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Ignition Potential of Muzzle-Loading Firearms

An Exploratory Investigation

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ABSTRACT

The National Technology and Development Program of the Forest Service, U.S. Department of Agriculture, was asked to conduct an exploratory study on the ignition potential of muzzle-loading firearms. The five independent variables investigated include projectile type, powder type, powder load, patch thickness, and patch lubricant treatment. Indoor testing was performed at 90 degrees Fahrenheit (°F) and 15 percent relative humidity (RH), the most extreme environmental conditions that could be simulated in the laboratory. Craft paper was used as the ignition receptor. No ignitions were obtained with patch-less (conical) projectiles, indicating that powder was not a source of ignition during our tests. Round ball patches were found to be a potential source of ignition. Dry (nonlubricated) patches had the highest probability of ignition. Ignition potential mitigation could include the use of conical projectiles or lubricated patches.

INTRODUCTION

The National Technology and Development Program's Fire and Aviation Steering Committee received a project proposal from the Virginia Department of Forestry to investigate muzzle-loading firearms as a potential ignition source for forest vegetation. The steering committee tasked the San Dimas Technology and Development Center (SDTDC) with completing this project.

Fall fire season in the eastern hardwood forests coincides with muzzle-loading hunting season. The ignition of forest vegetation by muzzle-loading (also known as "black powder") firearms has been cited anecdotally, especially when there was no other apparent cause of ignition. Two major ignition sources have been suggested historically – the ejection of a burning "patch," and the ejection of burning residual powder.

Libershal (2005) cited flaming wadding from a black-powder rifle discharged in a location of fine fuels as the source of the 1977 Middle Fire on the Angeles National Forest. John McPhee wrote about the Middle Fire in his book The Control of Nature (1990) and noted that facial tissue was used instead of conventional cotton patch material.

Suitable data on muzzle-loading firearms are not available as there are no known statistics on the modes by which muzzle-loader hunters can cause the ignition of wildland fuels (Babrauskas 2005). The task for SDTDC centered on determining: (1) if and which type of muzzle-loading firearm might ignite forest and field vegetation and, (2) under what conditions this ignition might occur.

This report presents the results of exploratory laboratory testing that was undertaken to help understand muzzle-loading firearms and their potential as an ignition source.

MUZZLE-LOADING FIREARM BASICS

Modern conventional firearms utilize cartridge ammunition, which consists of a projectile (bullet), powder, and a primer assembled in a cartridge case. Muzzle-loading firearms do not use a cartridge case – the term muzzleloader means that the firearm is loaded through the front or muzzle of the barrel. The powder and projectile are loaded separately into the muzzle and a priming device is installed externally prior to each shot. Muzzleloaders are also referred to as black-powder firearms, a reference to the type of powder originally used and still in use today.

Firearm types

There are two basic types of muzzle-loading firearms – flintlock and percussion. Flintlock rifles were widely in use by 1670. They rely on flint to ignite an external pan of powder, which in turn ignites the main powder charge inside the rifle barrel.

Side-hammer percussion rifles (figure 1) were developed about 1820. Percussion rifles use a small pressure-sensitive percussion cap, which when struck by the rifle hammer, creates an explosion that ignites the powder charge in the barrel. More modern “in-line” rifles place the percussion cap directly behind the barrel. The rifle used for this study was a Thompson-Center brand .50 caliber Hawken rifle (figure 1).

Figure 1— .50 caliber side-hammer percussion rifle (test rifle).

Projectiles

Conical bullets and “patched” spherical balls are the two basic types of muzzle loading projectiles (figure 2). The traditional muzzle-loader projectile is an undersized spherical lead ball that requires the use of a cloth “patch” or “wad,” which creates a gas seal between the firearm barrel and the round ball. If the barrel is rifled (has twisting grooves cut into the inside wall of the bore), the patch engages the rifling to impart spin on the ball and thereby improve ballistic accuracy. Patches include a variety of cotton and linen materials (figure 3). Commercial patch lubes, vegetable shortening (such as Crisco®), saliva, and various other "homemade recipes" are commonly used as patch lubricants.

