and without the parachute. The temperature of the gases in the chamber must be lower for the pressure to be lower when the parachute is present. In the enhanced model, it is assumed that all the exothermic energy not used to raise the temperature of the combustion products is initially absorbed by the air in the chamber, and not by the chamber walls. The chamber tests showed this to be a correct assumption. But with the parachute present, the parachute must absorb much of the exothermic energy, preventing the air temperature from increasing as much as it does without the parachute. The parachute must act to cool the black powder combustion gases as the gases pass through and around it so that the average temperature of the combination of gases is significantly lower when the parachute fills the chamber. To quantify this difference in pressure and temperature, a pressure chamber test was performed with the chamber filled with a parachute. The results of this test are described in the next section.

Another set of tests was run using the VTS-1 test fixture where only one half or one quarter of the volume was filled with a parachute, leaving part of the parachute tube empty. The parachute was packed in either the front or back of the tube (the charge canister is mounted to the bulkhead at the back end of the tube), thereby either leaving the space directly in front of the charge canister open or filled as it was in the case with two parachutes. When the parachute is packed directly in front of the charge canister, the charge fires directly into the chute protector covering the parachute. Table 9-5 shows the test results for the VTS-1 deployment fixture with one full size parachute filling half the volume, and one half size parachute filling one quarter of the volume.

BP Charge	Parachute	Parachute Tube	Deployment
0.3 gm	1 full size	Front half full	No
0.5 gm	1 full size	Front half full	Yes
0.5 gm	1 full size	Back half full	No
0.7 gm	1 full size	Back Half full	Partial
1.0 gm	1 full size	Back half full	Energetic
0.15 gm	1 half size	Back quarter full	No
0.3 gm	1 half size	Back quarter fill	Energetic
0.5 gm	1 half size	Back quarter full	Very energetic

Table 9-5 Test results for the VTS-1 deployment fixture with just one parachute and with two 2-56 shear pins

Table 9-6 shows a summary of the tests of the VTS-1 deployment fixture as a function of the parachute configuration. When the parachute is in the front of the tube, leaving the space in front of the charge canister open, the parachute must cool the combustion gases less than the rearward position, resulting in higher pressure. The results show that there is more than a 10 to 1 range in the quantity of black powder needed to deploy the system depending on how much of the volume is occupied by the parachute and the location of the parachute when the volume is not completely filled.

Parachute	BP Required for Deployment
No Parachute	0.15 gm
Parachute in front half	0.5 gm
Half size in back quarter	0.3 gm
Parachute in back half	1.0 gm
Two Parachutes	1.6 gm

Table 9-6 Summary of test results for the VTS-1 deployment fixture as a function of the parachute configuration

10 Pressure Chamber Testing – With Parachute

To quantify the impact the parachute has on the pressure generated by the black powder charge, a test was run in the test chamber filled with a parachute (Nomex wrapped cotton t-shirt). Figure 10-1 shows the initial pressure is 3.58 psi, compared to the mean of the empty chamber tests from Figure 7-5 of 28.49 psi. The final pressure, once the gas has cooled to the ambient temperature, is 1.3 psi, which is just due to the additional moles of gas created by the black powder combustion, which is the same as the tests without the parachute, as expected.

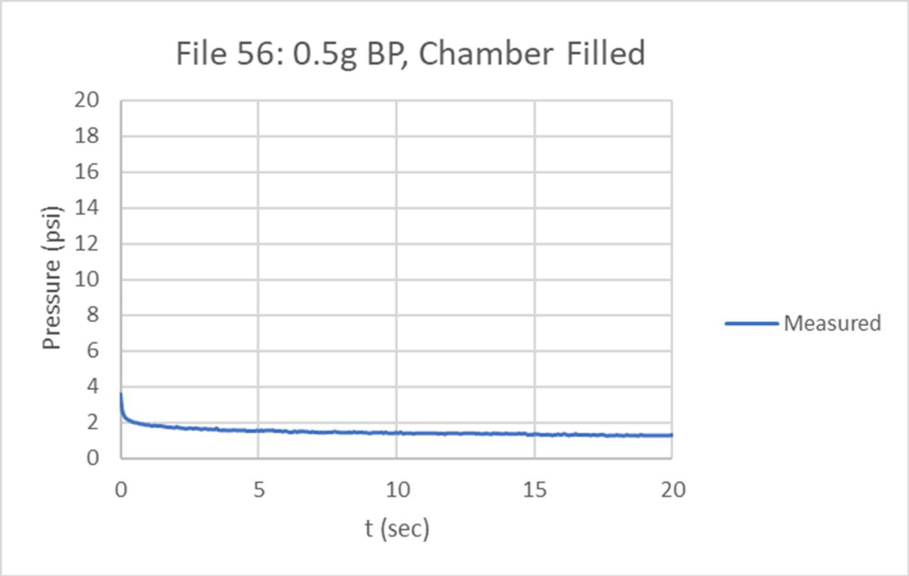


Figure 10-1 Chamber test with 0.5 gm black powder and the chamber space filled with a parachute - initial pressure: 3.58 psi, final pressure: 1.3 psi

From the initial pressure, the initial temperature of the gases can be calculated for the total number of moles of black powder combustion gases plus air

$$T_{coolmix} = \frac{\left(P_{coolmix} + P_{atm}\right) \cdot V}{\left(n_{BPcpgas} + n_{air}\right) \cdot R} = 341.27^{\circ} K = 154.62^{\circ} F \tag{10-1}$$

That is significantly lower than the modeled temperature of the mix of gases when it is assumed all the energy of the reaction is absorbed by the gases, which is $717.8^{\circ} K = 832.4^{\circ} F$.

The energy needed to raise the air and black powder combustion gases up to this temperature is

$$Q_{BPcoolmix} = \left(T_{coolmix} - T_{amb}\right) \cdot \left(\begin{array}{l} c_{vN2} \cdot m_{airN2} + c_{vO2} \cdot m_{airO2} + c_{vAr} \cdot m_{airAr} + c_{vCO2} \cdot m_{airCO2} \\ + c_{vN2} \cdot m_{BPcpgasN2} + c_{vCO2} \cdot m_{BPcpgasCO2} \end{array} \right) = 116.47 \cdot J \quad (10\text{-}2)$$

The total exothermic energy from the black powder combustion, Q_{BPc}, from equation (8-11) is $1049 \cdot J$, so the portion of the energy absorbed by the parachute is

$$\frac{-Q_{BPc} - Q_{BPcoolmix}}{-Q_{BPc}} = 88.9\% \quad (10\text{-}3)$$

so most of the energy is absorbed by the parachute in this test configuration.

11 Pressure Chamber Testing – High Altitude

If the heating of the air by the exothermic reaction energy accounts for most of the pressure resulting from the black powder combustion, then burning the black powder in a vacuum should result in significantly lower initial pressure because there is no air to heat. To test this, the pressure chamber can be evacuated prior to the test. Figure 11-1 shows the equipment used for this test. The vacuum pump can evacuate the chamber down to 3.3 psi, which is 11.4 psi below the nominal 14.7 psi sea level pressure. This is equivalent to approximately 39,000 feet ASL[37].

Figure 11-1 Equipment for testing black powder combustion in a near vacuum

---

[37] (Atmospheric Pressure, 2024)

When using black powder at high altitudes/low ambient pressure, extra measures must be taken to ensure the complete combustion of the powder. It has long been known within the high power rocket community that black powder does not burn completely at high altitude (over 20,000 feet). The theory is that even though black powder contains its own oxidizer, the lack of air prevents the conduction of heat from one grain of black powder to another which prevents complete combustion. Sealed surgical tubing that contains both the black powder, along with some air, has been used successfully as a high altitude charge canister. In 2011, Jim Jarvis wrote an article in Rockets Magazine[38] about high altitude parachute deployment where he showed that a longer charge canister tube works to burn the black powder completely, even when the open end of the canister is not sealed with an air-tight seal. The theory is the longer tube contains the black powder in close proximity long enough that it completely burns before the material leaves the length of the tube. With a shorter tube, some of the black powder is blown out of the tube before it has a chance to burn. Once it leaves the confinement of the tube, there is not enough air to conduct the heat from one grain to the next to complete the burning process.

Figure 11-2 shows three black powder charge canisters that were used for chamber testing in a near vacuum. The bottom canister is a 7/8" long 3-D printed canister that is just long enough to contain the e-match and 0.5 gm of black powder. The middle canister is a standard 2 cc centrifuge vial, and the top canister is a 3" long 3-D printed charge canister. For the tests, the 3" canister was wrapped in 2 layers of duct tape to help ensure the canister would not rupture.

Figure 11-2 7/8" printed, 2 cc centrifuge, and 3" printed charge canister

---

[38] (Jarvis, June, 2011)

Figure 11-3 shows the test result for 0.5 gm of black powder in the 7/8" printed charge canister with the chamber evacuated to -11.4 psi ambient pressure. The initial pressure of the test is 1.13 psi above the ambient pressure, and the final pressure is 0.4 psi above ambient. Figure 11-4 shows the black powder that remained unburned on the bottom of the chamber after the test. Pouring the powder back into the powder scoop showed only about a third of the powder had burned, which is consistent with the 0.4 psi final pressure being about a third of the final pressure from the sea level ambient pressure chamber test from Figure 7-4.

Figure 11-3 shows that the pressure rises slowly by about 0.2 psi between 5 and 20 seconds. The enhanced model shows that the initial pressure rises as the heated air and combustion product gases mix, but that process probably happens much faster than the 15 seconds. From just the pressure measurement data, it is not clear what causes the slow rise in pressure.

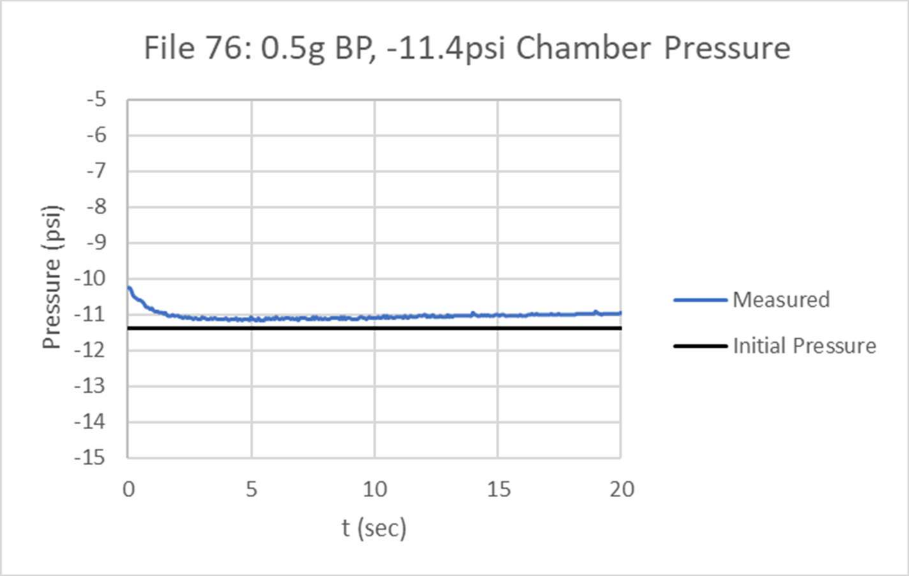


Figure 11-3 Test in evacuated chamber using 0.5 gm black powder in 7/8" printed charge canister - peak pressure above initial pressure: 1.13 psi, final pressure: 0.4 psi above initial pressure

Figure 11-4 Unburned black powder residue left in bottom of test chamber

Figure 11-5 shows the results for three tests of 0.5 gm of black powder in an evacuated chamber using a standard 2 cc centrifuge vial for the charge canister. Figure 11-6 shows how much of a 2 cc centrifuge canister is taken up by 0.5 gm of black powder. What is uniquely interesting about these three tests is the slow rise of the initial pressure. In all other pressure chamber tests, the pressure rises as fast as the response time of the pressure sensor, which has a 2 ms rise time. The actual pressure could rise much faster than that. In all three of these tests, there was very little black powder remaining on the bottom of the test chamber, so it burned nearly completely, but it must have burned slowly. The charge canister must have contained the black powder better than the 7/8” printed canister, but rather than being propagated by heated air, the flame front must have propagated through physical contact between the grains as they left the canister together. The sound of the combustion in the pressure chamber was also very different for these tests. Rather than a sharp but soft click which is usually heard, these tests sounded more like an extended “*ffffft*”, probably due to the longer burn time. Also note the large variability in both peak and rise time for the three tests.

