ANATOMY OF A SUCCESSFUL FAILURE

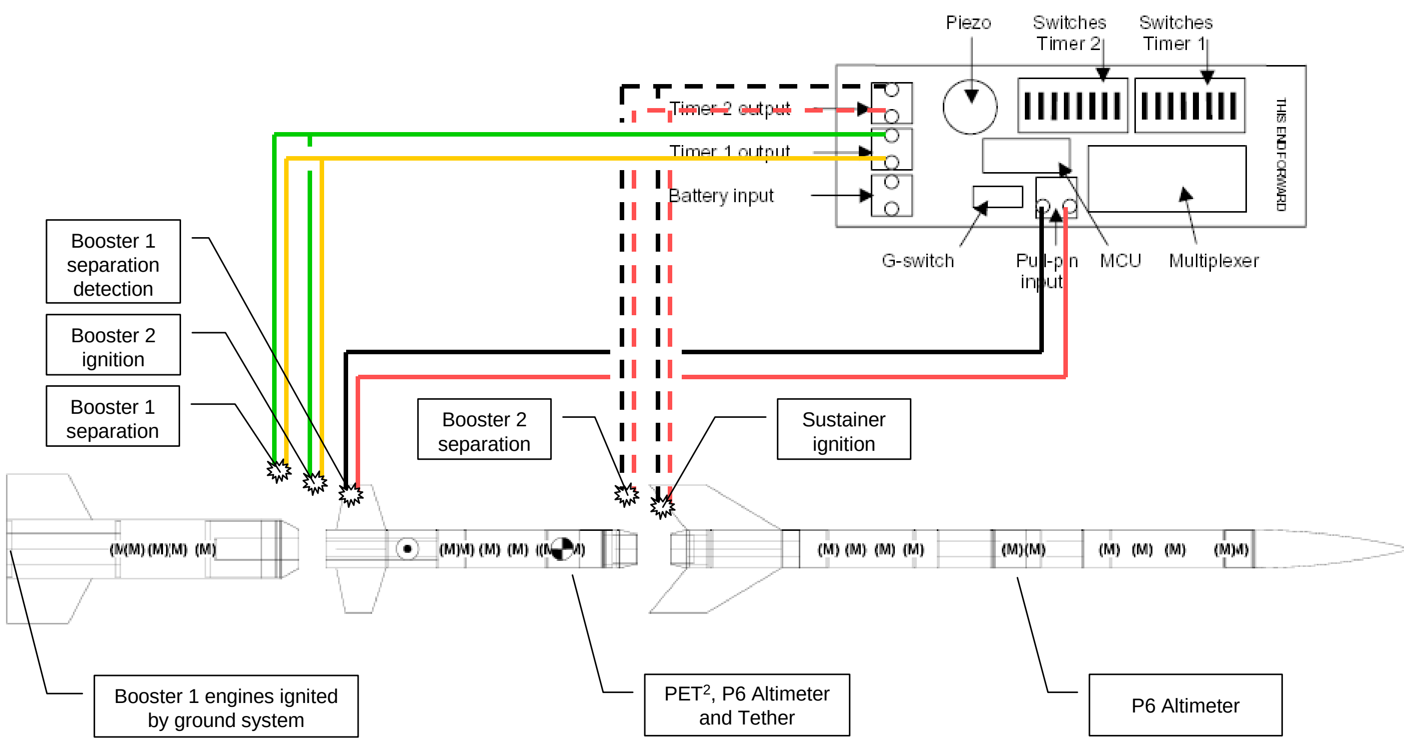
by Terry Markovich

High power rocketry is real rocket science and the more complex a project becomes the more real it gets. In designing, building, preparing and launching multi-stage rockets I have learned many lessons. Some have been from information available from others, but most have been learned the hard way – first hand experience. Many of these lessons can be applied to complex projects in general, so I would like to pass some of them along.