Figure 2—Projectiles (left-to-right): Sabot, Maxi-Ball, and patched ball.

Conical projectiles are used in modern muzzle-loading rifles to enhance accuracy and do not require a patch. Conical projectiles include Sabots, which are undersized conical bullets encased in a plastic sleeve, and projectiles, such as the Maxi-Ball, which has built-in lubricating grooves for ease of loading.

Figure 3—Patches (left-to-right): cotton (dry), pillow ticking (dry), and cotton (with commercial lube).

Powder

Black powder is the propellant originally used in muzzle-loading firearms and is made by the pulverized mixing of sulfur, potassium nitrate, and charcoal, in proportions of about 15 percent, 75 percent, and 10 percent by weight, respectively. Charcoal (carbon) provides fuel for the reaction, while the oxidizing agent is potassium nitrate, with sulfur acting as the binding agent. Black powder products of combustion are approximately 44 percent gases and 56 percent solids. (Haag 2001).

Few muzzleloaders, except for traditionalists, currently use black powder due to its limited availability and corrosive properties. Black powder has an ignition temperature of approximately 500 °F and is federally regulated as a Class A Explosive. Commercially available powder is granulated in sizes ranging from Fg (coarsest) to FFFFg (finest). See table 1.

Table 1. Black-powder applications (http://www.goexpowder.com/product-blackpowder.html)

Granulation	Application
Fg	Musket
FFg	Rifle
FFFg	Pistol
FFFFg	Priming

Black-powder substitutes, in comparison, have reduced controls for shipping, storage, etc. and have increased in popularity. A common substitute is Pyrodex®, which has an ignition temperature of approximately 750 °F and is regulated as a Class B flammable solid (Haag 2001).

METHODS

Testing was conducted in the research facilities at the Fire Sciences Laboratory of the Rocky Mountain Research Station in Missoula, Montana. Temperature, humidity, and windspeed were controlled in order to determine ignition conditions. High-speed video cameras captured features of the muzzle blast and trajectory of various ejecta. The general test layout is depicted in appendix A. Due to the exploratory nature of this investigation, the testing protocol did not require equal runs for all conditions as may be expected in more traditional research; however, a minimum of three replications of each combination of variables were performed.

The study was divided into two parts. The first part evaluated powder as a potential ignition source. In order to eliminate the patch and lubricant as variables, conical projectiles (.50 caliber, 370-grain Maxi-Ball) were used. Two powder types were tested – Goex FFg black powder and Hodgdon Pyrodex RS. The powder load was not varied, as a 100-grain load was assumed to have a higher likelihood of ignition than a 50-grain load.

For the second portion of the testing we evaluated patches and patch lubricants as potential ignition sources. Patched balls (Speer .490 round lead ball) were used exclusively in part two. The independent variables evaluated included powder type (Goex FFg black powder and Hodgdon Pyrodex RS), powder load (50 grain and 100 grain), patch thickness (0.010 inch and 0.018 inch) and lubrication treatment (dry, prelubricated commercial, and vegetable shortening). We were unable to test 0.018-inch-thick dry patches because excessive insertion forces were required and may have resulted in damaged equipment or dangerous firing conditions. Shortening was liberally applied by hand to dry patches (as is customary among shooters), and prelubricated commercial patches were tested as received.

Rolled brown paper served as the ignition receptor, and visual inspection (burn marks) served as indications of positive results. The paper was placed on the ground approximately 10 feet wide along the length of the chamber (between the test rifle and the bullet trap). The rifle was fired from a bench rest approximately 4 feet above the ignition receptor. Immediately after firing, patches (sometimes torn and scattered in more than one piece) were located and closely observed for smoldering. The paper, especially near a smoldering patch, was inspected after each firing.