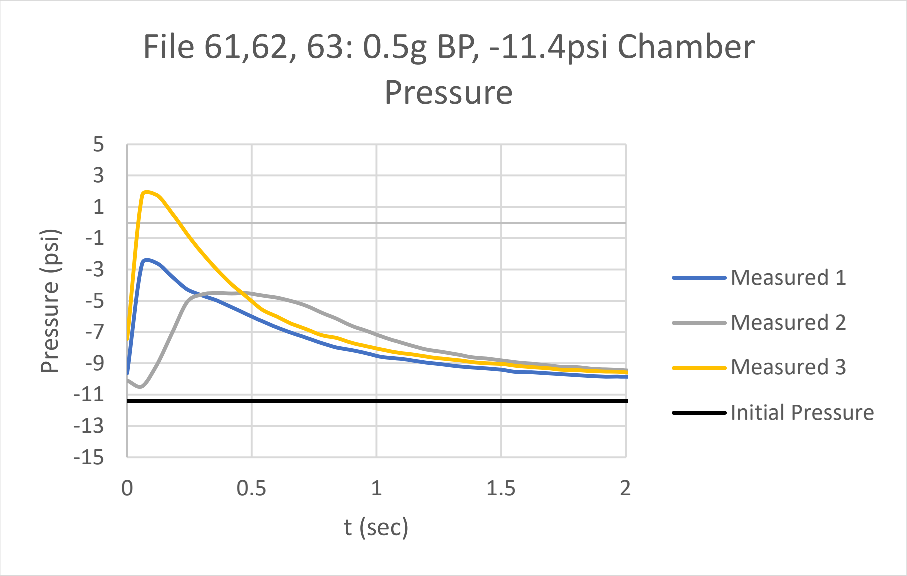


Figure 11-5 Three tests in evacuated chamber using 0.5 gm black powder in 2 cc centrifuge canister

Figure 11-6 0.5 gm of black powder in a centrifuge canister

Figure 11-7 shows the test using the 3” charge canister in the evacuated test chamber. The black powder is retained by a little shredded parachute wadding, but other than that, nothing is used to seal the open end of the tube to retain sea level pressure air. The black powder burned completely; no unburned black powder was left on the bottom of the test chamber. The pressure profile is back to having a very fast rise, so the burn is very fast. This is the test data that will be used to evaluate the impact of the vacuum on the pressure generated by the black powder as the powder burned rapidly and completely. For this test, the starting ambient pressure is -11.4 psi below sea level pressure, and the peak pressure is 10.21 psi above that ambient starting pressure, which is significantly less than the 28.49 psi mean of the sea level ambient pressure tests.

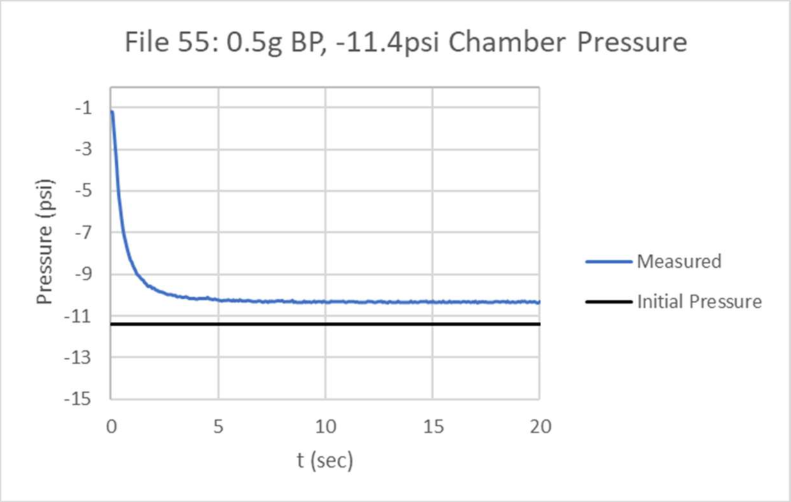


Figure 11-7 Chamber test using 3” charge canister - peak pressure above ambient: 10.21 psi, final pressure above ambient: 1.1 psi

Figure 11-8 shows the test result when the 0.5 gm of black powder in a 3” charge canister in an evacuated test chamber filled with a parachute. This is, by far, the worst case scenario of all the tests, as it shows that no more pressure is generated than is produced by the increase in the number of moles of gas from the black powder combustion at ambient temperature. No additional initial pressure comes from the heating of what little air is in the chamber at -11.4 psi because all the heat is absorbed by the parachute. Once again, the pressure rises a small amount slowly over the 20 seconds of the test as it did without the parachute.

This shows how ineffective black powder can be for deploying a parachute at high altitude. Generally, it has been assumed that black powder would be effective at high altitude as long as a means of containing it while it burns is used, such as sealed surgical tube or a long charge canister. But with or without a parachute, the pressure generated is significantly below the pressure generated at sea level. With a parachute filling the tube, it would be necessary to use enough black powder to ensure the increase in moles of gas alone produces the pressure needed to shear the shear pins and deploy the parachute.

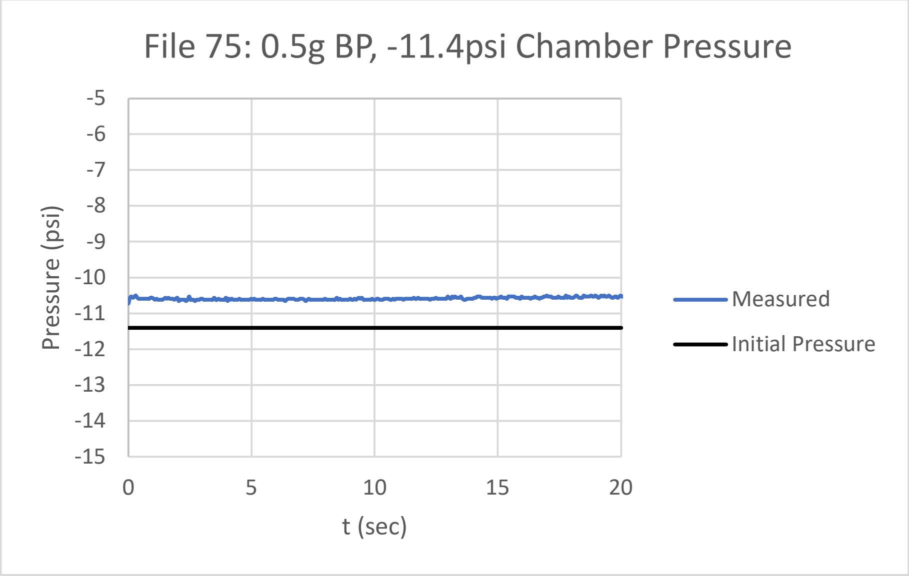


Figure 11-8 0.5 gm black powder in a 3” charge canister in an evacuated test chamber filled with a parachute - initial pressure: 0.8 psi, final pressure: 0.9 psi

12 Modeling High Altitude Deployment

The high altitude vacuum testing could only be done in the pressure chamber and not with the deployment test fixtures. Table 12-1 shows a summary of the pressure chamber test results from Sections 7 and 11 under all the test conditions including the vacuum tests. The maximum vacuum for the vacuum pump is -11.4 psi below sea level pressure, or 3.3 psi absolute, so the results for a complete vacuum can only be modeled.

Ambient Pressure	Parachute	Initial Test Pressure	Model
Sea Level (14.7 psi)	No Parachute	28.5 psi	23.8 psi
Vacuum (3.3 psi)	No Parachute	10.2 psi	20.1 psi
Total Vacuum (0 psi)	No Parachute	NA	12.3 psi
Sea Level (14.7 psi)	Full parachute	3.58 psi	2.42 psi
Vacuum (3.3 psi)	Full Parachute	0.9 psi	2.20 psi
Total Vacuum (0 psi)	Full Parachute	NA	1.73 psi
Ambient Temperature Pressure		1.0 psi	1.06

Table 12-1 Range of pressures generated by 0.5 gm of black powder under different conditions from test chamber measurements

The model using Chevreuil's equation underpredicts the sea level ambient initial pressure by a small amount, with and without a parachute. But, both with and without a parachute, the test results in the evacuated test chamber are significantly below the model's prediction.

At sea level, 14.7 psi, there are 0.102 moles of air in the test chamber. At 3.3 psi, there are 0.023 moles, which is still significantly more than the 0.0074 moles of gas produced by the 0.5 gm of black powder. At sea level pressure, most of the pressure comes from the air in the chamber being heated by the exothermic energy. Even at 3.3 psi ambient, half the modeled initial pressure, 20.1 psi, comes from the heated air. The modeled pressure under full vacuum is 12.3 psi. So, the measured pressure at 3.3 psi ambient is less than the modeled pressure under full vacuum. The measured ambient temperature pressure agrees very closely with the model, so the quantity of gas being produced by the black powder must agree with the model, meaning that the black powder is indeed being burned completely by the 3" charge canister. The difference in initial pressure, then, could be because of a different chemical reaction due to the lower ambient pressure, as observed by Noble and Able, or it could be due to the percentage of the exothermic energy that is absorbed by the gases in the chamber. The model assumes all the energy is absorbed by the gases, which is necessary to come close to matching the measured pressure at sea level ambient. But, at lower pressure, it could be that some of the energy is directly absorbed by the chamber walls. Measuring this would be difficult as the gases in the chamber and the walls of the chamber can be at different temperatures and those temperatures change rapidly after the combustion reaction. More work would be needed to understand the mechanisms that cause the low pressure values at low ambient pressure. For now, the model is not a good predictor at low ambient pressure.

13 Deployment Testing with a Piston

A piston is a common alternative to a recovery blanket for protecting the parachute from the hot ejection charge gases. It serves as a barrier between the hot ejection gases and the parachute so that a protective blanket is not needed. It can be more reliable than a blanket because it ensures the parachute is pushed out of the body tube by the combustion gases. When the recovery blanket is used, the combustion gases can bypass the parachute if it does not completely seal the tube, so a successful deployment must count on the momentum of the nosecone pulling the parachute out of the tube. But, when using a piston, the body tube and piston tube must be kept clean of black powder residue so that the piston can slide freely in the body tube, or the piston can jam in the tube.

The 3” VTS-1 deployment fixture was used for testing with a piston. Figure 13-1 shows the piston and the configuration of the piston in the deployment fixture. The piston’s length is normally the same as its diameter to minimize the chance of jamming in the body tube. The piston is connected to the rear half of the rocket with a length of Kevlar shock cord that is long enough to allow the piston to completely exit the parachute tube. The shock cord is coiled into the piston and the piston is located at the back end of the parachute tube against the rear bulkhead with the charge canister. The nosecone shock cord is attached to the front of the piston and the parachute is packed in front of the piston.

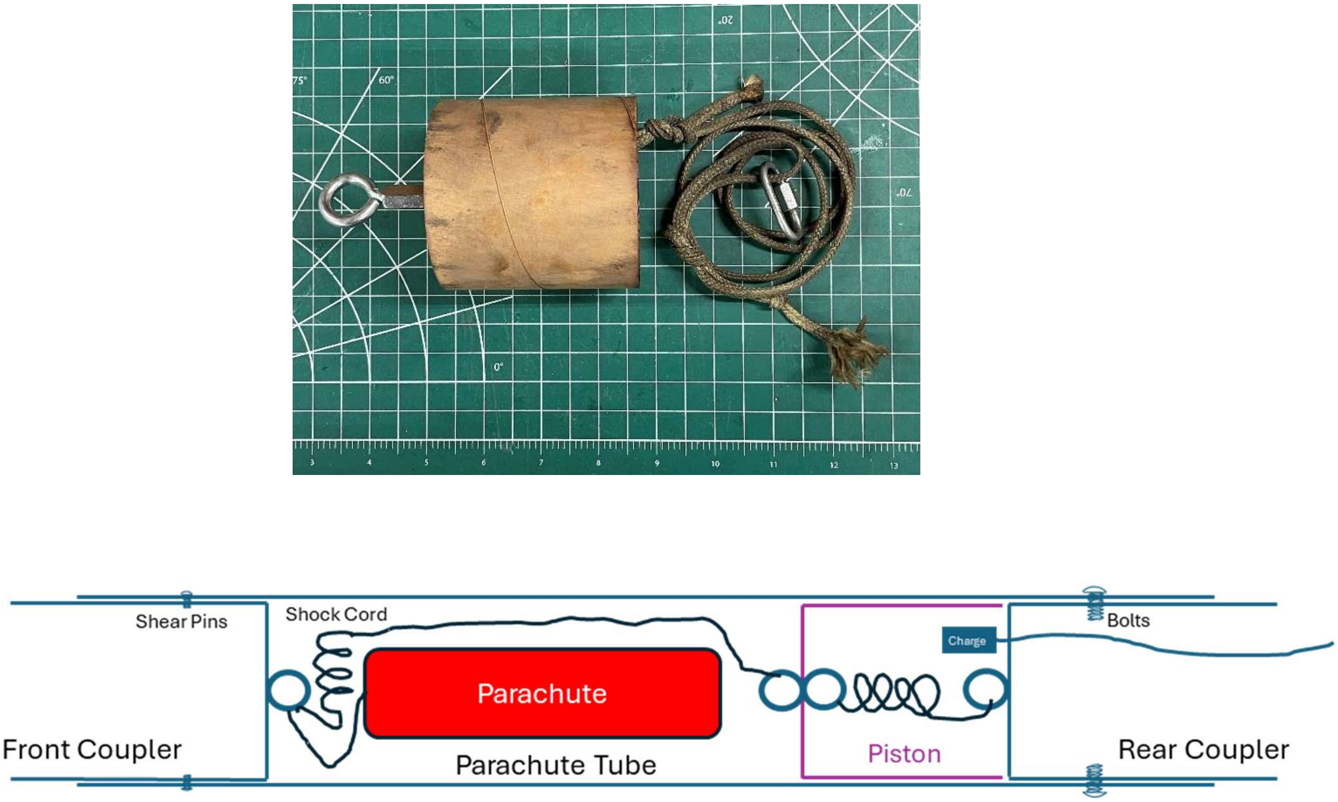


Figure 13-1 Piston and configuration of the deployment fixture with the piston

Table 13-1 shows the results of the piston deployment tests along with the recovery blanket results from Table 9-5 for comparison. To shear the shear pins, the piston required 0.5 gm of black powder, compared to 1.2 gm for the recovery blanket, or 40% as much black powder, so piston deployment does take less black powder. For a fully energetic deployment, it was 1.0 gm vs 1.9 gm, or about 50% as much. In the case of the 0.5 gm and 0.7 gm charges, the parachutes fully ejected, but the piston did not fully eject from the parachute tube and then slid back down to the bottom of the parachute tube. Note that the piston deployment still takes significantly more black powder than the 0.15 gm for the empty tube. This is probably due to two factors. First, the shock chord that is coiled inside the piston must absorb some of the energy. Second, there is less air below the piston, which might result in less pressure even though it is heated to a higher temperature than it is without the piston. This will be modeled in Section 14.