During a launch at the Spaceport Rocketry Association I attempted to launch my three-stage Black Brant XI. As sometimes happens not everything went as planned. Other than a damaged booster and bruised ego, there was no other collateral damage. The second booster failed to ignite and its recovery system failed to fully deploy, which obviously wasn't planned. The sustainer motor ignited, which in this case wasn't supposed to happen by design. I'll have more on these problems, and the lessons learned, later in the article.

I would call this flight a successful failure. Even though the flight suffered a failure, damage was limited to the rocket and the risk to other people and property was avoided. Successful failures do not occur by accident and that's the main point I cannot over-emphasize and the reason why I want to pass on what went wrong, and more importantly, what went right.

To appreciate why things happened as they did on this flight we need to understand the rocket and its configuration. Here are the basic design features of the rocket and the electronics used.



Here is how the design was intended to work and the planned flight profile.

- The first booster had a cluster of two Aerotech I-435T (38/600 Blue Thunder) motors with medium delays. The recovery system is a 72-inch main deployed by motor ejection. Expected peak altitude is around 1000 feet.
- The second booster was powered by a single Aerotech I-285R (38/480 Redline) motor with a medium delay. The 12-inch drogue and 72-inch main parachutes are deployed by motor ejection. The main is retained in a deployment bag until released by an altimeter at 400 feet. Peak altitude for this booster is around 2500 feet.
- The sustainer had a single, plugged I200W (29/360 White Lightning) motor. An altimeter deploys the 12-inch drogue parachute at apogee and the 96-inch main parachute at 400 feet. Sustainer apogee is typically 4500 feet with this motor combination.
- A two-event timer with a pull-pin feature is mounted in the second booster. This timer controls stage separations and the second booster and sustainer motor ignitions.
    - The first timer circuit detects the initial liftoff and ignites the first booster separation charge and the second booster motor simultaneously.
    - The pull-pin circuit detects the first booster separation.
    - The second timer circuit checks for pull-pin release and detects second booster ignition. If these two events do not occur, then sustainer separation and ignition are inhibited. If everything has gone as planned up to this point, then the second timer circuit ignites the second booster separation change and the sustainer motor simultaneously.

For every high power rocket launch we should be asking ourselves what could go wrong. For each possibility, we should have a way to minimize the chance of the failure occurring, or a way to minimize the risk of injury or damage if the failure does occur. The more complex a project becomes, the more that can go wrong. Here are some of the safety precautions to consider in each complex project launch and some of the safety features designed into the three-stage rocket.

- Keep designs from one rocket, or configuration, to another as simple and consistent as possible.
- Use a checklist during preparation for launch. It can be abbreviated but it must cover each component of the rocket, recovery system and electronics. It can also be used after preparation for a review to ensure all steps were completed.
- Always use a slight launch angle (2^o) away from spectators and preparation areas and towards a safe impact zone. If something goes wrong, falling pieces will not cause injury or damage.
- Do not launch in any conditions that would cause the rocket to deviation from the safe impact zone, especially high winds. I personally use 50 percent of the safety code allowable winds as rule-of-thumb for any complex project, even less depending on the launch site and the size of the available safe impact zone.
- Do not aim outside your safe impact zone planning on conditions (such as weather vane) to steer the rocket back on course. If conditions change, or if something goes wrong before the course has an opportunity to change, you've missed the impact zone.
- Choose launch conditions with the assumption that the main parachutes will deploy at apogee (drift). This is more of a recovery issue to ensure you get the expensive project back. But it is another reason for no high winds, especially for high altitude flights.