Testing was initially planned at the following three environmental conditions:

- 90 °F at 20-percent RH
- 80 °F at 50-percent RH
- 80 °F at 80-percent RH

If routine ignition occurred at the most extreme conditions (90 °F at 20-percent RH), additional testing would have been conducted at lower temperatures and higher humidity in order to establish a threshold for ignition. However, since routine ignition did not occur at the first environmental condition (90 °F at 20-percent RH), temperature and humidity were set and held at the most extreme conditions possible in the test building. The mean temperature during testing was 89.4 ° F (standard deviation = 2.2 °F) and the relative humidity was 14.7 percent (standard deviation = 3.3-percent RH). Under the conditions described above, the independent variables were analyzed using logistic regression.

The experiments were conducted in calm air conditions because there was no airflow control in the combustion chamber. Thus, any possible influence of wind on ventilating a smoldering ignition or ignition source could not be addressed by this study.

RESULTS AND DISCUSSION

Part 1—Evaluation of powder as an ignition source

No ignitions occurred in six total observations. See table 2.

Table 2. Test results with conical projectile

Number of Observations	Powder Type	Load (gr.)	Number of Ignitions
3	Black Powder	100	0
3	Pyrodex RS	100	0

Part 2—Evaluation of patches as an ignition source

Positive ignition results (burn indications on the ignition receptor) occurred in 12 out of 105 observations. Smoldering combustion of the patch was observed in 10 of the 12 positive ignition results. Five ignitions in 88 observations occurred with lubricated patches, and 7 ignitions in 17 observations occurred with dry (nonlubricated) patches. See table 3 and figures 4 through 6.

Table 3. Test results with patch and ball

Number of Observations	Powder Type	Load (gr.)	Patch Thickness (in.)	Lube Type:	Number of Ignitions
8	Pyrodex RS	50	0.10	Commercial	0
8	Pyrodex RS	100	0.10	Commercial	0
7	Pyrodex RS	50	0.10	Shortening	0
7	Pyrodex RS	100	0.10	Shortening	0
5	Pyrodex RS	50	0.10	No lube (dry)	1
4	Pyrodex RS	100	0.10	No lube (dry)	1
4	Pyrodex RS	50	0.18	Commercial	0
3	Pyrodex RS	100	0.18	Commercial	1
3	Pyrodex RS	50	0.18	Shortening	0
3	Pyrodex RS	100	0.18	Shortening	0
8	Black Powder	50	0.10	Commercial	0
8	Black Powder	100	0.10	Commercial	2
8	Black Powder	50	0.10	Shortening	1
9	Black Powder	100	0.10	Shortening	1
4	Black Powder	50	0.10	No lube (dry)	4
4	Black Powder	100	0.10	No lube (dry)	1
3	Black Powder	50	0.18	Commercial	0
3	Black Powder	100	0.18	Commercial	0
3	Black Powder	50	0.18	Shortening	0
3	Black Powder	100	0.18	Shortening	0

Figure 4—Smoldering patch, observation 103 (50-grain black powder, 0.010-inch-thick patch lubricated with shortening).

Figure 5—Smoldering patch, observation 110 (50-grain black powder, dry 0.010-inch-thick patch).

Figure 6. Positive indications of ignition on ignition receptor for observations 103 and 110.

Logistic regression was conducted on patched-ball observations. A model with the variables powder and lube were used to fit these data. The estimated probability of ignition for the different powder- and patch-lubricant treatment combinations are summarized in table 4.

Table 4—Estimates of probabilities (P) of ignition for patched-ball observations - Probit Model results

	Black Powder		Pyrodex	
	P	**(%)**	**P**	**(%)**
Dry Patch (No Lube)	0.5785	(57.85)	0.2621	(26.21)
Commercial	0.1198	(11.98)	0.0222	(2.22)
Shortening	0.0742	(7.42)	0.0113	(1.13)

The probabilities presented in table 4 can also be expressed as odds ratios with confidence intervals. In this case, these confidence intervals are sizeable, likely due to the limited number of observations for each combination of variables.

With 95-percent confidence, for a given lubricant treatment (commercial, shortening, or dry), the odds of ignition with black powder is 1.049 to 23.975 times the odds of ignition with Pyrodex.

