The Pacific Flying Machines (PFM) Piston

NARAM 52 Research & Development

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LUNAR Section 534

Modern piston launchers in ubiquitous use in competition are almost all of the zero volume or zero volume floating head design. These suffer from serious drawbacks, since by design they have no initial volume, and are very prone to oscillation. Also, the fit between the model and the piston is very subjective and prone to failure on either side of the too loose or too tight equation.

This report describes the design, construction and experimental testing of a new piston launcher. In the past, this was the “standard piston launcher” with a moving internal tube and a static outer tube and a large initial volume. Several key innovations were introduced including the use of magnetic hold downs, the placement of the hold downs on the static tube instead of the moving tube and significantly better materials for the seals and tubes. These innovations allow the piston to build up pressure before first motion and to accelerate the model throughout the entire piston stroke.

Several tests were conducted showing serious improvement over both rod and launch tower alone or modern zero volume floating head pistons. These tests included both separation speed as measured by high speed photography and altitude as measured by a recording altimeter. Over unassisted launch, a 300% improvement in altitude was shown. This is nearly double the altitude as compared to a zero volume floating head piston. The separation speed using the new piston was 80% higher than burnout speed of an unassisted launch. As fewer than a dozen test flights were done, these represent the baseline for future work in piston optimization and understanding and advancing the state-of-the-art in model rocketry.

Introduction

Objectives

The objectives of this project were to improve performance of piston launchers used in model rocketry by addressing two key problems faced by modern pistons. First, modern piston launchers of the zero volume or zero volume floating head type require a critical fit between the model and the top of the piston tube. If a zero volume piston is too tight, a large amount of momentum is lost when the stop is hit. Floating head zero volume pistons fixed this but introduced a new failure mode, since the model will stop accelerating once the piston reaches full extension until it releases from the piston tube, if the fit is too tight it will waste a significant amount of engine impulse before release. The first objective was to make the fit between the model and the piston less critical and less subjective. The second objective was to eliminate the oscillatory behavior of zero volume pistons, that is, the tendency to accelerate, stop accelerating, then start again. This will be discussed fully later. As a side effect, eliminating this behavior leads to the potential to work well with composite motors which suffer from even worse oscillatory modes. Overall, by eliminating these drawbacks to zero volume pistons, we hoped to significantly improve performance, which advances the state of the art in model rocketry, specifically competition rocketry. As work progressed it became obvious that the combination of a mechanical clamp and large initial volume enabled the generation of much larger than normal pressures in the piston and dramatically higher acceleration than has been seen in any other pistons to date.

Two Problems & Solutions

The obvious solution to the fit issue is to add a mechanical clamp, but this is a tough solution as it will add significant weight and introduces a timing problem to release at the appropriate time. Many clamps add more sliding friction or cause a momentum loss to the model. If the mechanical clamp is attached to the top of the piston tube then the entire weight must be accelerated by the motor exhaust, which would incur a significant penalty. Many clamp concepts were identified and discarded due to complexity, difficulty of manufacture, weight or momentum loss. A few of them were built, but none were promising enough to even launch test.

The solution to the oscillation problem is to add volume to the zero volume and revert to the previous “standard piston launcher” shown in the first figure, courtesy Geoff Landis. This moves the critical seal well away from the exhaust.

Initial Work / History

In 1989 a piston simulation was run, based on Geoff Landis’s 1975 paper, for S8E models (E-powered rocket gliders for FAI). These simulations showed that a low initial volume was prone to oscillation, but that you could go to large initial volume without a loss of performance. A particular goal of this effort was to “tame” the extreme initial acceleration caused by combining the very fast thrust rise time (only a few milliseconds from ignition to peak thrust) of the composite E6 motor. The simulations showed initial accelerations of hundreds of G’s followed by strong oscillations. While there are many unknown parameters (such as non-ideal gas dynamics of rocket exhaust, friction, leakage etc) it was felt that the simulations could at least identify problem areas and the overall nature of the problem. Geoff Landis showed moderately good correlation of the simulation results to his testing. The simulations showed that adding significant initial volume would both reduce the initial acceleration spike and greatly reduce the tendancy to oscillate.

While one way to do this is to just start a zero volume piston with some initial volume, it was realized at this point that the "standard" piston launcher had that initial volume, but also kept all the critical sliding seals well away from the engine exhaust. No piston was built during this phase of the project

In 2006, the innovation of using a hold down to keep the model and piston from moving while pressure was built up was discovered. This also gives smooth acceleration through the piston stroke. If there is enough initial volume and pressure before first motion, the piston internal pressure is always above ambient pressure and you always have positive pressure and positive acceleration throughout the piston stroke. For example, and assuming an ideal gas in the piston, if the initial volume is 1/3 the final volume (typical of a standard piston configuration) and if you keep the piston from moving until the gas pressure is 3x ambient, then at the end of stroke the internal pressure is at least ambient, even with no additional gas added by the engine. With positive pressure, the oscillatory effect completely disappears. The 2006 prototype of the piston had 3 new innovations 1) held down until pressurized 2) significant initial volume 3) release mechanism to avoid fit problem. This prototype was built but was mechanically marginal, so it was never tested.

In 2010, 2 additional innovations were added and the Mark 1 piston used in this report was built and tested as described later. The first innovation was the use of high strength magnets for hold downs instead of a complicated mechanical latch. The hold down force was adjusted by varying the number of locations and the mechanical advantage of the latch "lever" arms. Second, and a major simplification, was the realization that if the piston was pushing the model and providing more acceleration then there was no need to hold the model to the piston throughout the stroke by a mechanism or friction . If the piston helped, the model would stay attached. If the piston was not helping the model would depart. This meant the model only needed to be held down to the fixed base before first motion, thus the hold down mechanism would not be attached to the moving piston tube, so it did not need to be light weight or low friction. The only requirement for the piston to model fit was that it be a smooth slip fit, not a specific degree of friction.

This piston was successfully tested in April 2010. Its performance was dramatically greater than typical modern competition piston launchers. A few weeks later, the piston was measured and compared with a zero volume floating head piston. It is described in more detail later.

Based on this experience and data, a Mark 2 piston constructed during the course of this report. The piston tube was longer and made of fiberglass for higher strength, lower weight and smaller diameter. A single long hold down arm was used instead of 2 smaller hold down arms, which simplified the construction and allowed a larger range of breakout forces to be tested. Finally, since the original Mark 1 piston appeared to be leaky, better seals were designed, both for the piston/cylinder moving seal and the piston/cylinder static seal.


1a.

FIGURE 1a. Conventional closed-breech launcher.

In this launcher, a piston fits against the rear end of the rocket, which is slid into a tube. The rocket's exhaust gasses pressurize the volume behind this piston, and force the rocket up.


1b.

FIGURE 1b. Standard piston launcher.

George Helsier envisioned this launcher as a closed breech launcher with a piston elongated to permit the rocket to sit above the breech tube. The advantage thus gained is that the tube need not be large enough in diameter to fit the rocket inside.


1c.

FIGURE 1c. A Zero-Volume piston launcher.

In a zero-volume piston launcher, the outside tube is the one which moves with the rocket. It still works on the same principle as the closed-breech launcher, in that a pressurized space behind the rocket pushes the rocket forward.

FIGURES ONE:
Several closed-breech type launching devices

Figure showing launching devices courtesy Geoff Landis, 1975. The new piston described here is much like the standard piston launcher 1b with some additions.

Approach Taken

To date, this project has strictly been one of invention and development, with relatively minimal data collection. The data has only been to enable further development. In most cases only one or two flights have been done in each configuration tested. While no statistics have been done, so far the magnitude of the improvements encountered (factors of several in launch energy) has been much larger than expected experimental error (10%), and continuous improvements (and a few lessons about how NOT to do things) have been obtained. In the future, it will be appropriate to become more rigorous in the approach and attempt to isolate parameters.