- A long time of flight provides a longer time for the rocket to arc so, especially with multi-stage flights, limit the launch angle. I personally use 50 percent of the safety code allowable launch angle as the limit.
- Use a very stable design. Center of pressure is calculated and marked on the rocket. Stability is confirmed by measuring the center of gravity, for each stage, on every flight. An over stable design is very susceptible to winds on liftoff (weather vane), another reason for reduced wind limits.
- Booster motors that provide at least an initial 5.5:1 thrust to weight ratio. Confirmation through simulation that the rocket will reach a safe velocity and will be stable prior to reaching the end of the launch rod.
- First booster cluster motors are capable of safely getting the rocket off of the pad in the event that one motor does not ignite.
- Electric matches dipped in pyrogen are used to ignite all cluster motors and all motors that are to be ignited while airborne. Of all the methods that I have tried (including thermolite) I have found this method to be the most repeatable and reliable.
- Motors that are easy to ignite and reach full operating pressure relatively quickly (such as Aerotech Blue Thunder) are used for the first booster cluster. This provides the highest probability of igniting all motors simultaneously.
- Upper stage motors that are easy to ignite and that reach operating pressure quickly reduce the probability of timing errors or of a total failure to ignite. A good rule of thumb is that the longer a motor burns, the more difficult it will be to ignite.
- Positive motor retention is used (no friction fits) so the motors are not pulled from their mounts as stages separate.
- A positive method of keeping the igniter in each motor (including in the cluster motors on the pad) is used so the igniter is not pulled out of the motor during liftoff or stage separation. With the motors and igniters secured, a quick release is required in the igniter wires.
- Both cluster motors in the first booster are configured with the proper delays and ejections charges in case one motor did not ignite.
- Deployment of the sustainer recovery system is independent of motor ignition or ejection charge in case the motor does not ignite.
- The timer pull-pin function provides a safety inhibit of third stage ignition if the second stage does not separate and ignite.
- Timing (ignition) delays selected to control coast time between stage separations. The rocket will continue arcing over during these coast times.
- If the power level of each battery cannot be checked between flights then new batteries are used.

With all of these safety precautions and features what went wrong? As with most accidents there was a string of events.

- The first cause was human error; the connections for the timer circuits were reversed.
  - The first timer circuit (meant for the first booster) detected liftoff, and after the proper delay, separated and ignited the sustainer.
  - The second timer (intended for the sustainer) was looking for the first booster separation and ignition, which never occurred.
- The sustainer operated and recovery normally.
- The two boosters separated when the recovery system on the first booster deployed.
- The first booster recovered normally.

- The second cause was a design flaw; recovery system deployment in the second booster was dependent on motor ignition (ejection charge). The altimeter released the main from the deployment bag, but it was still inside the airframe.

So, what are the lessons learned?

- Let's start with the design flaw. One of the safety precautions above is to have the deployment system of the sustainer independent of motor ignition. This is necessary because ignition systems are known to fail (on the pad or in the air). This same precaution should have been applied to the second booster. The apogee (drogue) circuit of the altimeter in the second booster was available but not used. An ejection charge should have been run from the interstage coupler into the airframe as a backup to motor ejection to deploy the recovery system.
- The second lesson learned concerns the improper connections. Even with a checklist, the error was overlooked. The same timer is used for two and three-stage launches. The first timer circuit is used for the sustainer on two-stage designs but for the first booster on three-stage designs. The second timer circuit is only used on three-stage designs where it is used for the sustainer (instead of the usual first timer circuit). This swapping of timer functions based on staging configuration adds complexity, and potential confusion, to the preparation of multi-stage rockets. An opportunity to keep it simple and consistent was overlooked. The timer circuits are also labeled Timer 1 and Timer 2. Adding Booster and Sustainer to the labels would add clarity and reduce confusion.

In spite of these errors and failures, there were things that went right. These directly contributed to making this a successful failure.

- The rocket was flown towards a safe impact zone.
- The flight was conducted in conditions that ensured the rocket did not stray from the safe impact zone.
- The pull-pin feature prevented the motor from igniting in the second booster. Had this feature not worked, the booster could have been powered out of the safe impact zone with dire consequences.

Complex high power rocketry projects can be extremely challenging and certainly very rewarding. Flights may not always go as planned, but with the right precautions we can continue with high power rocketry's unprecedented safety record. I would encourage everyone to continue to raise your sights and explore the many options that amateur rocketry has to offer. And may all your failures be successful.