BP Charge	Piston	Parachute	Parachute Tube	Deployment
0.15 gm	No	None	Empty	Very energetic
0.5 gm	Yes	1 full size + 1 half size	Full	Chutes ejected / Piston remains in tube
0.7 gm	Yes	1 full size + 1 half size	Full	Energetic - chutes ejected / Piston remains in tube
1.0 gm	Yes	1 full size + 1 half size	Full	Very energetic – everything ejected
1.0 gm	No	2 full size	Full	No
1.2 gm	No	2 full size	Full	1 of 2 chutes deploy
1.6 gm	No	2 full size	Full	Both chutes deploy
1.9 gm	No	2 full size	Full	Very energetic

Table 13-1 Piston deployment and Recovery Blanket test results for VTS-1 with two 2-56 shear pins

Figure 13-2 shows a frame from the 0.7 gm deployment with the piston almost out of the parachute tube before sliding back down. The parachutes and nosecone can be seen just above the piston. Since the shock cord has not yet reached its limit, this shows that the piston has pushed the parachutes out rather than having the momentum of the ejected nosecone pull the parachutes out.

Figure 13-2 0.7 gm piston deployment

Figure 13-3 shows two frames from the video of the 1.0 gm piston deployment test. The left hand picture shows the hot orange colored gases that follow the piston as it first leaves the parachute tube. The frame of the 1.9 gm deployment without the piston in Figure 9-6 does not show any signs of hot gases exiting the tube, even though nearly twice the black powder is being used. This shows quite dramatically how the parachute cools the combustion gases without a piston. With the piston, there would still be some cooling due to the shock cord, but much less than when the black powder charge fires directly into the parachute blanket.

The right hand picture in Figure 13-3, a closeup of the next frame in the video 33 ms after the frame on the left, shows long streams of burning material exiting the tube. These are pieces of the shredded recovery wadding, used to pack the black powder in the charge canister, that followed the piston as it was ejected. The temperature in the piston was high enough to ignite the recovery wadding. It is clear from later frames that these are burning recovery wadding and not particles of burning black powder.

Figure 13-3 Two frames of the 1.0 gm piston deployment

14 Modeling the Piston

This section will model the pressure generated by the piston, using VTS-1 and 0.5 gm of black powder as the worked example. From the piston tests, 0.5 gm of black powder created enough force to shear the pins and deploy the parachutes, but not enough to eject the piston.

For a piston length of $L_{piston} = 3 \cdot in$, the volume of the piston is

$$V_{piston} = \pi \cdot \left(\frac{D_r}{2}\right)^2 \cdot L_{piston} = 21.20 \cdot in^3 \tag{14-1}$$

The length of the parachute tube is $L_r = 15 \cdot in$, so the number of moles on either side of the piston is the proportionate number of the total moles of air in the tube found using equation (8-12) . $n_{airpiston}$ is the number of moles of air on the black powder charge side of the piston, and $n_{airchute}$ is the number of moles of air on the parachute side of the piston

$$\begin{aligned} n_{air} &= 0.072 \cdot mol \\ n_{airpiston} &= n_{air} \cdot \frac{L_{piston}}{L_r} = 0.014 \cdot mol \\ n_{airchute} &= n_{air} \cdot \frac{L_r - L_{piston}}{L_r} = 0.058 \cdot mol \end{aligned} \tag{14-2}$$

and the mass of the air is found by multiplying by the molar mass

$$\begin{aligned} m_{airpiston} &= n_{airpiston} \cdot M_{air} = 0.419 \cdot gm \\ m_{airchute} &= n_{airchute} \cdot M_{air} = 1.677 \cdot gm \end{aligned} \tag{14-3}$$

Figure 14-1 shows the steps for calculating the equilibrium pressure when using a piston. This assumes that the nosecone remains intact, so the maximum pressure generated by the black powder can be determined. In actuality, the shear pins would shear once the shear force is reached.

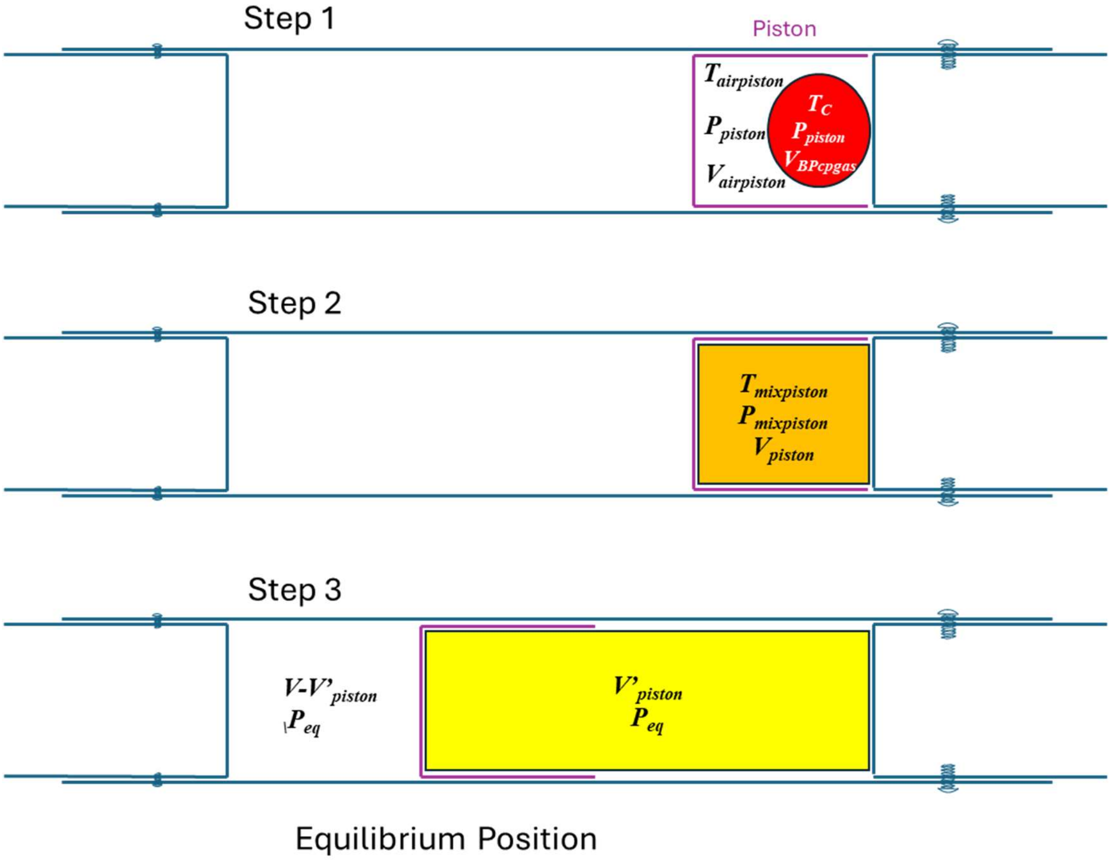


Figure 14-1 Steps for calculating the equilibrium pressure with a piston

Immediately after the reaction, the air in the piston absorbs the exothermic energy of the black powder reaction. The temperature of the air in the piston is given by

$$T_{airpiston} = \frac{Q_{BPexcess}}{c_{vair} \cdot m_{airpiston}} + T_{amb} = 2055^{\circ} K \tag{14-4}$$

where the excess energy is calculated for the 0.5 gm of black powder using equation (8-19).

Again, assume the air and black powder gases each occupy separate volumes within the piston's volume, then similar to equation (8-22)

$$V_{airpiston} = V_{piston} \cdot \frac{n_{airpiston} \cdot T_{airpiston}}{n_{BPcpgas} \cdot T_C + n_{airpiston} \cdot T_{airpiston}} = 14.532 \cdot in^3$$
$$V_{BPcpgas} = V_{piston} - V_{airpiston} = 6.674 \cdot in^3 \tag{14-5}$$

The initial pressure in the piston before the gases mix and before the piston moves is

$$P_{piston} = \frac{n_{airpiston} \cdot R \cdot T_{airpiston}}{V_{airpiston}} - P_{atm} = 135.082 \cdot psi \tag{14-6}$$

After the air and black powder combustion products mix in the piston, the temperature is

$$T_{mixpiston} = \frac{c_{vair} \cdot m_{airpiston} \cdot T_{airpiston} + c_{vBPcp} \cdot m_{BP} \cdot T_C}{c_{vair} \cdot m_{airpiston} + c_{vBPcp} \cdot m_{BP}} = 1940^\circ K \tag{14-7}$$

and the initial pressure in the piston, after the gases mix but before the piston moves, is

$$P_{mixpiston} = \frac{\left(n_{BPcpgas} + n_{airpiston}\right) \cdot R \cdot T_{mixpiston}}{V_{piston}} - P_{atm} = 131.98 \cdot psi \tag{14-8}$$

The pressure in the piston forces the piston down the parachute tube. If the nosecone remains attached, then the pressure on the parachute side of the piston will increase as the volume decreases, and the piston will reach an equilibrium position when the pressure on either side is equal. The volume on the piston side of the bulkhead at equilibrium will be

$$V'_{piston} = \frac{\left(n_{BPcpgas} + n_{airpiston}\right) \cdot R \cdot T_{mixpiston}}{P_{eq}} \tag{14-9}$$

where P_{eq} is the equilibrium pressure. The volume on the parachute side of the piston bulkhead is

$$V'_{airchute} = \frac{n_{airchute} \cdot R \cdot T_{amb}}{P_{eq}} \tag{14-10}$$

Together, these two volumes sum to the total volume of the parachute tube, so

$$\frac{\left(n_{BPcpgas}+n_{airpiston}\right)\cdot R\cdot T_{mixpiston}}{P_{eq}}+\frac{n_{airchute}\cdot R\cdot T_{amb}}{P_{eq}}=V \tag{14-11}$$

Then, solving equation (14-11) for P_{eq}

$$P_{eq}=\frac{R\cdot\left(\left(n_{BPcpgas}+n_{airpiston}\right)\cdot T_{mixpiston}+n_{airchute}\cdot T_{amb}\right)}{V}-P_{atm}=26.396\cdot psi \tag{14-12}$$

and substituting equation (14-12) back into equation (14-9), the volume on the piston side of the bulkhead at equilibrium is

$$V'_{pistom}=\frac{\left(n_{BPcpgas}+n_{airpiston}\right)\cdot T_{mixpiston}\cdot V}{\left(n_{BPcpgas}+n_{airpiston}\right)\cdot T_{mixpiston}+n_{airchute}\cdot T_{amb}}=75.688\cdot in^{3} \tag{14-13}$$

The equilibrium volume of the piston side is V'_{piston}/V = 71.4% of the total volume.

The initial pressure in the piston after the gases mix, but before the piston moves, is very high, at 131.98 psi. This is due to all the exothermic energy being absorbed by the small volume of air plus the combustion gases, which heats the combined gases to $1940^{\circ}K$, much hotter than when a piston is not being used and the energy is absorbed by all the air in the parachute tube. But after the piston moves and comes to an equilibrium position, the pressure drops dramatically to 26.4 psi. By comparison, if 0.5 gm of black powder is used with no piston in an empty parachute tube, so no energy is absorbed by a parachute, the temperature of the mixed gases, from equation (8-26) is $863.985^{\circ}K$, cooler than the gases with the piston. But the pressure in the tube, from equation (8-27) is 32.90 psi, more than the pressure generated using the piston. So, even though the piston causes the gases to be heated to a higher temperature, the smaller volume of gases with the piston produces a lower pressure than the system without a piston, once the system comes to equilibrium.