Two pistons were made, as well as 2 different hold down mechanisms. The basic features common to all of them are:

1) "standard piston configuration" with an inner, moving tube, of approximately the same diameter as the engine, a fixed outer tube, and a sliding seal at the bottom of the moving piston
2) a magnetic hold down latch to keep the model from moving until a preset "break out" vertical force was achieved by the combination of engine thrust and piston pressure. The force could be varied by changing the number and location of the magnets relative to the pivot of the hold down beam(s). The break out force was measured with a digital "spring scale"
3) a spring to decelerate the piston at the end of the stroke
4) a metal outer tube. ("cylinder") This does not move, and its more critical to have a smooth round, non-corrosive inner bore than it is to have light weight. The use of copper and brass tubes with copper household plumbing fittings has been very convenient.
5) A vent hole in the top of the cylinder tube to vent the pressure prior to the piston hitting the deceleration spring

Details of the pistons are shown below.

We used a series of test models of similar construction. The models had a length of 13mm tube to hold the engine and recovery system. Engines were press fit into the tube, Estes 1/4A3-3T were used for all flights. Fins were clipped deltas, attached backwards so the leading edge was flat and suited for the hold-downs. All hold-downs used went over 2 opposite fins, so all models had 4 precut fiberglass fins, slightly over one inch in length and width. These were attached with strips of 0.75 oz/yd fiberglass and epoxy between two adjacent fins. Each model recovery system had a snap swivel for easy attachment to the altimeter bay. The altimeter bay had a transition to 18mm, a short section of tube with punched holes and a plastic nosecone. The RAM3 recording altimeter and battery fit into this section. Model launch mass was 31 grams.

The RAM3 recording altimeter was carried for all flights and recorded an altitude either 5 or 10 times a second. It is a model aircraft type altimeter, and could run for several hours, taking data continuously. This was great convenience when doing many test flights within a limited time. The data was read from the altimeter using a computer after a day's worth of flying. This data showed the overall altitude reached by each flight. Note, while this is a proven, accurate altimeter, we think it may have some filtering software in it that limits the accuracy in high speed boosts. The peaks should be fine, but it is probably not appropriate to differentiate the altitude vs time curve to obtain a velocity!

The Casio EX-FH25 high speed camera was used to take video of most flights. This is a relatively new consumer level camera capable of doing both high speed, low resolution video, and fast motor drive mode still photos. Video was taken at 1000 frames per second, 33 times faster than typical video. A measuring stick consisting of one inch stripes was attached to the launcher so that separation speed could be computed by counting frames it took the model to clear a section of stripes. Additionally, the high speed video allowed the piston extension out of the cylinder tube to be measured and various operational features to be analyzed. This was invaluable for diagnosing problems when they occurred.

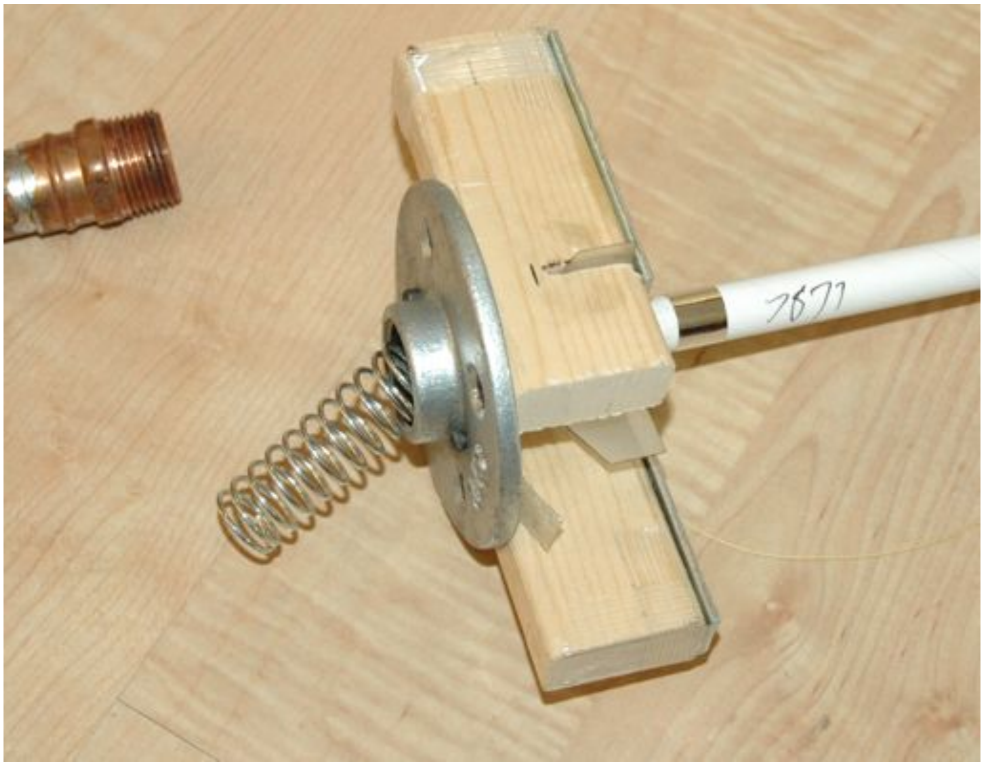
Detail Description of Pistons

The first iteration of the new piston is called the Mark 1 piston. It is shown in the following photos.

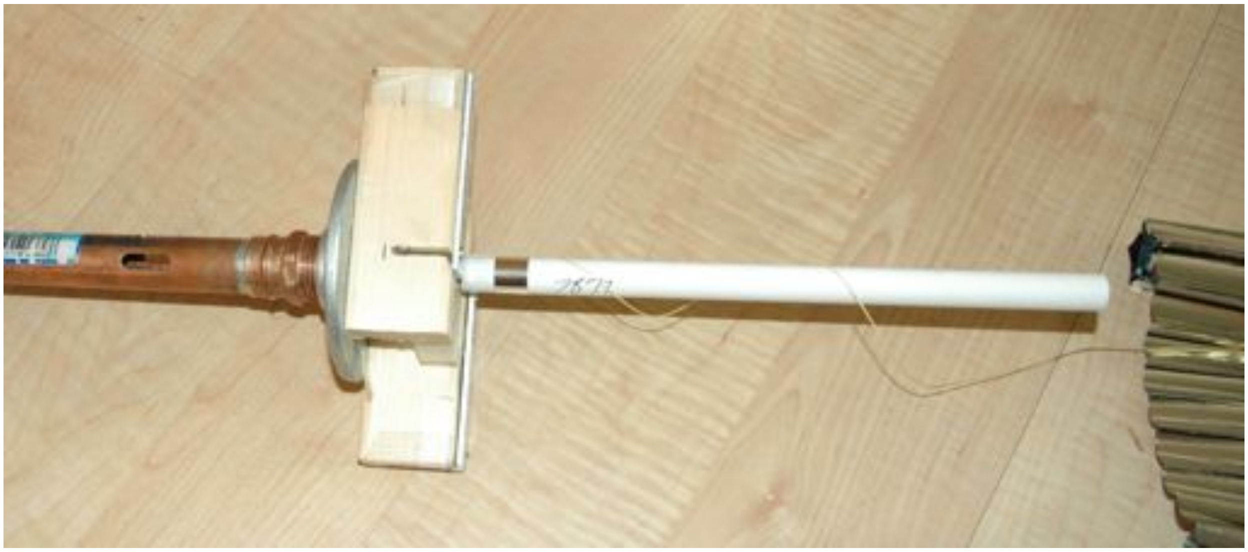
Piston tube (top, white) and cylinder tube (bottom, copper) of Mark 1 piston. The piston tube is 13mm paper body tube, with two layers of fiberglass added for strength. At the left you can see a short length of 18mm tube which was a spacer to provide some extra initial volume. The cylinder tube is ¾” copper plumbing pipe. Unfortunately, this tube was not perfectly round, and the .01” variation resulted in gas leakage and reduced performance.

Bottom of piston tube showing sliding seal of Mark 1 piston. The actual seal is made from solid Teflon for low friction. The Teflon is a very thin wall “cup” in the back, with the hope that it would be flexible enough to follow the variations in the out of round cylinder. Since the Teflon will not stick to normal glues, there are paper engine block rings in front and in back (inside the cup) to take the acceleration and deceleration loads, and transfer them into the piston tube.

