Direct Non-electronic Staging from Reloadable Composite Motors to Black Powder Motors

Jay Calvert
NAR # 71767
C Division

Presented at NARAM-46
Great Meadow, The Plains, Virginia
August 2004

Objective

The objective of this study was to determine whether direct pyrotechnic staging, without the use of onboard electronic ignition systems, could be used to reliably ignite a black powder (BP) sustainer motor from a reloadable ammonium perchlorate composite propellant (APCP) booster motor.

Direct BP to BP staging is a commonly used method in model rocketry to achieve higher altitudes than would otherwise be possible with single stage vehicles. In this case the booster motor, which lacks a delay train and ejection charge, throws flame and chunks of burning propellant into the nozzle of the sustainer motor. The two motors are either placed in direct contact and held together with a wrap of cellophane tape, or separated by a gap of up to a few inches. Reliability of upper stage ignition is high (>90%), except in the case of relatively long gaps between the motors. There is little or no perceptible delay between booster burnout and sustainer ignition.

In contrast, it is a commonly held believe in the hobby that direct staging between composite motors, or between a composite motor and a black powder motor, is not achievable with any reasonable degree of reliability. A battery powered electronic staging timer and low-current electric match are generally used to ignite the sustainer. Although quite reliable in experienced hands, an onboard ignition system adds considerable weight and expense to projects in the model rocket size range (as opposed to high power rocketry, where the added weight and expense are a smaller percentage of the whole).

APCP motors require much higher temperatures to ignite than BP motors, and can suffer from "chuffing" problems if ignited from the nozzle end rather than the forward end. For these reasons, attempts to stage from a BP booster motor (or from the ejection charge of another APCP motor) typically fail. Electric igniters or high temperature pyrotechnic delay trains (such as sheathed Thermalite) are required to consistently ignite APCP sustainer motors. Unfortunately Thermalite is considered a regulated explosive material and is also no longer commercially available.

On the other hand, it should be possible (using unregulated commercial pyrogen) to augment the flame of the delay element in a reloadable APCP booster motor in such a way that it mimics the flame and propellant chunks of a BP booster motor, thereby igniting a BP sustainer motor. Inspired largely by the rules of the 2003 and 2004 TARC contests, I set out to determine if this staging method is possible.

Approach

This project was undertaken in three phases, which overlapped to some degree. Initial staging trials were performed in simple BT60-based sport rockets. Before risking a two-stage flight, tests were done in "booster tie down mode". In these trials the a few wraps of masking tape were placed on the launch rod above the booster's launch lug, but below the sustainer's launch lug. Upon ignition the rocket remained on the pad during the booster burn and delay. If and when successful staging occurred, the sustainer would launch on its own and experience a normal single stage flight. Some of these flights were recorded in digital video, so that precise measurements of the staging delay could be made.

Once successful staging methods were developed in booster tie down mode, fully functional two staged flights were attempted in BT60 sport rockets. Several precautions were taken to protect objects on the ground and the rocket itself: (1) flights were angled away from the flight line and announced as "heads up", (2) the total launch weight of the test vehicle was kept below 1/2 pound (8 ounces), (3) the rear half of the sustainer, which includes the motor mount, fins, and launch lug, were reinforced internally with couplers and/or externally with strakes while the front half of the rocket was left as a "crumple zone". In the event of a lawn dart or power prang, the forward section of BT60 would collapse and absorb most of the energy of impact, leaving the rear section and nose cone intact. Replacement of the crumple zone with a fresh length of BT60 is a simple operation that can be done in the field.

Finally, the staging techniques were applied to a larger "TARC style" rocket capable of carrying an altimeter and two eggs to an altitude of 1500 feet. For safety reasons, and in order to avoid an expensive crash, this rocket was rigged for altimeter-based dual deployment.