In actual operation, the piston will start to move as soon as the black powder reaction starts, so the peak pressure may be lower than calculated in equation (14-8) . Also, as soon as there is enough pressure to shear the shear pins, the nosecone will separate, and the pressure will drop, just as it does without the piston, so again, the pressure of equation (14-12) will not be reached. But, with a parachute, the piston will isolate the hot gases from the parachute, the parachute will not cool the gases, and the full pressure can be reached. So, with a parachute, the pressure will be greater for the system with the piston, and as a result, less black powder will be needed.

The large initial temperature and pressure could be a reason for concern when using a piston. The pressure could exceed the strength of the materials, so it is important not to use more black powder than necessary with a piston. When 1.0 gm of black powder is used, which was the quantity from the tests needed to energetically eject the parachutes and the piston, the initial pressure from the model before the piston moves is 233.25 psi, and the temperature is 3947 deg F. Figure 13-3 is a dramatic demonstration of the temperature of the gases that are produced when using 1.0 gm of black powder with the piston.

15 Upper Limit Margin Testing

The recovery system will fail to deploy if too little black powder is used, but it can also be a failure if too much is used resulting in damage to the rocket airframe. The lower limit for deployment was determined by how much black powder was needed to shear the shear pins, even if the parachute did not deploy fully. Then the amount of black powder was increased until an energetic deployment was achieved, where energetic was defined by the nose cone rapidly extending to the limit of the shock cord. The additional amount of black powder, around 40%, was the safety margin needed to ensure a reliable, energetic deployment. But how much margin is there, above that amount, before the black powder charge damages the rocket? In this case, the pressure caused by the black powder would be so great that the airframe would fail before the nosecone has the time to separate from the body tube and release the pressure. The amount determined for an energetic deployment could be right on the edge of structural failure, so without testing above that amount, there is no way of knowing how close to causing failure that amount is. To determine this margin, the deployment fixture was tested starting with the amount that gave an energetic deployment, and increasing the amount of black powder until airframe damage occurred.

The test fixture that was used was the same design as the VTS-1 test fixture, but with no fiberglass wrap. Since a fiberglassed tube is significantly stronger, this will test the margin for the less strong construction technique. All the tubing is PML phenolic tubing.

The parachute tube was filled completely by the parachute, so the quantity of black powder for an energetic deployment, from Table 9-4, is 1.9 gm. Table 15-1 shows the results of the upper limit margin testing, starting at 2.5 gm of black powder. At 2.5 and 3.0 gm, the fixture deployed fine, with no damage to the airframe. But at 4.0 gm, the airframe split around its circumference at the location of the black powder charge canister, releasing the pressure before the shear pins were able to shear. 4.0 gm of black powder is a very large amount for a rocket the size of VTS-1. Figure 15-1 is a frame from the test video at the moment of the failure, showing the release of the hot combustion gases, and Figure 15-2 shows the resulting damage to the airframe. Only the intact parachute is holding the airframe together. The charge canister was ejected out the side of the airframe, still attached by its wires. The shear pins are still intact. The hypothesis for the failure mechanism was that the pressure would be so great that the body tube would fail before the nosecone would have time to slide the length of its shoulder. Since the pressure needed to shear the pins is less than the pressure needed to rupture the body tube, it was assumed that the shear pins would still shear. But the shear pins did not shear, meaning the pressure at the front of the airframe must not have been as great as the local pressure at the rear where the charge canister was located. It must take time for the pressure wave to propagate down the length of the tube, so the tube failed before the pressure wave reached the front end of the tube. It takes about 1 ms for the shock wave to travel the 15 inches from the charge canister to the base of the front bulkhead at 1125 ft/s, the speed of sound, so this is plausible. The other possibility is that the charge canister struck the tube which weakened it and allowed the pressure to split the tube before reaching the shear pressure, but this seems less likely given the tube split cleanly completely around the circumference of the tube, above the location where the canister exited the tube.

Since the failure occurs somewhere between 3 and 4 gm, the margin is somewhere between 1.5 and 2 x over the 1.9 gm of black powder needed for an energetic deployment. The airframe failed due to the tension stress placed on it by the pressure. Had the phenolic tube been fiberglassed, it would have been significantly stronger to tension forces, and probably not have failed at this level, so the margin for a fiberglassed rocket is greater than 1.5-2 x, which should be plenty of margin.

BP Charge	Parachute	Deployment Result
2.5 gm	Two	Very energetic – no damage
3.0 gm	Two	Very energetic – no damage
4.0 gm	Two	Airframe failed before pins sheared

Table 15-1 Upper limit margin testing for the VTS-1 deployment fixture without fiberglass reinforcement

Figure 15-1 Failure of the airframe at 4.0 gm of black powder

Figure 15-2 Damage to airframe from 4.0 gm of black powder showing the shear pins and nosecone still intact and the charge canister outside the tube

16 A New BP Calculator Model

A new model for a black powder calculator, based upon the enhanced black powder combustion model of Sections 6, 8, and 14 and Chevreuil's equation can now be developed.

Equation (6-1) describes the force needed to shear the shear pins, but an additional margin of pressure is necessary for an energetic deployment as was seen in the deployment fixture testing. A certain amount of black powder was needed to shear the shear pins and marginally deploy the parachute, but a larger amount was needed for an energetic deployment. For an energetic deployment, the nosecone rapidly deploys to the full extent of the shock cord. From Table 9-3 for TR-1, it took 1.0 gm of black powder to deploy the parachute, but it took 1.3 gm for an energetic deployment. From Table 9-4, it took 1.6 gm of black powder to deploy the parachutes for VTS-1, but it took 1.9 gm to deploy the parachutes energetically. The margin above the minimum quantity that sheared the pins needed for an energetic deployment for both fixtures was around 40%. The 40% margin should also be adequate to cover the 14% variance seen in the black powder pressure testing in Figure 7-5. This factor will multiply the total force needed to shear the shear pins by a factor of $\left(1+SafetyFactor\right)$. With this, Equation (6-1) becomes

$$F_{shear}=\pi\cdot\left(\frac{D_{minor}}{2}\right)^2\cdot SS\cdot n_{shear}\cdot\left(1+SafetyFactor\right) \tag{16-1}$$

where D_{minor} is the minor diameter of the shear pins, SS is the shear strength of the shear pin material, and n_{shear} is the number of shear pins.

The pressure generated by the black powder from Equation (8-27) is

$$P_{mix}=\frac{\left(n_{BPcpgas}+n_{air}\right)\cdot R\cdot T_{mix}}{V}-P_{atm} \tag{16-2}$$

Where V is the total internal volume of the parachute tube that is filled by air and the gases generated by the black powder. When including the parachute, it is assumed that the volume taken up by the parachute is minimal compared to the volume of the tube, even if the parachute fills the tube. This is because most of the space occupied by the parachute is air. If a parachute is folded flat and compressed, it takes up very little volume.

The initial force generated by the black powder is the pressure from Equation (16-2) times the cross sectional area of the rocket

$$F_{mix} = \left(\frac{\left(n_{BPcpgas} + n_{air}\right) \cdot R \cdot T_{mix}}{V} - P_{atm} \right) \cdot \pi \cdot \left(\frac{D_r}{2} \right)^2 \tag{16-3}$$

The force must be expressed in terms of the known quantities which are the mass of the black powder, the physical dimensions of the rocket, Chevreuil's equation for the combustion of black powder, and the physical attributes of the constituent chemicals

From Equation (8-8)

$$n_{BPcpgas} = \frac{m_{BP}}{M_{BPcpgas}} \tag{16-4}$$

and from Equation (8-12)

$$n_{air} = \frac{P_{atm} \cdot V}{R \cdot T_{amb}} \tag{16-5}$$

The total exothermic energy of the black powder combustion must be modified by a factor that is needed to account for the portion of the energy that is absorbed by the parachute and therefore does not go to heating the air and black powder combustion products. The absorption factor will multiply the value of Q_{BPc} in the equation to calculate the temperature of the mix of products, Equation (8-26), by $\left(1 - A(Pf)\right)$, where $A(Pf)$ is the absorption fraction. $A(Pf)$ is a function of the packing factor of the parachute, Pf, where Pf expresses how much of the parachute tube is filled by the parachute.

$$T_{mix} = \frac{-Q_{BPc} \cdot \left(1 - A(Pf)\right) + c_{vair} \cdot m_{air} \cdot T_{amb} + c_{vBPcp} \cdot m_{BPcp} \cdot T_{amb}}{c_{vair} \cdot m_{air} + c_{vBPcp} \cdot m_{BPcp}} \tag{16-6}$$

where, from Equation (8-11)

$$Q_{BPc} = \frac{m_{BP}}{M_{BP}} \cdot \Delta H_{BP} \tag{16-7}$$

and, from Equation (8-5)

$$n_{BP} = \frac{m_{BP}}{M_{BP}} \tag{16-8}$$

The masses of the individual gases are given by (8-9)

$$\begin{aligned} m_{airN2} &= .78 \cdot n_{air} \cdot M_{N2} \\ m_{airO2} &= .21 \cdot n_{air} \cdot M_{O2} \\ m_{airAr} &= .009 \cdot n_{air} \cdot M_{Ar} \\ m_{airCO2} &= .001 \cdot n_{air} \cdot M_{CO2} \end{aligned} \tag{16-9}$$

$$\begin{aligned} m_{BPcpN2} &= n_{BPcpN2} \cdot M_{N2} \\ m_{BPcpCO2} &= n_{BPcpCO2} \cdot M_{CO2} \\ m_{BPcpK2S} &= n_{BPcpK2S} \cdot M_{K2S} \end{aligned}$$

Substituting Equations (16-4) to (16-8) into Equation (16-3) expresses the pressure in the necessary terms

$$P_{mix} = \left(\frac{m_{BP}}{M_{BPcpgas}} + \frac{P_{atm} \cdot V}{R \cdot T_{amb}} \right) \cdot \frac{R}{V} \cdot \left(\frac{-\left(\frac{m_{BP}}{M_{BP}} \cdot \Delta H_{BP} \right) \cdot \left(1 - A\left(P \right) \right)}{c_{vair} \cdot \frac{P_{atm} \cdot V}{R \cdot T_{amb}} \cdot M_{air} + c_{vBPcp} \cdot m_{BP}} + T_{amb} \right) - P_{Atm} \tag{16-10}$$

Plotting Equation (16-10) in Figure 16-1 shows that the pressure is close to a linear function of the mass of the black powder, meaning that twice the black powder produces almost twice the pressure. So the 40% margin in black powder mass needed for an energetic ejection translates into the 40% safety margin in force.

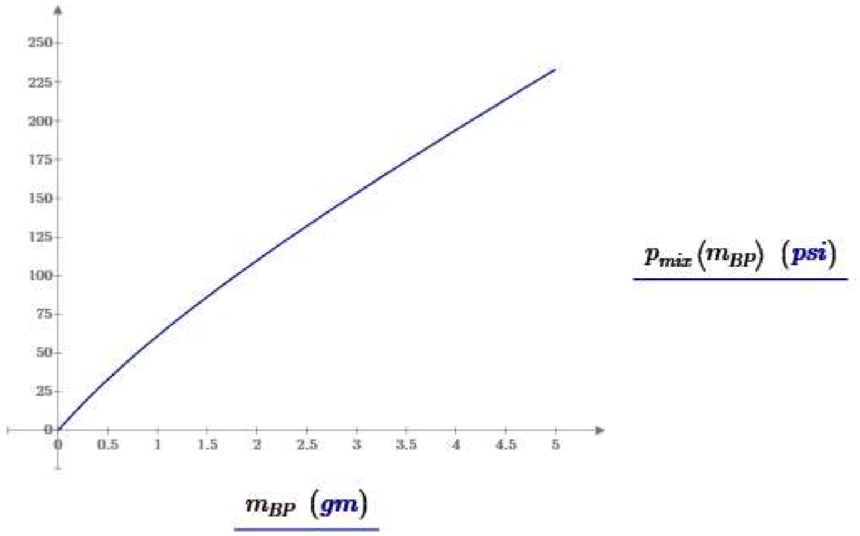


Figure 16-1 Pressure vs. black powder quantity for VTS-1

Equating the pressure from Equation (16-10) to the force to shear the shear pins from Equation (16-1) results in

$$\left(\left(\frac{m_{BP}}{M_{BPcpgas}}+\frac{P_{atm}\cdot V}{R\cdot T_{amb}}\right)\cdot\frac{R}{V}\cdot\left(\frac{-\left(\frac{m_{BP}}{M_{BP}}\cdot\Delta H_{BP}\right)\cdot\left(1-A(P)\right)}{c_{vair}\cdot\frac{P_{atm}\cdot V}{R\cdot T_{amb}}\cdot M_{air}+c_{vBPcp}\cdot m_{BP}}+T_{amb}\right)-P_{Atm}\right)\cdot\pi\cdot\left(\frac{D_r}{2}\right)^2 \tag{16-11}$$

$$=\pi\cdot\left(\frac{D_{minor}}{2}\right)^2\cdot SS\cdot n_{shear}\cdot\left(1+SafetyFactor\right)$$

