Compressed-Air Spud Cannon and Performance Assessment

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Synopsis

It is unusual to live in California and not be in or near "fire country". Since I did not want to see myself on the 6:00 PM news sporting the headline, "Local idiot starts major brush fire," I did not want to use anything combustible in my potato cannon. Most spud cannons I have seen exhibit erratic behavior from one shot to the next because fuel-air mixtures are not well controlled, and the ignition methods tend to be very amateurish. Since, I wanted to let kids shoot the cannon without any fear on my part of an accident due to an excessively powerful explosion, I have opted to use the air compressor in my workshop as the means for propelling the spuds in which case I know first-hand what all of the (maximum) pressure levels are for every shot.

*To finish off the project, I had to know how well the cannon was performing. I contemplated using a ballistic chronograph, but since the potatoes literally explode when they hit anything, I knew that I would lose a lot of kinetic energy in the measurements due to pieces of potato flying everywhere. There are many optical chronographs you can purchase for under $100 on Ebay and elsewhere, but catching a potato in flight is messy business! If you measure too close to the muzzle of the cannon, it is easy to get false readings due to all of the potato juice exploding out of the barrel (*Figure 3*). If you move the chronograph further away from the muzzle, the relatively poor aiming accuracy will probably mean kissing your $100 chronograph good-bye after only a few shots. I subsequently came up with my own way to measure spud velocity quite accurately.*

1 Introduction

When it comes to cannons that shoot almost anything, there are some real crazies out there! If you want to see people blowing themselves up, just visit YouTube and look for *potato cannon*. I don't recall what the guy in Figure 1 shoots out of his cannon, but an equally interesting question is where the heck the guy goes to shoot this monster.

My venture into potato cannons is far more tame as shown in Figure 2. Theoretically, a well-fitting spud should exhibit a muzzle exit velocity on the order of 400 feet-per-second with my cannon. Shooting the cannon straight up generally results in a hang-time on the order of 15 seconds, and if I'm going for maximum range, I can easily get to 1000 feet or more. (It's a good thing I have no neighbors more or less.)

Figure 1 A serious big-boy cannon for shooting who-knows-what

Figure 2 My completed spud cannon short of its camo paint job

Figure 3 First shot- with a lucky exposure capturing the potato juice plume at the barrel output. Small air compressor shown attached.

1.1 Closer Look

The most important guideline to observe when building a spud cannon is pressure ratings. I would have preferred making the cannon using ABS piping instead of PVC but I was unable to buy the ABS in the desired sizes and ratings without going to a specialty supplier. If an ABS pipe fails, it normally just splits open along a side but otherwise remains more or less in one piece. When a PVC pipe fails, however, it shatters and sharp pieces go everywhere. Observe pressure ratings!

Most spud cannons use some type of combustible explosion to create the high-pressure gas involved with launching a projectile. Generally speaking, you can get greater range with far more safety margin using compressed air rather than a rather uncontrolled explosion.

The entire cannon is shown in Figure 4 with close-ups of the key component areas shown in Figure 5 and Figure 6.

Figure 4 Spud cannon built primarily using 2” PVC. A 1” modified lawn sprinkler valve is used as the control valve between the pressurized air reservoir and the barrel. The ruler is 48” long.

Figure 5 View of the trigger assembly. All materials purchased as Home Depot / Lowes.