With 95-percent confidence, for a given type of powder (Pyrodex or black powder), the odds of ignition with no lubricant is 2.433 to 63.816 times the odds of ignition with the commercial lubricant. With 95-percent confidence, for a given type of powder (Pyrodex or black powder), the odds of ignition with no lubricant is 3.142 to 122.609 times the odds of ignition with shortening.

For patches treated with shortening, the overall surface area of the lubed cotton weave may have been reduced due to thicker application of the lubricant relative to the prelubricated commercial patches. This reduction in surface area may explain the lower likelihood of ignition for patches lubricated with shortening. Lubricant ignition temperatures may also help explain differences in probability of ignition for the two lubricants.

No ignitions occurred with either powder type using conical “patch-less” projectiles. Black powder had a higher probability of ignition, regardless of lubricant treatment. Moreover, regardless of powder type, the probability of ignition drops dramatically when patch lubricant is used. The complete statistical analysis is presented in appendix B.

CONCLUSION

This exploratory investigation demonstrated the existence of ignition potential with muzzle-loading firearms under extreme laboratory conditions with a limited number of replications and independent variables. Dry patches demonstrated the highest probability of ignition under these conditions. Conservative fire prevention measures could preclude the use of dry patches when outdoor conditions approach similar high temperatures accompanied by low relative humidity (although dry patches are not commonly used by shooters anyway). However, it is important to bear in mind that laboratory ignitions on craft paper do not necessarily reflect the ignition potential on a forest floor. As such, care should be taken to apply the results of this exploratory study appropriately.

FUTURE RESEARCH

Although we found no indication that burning powder is a source of ignition for forest vegetation, the rifle was tested at an approximate height of 4 feet above the ignition receptor (similar in height as if the rifle were fired from standing or kneeling position). Further testing could be performed in direct proximity to the ignition receptor to simulate firing from a prone position. Additional ignition receptors, powders, patches, and lubricants could be studied with a greater number of replications. Testing could also be performed at lower temperatures and higher humidity to determine a more refined threshold for patch ignition.

Interest has also been expressed by fire prevention officers regarding the ignition potential of conventional firearms, specifically related to recreational shooting. Tracer ammunition, exploding targets, and armor-piercing (steel core) bullets have been cited anecdotally as ignition sources; scientific testing could provide additional insight on the topic.

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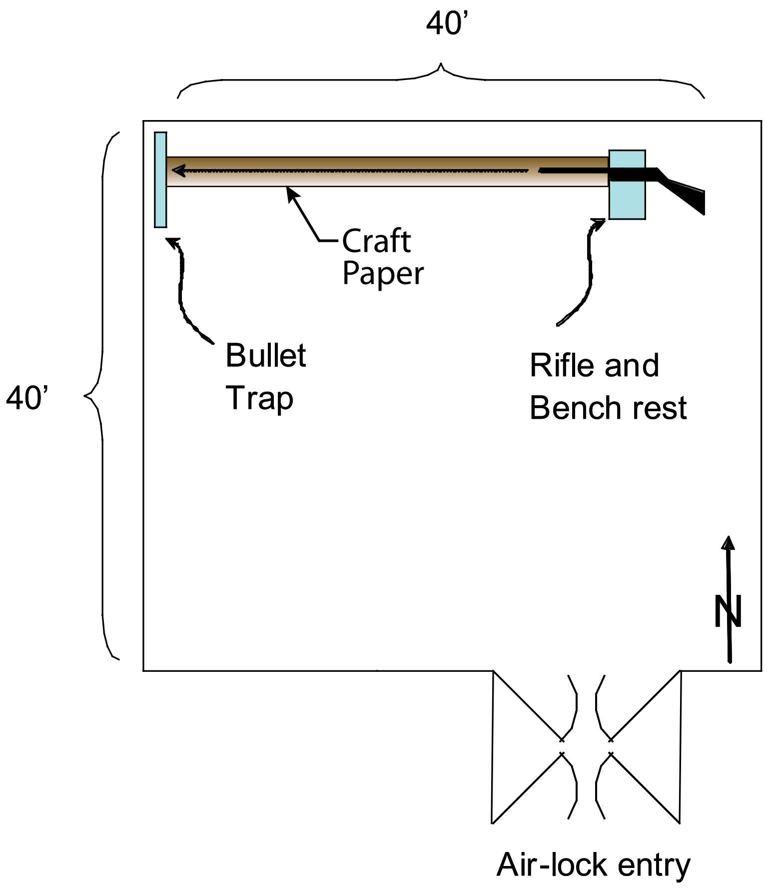
APPENDIX A