The next step is to solve Equation (16-11) for m_{BP}, the quantity the calculator must determine. To simplify this, all of the terms that multiply m_{BP} are represented by single letter placeholders, so (16-11) becomes

$$\left(\left(\frac{m_{BP}}{a}+b\right)\cdot n\cdot\left(\frac{m_{BP}\cdot c}{d+m_{BP}\cdot f}+g\right)-h\right)\cdot j=k \tag{16-12}$$

where the placeholder coefficients are

$$\begin{aligned}
a&=M_{BPcpgas}\\
b&=\frac{P_{atm}\cdot V}{R\cdot T_{amb}}\\
c&=\frac{1}{M_{BP}}\cdot\Delta H_{BP}\cdot\left(1-A(Pf)\right)\\
d&=c_{vair}\cdot\frac{P_{atm}\cdot V}{R\cdot T_{amb}}\cdot M_{air}\\
f&=c_{vBPcp}\\
h&=P_{atm}\\
j&=\pi\cdot\left(\frac{D_r}{2}\right)^2\\
k&=\pi\cdot\left(\frac{D_{minor}}{2}\right)^2\cdot SS\cdot n_{shear}\cdot\left(1+SafetyFactor\right)\\
g&=T_{amb}\\
n&=\frac{R}{V}
\end{aligned} \tag{16-13}$$

The symbolic analysis capability of Mathcad can be used to solve Equation (16-12) for m_{BP}. The solution from Mathcad is

$$m_{BP}=\frac{\sqrt{\begin{array}{l}\left(\left(a^2\cdot b^2\cdot f^2-2\cdot a\cdot b\cdot d\cdot f+d^2\right)\cdot g^2+\left(2\cdot a^2\cdot b^2\cdot c\cdot f-2\cdot a\cdot b\cdot c\cdot d\right)\cdot g+a^2\cdot b^2\cdot c^2\right)\cdot j^2\cdot n^2\\+\left(\begin{array}{l}\left(\left(2\cdot a\cdot d\cdot f-2\cdot a^2\cdot b\cdot f^2\right)\cdot g+\left(4\cdot a\cdot c\cdot d-2\cdot a^2\cdot b\cdot c\cdot f\right)\right)\cdot j\cdot k\\+\left(\left(2\cdot a\cdot d\cdot f-2\cdot a^2\cdot b\cdot f^2\right)\cdot g+\left(4\cdot a\cdot c\cdot d-2\cdot a^2\cdot b\cdot c\cdot f\right)\right)\cdot h\cdot j^2\end{array}\right)\cdot n\\+a^2\cdot f^2\cdot k^2+2\cdot a^2\cdot f^2\cdot h\cdot j\cdot k+a^2\cdot f^2\cdot h^2\cdot j^2\end{array}}\\+\left(a\cdot f\cdot k+a\cdot f\cdot h\cdot j-\left(\left(a\cdot b\cdot f+d\right)\cdot g+a\cdot b\cdot c\right)\cdot j\cdot n\right)}{2\cdot j\cdot n\cdot\left(f\cdot g+c\right)}\qquad(16\text{-}14)$$

This is a seemingly long equation, but once incorporated into a calculator, it solves for the mass of the black powder in closed form.

The equivalent equation for the piston model starting from Equation (14-12) and expressing it in terms of m_{BP} is

$$\left(\left(\left(\frac{m_{BP}}{M_{BPcpgas}}+\frac{P_{atm}\cdot V}{R\cdot T_{amb}}\cdot\frac{L_{piston}}{L_r}\right)\cdot\frac{R}{V}\cdot\left(\frac{-\left(\frac{m_{BP}}{M_{BP}}\cdot\Delta H_{BP}\right)\cdot\left(1-A(P)\right)}{c_{vair}\cdot\frac{P_{atm}\cdot V}{R\cdot T_{amb}}\cdot\frac{L_{piston}}{L_r}\cdot M_{air}+c_{vBPcp}\cdot m_{BP}}+T_{amb}\right)+\frac{P_{atm}}{T_{amb}}\cdot\frac{L_r-L_{piston}}{L_r}\cdot T_{amb}\right)-P_{Atm}\right)\cdot\pi\cdot\left(\frac{D_r}{2}\right)^2$$
$$=\pi\cdot\left(\frac{D_{minor}}{2}\right)^2\cdot SS\cdot n_{shear}\cdot\left(1+SafetyFactor\right)$$

(16-15)

The simplified representation of equation (16-15) is the same as Equation (16-12), but with different coefficients

$$\begin{aligned}
a &= M_{BPcpgas} \\
b &= \frac{P_{atm} \cdot V}{R \cdot T_{amb}} \cdot \frac{L_{piston}}{L_r} \\
c &= \frac{1}{M_{BP}} \cdot \Delta H_{BP} \cdot \left(1 - A\left(Pf\right)\right) \\
d &= c_{vair} \cdot \frac{P_{atm} \cdot V}{R \cdot T_{amb}} \cdot \frac{L_{piston}}{L_r} \cdot M_{air} \\
f &= c_{vBPcp} \\
h &= P_{atm} \cdot \frac{L_r - L_{piston}}{L_r} - P_{atm} \\
j &= \pi \cdot \left(\frac{D_r}{2}\right)^2 \\
k &= \pi \cdot \left(\frac{D_{minor}}{2}\right)^2 \cdot SS \cdot n_{shear} \cdot \left(1 + SafetyFactor\right) \\
g &= T_{amb} \\
n &= \frac{R}{V}
\end{aligned} \tag{16-16}$$

The solution for the black powder needed for a piston system is the same as Equation (16-14), but using the coefficient values from (16-16).

The parachute absorption function, $A\left(Pf\right)$, can be determined empirically using the pressure chamber test data. The absorption factor will range from a value of 0 when there is no parachute, where the parachute packing factor is $Pf = 0$, to some maximum value when the parachute tube is completely filled, where the packing factor is $Pf = 1$. The pressure chamber tests showed that the absorption factor is around 90% from Equation (10-3) when the volume is completely filled by a parachute. Using a little higher value of $A(1) = .94$ (94% absorption) gives a better match to the deployment fixture tests. Using that value and solving Equation (16-14) for the mass of the black powder needed to deploy the parachutes energetically for VTS-1 results in 2.0 gm, which is close the 1.9 gm from the deployment fixture test as shown in Table 9-4.

When the parachute fills half the parachute tube, where the packing factor is $Pf = .5$, there are two different amounts of black powder needed to deploy the parachute depending upon whether the parachute is situated directly in front of the black powder charge, toward the rear, or in the opposite end of the parachute tube, toward the front. This will generate two different absorption curves, one representing the minimum amount of absorption when the parachute is furthest from the charge, and one that represents the maximum absorption when the parachute is closest to the charge. To get the absorption factor for the single parachute, Equation (16-14) is solved by trial and error to determine what absorption factors result in 0.5 gm of black powder being needed when the parachute is in the front half and 1.0 gm being needed when the parachute is in the back half, based on the deployment measurement results shown in Table 9-5.

From the end points and one intermediate point, two curves for the value of $A\left(Pf\right)$ can be generated. The first curve is defined by the points $Pf = 0, 0.5, 1$, $A(Pf) = 0, 0.65, 0.94$, and the second curve by the points $Pf = 0, 0.5, 1$, $A(Pf) = 0, 0.85, 0.94$. Using an exponential curve fit function in Mathcad results in two functions for $A(Pf)$ where $A_H(Pf)$ is the high absorption function and $A_L(Pf)$ is the low absorption function.

$$\begin{aligned} A_L(Pf) &= 1.174 \cdot \left(1 - e^{-1.614 \cdot Pf}\right) \\ A_H(Pf) &= 0.951 \cdot \left(1 - e^{-4.491 \cdot Pf}\right) \end{aligned} \tag{16-17}$$

Figure 16-2 shows a plot of the absorption function Equations (16-17). An exponential curve is used because, for a simple function, it has a close fit to the data. Only three points are used to define each of the curves, the two end points, and the value for $Pf = 0.5$. If the fourth point for the half sized parachute for $Pf = 0.25$ is included in the exponential curve fit for A_H, the overall fit of the curve becomes worse above $Pf = 0.5$. It is more important to have the curve be a close match for the larger absorption values so that it does not underestimate the amount of powder needed, so the three point fit was used. At either end of the attenuation functions, when the tube is completely full or empty, there is only one value for the attenuation function as the two curves meet at these points. But in between, when the parachute can move closer to or further from the black powder charge, the attenuation value will fall between two limits defined by the two curves, with the uncertainty greatest in the center of the packing factor range. The curves are not an exact solution, but rather an approximation of the test data for the energy absorption of the parachute to use in the model.

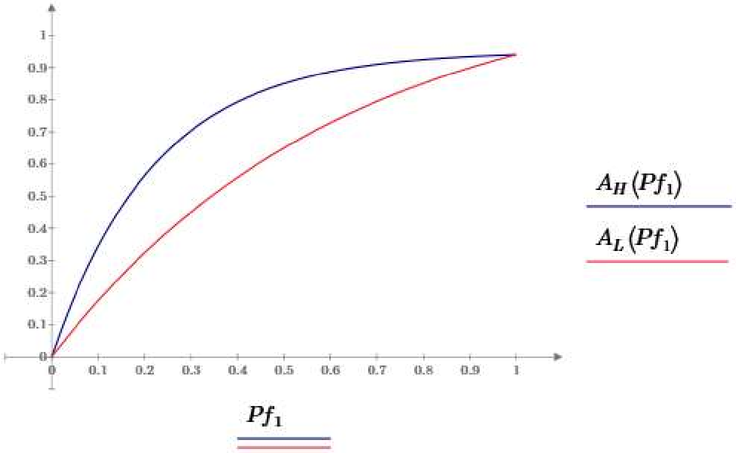


Figure 16-2 Plot of absorption factor Equation (16-17)

Some black powder calculators calculate the force generated by the difference between the internal pressure of the parachute tube and the external atmospheric pressure, assuming that the parachute tube is completely sealed and retains the ambient ground level pressure as the rocket reaches its maximum altitude. They use this force to calculate the minimum strength needed for the shear pins. But the deployment testing, where the charge was not strong enough to shear the shear pins and separate the nosecone, showed from the visible combustion gases, that the pressurized gases in the rocket very quickly leaked out of the tube, so likewise, there would not be a pressure difference as the rocket gains altitude. This leaves the key reason for using shear pins being to prevent the force differential between the two halves of the rocket as it decelerates after motor burnout from separating the two halves. This is called drag separation.

Now the calculator model is complete and can be compared to the deployment tests. The results are summarized in Table 16-1. In this table, the smaller amount of black powder is the amount that first caused the shear pins to shear and deploy the nosecone, even if the parachute did not fully deploy. The larger amount was the amount needed for energetic deployment, where the nosecone rapidly traveled to the full length of the shock cord. The smaller amount should correspond to the amount of black powder the model predicts is needed to shear the shear pins without the safety factor, and the larger amount should correspond to the amount the model predicts, including the safety scaling factor. The amount predicted by the model used by the old Info Central based black powder calculators is shown in the last column for comparison. The new model matches the measured results closely, which is expected, because the model was created to match this set of measurements. More testing would be needed to verify this model matches a wider range of rocket sizes. The new model is much closer to the test results than the Info Central model which significantly underpredicts the amount of black powder needed to energetically deploy the parachute for most configurations.

Rocket	Parachute	Measured Charge for Deployment	Measured Charge for Energetic Deployment	Packing Factor	Absorption Factor	New BP Calculator w/o Safety Factor	New BP Calculator w/ Safety Factor	Old BP Calculator
TR-1	Full	1.0 gm	1.3 gm	1	.94	0.89 gm (A_H)	1.28 gm (A_H)	0.28 gm
VTS-1	Full	1.2 gm	1.9 gm	1	.94	1.39 gm	2.0 gm (A_H)	0.47 gm
VTS-1	Half - rear	0.7 gm	1.0 gm	.5	.85	0.73 gm (A_H)	1.05 gm (A_H)	0.47 gm
VTS-1	Half -front	?? gm	0.5 gm	.5	.65	0.22 gm (A_L)	0.49 gm (A_L)	0.47 gm
VTS-1	Quarter rear	0.3 gm	0.5 gm	.25	.42	0.33 gm (A_H)	0.48 gm (A_H)	0.47 gm
VTS-1	Full	0.5 gm	0.7 gm	.3 (piston)	.7	0.49 gm (A_H)	0.73 gm (A_H)	0.47 gm

Table 16-1 Summary of the energetic parachute deployment tests from Table 9-3, Table 9-4, Table 9-5 and Table 13-1

17 How the Model Predicts the BP Charge Scales with Rocket Size

Although it may seem counter intuitive, a rocket with a larger volume parachute tube may require less black powder than a rocket with a smaller volume tube. The pressure generated by the black powder charge is inversely proportional to the volume of the parachute tube. The larger the volume, the larger the black powder charge required. But the force is the pressure multiplied by the cross sectional area, which is proportional to the square of the diameter of the rocket. As the diameter of the rocket increases while holding the volume constant, the force increases rapidly. Because of this, seemingly larger rockets will not necessarily need more black powder than smaller rockets.