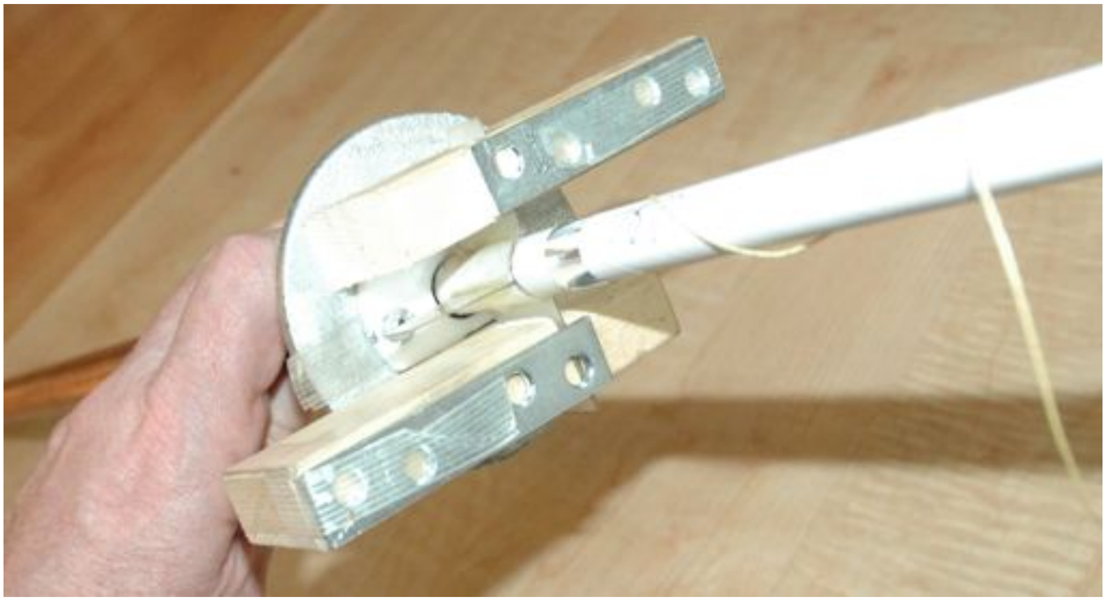
Top of piston tube where model is inserted of Mark 1 piston. This was very simple. There is a normal engine block ring inside the tube and there are two small slots in the piston tube so the standard Estes igniter leads can get out. Normal, smooth jaw micro clips are used to connect the ignition system, and they just pull off the leads at first motion. (this is critical! Alligator clips can grip so hard that the piston cannot move!)



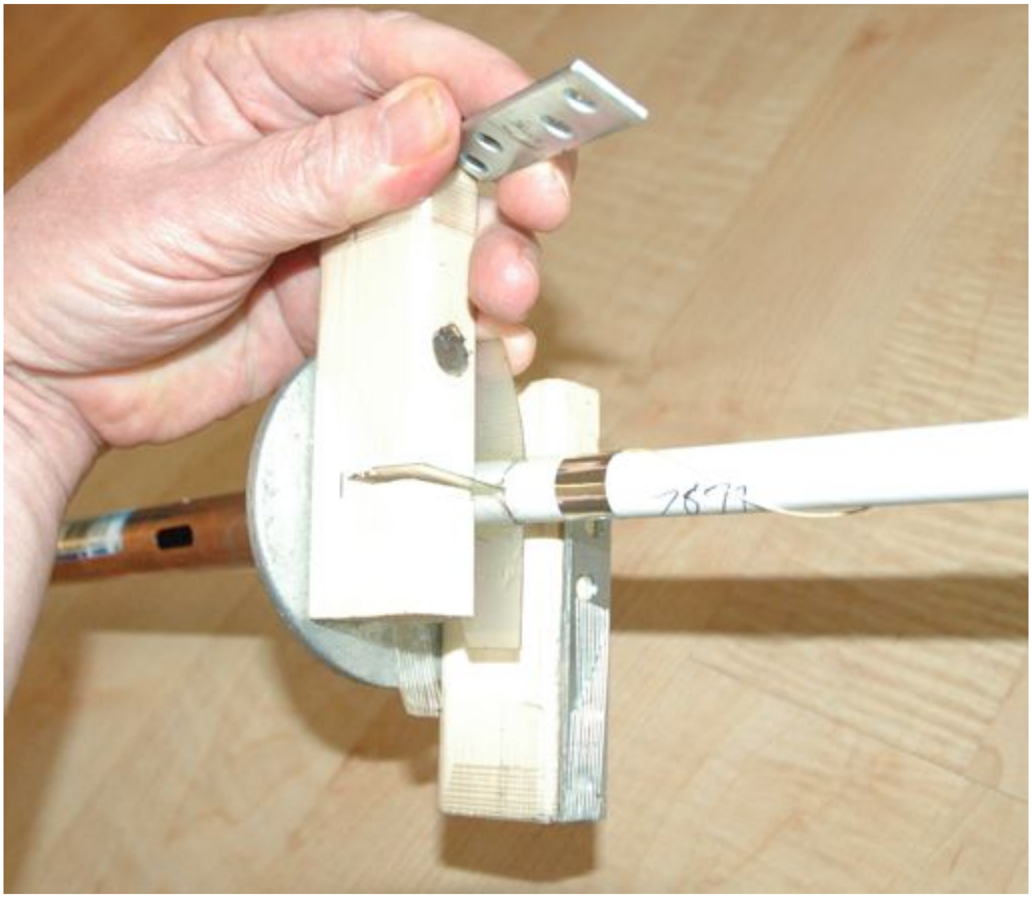
Top of cylinder tube, bottom of hold downs. The silver part is a standard plubming flange, and screws onto the fitting soldered to the cylinder tube. The hold down blocks are screwed to the flange. Note spring that stops piston tube travel, model inserted into hold downs, and is being held in place by the clamps. Note the threaded upper end of the cylinder tube in the background. Analysis of the video showed that the 15 gram piston assembly was hitting the spring hard enough to fully compress it, which was a deceleration force of up to 25 Newtons, over 150G's



The assembled piston with model. Note the vent slots in the cylinder tube. The piston seal passes these slots, venting the gas pressure, just before it contacts the deceleration spring.