Equipment

Test vehicles. Four rockets were used. Initial booster tie down tests used a rocket I had previously built, called the Maxi Geek. It is essentially a BT60 sized scale model of a number 2 pencil, with a custom turned conical balsa nose cone, clear plastic fins, and a 24 mm motor mount. A simple BT60 booster stage for 24 mm motors was built to fit this rocket. When I started with the functional two staged flights, I wanted to use something a little more durable and…expendable. "Direct Staging Test Vehicle-1" (DSVT-1) was assembled. Think of it as an Estes Mean Machine shortened to about two and a half feet, and with some modifications. The lower half was reinforced with couplers and strakes, while the forward half served as a disposable crumple zone. The plastic parabolic nose cone is both durable and relatively safe (no point). DSTV-1 uses the same booster as Maxi Geek. A lighter version of DSTV-1 (DSTV-1a) was built to increase the coast time between stages (Figure 1). DSTV-1a lacks the couplers and strakes found in its predecessor, and is essentially one big crumple zone. A much larger test vehicle, "DSTV-2" was built for the final series of flights (Figure 2). It is built around an Estes Executioner (BT80 airframe and 24 mm motor mount), with modifications. An avionics bay houses a G-Wiz Deluxe LC altimeter/accelerometer that's programmed to deploy a drogue chute at apogee and a main chute at 800 feet. An optional payload section can carry two eggs. A booster was assembled using BT80 airframe, fiberglass fins, and a 29 mm motor mount intended for Aerotech 29/40-120 and 29/120 hardware (G64W and G79W reloads, respectively). Because the booster is too heavy for tumble recovery, it was outfitted with a small parachute that fits into a side pod on the sustainer and is pulled free at booster separation.

Figure 1. DSTV-1a and DSTV-2.

Motor selection - booster stage. Reloadable composite motors were used for all flights, since I would have had to remove the ejection charge from single use composite motors (a safety code violation). Reload kits come with a separate BP charge that is more than adequate for most rockets. An appropriate amount of powder (or none at all) can be added to the ejection well of the motor, depending on the application. For the booster tie down tests, the thrust curve and delay time are not critical. D9-7W and E11-3J reloads for the Aerotech 24/40 case were used. For the functional two staged flights, it's important to use a booster motor with high average thrust and total impulse, and with as short a delay as possible. The F24-4W and E28-4T reloads (24/40 case) were used for DSTV-1 flights, while G64-4W (29/40-120 case) and G79-6W (29/120 case) reloads were used for DSTV-2 flights.

Motor selection - sustainer stage. All test vehicles contained a 24 mm motor mount to accommodate Estes C11, D12, or E9 black powder motors. These have a relatively large nozzle and can readily accept a staging igniter. In most cases, short burn / short delay motors were favored over long burn / long delay motors. In the event of late (horizontal) staging, the rocket would not cover as great a down range distance before ejecting a chute. In the event of very late (downward) staging, there is a better chance of ejection saving the rocket from a hard impact. The final flight of DSTV-2 (flight #5), which used an E9-8 in the upper state, deviated from this rule of thumb since the altimeter guaranteed that the drogue chute would be deployed at apogee regardless of the staging delay.

Staging igniters. Several techniques were tried to give rapid and reliable ignition of the sustainer motors using the booster delay element as an initiator. The simplest of these was to forgo any additional pyrogen and place the nozzle of the sustainer directly above the ejection port of the booster motor, relying on the flame of the burning delay element for ignition. A variant of this approach was to use a portion of the BP charge supplied with the booster motor in the booster ejection well and a portion in the nozzle of the sustainer motor. In both cases a single layer of cellophane tape, which melts easily, was used to hold the powder in place. A more reliable method was to use a length of material coated in pyrogen as a staging ignitor. In some tests, the heads of Copperhead ignitors were cut off and inserted into both the booster ejection well and the sustainer nozzle, such that they were in direct contact. Finally, I manufactured some custom staging ignitors from 1 inch lengths of insulated electrical wire (from used Daveyfire ematches) dipped in Igniterman pyrogen mix. These extended up from the ejection well of the booster motor and were the correct length to insert completely into the sustainer nozzle and contact the BP propellant. These are essentially a scaled up version of the staging igniters previously sold by Apogee Components for use with their 10.5 mm micro black powder motors.

Data Collected

Three booster tie down flights were attempted, and six functional 2-staged flights were made. Most flights were recorded using either digital video or digital still photography. The actual staging delay was counted off in seconds, and verified using the video in some cases. After each test, and especially after staging failures, the interface between the booster and sustainer motors was carefully examined.

Results

The results of the three booster tie down tests are summarized in Table 1. The results of the six functional two stage flights are presented in Table 2. Figures 2 and 3 are photographs from BTD-2 and flight 5, respectively. Analysis and discussion of the data are in the Conclusions section of this report.