Table 17-1 shows the charge calculated by the model from Section 16 for different size rockets, the only differences being the diameter and length of the parachute tube. A parachute packing factor of 0.5 in the high absorption curve is used. The black powder charges shown in the table include the 40% safety factor shown in the model from Section 16. For a given diameter, the volume is proportional to the length of the parachute tube, so the black powder charge scales up with the length. The 2 in diameter by 40 in long parachute tube has the same volume as the 4 in diameter by 10 long parachute tube but requires 4.75 times more black powder because the force scales with the square of the diameter. The 4 in diameter by 40 in long parachute tube requires a little less black powder than the 2 in diameter tube of the same length, even though it has twice the volume. The black powder charge scales roughly in proportion to the size of the rocket if both the length and diameter are scaled by the same factor. The 4 in x 20 in rocket is twice the scale as the 2 in x 10 in rocket and requires a little less than twice the black powder. The same holds for the 8 in x 40 in rocket compared to the 4 in x 20 in rocket. In practice, a larger rocket would require more or larger shear pins to prevent drag separation, so the larger rocket practically would require more powder than shown in the table.

Diameter	Length	Volume	Shear Pins	Shear Force	Parachute (*Pf*)	Calculated BP
2 in	10 in	31.42 in^2	2 x 2-56	62.0 lbf	0.5	0.96 gm
2 in	20 in	62.83 in^3	2 x 2-56	62.0 lbf	0.5	1.9 gm
2 in	40 in	125.66 in^3	2 x 2-56	62.0 lbf	0.5	3.8 gm
4 in	10 in	125.66 in^3	2 x 2-56	62.0 lbf	0.5	0.8 gm
4 in	20 in	251.3 in^3	2 x 2-56	62.0 lbf	0.5	1.6 gm
4 in	40 in	502.65 in^3	2 x 2-56	62.0 lbf	0.5	3.2 gm
8 in	10 in	502.7 in^3	2 x 2-56	62.0 lbf	0.5	0.7 gm
8 in	20 in	1005.3 in^3	2 x 2-56	62.0 lbf	0.5	1.3 gm
8 in	40 in	2010.6 in^3	2 x 2-56	62.0 lbf	0.5	2.7 gm

Table 17-1 BP charge for various size rockets using $P_f = 0.5$

Table 17-2 shows the effect of the shear pin size and number on the charge when the size of the rocket remains constant. Doubling the number of shear pins doubles the shear force and a little more than doubles the black powder charge.

Diameter	Length	Volume	Shear Pins	Shear Force	Parachute (*Pf*)	Calculated BP
4 in	20 in	251.3 in^2	3 x 2-56	92.9 lbf	0.5	2.1 gm
4 in	20 in	251.3 in^2	3 x 4-40	149.5 lbf	0.5	3.5 gm
4 in	20 in	251.3 in^2	6 x 4-40	299.0 lbf	0.5	7.8 gm
4 in	20 in	251.3 in^2	3 x 6-32	224.8 lbf	0.5	5.6 gm

Table 17-2 Shear force and BP charge for different shear pin sizes

18 Flight Results

Since developing the updated model, TR-1 has been flown twice successfully using 1.1 gm of black powder and VTS-1 has been flown 11 times successfully using 2 gm of black powder, as recommended by the new model and deployment tests. The parachute completely fills the volume of the parachute tube for both rockets. Both quantities are twice what had been flown when each of these rockets had failed deployments on their second flights using the amount of black powder based on the old calculator model.

Rocket	Old BP Calculator	Original BP Amount Flown	Number of Flights	New BP Calculator	New BP Amount Flown	Number of Flights
TR-1	0.32 gm	0.5 gm	2	1.3 gm	1.1 gm	2
VTS-1	0.53 gm	1.0 gm	2	2.0 gm	2.0 gm	11

Table 18-1 Flight deployment results using the new guidelines

19 Summary of Conclusions, Recommendations, and Next Steps

Summary of Conclusions

- The heating of the air by the exothermic energy accounts for most of the maximum possible pressure generated by the black powder reaction, and not the gases produced by the black powder
- The parachute (and shock cord) absorbs much of the exothermic energy, significantly reducing the maximum pressure - there is more than a ten-to-one range in pressure generated by the black powder depending upon the size and location of the parachute
- Once the gases have cooled to ambient temperature, the pressure due to the additional gas generated from the black powder reaction is far smaller than the initial pressure
- Chevreuil’s equation, used by most web calculators, gives a close match to measured results when the heating due to the total exothermic energy is included in the pressure calculation

- The model used by BP calculators does not include the effects of the total exothermic energy heating of the gases, so it underpredicts the maximum possible initial pressure with no parachute, but it overpredicts the actual pressure in most cases because it does not account for the energy absorbed by the parachute
- The model used by the black powder calculators to calculate the force required to shear the shear pins is accurate
- It takes about a 40% safety margin above the minimum amount of black powder needed to shear the shear pins to guarantee an energetic deployment
- There is 50-100% margin between the recommended amount of black powder needed for an energetic deployment and the amount that causes body tube failure for phenolic tubing, and more margin for fiberglass tubing
- A piston isolates the parachute from the combustion gases, so not as much energy is absorbed and not as much black powder is required, but the initial pressure and temperature in the piston can be very large
- Using 20 year old black powder shows no degradation in the pressure generated
- The model shows less air at low ambient pressure (high altitude) results in a lower pressure from the black powder reaction, even if measures are taken to ensure the complete combustion of the black powder - the measurements show the pressure is even lower than the model predicts by a significant factor

Recommendations

The test results showed that significantly more black powder is needed under most conditions to reliably deploy a parachute than recommended by the current black powder calculators. The measurements show that there is nearly a ten-to-one range in pressure generated by the black powder depending upon the size and location of the parachute. Not knowing for sure how much of an impact the parachute will have makes it difficult to accurately predict the pressure, and therefore the size of the black powder needed for deployment. Ground testing has always been recommended to verify the quantity of black powder, but these results show that ground testing with the parachute and shock cord in their flight configuration is essential. The new model presented here gives a better estimate of the quantity of black powder needed for a successful deployment, as well as a better understanding of the mechanisms by which black powder combustion acts to generate the pressure needed. But the model should still only be used as the starting point recommendation for ground testing.

Next Steps

- Create a spreadsheet black powder calculator based on the new model that gives a better starting point for ground testing than the current calculators
- Test the model against ground deployment tests for a wider range of rocket sizes
- Look further into the mechanisms affecting the pressure generated at low ambient (high altitude) pressure

20 Appendix 1 – Explicit Units and Reconciling the Info Central Pressure Equation

Figure 20-1 shows the pressure calculation equation (4-5) with and without explicit units for each input parameter and the appropriate unit conversion factors where necessary. The native units system is the USCS, or "English" system of units, where the native units are lb (mass), feet, seconds, deg K, and moles. The inputs are in units of grams, cubic inches, degrees Rankin, and the output is in units of psi. The numbers circled in blue are the inputs. A unit conversion factor is needed for each parameter that is not in the native units of the units system. The numbers circle in red are the conversion factors to convert the non-native inputs into the native USCS units. The method would be the same if the native units system were the SI metric or CGS metric systems, the unit conversion factors would just change.

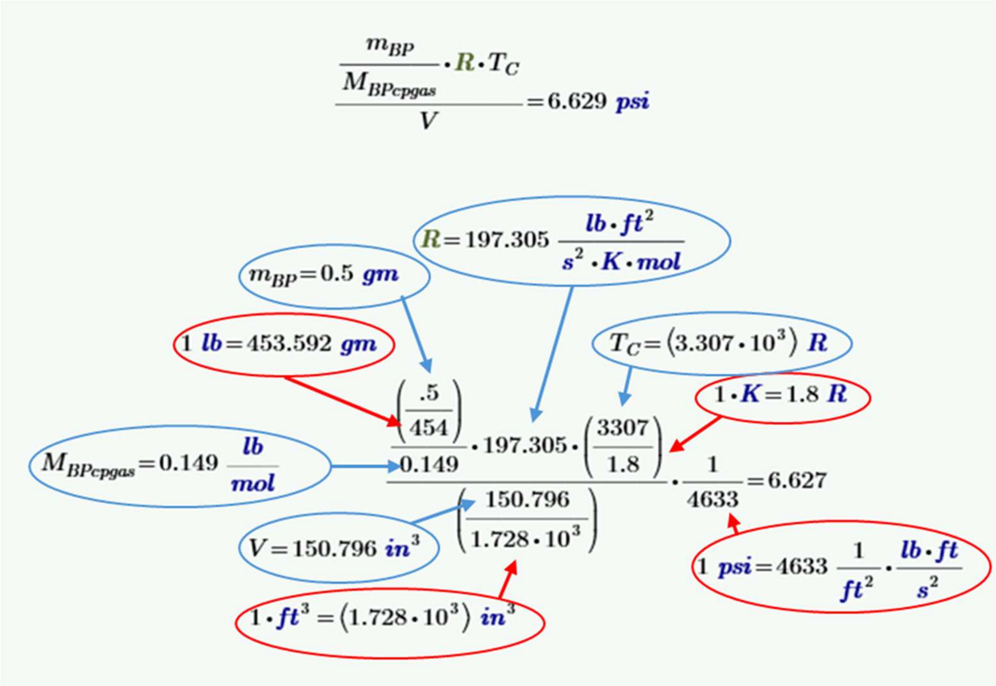


Figure 20-1 Pressure calculation with explicit units conversion factors

Figure 20-2 shows the model equation (5-3) from the Info Central web page with the explicit unit conversion factors for USCS native units. The slight difference in pressure from the equation in Figure 20-1 is due to a slightly different value for $M_{BPcpgas}$ as explained in Section 5. The Info Central model uses $0.154 \cdot lb/mol$ for the molar mass of the black powder, slightly different than the $0.149 \cdot lb/mol$ derived for Chevreuil's equation. Like the previous model, the inputs are in units of grams, cubic inches, degrees Rankin, and the output is in units of psi. The numbers circled in blue are the inputs, and the numbers circled in red are the conversion factors. A unit conversion factor is needed for each parameter that is not in the native units of the units system.

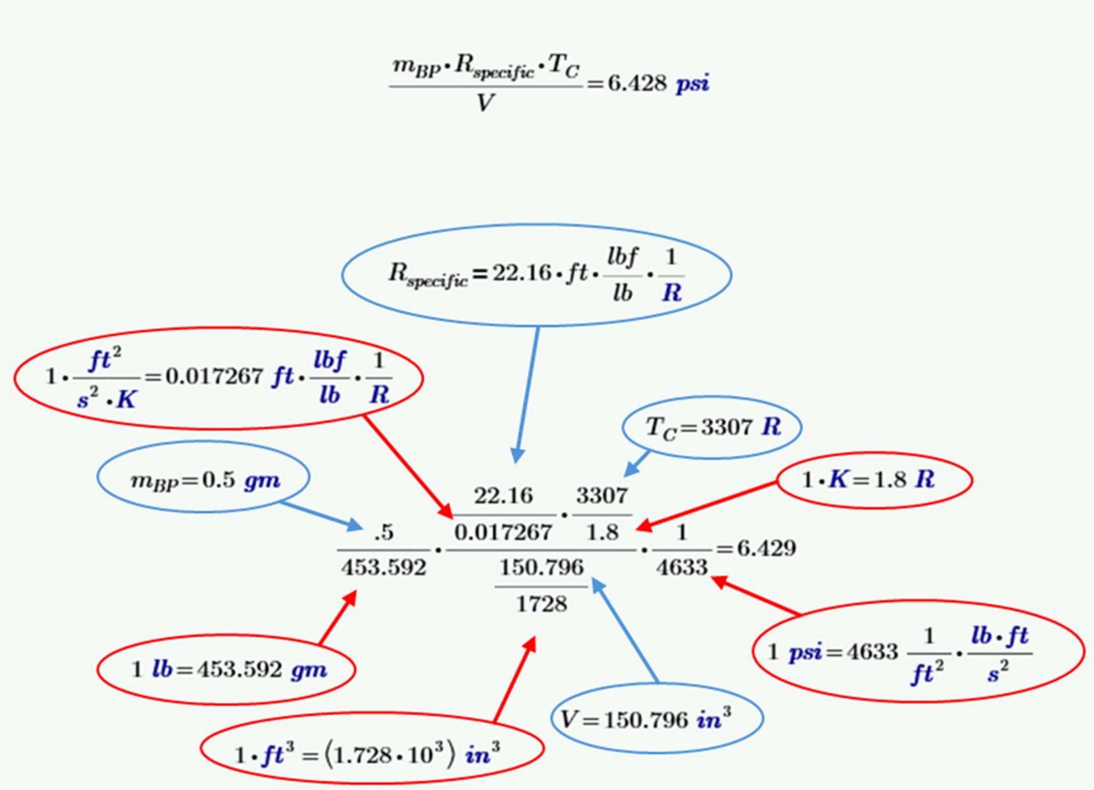


Figure 20-2 Info Central web page model with unit conversion factors

The actual equation from the Info Central web page is the bottom equation in Figure 20-3 with only two conversion factors, the 453.592 conversion factor from grams to pounds mass, and the conversion factor 12. The 12 is a roll up of all the other conversion factors shown in Figure 20-2. The upper equation in Figure 20-3 breaks out all the other conversion factors explicitly, showing that the product of all the factors equals 12. This shows that the Info Central equation is the same as the equations presented in Section 5