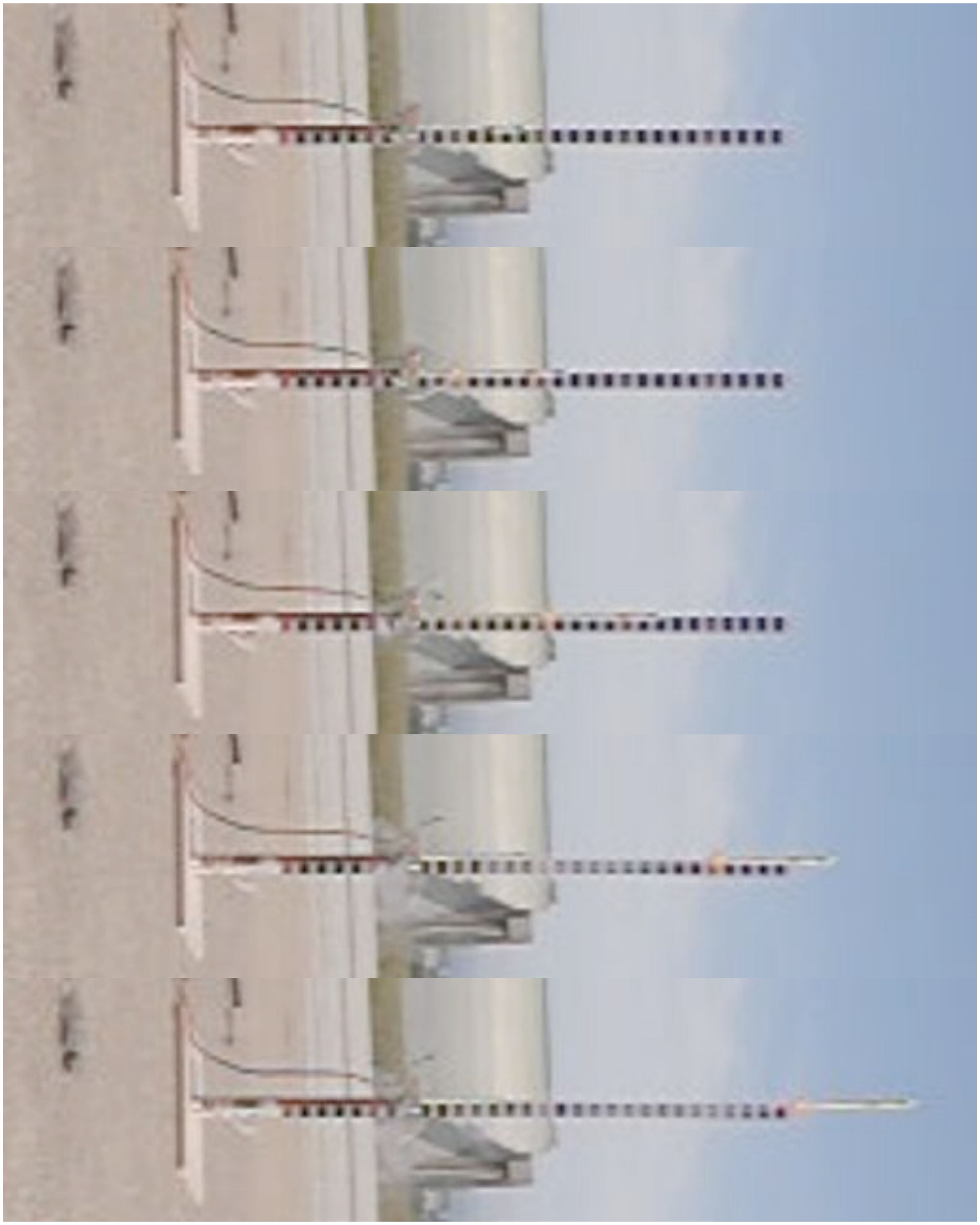
Another view of model and complete piston. Hold downs are down in this photo.



One hold down being held up, showing slot for fin. In this case, a single magnet is in the wood block. The steel hold down strap is attached to the wood block with a strapping tape "hinge". This was adequate for the initial concept test. In this case, the magnets gave a total break out force of about 20N

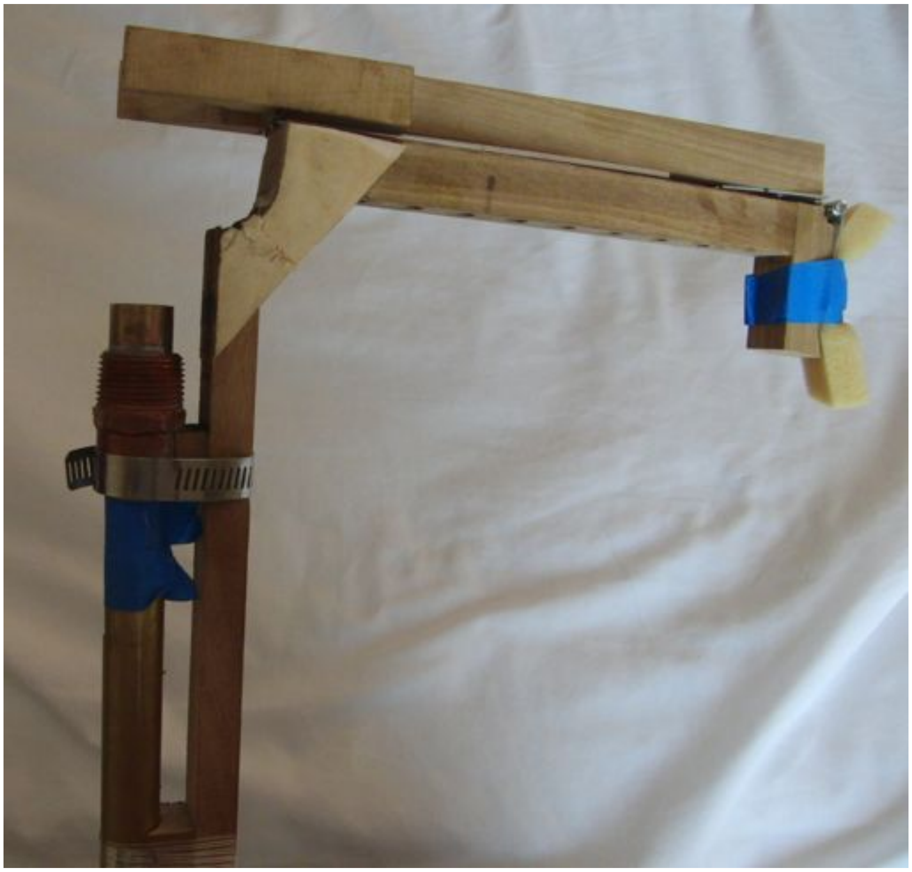
The Mark 1 piston was first used in Streamer Duration at a LUNAR competition at Snow Ranch with 1/2A3-4T motors. Surprisingly, everything worked, which encouraged further study. The speed out of the launcher was dramatically higher than any other model at the meet, and the altitude was also obviously higher, even compared to lighter models launched from normal competition pistons.

The first test model that carried an altimeter bay was constructed as described and test flown at a LUNAR sport launch at NASA Ames Moffett Field, using 1/4A3-3t motors. The model was flown off a rod and with 2 flights using different hold down forces, 10N and 35N. Video was only obtained for the launch rod and 35N flight, while the altimeter worked for all 3 flights.



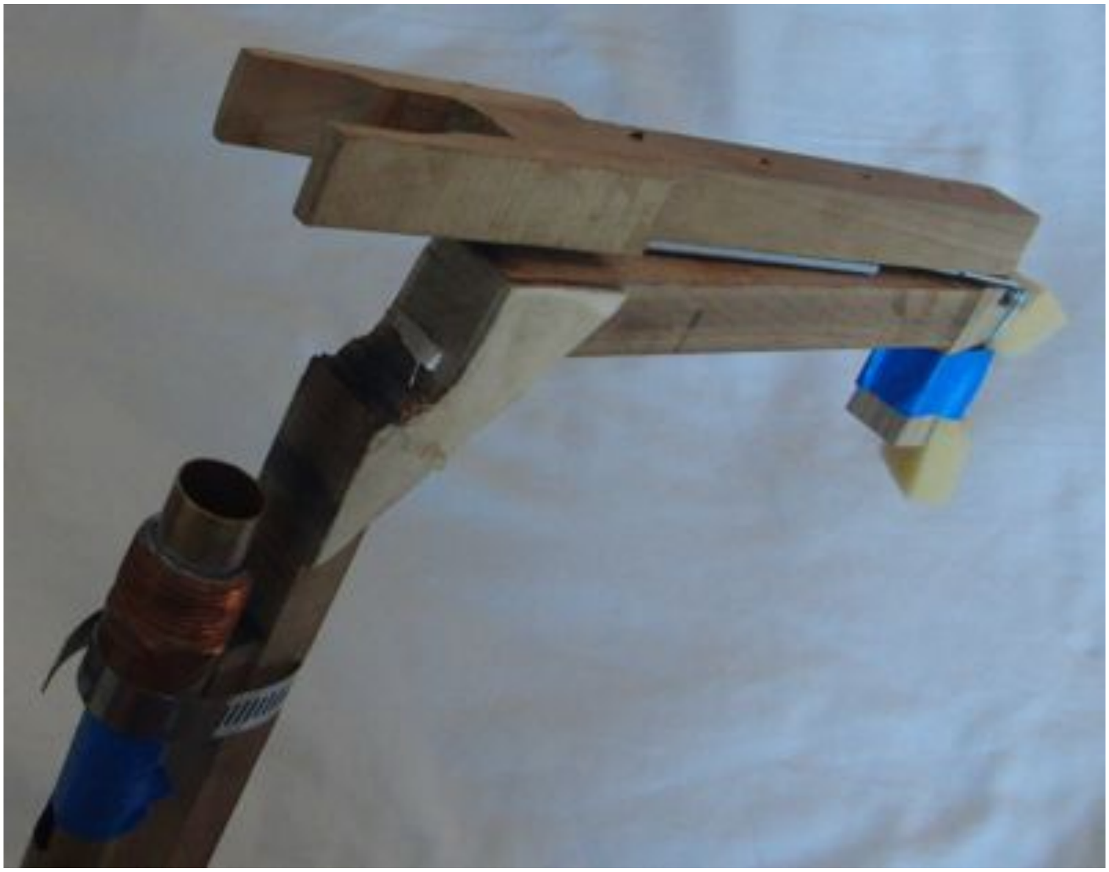
A series of framegrabs from the Mark 1 piston test with 35 Newton breakout force at NASA Ames. If the first frame is time 0, the following 4 frames are 0.02, 0.035, 0.058 and 0.068 seconds later. Careful examination of the frames will show the latch beams swinging out of the way, the piston extending fully and then rebounding, and the puff of exhaust gas out of the cylinder vent port. A sense of the timing of the images can be had by noting how far the ignition clips move during the sequence!