Plan view of combustion chamber showing entrance through air-lock entry and location of bullet trap and rifle.



APPENDIX B

Data Analysis

An initial contingency analysis was run on each individual variable versus whether or not an ignition occurred. The only variable that was significant at the α=0.05 level was the presence of lubricant.

In order to determine if interaction between independent variables was present, six different methods were used to determine the appropriate statistical model during the variable selection process: (1) forward conditional, (2) forward likelihood ratio (based on a difference in the chi-square), (3) forward Wald (based on the Wald test), (4) backward conditional, (5) backward likelihood ratio, and (6) backward Wald[1,2].

Table B1—Results of model selection

	FORWARD SELECTION			BACKWARD SELECTION		
	Conditional	**Likelihood Ratio**	**Wald**	**Conditional**	**Likelihood Ratio**	**Wald**
Powder	*	*	*	***	***	**
Load						
Patch						
Lube	***	***	***	***	***	***
Powder × Load				***	***	
Powder × Patch				***	**	**
Powder × Lube				***	*	
Load × Patch				***	***	**
Load × Lube	*	*	*	***	***	**
Patch × Lube				***	**	

*Note: * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$*

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[1] "Forward" means that one variable at the time is entered into the model and if the variable is significant it stays in the model. If the variable is not significant then it is removed and the next variable is entered. This process continues until the "optimal" model is achieved.

[2] "Backward" means that all the variables start in the model. Insignificant variables are removed one by one until the "optimal" model is achieved.

The results of the model selection suggest that there are three possible models to fit to these data.

- MODEL 1: Powder, Load, Lube, Load × Lube
- MODEL 2: Powder, Load, Patch, Lube, Powder × Load, Powder × Patch, Powder × Lube, Load × Patch, Load × Lube, Patch × Lube
- MODEL 3: Powder, Load, Patch, Lube, Powder × Patch, Load × Patch, Load × Lube

The reason Load is included in Model 1 even though it was not selected in any of the forward selection methods is because the interaction between Load and Lube is included in the model. That same logic is the reason why Load and Patch are included in Model 2 and Model 3.

Three measures of goodness of fit were computed for each of the three models: Akaike information criteria (AIC), Bayesian information criteria (BIC), and corrected Akaike information matrix (CAIC). Basically, the smaller the value of each of these goodness of fit measures, the better the model fits the data.

Table B2—Goodness of fit measures

	MODEL 1	MODEL 2	MODEL 3
AIC	63.636	67.125	64.236
BIC	82.214	104.3	90.775
CAIC	89.214	118.3	100.8

By all three goodness of fit measures, the “best” fitting model is Model 1, the model with Powder, Load, Lube, and the interaction between Load and Lube.

For the main analysis, a logistic regression was performed on the ignition data. In general, the logistic regression model takes on the form:

$$\ln \left[\frac{\pi(x)}{1 - \pi(x)} \right] = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \dots + \beta_k x_k$$

where $x = (x_1, x_2, \dots, x_k)$ are the values for k explanatory variables.