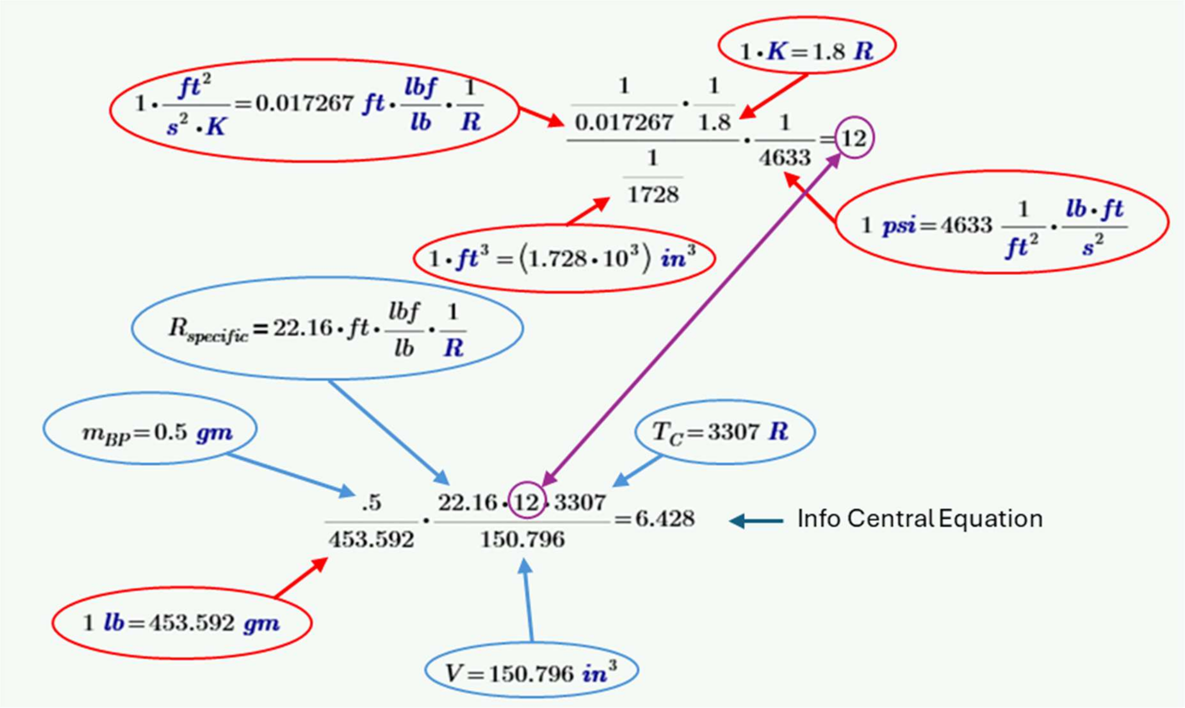
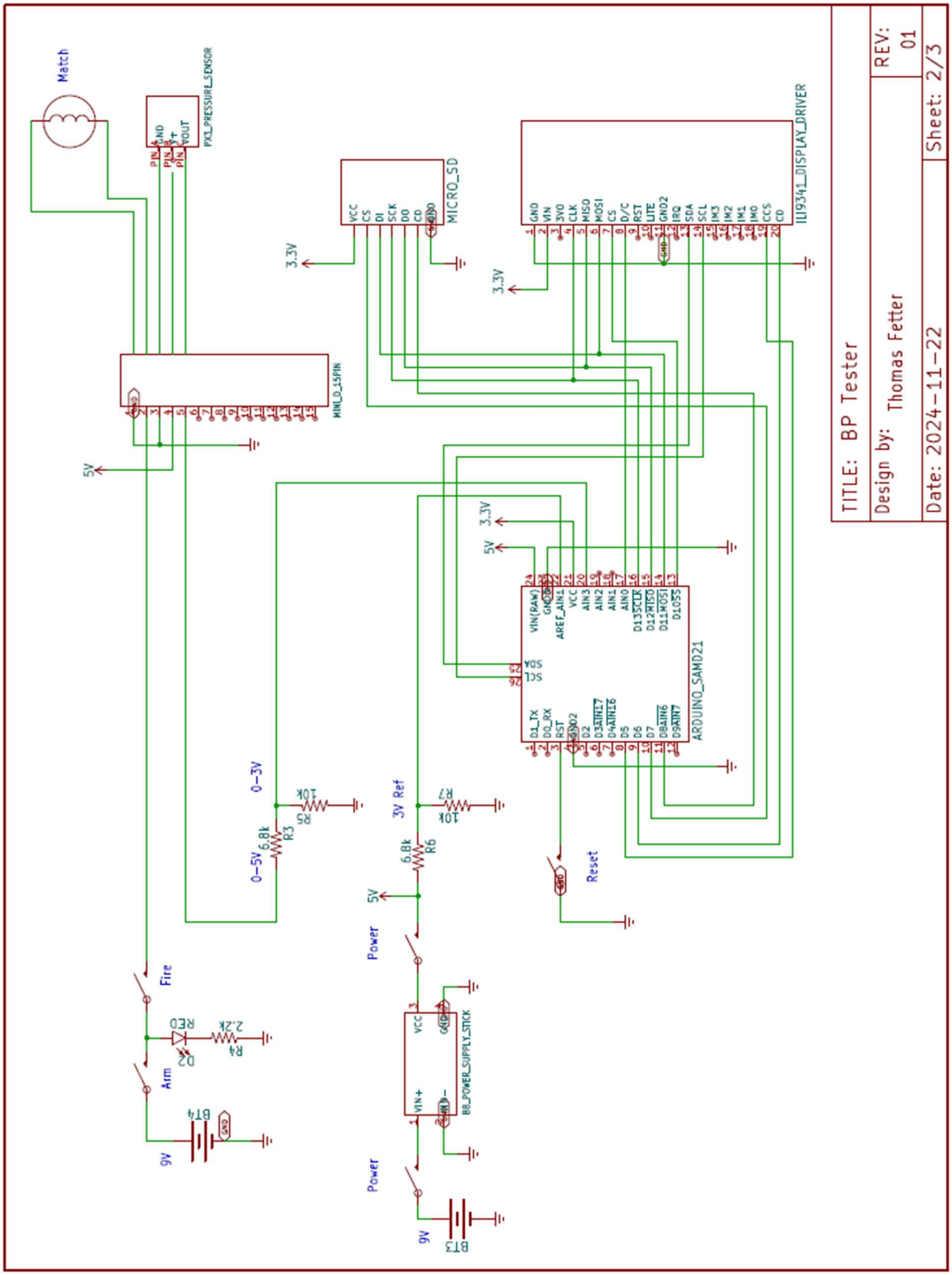


Figure 20-3 Reconciling the conversion factors from the Info Central pressure equation

21 Appendix 2 - Pressure Chamber Data Logger



22 Appendix 3 - Project Roadmap

Starting Problem Statement: Rockets are failing to deploy successfully when the amount of BP based on the BP calculators is used

Hypothesis: Web BP calculators overpredict pressure generated by BP

Method: Pressure chamber testing

Result: Black powder products more pressure than the BP calculators predict

Theory: A new model is developed that includes the effect of heating the air that matches the pressure chamber test results

Hypothesis: Old BP produces less pressure than new BP

Method: Pressure chamber testing

Result: Old BP generated the same pressure as the new BP

Theory: The components of black powder (charcoal, Sulphur, & potassium nitrate) are stable compounds when stored in a dry environment

Hypothesis: Shear pins require more force to shear than the model used by the BP calculators predict

Method: Deployment testing using the quantity of black powder determined by the pressure chamber testing needed to produce the pressure determined by the shear force model

Result: The shear force model accurately predicts the pressure needed to shear the pins

Theory: The existing shear force model is confirmed

Hypothesis: The parachute must act to cool the gas temperature and reduce the pressure produced by the black powder

Method: Deployment testing and pressure chamber testing with the volume filled with a parachute

Result: The amount of black powder needed for the deployment is greater than the BP calculator predicts, and the pressure reduction is confirmed by the chamber testing

Theory: A guideline for the portion of the energy that is adsorbed by the parachute based on the measured pressure is determined that can be applied to an updated BP calculator model

Hypothesis: High altitude BP deployments will produce significantly less pressure even when measures are taken to ensure all the BP burns

Method: Pressure chamber testing in an evacuated chamber

Result: The pressure is significantly lower than the sea level pressure test. Adding a parachute reduces the pressure to the ambient temperature pressure

Theory: The new model shows less pressure is produced at high altitude but overpredicts the pressure compared with the measurements

Hypothesis: A piston deployment system should require less BP than chute protector system since the initial pressurized volume is less

Method: Deployment fixture testing with a piston

Result: The piston requires about half as much black powder as the chute protector

Theory: The model shows less black powder is needed because the piston isolates the heated gases from the parachute, so the gases are not cooled, and greater pressure is created

Hypothesis: With too much black powder, the body tube will be damaged before the nosecone deploys

Method: Deployment fixture test until failure

Result: The unreinforced phenolic tube failed a 2 x the amount of black powder recommended by the model to guarantee an energetic deployment

Theory: The airframe fails locally before the pressure forces reaches the shear pins

Final Recommendation: A new model for the BP calculators is proposed as a starting point for determining the amount of BP required for successful deployment

23 Appendix 4 – Tools, Equipment, Facilities, & Budget

- Mathcad was the main tool used on this project for modeling, numerical analysis, and symbolic analysis
- Microsoft Office Word was used to write this paper
- MathType embedded app for Office was used to create the equations in MS Word
- PowerPoint was used to create the figures
- Excel was used for test data graphing and to create some of the tables
- The deployment fixtures, pressure chamber, and Arduino pressure data logger used for this project were constructed by the author in his home shop
- The vacuum pump is one normally used by the author for vacuum bagging
- A Dremel 3D45 printer was used to print some of the charge canisters
- All testing was done in the author's back yard
- Videos and photographs were captured on an iPhone

Budget

	Price	Unit	Used	Cost
Pressure Chamber				
4" PVC FSFT	$ 25.00	1	1	$ 25.00
4" PVC FSFS	$ 13.00	1	1	$ 13.00
4" PVC MT Plug	$ 15.00	1	1	$ 15.00
4" PVC MS Plug	$ 12.00	1	1	$ 12.00
1/2" brass ball valve	$ 11.99	1	1	$ 11.99
Misc Brass fittings	$ 5.00	1	3	$ 15.00
Honeywell Pressure Sensor	$ 105.00	1	1	$ 105.00
Total				**$ 196.99**
Deployment Fixtures				
2" tube	$ 21.29	36	15	$ 8.87
3" tube (two fixtures)	$ 25.79	36	44	$ 31.52
4" tube	$ 28.04	36	20	$ 15.58
2" Coupler	$ 23.54	36	6	$ 3.92
3" Coupler (two fixtures)	$ 29.16	36	16	$ 12.96
4" Coupler	$ 33.65	36	10	$ 9.35
Misc Hardware	$ 5.00	1	1	$ 5.00
Total				**$ 87.20**
Data Logger				
Arduino SAMD21	$ 22.50	1	1	$ 22.50
Adafruitr ILI9341Display Driver & Display	$ 34.95	1	1	$ 34.95
uSD card reader	$ 5.50	1	1	$ 5.50
Power supply stick	$ 13.95	1	1	$ 13.95
Board	$ 13.00	5	1	$ 2.60
Case	$ 11.99	1	1	$ 11.99
Total				**$ 91.49**
Black Powder Charges				
e matches	$ 66.00	80	50	$ 41.25
Charge containers	$ 3.00	15	50	$ 10.00
Black powder (gm)	$ 30.00	454	36	$ 2.38
Total				**$ 53.63**
Project Total				**$ 429.31**