The encouraging results of the Mark 1 piston led to the construction and testing of the Mark 2 piston. This had the benefit of a lighter internal piston tube, longer stroke. Additionally the cylinder tube was more cylindrical and there were better seals and a better piston head.



The side view of the top of the Mark 2 piston and new hold down arm. Between the wood pieces is the steel plate, the magnets are inserted into holes underneath and the hold down force can be varied across a range.

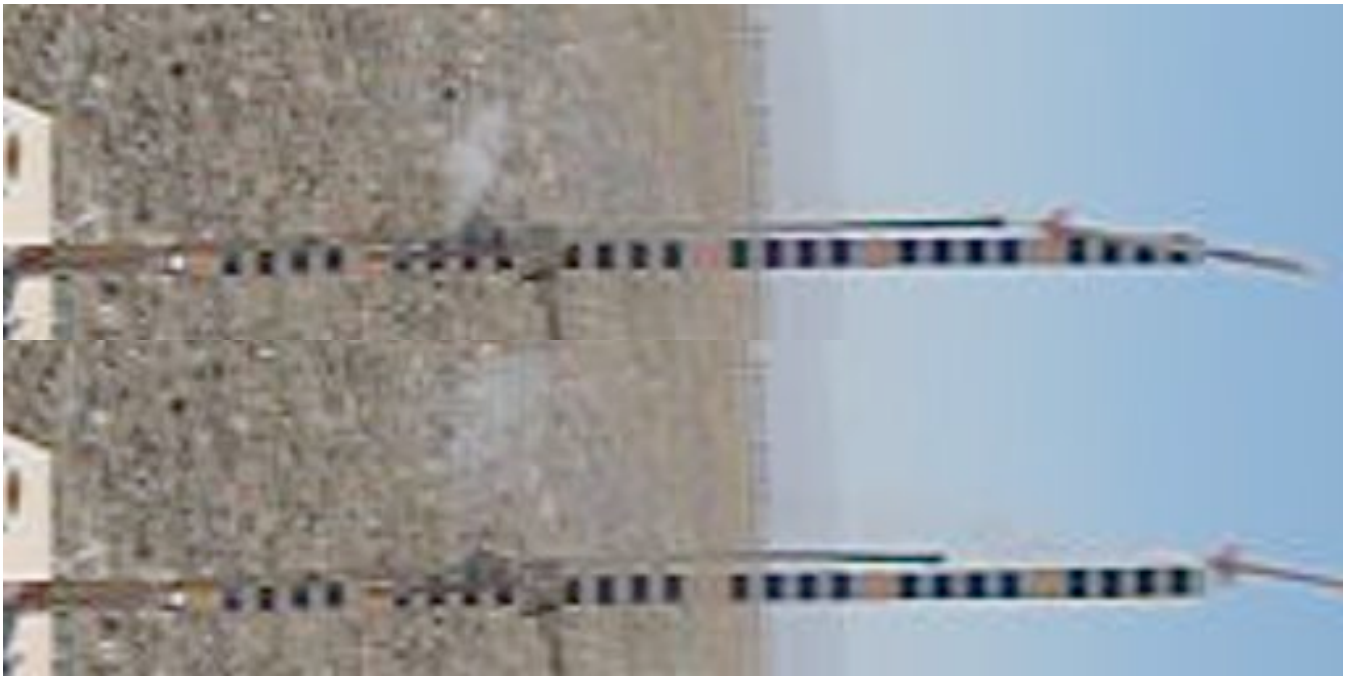
The bottom view of the Mark 2 piston hold down showing the magnet holes. The arm was attached to the piston with hose clamps. The hose clamps distorted the cylinder, causing the piston to bind and are NOT recommended!



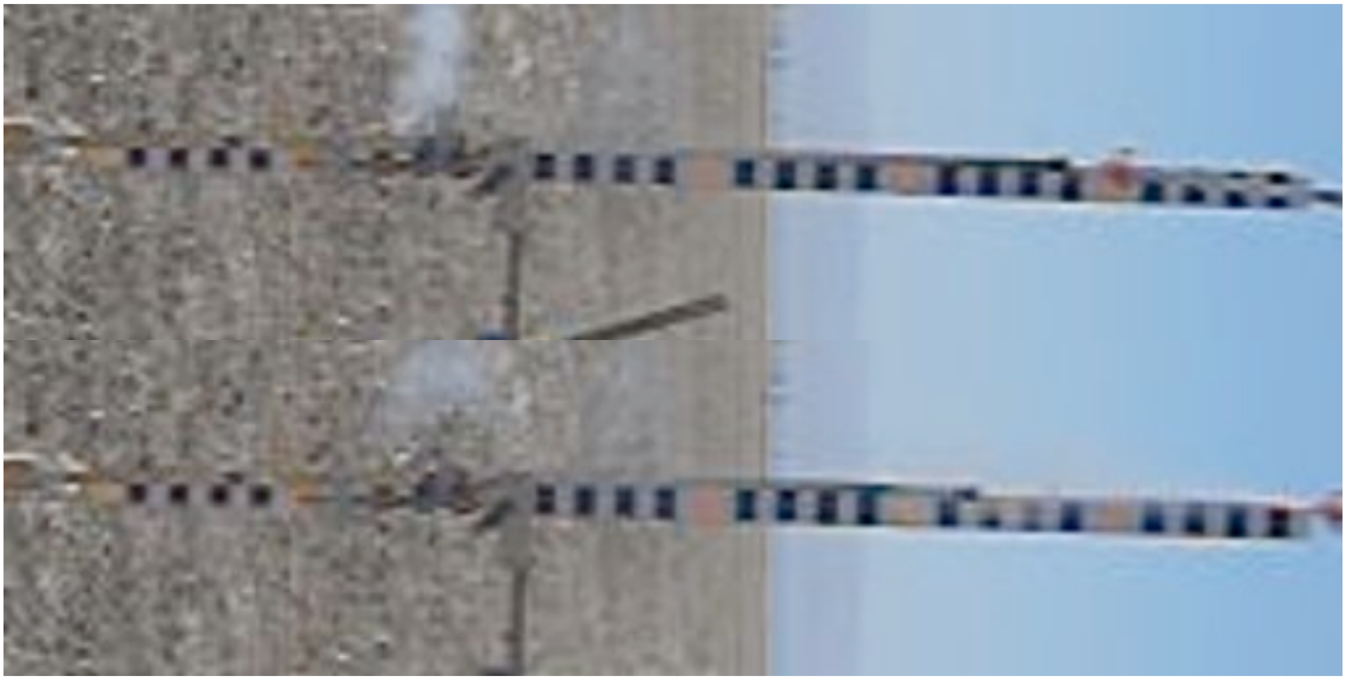
The top view showing the hold down arms that fit around the model and the steel attached to the swinging arm.