Table 1. Booster tie-down test flights

Flight Number	**Date and Location**	**Test Vehicle**	**Booster Motor**	**Staging Igniter**	**Sustainer Motor**	**Results**
BTD-1	10/11/03 SMASH launch. Plainwell, MI	BT60 Pencil Geek plus booster	Aerotech D9-7W reload	none	Estes C11-3	Staging failed. Flame from delay element is not hot enough to ignite sustainer motor.
BTD-2	10/11/03 SMASH launch. Plainwell, MI	BT60 Pencil Geek plus booster	Aerotech D9-7W reload	Two Copperhead pyrogen heads (one extending up from ejection well, one extending down from booster nozzle)	Estes C11-3	Successful staging and recovery of sustainer. Elapsed time between booster burn out and staging was 6.9 seconds (i.e. no apparent staging delay due to pyrogen).
BTD-3	4/10/04 JMRC launch. Jackson, MI	DSTV-1a (simple BT60 vehicle)	Aerotech E11-3J reload	Three Copperhead pyrogen heads (two extending up from ejection well, one extending down from booster nozzle)	Estes C11-3	Successful staging and recovery of sustainer. Elapsed time between booster burn out and staging was ~5 seconds (i.e. ~2 seconds apparent staging delay due to pyrogen).

Table 2. Fully two staged test flights

Flight Number	Date and Location	Test Vehicle	Booster Motor	Staging Igniter	Sustainer Motor	Results
1	10/11/03 SMASH launch. Plainwell, MI	DSTV-1 (simple BT60 vehicle)	Aerotech F24-4W reload	Two Copperhead pyrogen heads (one extending up from ejection well, one extending down from booster nozzle)	Estes C11-7	Successful staging, but delay between stages was too long (~10 seconds). Sustainer fired nearly straight down, resulting in prang. Crumple zone worked.
2	10/26/03 SMASH launch. Plainwell, MI	DSTV-1 (simple BT60 vehicle)	Aerotech E28-4T reload	Small amount of BP in ejection well of booster, covered with a layer of cellophane tape. BP in sustainer nozzle, held in with a single layer of cellophane tape.	Estes C11-3	Good boost, but no staging. Ballistic landing. Crumple zone worked. The BP in the ejection well burned through the cellophane tape holding it in, but failed to burn through the tape holding the BP into the nozzle of the upper motor.
3	10/26/03 SMASH launch. Plainwell, MI	DSTV-2 (BT80-based with altimeter, rigged for dual deploy)	Aerotech G64-4W reload	Small amount of BP in ejection well of booster, covered with a layer of cellophane tape. BP in sustainer nozzle, held in with a single layer of cellophane tape.	Estes D12-3	Considerable weather cocking on boost. Staging failed, but altimeter saved the vehicle. No damage. The BP in the ejection well burned through the cellophane tape holding it in, but failed to burn through the tape holding the BP into the nozzle of the upper motor.
4	4/10/04 JMRC launch. Jackson, MI	DSTV-1a (simple BT60 vehicle)	Aerotech E28-4T reload	Three Copperhead pyrogen heads (two extending up from ejection well, one extending down from booster nozzle)	Estes C11-5	Successful staging, but delay between stages was too long (~7 seconds). Sustainer fired at a downward angle. Sustainer ejection occurred well before impact. No damage.
5	7/18/04 Michigan Team-1 launch. Manchester, MI	DSTV-2 (BT80-based with altimeter, rigged for dual deploy)	Aerotech G79-6W reload	One-inch length of 2-strand insulated wire (from Daveyfire) dipped in Igniterman pyrogen.	Estes E9-8	Good straight boost and successful staging, but delay was too long (~5 seconds). Sustainer fired at a slight upward angle and traveled horizontally. Dual deployment worked fine (no damage), and altimeter registered 837'.
6	7/18/04 Michigan Team-1 launch. Manchester, MI	DSTV-1a (simple BT60 vehicle)	Aerotech E28-4T reload	One-inch length of 2-strand insulated wire (from Daveyfire) dipped in Igniterman pyrogen.	Estes C11-5	Successful staging, but delay between stages was too long (~6 seconds). Sustainer fired at a slight upward angle as rocket was tailsliding, and went unstable. Both stages recovered with no damage.