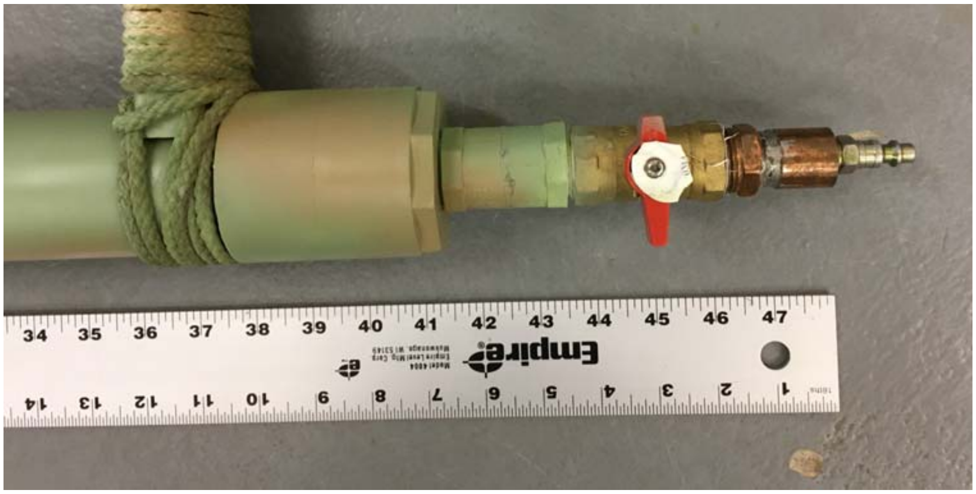

Figure 6 View of the air reservoir charging port. A standard 1” ball-valve was used with reduction down to the quick-connect which works with my workshop air compressor. Sweating the copper elements together was the only construction step which required special consideration.

2 Spud Cannon Theory

There are quite a few articles on the Internet about spud cannon design theory. The peak-activity on the spud cannon topics seems to have occurred between 2006 and 2008. Consequently, there are quite a few broken links to spud cannon articles on the Internet.

The theoretical elements underlying the spud cannon vary significantly depending upon the underlying assumptions employed. At the amateurish level, important quantities like coefficients of friction and valve flow-rate are generally not known. Even so, the simplified theory is helpful in determining a performance ceiling for a given set of design parameters.

The simplified model adopted here is based upon a paper by Rohrbach et al.[1] in which the simplified cannon model consists of a pressurized air chamber, an air valve, a projectile of mass *m*, and a barrel of length *L* with cross-sectional area *A* as shown in Figure 7.

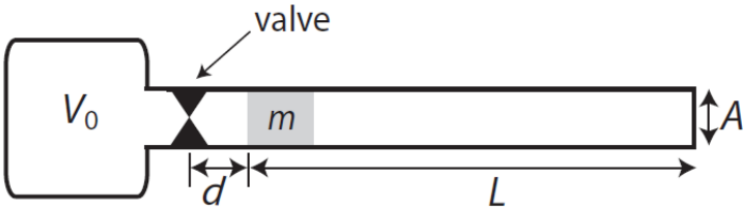

Figure 7 Potato pressurized-air cannon model

The air reservoir of volume V_o is initially pressurized to P_o. Once the valve is opened, this allows the pressurized air to flow, and the pressure exerts force on the projectile of mass *m* which causes it to accelerate down the length of the barrel.

Three different modeling formula are provided in the cited reference. For the first model, no valve-loss is included, no air-leakage around the projectile is assumed, and the gas expansion is assumed to be quasi-static and isothermal. Under these assumptions, the muzzle velocity for the projectile at the barrel opening is given by

$$v(L)=\sqrt{\frac{5P_oV_o}{m}\left[1-\left(\frac{V_o}{AL+V_o}\right)^{2/5}\right]-2ALP_{atm}-2Lf} \tag{1}$$

where

m	Mass of the projectile, kg
P_o	Initial pressure in the air reservoir, Pascals
V_o	Air reservoir volume, m^3
A	Cross-sectional area of the barrel, m^2
L	Length of the barrel, m
P_{atm}	Standard atmospheric pressure, 101325 Pascals at sea level
f	Barrel friction

In the second model, the gas expansion is assumed to be quasi-static and isothermal in which the muzzle velocity versus barrel length is given by

$$v(L)=\sqrt{\frac{2}{m}\left[P_oV_o\log_e\left(1+\frac{AL}{V_o}\right)-ALP_{atm}-Lf\right]} \tag{2}$$

Neither of these models include any provision for valve-related loses, pressure-wave propagation time, or any complications of potentially turbulent air-flow.

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[1] "The Projectile Velocity of an Air Cannon," *Wabash Journal of Physics*, Z.J. Rohrbach, T.R. Buresh, and M.J. Madsen, May, 2011.

Unfortunately, the cited reference reports that neither of these formula give very accurate results. A third model (much more complicated involving the solution of 4 nonlinear differential equations) fared better, but the results were still not very satisfactory. Consequently, there is little motivation to expend substantially more computational effort to obtain a still less than satisfactory answer. It would seem that the best course of action is to recognize that both of the models presented here represent an upper performance bound for the cannon which may be quite optimistic.