Two stills from the first flight of the Mark 2 piston, one shortly after ignition and one later. Note that the piston tube did not move as it was held down by the igniter clips and leads. Note also the extreme angle of the model. This flight was zoomed in closer than other flights.

Two stills from the third flight of the Mark 2 piston, which was moderately successful. Note in the first still the puff of smoke out the side of the cylinder tube and the fully extended piston tube. The arm is almost out of the photo. This pair demonstrates how the separation speed was measured, from the rear of the rocket at the bottom of the top orange stripe to the rocket rear clearing the speed stick. This flight had 13N of breakout force.



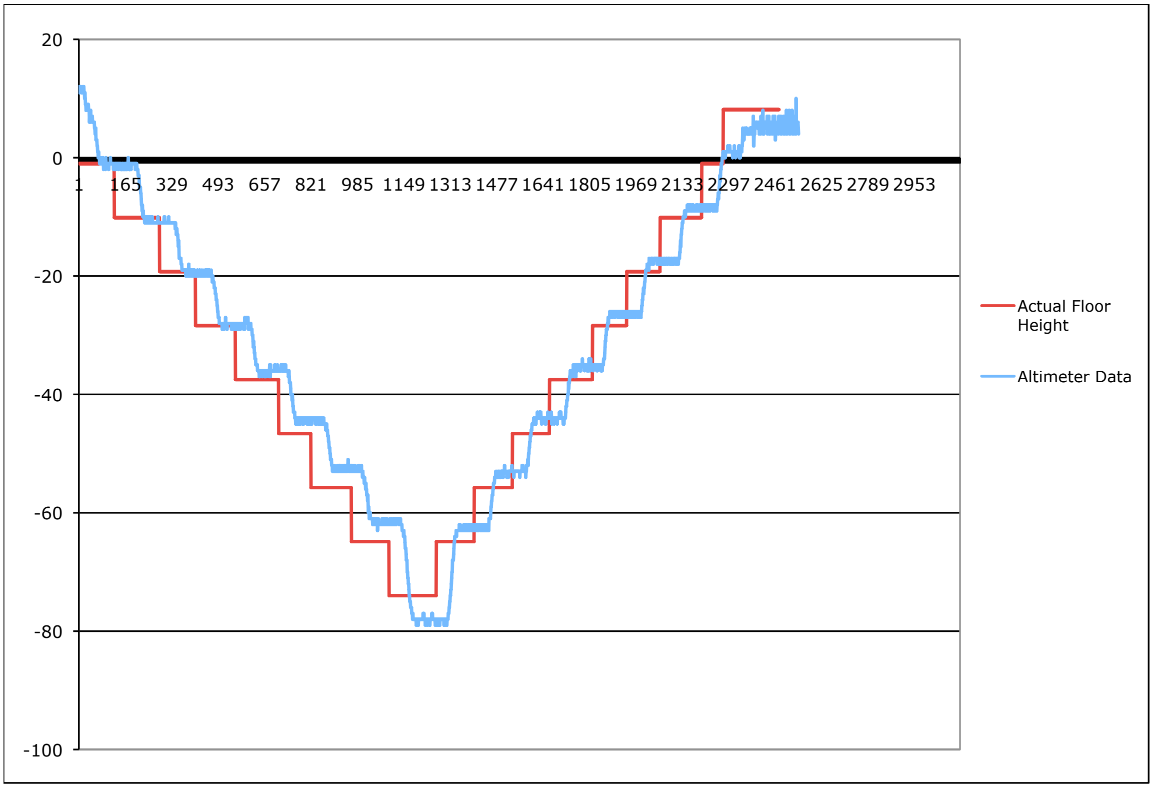
Two stills from the fourth flight of the Mark 2 piston, using 20N breakout force. Note the extended piston and the angle of the rocket. Also, note the flex of the piston tube in the second frame. In spite of the very high angle of the rocket at release (due to compressive buckling of the rocket and piston combination under the high acceleration compression load), the flight went straight up, and we did not even realize there had been the buckling problem until we saw the video later.



Two stills from the fifth flight of the Mark 2 piston, using only 6N of breakout force.

Data

We did a simple "sanity check" calibration of the altimeter, by logging data in an elevator in a 10 story building, pausing at each floor. We then measured the height of a floor in a stairway with a tape measure. The results are shown below. While not perfect, the data is reasonably accurate, within the range expected by atmospheric variations. And the errors are small compared to the results we measured in flight test.



A plot of the altimeter data taken in an elevator, stopping at every floor, along with a calculated floor level. This shows that the altimeter is within atmospheric variation.

Several plots of the altitude data follow. First a comparison of the unassisted flights (one rod, one tower) and two flights using zero volume floating head pistons, the common contemporary piston launcher. Maximum altitude unassisted is about 40 feet, maximum altitude of the zero volume floating head piston flights is about 100 feet. One piston flight ejected VERY early, a delay time of only 1 second, resulting a lower altitude. The second piston flight ejected just after apogee, so it probably a good baseline of what a typical competition piston would do.

Both of the unassisted flights nearly crashed, ejecting at about 10 ft altitude and shooting the payload compartment into the ground.

The zero volume floating head piston was 10” stroke, similar to the result obtained by Crunch Birds team in their optimization study. Note that the altitude is more than double that of the unassisted flights.

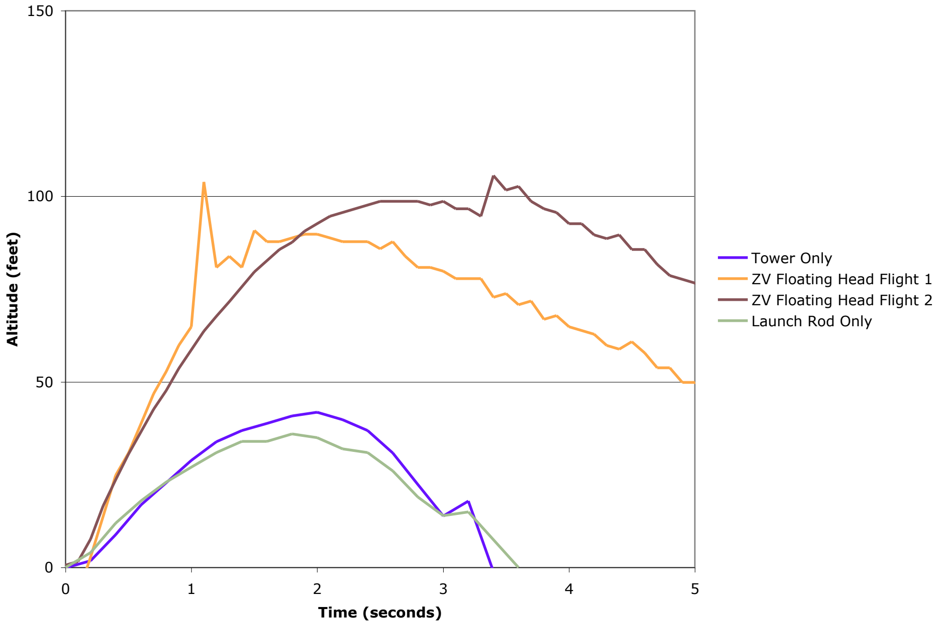


Figure 1 Baseline test flights

Next are the two flights of the Mark 1 piston, at 10N and 35N. Both flights are well above the altitude from the baseline piston. The 35n breakout flight ejected before apogee, and may have shot the payload compartment up a few feet higher. It went slightly over 150 feet, nearly 4 times the height of the unassisted launches.