Table B3—Type I and type III tests of model effects

	Type I			Type III		
	Wald Chi-Square	df	p-value	Wald Chi-Square	df	p-value
Powder	.000	1	0.995	9.302	2	0.010
Lube	9.611	2	0.008	4.310	1	0.038
Load	.000	1	0.999	.000	1	0.999
Load × Lube	.736	2	0.692	.736	2	0.692

Initial results for model 1 suggest that Load and the interaction between Load and Lube are insignificant. The Type I tests are sequential, i.e., the order the variables are listed is the order that they are entered into the model. For example, the test for the interaction between Load and Lube assumes all of the other variables are already in the model. The test for Load is assuming that only Powder and Lube are in the model. These tests indicate that Load and the interaction term can be left out of the model. The Type III tests are assuming all of the other variables are in the model, i.e., the variable of interest is the last one entered into the model. A simpler model with the variables Powder and Lube can be used to fit these data.

Table B4—Logistic regression – Logit Model: Powder and Lube

			95% Wald Confidence Interval	
Parameter	β	Standard Error	Lower	Upper
Powder (Pyrodex vs. BP)	-1.613	0.7983	-3.177	-0.048
Lube (Commercial vs. No Lube)	-2.523	0.8333	-4.156	-0.889
Lube (Shortening vs. No Lube)	-2.977	0.9347	-4.809	-1.145

To interpret the results, take the exponential function, *e*, to the lower and upper values of the confidence interval. This results in a 95-percent confidence interval of an odds ratio for ignition. For example, taking the confidence interval for Powder,

$e^{-3.177} = 0.0417$ and $e^{-0.048} = 0.953$.

With 95 percent confidence, for a given type of lubricant (commercial, shortening, or dry), the odds of ignition with Pyrodex is 0.0417 to 0.953 times the odds of ignition with black powder. An easier interpretation can be made with the reciprocal of this interval. With 95 percent confidence, for a given type of lubricant (commercial, shortening, or dry), the odds of ignition with black powder is 1.049 to 23.975 times the odds of ignition with Pyrodex.

The results for Lube can be interpreted in a similar manner. With 95 percent confidence, for a given type of powder (Pyrodex or black powder), the odds of ignition with no lubricant is 2.433 to 63.816 times the odds of ignition with the commercial lubricant. With 95 percent confidence, for a given type of powder (Pyrodex or black powder), the odds of ignition with no lubricant is 3.142 to 122.609 times the odds of ignition with shortening.

An odds ratio can be constructed to compare the commercial lubricant with shortening. Using entries from the covariance matrix of the parameter estimates, the standard error for the difference of the parameter estimates for commercial lubricant and shortening can be evaluated. With 95 percent confidence, for a given powder (Pyrodex or black powder), the odds of ignition with the commercial lubricant is 0.244 to 10.145 times the odds of ignition with shortening. Since 1 falls inside this confidence interval, there is no significant difference between the commercial lubricant and the shortening.

Further regression analysis was conducted using the probit model,

$$\phi^{-1} [\pi(x)] = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + ... + \beta_k x_k$$

where $x = (x_1, x_2, ..., x_k)$ are the values for k explanatory variables, and $\phi^{-1}(\bullet)$ is the inverse of the standard normal cumulative distribution function.

Table B5—Logistic regression – Probit Model: Powder and Lube

			95% Wald Confidence Interval	
Parameter	**β**	**Standard Error**	**Lower**	**Upper**
Intercept	0.198	0.3774	-0.542	0.937
Powder (Pyrodex vs. BP)	-0.835	0.4096	-1.638	-0.033
Lube (Commercial vs. No Lube)	-1.374	0.4433	-2.243	-0.505
Lube (Shortening vs. No Lube)	-1.643	0.4917	-2.606	-0.670

Estimates of probabilities of ignition were determined as follows:

Dry patch and black powder: $P(Z \leq 0.198) = 0.5785$
Dry patch and Pyrodex: $P(Z \leq 0.198-0.835) = 0.2621$

The estimated probability of ignition for the different powder and lubricant combinations are summarized in table B6.

Table B6—Estimates of probabilities of ignition – Probit Model Results

	Black Powder	**Pyrodex**
Dry Patch/No Lube	0.5785	0.2621
Commercial	0.1198	0.0222
Shortening	0.0742	0.0113

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