For the potato cannon of Figure 2 and Figure 3, adopted design parameter values are as follows:

m	0.15 lb.
P_o	120 PSI
V_o	113 in^3
A	3.14 in^2
L	60 in.
P_{atm}	14.7 PSI
f	5 lb.

Equations (1) and (2) are plotted in as a function of barrel length and show good agreement in Figure 8. As already mentioned, however, pressure loss across the valve, potentially turbulent air flow, and gas velocities approaching the speed of sound reduce the velocity estimates substantially (e.g., 50% loss is not uncommon) in real life.

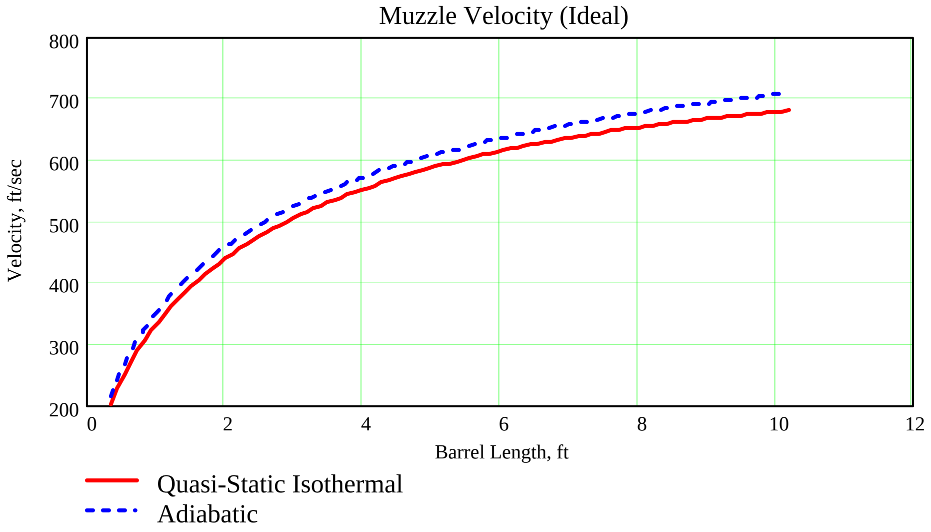

Figure 8 Muzzle velocity versus barrel length for the quasi-static case (2) and the adiabatic expansion case (1)

3 Performance Assessment

The unsatisfying theoretical results of the previous section amplify the desire to make reliable measurements of the potato cannon's performance. Since individual potato projectiles will likely vary quite a lot, two series of measurements will be made. The first series will make repeated use of a well-fitting wooden projectile. The projectile will be shot into a pile of foam rubber in order to prevent damage to the projectile from shot to shot. This will avoid the *liquid plume* problem at the output of the barrel (e.g., Figure 3) while also eliminating projectile-related variations. The second round of measurements will use actual potatoes.

> NOTE: The fire-power of such spud cannons should not be underestimated! They should always be treated as if they were a real loaded shotgun.

3.1 A Chronometer Suitable for Spud Cannons

The desire to accurately measure cannon performance with real potatoes is synonymous with addressing the *liquid plume* problem shown in Figure 3. To be successful, the measuring apparatus needs to be geared for high-contrast (optical) measurements in order to discriminate between the plume and the passing potato projectile.

Side Note: I did look into the availability of radar guns and other velocity measuring equipment with price-tags less than roughly $200. None of the radar guns would operate above 200 miles-per-hour which is likely insufficient.

The speed measurement approach adopted here entails measuring the time required for the projectile to pass between two time-gates. Assume that the maximum spud velocity that will ever need to be measured is 600 miles per hour for healthy margin. This equates to 880 feet per second. The velocity measurement will be done by measuring how long it takes the projectile to traverse a known distance- taken to be 2 feet here. At 880 fps, the time to traverse 2 ft will be only 2.27 msec and a 1% measurement error dictates a time-measurement precision on the order of 22.7 μsec or better. This is a relatively benign requirement, but still beyond the measurement speed of the Arduino-class microprocessors. Some auxiliary measurement circuitry will have to assist the adopted Arduino processor in making the time measurements.

Assume that the time-base used for the high-speed time measurements uses 1 μsec ticks. Assume further that the minimum spud velocity of interest is 40 MPH in which case the flight-time required to traverse 2 ft will be about 34.1 msec. This longer flight-time translates into about 34,091 ticks of the 1 MHz time-base clock (or about 16 binary bits for a counter).