24 Appendix 6 – Complete Test Data Summary

Chamber Test Log

	Figure	File #	BPCharge (gm)	Powder	Canister	Wadding	Chamber Fill	Starting Pressure	Peak Pressure	Final Pressure	Used to Show
1		1									
2	6-4	4	0.5	Old	Centerfuge	RW	None	Ambient	31.8	na	Old vs. new black powder
3	6-5	5	0.5	New	Centerfuge	RW	None	Ambient	34.0	na	Old vs. new black powder
4	6-3	12	0								Chamber pressure holding test
5		13	0.5	?	Centrifuge						
6	6-6	15	0.5	Old	Centrifuge	RW	None	Ambient	25.3	1.0	Final pressure @ 120 sec
7	6-7	16	0.5	Old	Centrifuge	RW	None	Ambient	36.6	na	Average & standard deviation
8	6-7	18	0.5	Old	Centrifuge	RW	None	Ambient	26.8	na	Average & standard deviation - used mechanical guage
9	6-7	19	0.5	Old	Centrifuge	FG	None	Ambient	23.1	na	Average & standard deviation
10	6-7	20	0.5	Old	Centrifuge	FG	None	Ambient	27.1	na	Average & standard deviation
11	6-7	21	0.5	Old	Centrifuge	loose FG	None	Ambient	26.3	na	Average & standard deviation
12	6-7	22	0.5	Old	Centrifuge	tight FG	None	Ambient	30.2	na	Average & standard deviation
13		23	0.5	Old	Centrifuge	loose FG	None	Ambient	30.24	na	No impact using fiberglass vsdor barf
14		50	0.5	Old	1" Centrifuge	RW	None	-11.4 psi	1.86	na	
15	10-7	55	0.5	Old	3" printed	RW	None	-11.4 psi	10.21	1	Impact of long charge canister & result for test under vacuum
16	9-1	56	0.5	Old	Centrifuge	RW	Filled	Ambient	3.58	1.3	Impact of parachute on initial pressure
17	10-4	61	0.5	Old	Centrifuge	RW	None	-11.4 psi	1.32	1.0	Slow burn with centerfuge canister
18	10-4	62	0.5	Old	Centrifuge	RW	None	-11.4 psi	3.97	1.4	Slow burn with centerfuge canister
19	10-4	63	0.5	Old	Centrifuge	RW	None	-11.4 psi	1.78	1.0	Slow burn with centerfuge canister
20	10-8	75	0.5	Old	3" printed	RW	Filled	-11.4 psi	0.68	1.0	Filled evaculated chamber
21	10-3	76	0.5	Old	7/8" Printed	None	None	-11.4 psi	1.13	0.4	Small charge canister at low pressure
Total			**9.5**								

Deployment Test Log

Test #	Date	Test Fixture	Charge Vol (cc)	Shear Pins	Parachute	Parachute Tube	Deployment	Video
1	4/26/2023	TR-1	0.30	2x2-56	1	full	no	IMG_2083
2	4/26/2023	TR-1	0.50	2x2-56	1	full	no	none
3	4/26/2023	TR-1	0.70	2x2-56	1	full	no	IMG_2085
4	4/26/2023	TR-1	1.00	2x2-56	1	full	clean	IMG_2086
5	4/26/2023	TR-1	1.30	2x2-56	1	full	very enerjetic	IMG_2088
6	4/26/2023	TR-1	0.30	2x2-56	no	empty	very enerjetic	IMG_2087
7	4/26/2023	VTS-1	1.00	2x2-56	2	full	no	IMG_2089
8	4/26/2023	VTS-1	1.30	2x2-56	2	full	only 1 of 2	IMG_2090
9	4/26/2023	VTS-1	1.60	2x2-56	2	full	both	IMG_2091
10	4/26/2023	VTS-1	1.90	2x2-56	2	full	both	IMG_2092
11	11/6/2024	Large	0.15	6x2-56	no	empty	no	IMG_4156
12	11/6/2024	Large	0.30	6x2-56	no	empty	very energetic	IMG_4157
13	11/7/2024	TR-1	0.15	2x2-56	no/heavy shock cord	quarter full	no	IMG-4161
14	11/7/2024	TR-1	0.15	2x2-57	no/thread shock cord	empty	very energetic	IMG-4162
15	11/7/2024	VTS-1	0.15	2x2-56	no/thread shock cord	empty	very energetic	IMG_4166
16	11/7/2024	VTS-1	0.50	2x2-56	1	front half full	yes	IMG_4167
17	11/7/2024	VTS-1	0.30	2x2-56	1	front half full	no	IMG_4169
18	11/7/2024	VTS-1	0.50	2x2-56	1	back half full	no	IMG_4171
19	11/7/2024	VTS-1	0.70	2x2-56	1	back half full	partial	IMG_4172
20	11/7/2024	VTS-1	1.00	2x2-56	1	back half full	energetic	IMG_4174
21	12/3/2024	VTS-1	0.50	2x2-56	small	back quarter full	very energetic	IMG_4222
22	12/3/2024	VTS-1	0.30	2x2-56	small	back quarter full	energetic	IMG_4223
23	12/3/2024	VTS-1	0.15	2x2-56	small	back quarter full	no	IMG_2224
24	12/3/2024	VTS-1	0.50	2x2-56	1 & small plus piston	full shock cord in piston	parachutes ejected piston remained in tube	IMG_4227
25	12/3/2024	VTS-1	0.70	2x2-56	1 & small plus piston	full shock cord in piston	energetic - parachutes ejected piston remained in tube	IMG_4228
26	12/3/2024	VTS-1	1.00	2x2-56	1 & small plus piston	full shock cord in piston	very energetic - everything ejected	IMG_2449
27	1/9/2024	VTS-1	2.50	2x2-56	2	full	very enerjetic	IMG_4423
28	1/9/2024	VTS-1	3.00	2x2-56	2	full	very enerjetic	IMG_4424
29	1/9/2024	VTS-1	4.00	2x2-56	2	full	Parachute tube (no fiberglass) split at location of the charge - pins did not shear	IMG_4425
Total			**26.45**					

25 Appendix 7 – Chemical Properties Summary

Molecule	Name	state	Molar Mass	Enthalpy	Specific Heat Constant Pressure	Specific Heat Constant Volume
			M_X (gm/mol)	ΔH_X (kJ/mol)	c_{pX} (J/(kg*K)	c_{vX} (J/(kg*K)
H	Hydrogen	gas	1.0	0.0		
N	Nitrogen	gas	14.1	0.0		
O	Oxygen	gas	16.0	0.0		
Ar	Argon	gas	40.0	0.0	520.0	312.0
CO	Carbon Monoxide	gas	28.0	-110.5		720.0
CO_2	Carbom Dioxide	gas	44.0	-393.5	844.0	655.0
H_2	Molecular Hydrogen	gas	2.0	0.0		10160.0
N_2	Molecular Nitrogen	gas	28.2	+191.610	1040.0	743.0
O_2	Molecular Oxygen	gas	32.0	-205.2	919.0	659.0
CH_4	Methane	gas	16.0	-74.9		1700.0
H_2S	Hydrogen Sulfide	gas	34.1	-20.6		782.9
H_2O	Water	liquid	33.0	-285.8	2283.0	
C	Carbon	solid	12.0	0.0	889.3	
S	Sulfur	solid	32.1	0.0		1938.0
K	Potassium	solid	39.1	0.0		
KNO_3	Potassium Nitrate	solid	101.2	-494.6		
K_2S	Potassium Sulfide	solid	110.3	-376.6	677.2	
K_2CO_3	Potassium Carbonite	solid	138.2	-1150.2	824.8	
K_2SO_4	Potassium Sulfate	solid	174.3	-1437.7	797.7	
$K_2S_2O_3$	Potassium Thiosulfate	solid	190.3	-1400.0	800.0	
KCNS	Potassium Thiocyanate	solid	97.3	-1400.0	910.1	
$NH_4(2CO_2)$	Ammonium Carbonite	solid	106.2	-1400.0	800.0	
C_6H_2O	Charcoal	solid	105.1	-285.8		

The values in the table above are from the NIST Chemistry Webbook[39] and The Engineering Toolbox[40]. The numbers in red are guesses as the data for these could not be found. The guesses are used only for calculating the initial pressure of Kast's black powder equation and are not used for the new black powder calculator model

---

[39] (NIST, 2023)

[40] (Gases - Specific Heats and Individuel Gas Constants, 2024)

26 Appendix 8 – Variables

c_p	Specific heat at constant pressure
c_v	Specific heat at constant volume
m_x	Mass of x
n_{shear}	Number of shear pins
n_x	Number of moles of x
D_{minor}	Minimum diameter of the shear pins
D_r	Diameter of the rocket
F	Force
F_{shear}	Total shear forces needed to shear the shear pins
L_r	Internal length of the parachute tube
M_x	Molar mass (molecular weight) of x
Pf	Packing factor for the parachute
P	Pressure
P_{atm}	Atmospheric pressure
Q	Energy
R	Universal gas constant
SG	Specific gravity
SS	Shear strength of the shear pin material
T	Temperature
T_{amb}	Ambient temperature
T_C	Temperature of combustion for black powder
V	Volume of the parachute tube or pressure chamber
ΔH_x	Change in enthalpy of x

27 References

Air - Composition and Molecular Weight. (2024). Retrieved from The Engineering ToolBox: https://www.engineeringtoolbox.com/air-composition-d_212.html

Atmospheric Pressure. (2024). Retrieved from Wikipedia: https://en.wikipedia.org/wiki/Atmospheric_pressure

BP Estimator. (2021). Retrieved from Rocketry Calculator: https://rocketrycalculator.com/rocketry-calculator/bp-estimator/

Cook, J. (2015-2022). *FFFg Black Powder Calculator*. Retrieved from Insane Rocketry.

Damerau, D. (2002-2011). *Shear Pins*. Retrieved from RocketMaterials.org: https://web.archive.org/web/20150218234304/http://www.rocketmaterials.org/datastore/cord/Shear_Pins/index.php

Davis, T. L. (1941). *The Chemistry of Powder and Explosives.* Parker Publishing Company.

Davis, T. L. (1941). *The Chemistry of Powder and Explosives.* Parker Publishing Company.

Feretich, B. (2024). *Shear Pin/Screw Calculations*. Retrieved from Rocketry: https://www.feretich.com/Rocketry/Resources/shearPins.html

Fetter, T. (2015-2024). *Spreadsheets & Calculators*. Retrieved from Speedmotion Rockets: http://speedmotionrockets.com/Spreadsheets.html

Gases - Specific Heats and Individuel Gas Constants. (2024). Retrieved from The Engineering ToolBox: https://www.engineeringtoolbox.com/specific-heat-capacity-gases-d_159.html

Gunpowder. (2024). Retrieved from Wikipedia: https://en.wikipedia.org/wiki/Gunpowder

How to Size Ejection Charge. (n.d.). Retrieved from HARA (Huntsville Area Rocketry Association): http://hararocketry.org/hara/resources/how-to-size-ejection-charge/

Hussain, G., & Rees, G. J. (1990). Combustion of Black Powder. Part 1: Thermo-Analytical Studies. *Propellants, Explosives, Pyrotechnics*, 43-47.

Hussain, G., & Ress, G. J. (1991). Combustion of Black Powder. Part II: FTIR Emission Spectroscopic Studies. *Propellants, Expolsives, Pyrotechnics*, 6-11.

Jarvis, J. (June, 2011). High-Altitude Deployment. *Rockets Magazine*, 58-61.

Maltitz, I. v. (2003). *Black Powder Manufacturing, Testing & Optimizing.* Dingmans Ferry: American Fireworks News.

Mathcad Home Page. (2024). Retrieved from https://www.mathcad.com/en/

NIST. (2023). *NIST Chemistry WebBook*. Retrieved from NIST (National Institute of Standards and Technology): https://webbook.nist.gov/chemistry/

Noble, C., & Abel, F. A. (1875). Researches on Explosives, Fired Gunpowder. *Philosphical Transactions of the Royal Society*, 49.

Periodic Table. (2024). Retrieved from Wikipedia: https://en.wikipedia.org/wiki/Periodic_table

RockSim. (2024). Retrieved from Apogee Rockets: https://www.apogeerockets.com

Roth, D. A., McDonald, D., & Apke, T. (1996-2000). *Black Powder Sizing*. Retrieved from Info Central - Archive: https://info-central.rocketlabdelta.com/archive/recovery_powder

Roth, D. A., McDonald, D., & Apke, T. (2020, 11 02). *Black Powder Sizing*. Retrieved from Info Central: https://info-central.rocketlabdelta.com/recovery/black-powder-sizing/

Sasse, R. A. (1985). *A Comprehensive Review of Black Powder.* Aberdeen Proving Ground, Maryland: US Army Ballistic Research Laboratory.

Wark, K. (1977). *Thermodynamics.* New York: McGraw-Hill Book Company.

Wendt, M. (2018). *Safety Data Sheet-Black Powder.* Doyline, LA: GOEX Powder, Inc.