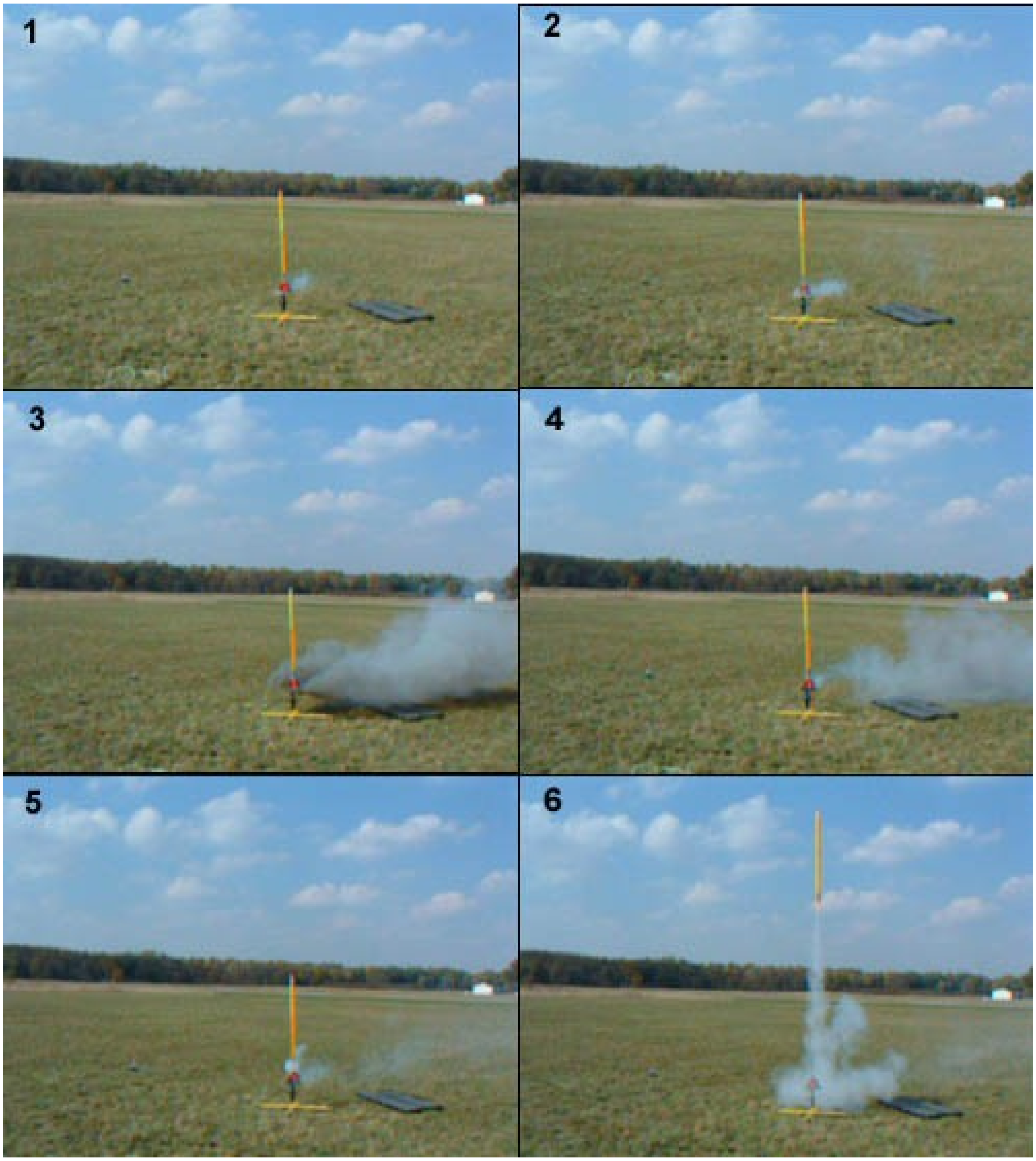

Figure 2. Video frame capture from booster tie-down test BTD-2.

2-1) At -0.5 seconds, the booster igniter burns.
2-2) At 0.0 seconds, the D9-7W booster motor is up to pressure.
2-3) At 1.5 seconds, the booster is in mid burn.
2-4) At 2.2 seconds, the booster motor has just burned out.
2-5) At 9.1 seconds, the C11-3 sustainer has just fired.
2-6) At 9.2 seconds, the sustainer is leaving the launch rod.

Figure 3. DSTV-2 after E9-8 ignition during flight # 5.

Conclusions

The objective of this study was to determine whether direct pyrotechnic (non-electronic) staging could be used to ignite a black powder motor from a reloadable APCP motor. The study was a qualified success. Although six out of six (100%) attempts using a pyrogen coated staging igniter were successful, there appears to be a variable hesitation between the end of the booster's delay element and ignition of the sustainer motor. This hesitation can range from as little as 0 seconds (flights BTD-2 and 5) to as much as 6 seconds (flight 1). It is quite possible that some of this variability is due to Aerotech "bonus delays" (i.e. batches of delay elements that take longer to burn than the advertised and certified value).