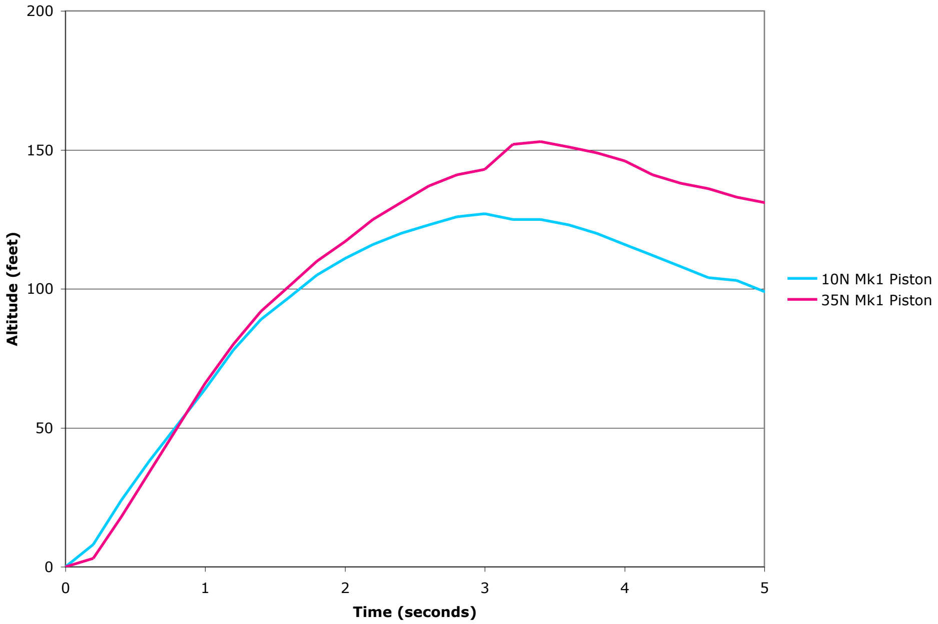


Figure 2 Mark 1 piston test flights

The 4 successful flights of the Mark 2 piston are shown next. The first two attempts with this piston failed due to the very strong alligator clips on the ignition leads getting caught in the piston head mechanism, and preventing the piston from moving at all.

These 4 flights include 2 flights of the same 13N breakout force, but one of these was after the 2 initial failures and the cylinder tube was not cleaned, which absorbed some of the acceleration, probably causing the difference in altitude.

The 6N breakout flight was very "clean" with the model coming off straight. The flight went over 150 ft, higher than the Mk 1 at 35N breakout, showing that the improvements in cylinder quality and resulting better seals and lower friction paid off. This flight ejected at roughly 2.75 seconds after first motion, implying a delay time of about 2.5 seconds, about typical for this engine.

The good 13N breakout flight went 180 ft, ejected at 2.5 seconds, which is slightly short, and was visibly well before apogee. This was in spite of being launched at rather high angle of attack due to the buckling mode of the pistion/model combination.

Finally, the 20N flight , while it did not go any higher than the 13n, it had a very short delay time of under 2 seconds. It was visibly in a VERY rapid climb and well before apogee at ejection. It appears from the slope of the curve to have been at roughly 50 fps, which is higher than the burnout speed of the unassisted model. If that is true, it would have coasted roughly another 50 ft to apogee, resulting in a 220 ft altitude, well over double the performance of the zero volume floating head piston with the same model.

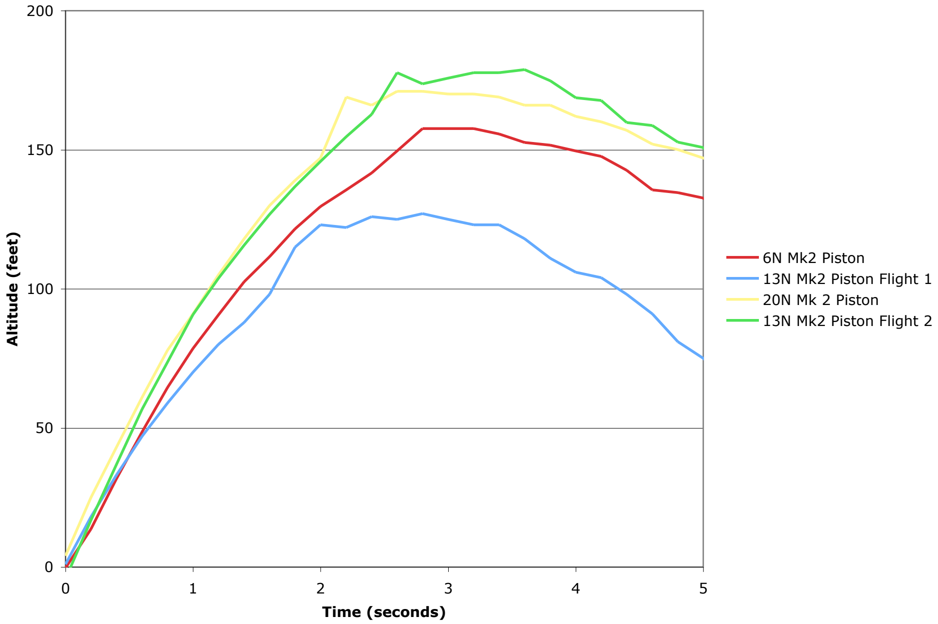


Figure 3 Mark 2 piston flight tests

Finally a plot highlighting a comparison between the different launchers is shown. Note that the 6N Mark 2 model goes a lot higher than the 10N (and 35N) Mark 1 piston, indicating the better seals and lower friction of the Mark 2 piston.

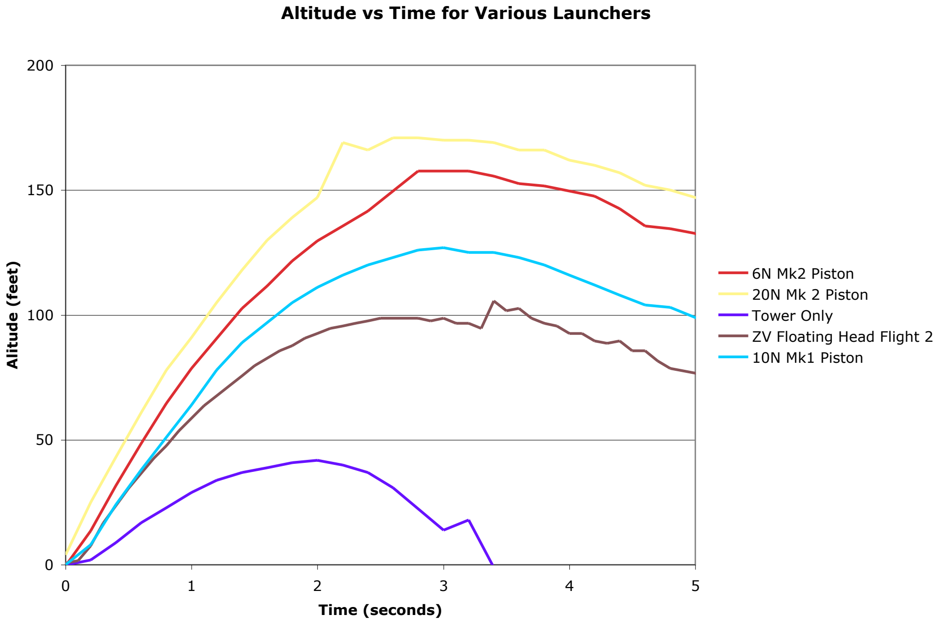


Figure 4 Comparison of different launchers.

The separation speed was measured from the high speed video as described earlier. 6 of these flights are plotted in the next figure. The tower flight, using 0N as the breakout force, had a very low separation speed. The dirty 13N Mark 2 piston flight had a low separation speed. The 3 different good Mark 2 piston flights had a linear correlation between the breakout force and the separation speed, though note there are only 3 points on this line. The line is extended to see how higher and lower breakout forces might perform, though this needs additional testing. The 35N Mark 1 piston flight is shown, the deviation here is explained by the poorer quality seals.