The measurement setup then consists of two time-gates which are separated by 2 ft. A conceptual diagram for one of the time-gates is shown in Figure 9 in which a line-generating type laser diode illuminates a credit-card-sized Fresnel lens in order to convert the light into a parallel set of rays.[2] Spreading the laser light out in this manner results in a much more reliable detection of the potato projectile and better discrimination against false detections of large plume particles. A second Fresnel lens refocuses the laser line down to the PIN diode detector region. The laser diode can be a quality device (like that from Digikey) or Chinese knock-offs can be bought from Amazon. The detailed bill of materials will be provided in part two of this article.

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[2] As far as I know, using a line-generating laser diode plus Fresnel lenses in this manner is new.

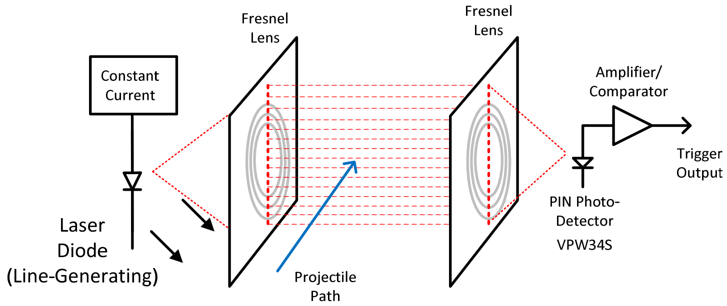

Figure 9 Conceptual diagram for one time-gate

As mentioned previously, the ADC and interrupt structures of the Arduino microprocessor family (16 MHz clock) are not fast enough to provide anything close to 1 μsec time resolution. The simple auxiliary circuit shown in Figure 10 can do the needed time measurement very effectively though. An Arduino is used to set up the circuitry for a time measurement (simply resets everything) and once both time-gates have been triggered by the passing projectile, the same Arduino is used to query the 16-bit binary counter for the number of 1 μsec ticks required for the projectile's passing between the two time-gates. Given the separation distance and transit-time, projectile velocity immediately follows.

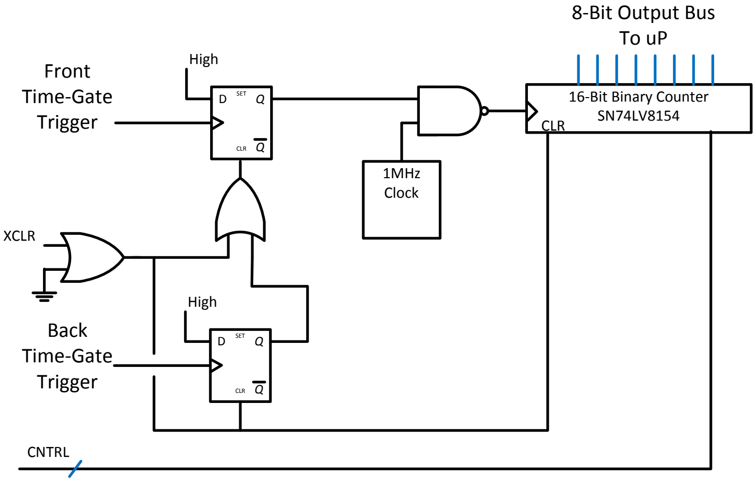

Figure 10 Auxiliary time-gate measurement circuitry using 1 MHz time-base

4 Looking Forward to Part II

The final portion of this memo will provide the detailed schematics, bill of materials, and photographs of the final hardware. In addition, measurement results using (i) the wooden projectile and (ii) potatoes will be reported as mentioned earlier.

5 Internet Materials

There are many many articles available on the Internet about potato cannons. There is a wealth of information on Youtube in particular. Most people are interested in just playing with the cannons rather than delving into the underlying theory, but a few of the more interesting internet articles which have survived as of this writing include the following:

https://www.spudfiles.com/spud_wiki/index.php?title=Chamber_to_barrel_ratio

http://www.iontrap.wabash.edu/adlab/papers/S2011_Buresh_Rohrbach_air_cannon.pdf

https://www.usna.edu/Users/physics/mungan/_files/documents/Publications/EJP5.pdf

http://www.kiledjian.elac.org/phys%20001/Ballistics%20of%20Air%20Gun.pdf