None of the "successful" staged flights resulted in a vertical sustainer flight, as intended. In addition to the staging igniter hesitation described above there are two reasons for this. Firstly, there are no commercially available and certified reloads kits with very short (1-2 second) delays. Aerotech makes a number of appropriate reloads with 4 second delays in the 18 mm (D13-4W, D24-4T), 24 mm (E18-4W, E28-4T, F24-4W), and 29 mm (F40-4W, G64-4W) sizes. Careful drilling of the delay element could certainly produce the desired 1-2 second delay, but this would be a violation of the NAR safety code and is therefore not allowed at NAR sanctioned launches. One promising motor that was not tested as part of this study is the Cesaroni Pro38 G69. This motor is supplied with a 12 second delay, but the manufacturer recommends using the delay adjustment tool (DAT) to remove (by drilling) up to 9 seconds of delay. The resulting G69-3 is certified and safety code compliant, and would make a good booster for direct APCP to BP staging as described here. The second reason for non-vertical sustainer flights has to do with selection of an appropriate rocket. In retrospect, my choice of test vehicles was not optimal. Both the BT60-based simple rockets and the BT80-based altimeter equipped rocket are relatively fat (high drag) and heavy for the booster motors used. A very light and streamlined rocket, at or near minimum diameter for the motors used, should be much less sensitive to a longer than expected staging delay. In other words, by maximizing the upwards coast time following booster burnout one creates a wider and more forgiving window during which sustainer ignition can occur.

As an extreme example of the above logic, direct staging might be very useful in setting a G altitude record. A G64-4W motor in a 29 mm booster could be staged to an E9-8 motor in a 24 mm sustainer (total impulse = 148.5 Newton-seconds), or to even to a D12-0 / D12-7 combination (total impulse = 154 Newton-seconds). The rocket would not exceed mach, no electronic would be needed, and the staging delay should enhance altitude. Plenty of tracking powder should be used in the upper stage!

It should be noted here that two staging methods did *not* work. Unaugmented staging failed in a single booster tie down trial (BTD-1). Presumably the flame of the delay element is not intense enough to ignite a BP motor without help. Likewise, the BP / cellophane / cellophane / BP sandwich did not work on either of two attemps (flights 2 and 3). The burning of the BP in the booster ejection well melted the tape that was holding it in, but failed to melt the tape covering the BP-filled sustainer nozzle. Increasing the amount of BP in the booster ejection well may overcome this problem, but at the risk of blowing the stages apart without lighting the sustainer. I can not recommend either of these techniques.

Budget

Materials that were purchased specifically for this project:

DSTV-1 and DSTV1a parts	$12
DSTV-2 booster parts	$5
Booster reload kits	$50
Sustainer BP motors	$25
TOTAL	**$92**

Materials that were already available:

Maxi Geek	$15
DSTV-2 (stretched Executioner)	$50
G-Wiz Deluxe LC	$125
24/40, 29/40-120, and 29/120 hardware	$120
Igniterman kit	$25
Fujifilm digital camera 3800	$400
Low and mid power launch pads	$60
Pratt 12V relay launch control system	$100
TOTAL	**$895**

Time investment:

Background research, planning, ordering	5 hours
Rocket construction and prepping	10 hours
Flights	3 hours
Image and video processing	2 hours
R&D report, Powerpoint presentation	10 hours
TOTAL	**30 hours**

References

Good, Ken. The Quest for High Altitude.
http://www.rimworld.com/tripoli_pgh/rack%20rocket/rackrocket.html

Stine, G. Harry. Multistaged Model Rockets. Chapter 11 in Handbook of Model Rocketry, sixth edition (1994). John Wiley & Sons, Inc., New York.

Van Milligan, Tim. How Multi-Stage Model Rockets Work - Part 1. Apogee Peak of Flight Newletter. Issue 98.
http://www.apogeerockets.com/education/downloads/newsletter98.pdf

Van Milligan, Tim. Electronic Staging of Composite Propellant Rocket Motors. Apogee Peak of Flight Newletter. Issue 91.
http://www.apogeerockets.com/education/downloads/newsletter91.pdf

Van Milligan, Tim. Composite Propellant Booster Motors? Apogee Peak of Flight Newletter. Issue 49.
http://www.apogeerockets.com/education/downloads/newsletter49.pdf

Van Milligan, Tim. Staging Techniques for Apogee "Micro" Rocket Motors. Apogee Components Technical Publication #6.
http://www.apogeerockets.com/technical_publication_06.asp