Note that these velocities are well above the 20 to 35 fps separation speeds measured in previous reports (Crunch Birds, Landis), and there is reason to expect that the combination of higher breakout force and good quality seals can give still higher performance

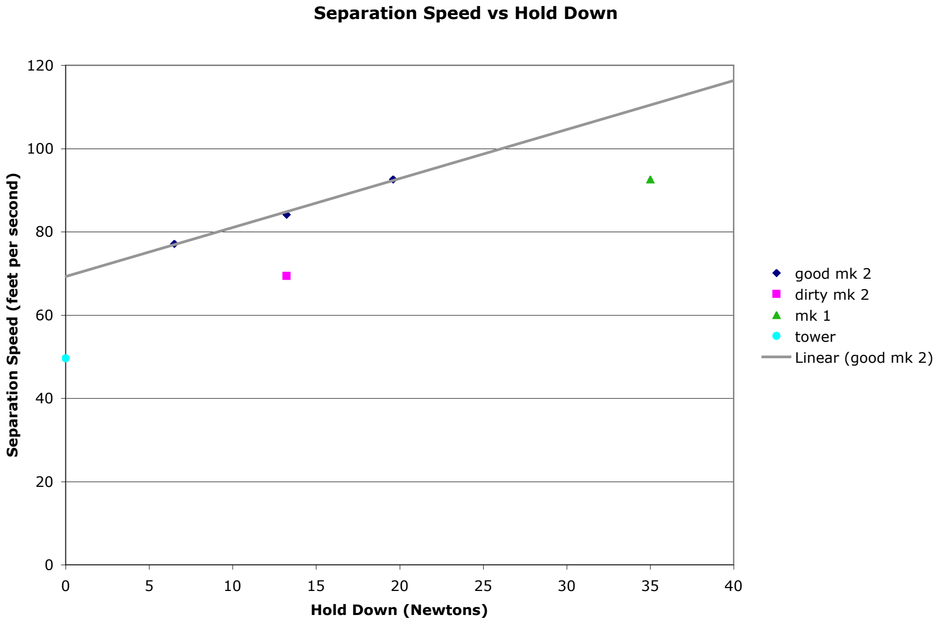


Figure 5 Comparison of hold down forces and separation speeds.

Conclusions

Even without enough repeated tests to have statistical significance, the new piston is obviously superior to the zero volume floating head style piston or a launch tower or rod alone given the clear differences in launch speed and altitude. Extrapolating the high performance Mk2 piston flights to apogee, as if they had a longer delay engine, would seem to indicate that its possible to launch the test model to altitudes of over 200 ft, and possibly over 220 ft. this is over double the performance of the state of the art competition piston launchers, and, in this case, over 5 times the altitude of an unassisted launch.

The piston has certainly met the goals of eliminating the very subjective fit required to properly prep a zero volume piston.

Prep is just a matter of putting in a normal igniter, with the usual plug, slip the model into the piston, flip the latch closed, hook up the clips and launch. The one complication that we have noted is that the cylinder walls get very dirty, and must be cleaned after every flight.

The one test that was run twice was the 13N Mark 2 piston test, which produced strikingly different results in both separation speed and altitude. The presumed reason for this is that the cylinder tube was dirty from 2 flight failures and was unfortunately not cleaned. This additional friction stopped the piston tube from full extension and wasted some of the force produced by the motor and piston.

Several critical lessons were learned while developing the piston. First, do not let the model tilt on the piston. Our next revision will have short guide rails added to the piston head. Second, the igniter is still critical, care should be taken to ensure that the clips can slip free of the igniter after ignition so the igniter and clips do not prevent the piston tube from extending.

As shown be the still frames from the video testing, the piston tube is significantly bending, so the stiffness of the piston tube is important. Addition of some carbon fiber should help this.

Finally, care must be used to avoid leaks. The O rings used in the Mk 2 piston seem to work well, but only if you remember to install them!

Further Work

We hope to develop a good computer simulation of the new piston, which along with further tests will allow us to determine the correct parameters like friction and gas parameters. In turn, this would allow for optimizing pistons for various applications and events. A simulation would also allow determination of the effect of piston tube diameter on performance and the effect on gas flow losses. A simulation and appropriate testing would allow the pressures inside the piston to be calculated, and some effort to understand the gas flow dynamics could be made. The diameter ratio between the piston tube and the cylinder tube could be explored, which depends on the pressure between the top and the bottom. We are convinced that exhaust jet pumping effects and viscous gas flow effects give very unequal pressures within the piston, and this effect should be verified, and hopefully measured. Much of this impression comes from looking at where exhaust "grunge" is concentrated in the piston after a launch.

Additionally, we hope to find more reasonable cylinder tubes to replace the copper tubes, which work well and are somewhat affordable. Plumbing pipe is readily available, but is not always round. The use of solder on plumbing fittings is very convenient!

Currently a spring is used for the end of stroke energy absorber, but a replacement that does not rebound would be beneficial. Right now, the rebounding piston runs into a very dirty cylinder, which compresses the grunge into a hard ring that is very difficult to remove. The piston seal material and design should be analyzed to find the right balance between sealing and friction.

Testing of model construction should be undertaken to determine how to appropriately build models that can take the necessary hold down forces, and what the limits of model construction are. Additionally, design of new hold down mechanisms that don't compromise the model would be desirable, since currently the models must be custom built for the piston.

Author Contributions

Bob Parks worked on initial piston simulations, did the background research, designed and built the piston launchers and hold-down mechanisms and initial test models. Ryan Coleman built additional test models and tested the performance of the zero volume floating head piston. Both authors tested the pistons, analyzed the results, and wrote the report.

No previous R&D reports on this subject have been entered by either author. Ryan Coleman has entered R&D reports on optimizing parachutes and examining reasons why heavier motors fly higher, none of which has any relation to this report.

References

US Patent 3089388, May 14,1963, Rocket Launchers, describing the Atlantic Research ARCAS closed breech launcher. This patent also shows oscillatory behaviour of a piston launcher, and the use of additional initial volume to eliminate oscillations.

The Floating Head Piston Launcher, NARAM 28 R&D report by Odd Couple team, Chuck Weiss and Jeff Vincent. This report covers flight test measurements of floating head pistons on 13mm models with 1/2A3-4t motors. The conventional piston gave separation speeds of 23 fps, and the floating head gave 30 fps.

Empirical Evaluation of Optimum Piston Tube Length for a Floating Head Piston Launcher, NARAM 30 R&D report by Crunch Birds Team, Chuck Weiss and Jeff Vincent. This report shows no advantage to longer piston tube lengths than about 9 inches for 13mm models with 1/2A3-4t motors.

Thoelen, Bauer, & Porzio. "Optimization of the Zero Volume Piston Launcher", NAR Technical Review, Vol 2, No 1 , 1974. We do not have a copy of this report but Crunch Birds says that it showed no advantage to long zero volume piston launcher for lightweight models, again, supporting the existence of oscillatory behavior.

Investigation of the Physics of the Zero Volume Piston Launcher, Geoffry Landis, July 1975. Discusses computer simulation of piston launchers, with some experimental verification. Proved the existence of oscillatory behaviour in piston launchers. Extensive bibliography which is not reproduced here.

Pressurization Effect Launchers. Trip Barber, Journal of the MIT Rocket Society, January 1974. This report details the many forces and effects on pressurization effect launchers including standard pistons, closed-breech launchers and zero volume pistons, including detailed equations for many parameters. It suggests use of experimental measurements and computer simulations to determine the correct parameters for any piston.

Vented Piston Launcher. Chad Ring. NARAM 50 Research & Development report. 2008. In this report, a zero volume piston launcher was modified so that it was initially unsealed and could vent until the piston had moved significantly, where it became sealed until the full extension was reached where it would break free of the friction fit as normal zero volume pistons do. A significant altitude increase was reported.

Equipment & Facilities

The following equipment and facilities were used to build and test the new pistons:

- 1 machine shop provided by an author used for making piston parts (lathe, mill, drill, saws)
- Launch equipment and fields provided by LUNAR (Livermore Unit of the National Association of Rocketry) and TCC (Tripoli Central California).
- Casio EX-FH25 high speed camera ($400), owned by one author
- RAM3 recording altimeter for R/C airplanes ($70), owned by an author
- Computers to read altimeter data, write report, etc.
- Spring scale to measure hold down force
- Apogee Medalist tower used for comparison test flights. ($150/donation from Kevin Johnson)

The following supplies were consumed to construct test pistons and test models, the total consumed cost was around $150.

- parts for test pistons ($100)
- rocket motors for test flights (dozen 1/4A3-3Ts, $25)
- rocket parts ($20)
- zero volume floating head pistons ($5)