UNIQUE PUBLIC SAFETY ISSUES ASSOCIATED WITH ROCKET SHOWS

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ABSTRACT

The X Prize Foundation has conducted two "rocket shows" from the Las Cruces International Airport in the past two years: 1) the Countdown to the X Prize Cup, October 9, 2005, and 2) the Wirefly X Prize Cup, October 20-21, 2006. Although seemingly similar to an air show, launching rockets in front of a large crowd of spectators as part of a show presents a number of unique public safety issues. This paper discusses characteristics of a rocket show, important safety measures to consider, including some lessons learned from past shows, and the future of rocket shows.

1. INTRODUCTION

As a follow-on to the successful completion of the $10 million X Prize in 2004, the X Prize Foundation began to sponsor the X Prize Cup, an annual event designed to showcase the entrepreneurial space launch industry. The first event, the Countdown to the X Prize Cup, was held on October 9, 2005 at Las Cruces International Airport, Las Cruces, New Mexico. Although numerous guided and unguided rocket launches were planned, weather and other factors limited rocket activity to one launch. Aviation activities, numerous static displays, and space related entertainment made for a very successful event nonetheless.

The Wirefly X Prize Cup was held from October 20-21, 2006, also at Las Cruces International Airport. This show was expanded from the year before, featuring flights of lunar lander-type launch vehicles, amateur sounding rockets, and flights of a one man rocket belt.[1] The show also included static test firings of liquid, hybrid, and solid rocket motors, and aircraft flights. The showcase event was the Northrop Grumman Lunar Lander Challenge, a competition funded by the National Aeronautics and Space Administration under its Centennial Challenges program. The competition is divided into two levels. Level 1 requires a rocket to take off from a designated launch area, fly up to 50 meters (164 feet) altitude, then hover for 90 seconds while landing on a 10 meter (32.8 feet) landing pad 100 meters (328 feet) away. The flight must then be repeated in reverse. Both flights, along with all of the necessary preparation for each, must take place within a two-and-a-half-hour period. The level 2 competition is similar, but the rocket must hover for twice as long, and the landing pad is a simulated lunar surface, with craters and boulders to mimic actual lunar terrain [1].

The launching of rockets in front of spectators is nothing new. Rocket launches are spectacular events that naturally draw a crowd. For example, spectator viewing stands are full for most government and commercial unmanned launches from Cape Canaveral Air Force Station, Florida, and for launches of the Space Shuttle from neighboring Kennedy Space Center. Range safety organizations devote a great deal of effort protecting spectators, and many of the safety measures used by range safety are pertinent to rocket shows.

It is also reasonable to assume that the conduct of multiple launches in front of spectators during a day long event requires many of the same safety techniques as used in air shows. Indeed, many safety measures used in air shows are useful for rocket shows as well. During air shows, a crowd line is established that creates a physical barrier between spectators and flying vehicles.[2] All aerobatic flight is performed away from spectators. Emergency procedures are well planned out, usually involving the local fire department's emergency rescue squad, parametics, or emergency medical technicians. The need for an event director and an independent safety observer is recognized, as well as the need for a written event checklist. The Federal Aviation Administration air traffic organization separates nonparticipating aircraft from participating aircraft [2].

However, rocket shows such as the X Prize Cup events present unique characteristics and challenges that bear special consideration. Characteristics of a rocket show are discussed below, followed by a discussion of unique

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[1] A rocket belt is a rocket powered back-back, normally using hydrogen peroxide as fuel.

[2] This line is at minimum 152 m (500 ft) from a show line, which is a ground reference that serves as the horizontal axis for the show [2].

safety measures to be considered, and lessons that the Federal Aviation Administration (FAA) has learned from its experience authorizing the two X Prize Cup events held so far. Lastly, the future of rocket shows is discussed.

2. CHARACTERISTICS OF A ROCKET SHOW

2.1. Large Fixed Crowd.

A rocket show is designed to entertain thousands of spectators. The X Prize Foundation estimates that 15,000 spectators attended the 2006 X Prize Cup. The X Prize Foundation is expecting even more in 2007 at the WireFly X Prize Cup held in conjunction with Holloman Air Force Base's Air and Space Expo. These spectators tend to be concentrated in a relatively small area [3][3].

Not only is the crowd potentially large, the location of the crowd in relation to the launch activities is generally fixed. In past X Prize Cup events, the spectator area was in the apron area of the airport, while flight activities took place around the runways. There is no option of significantly moving the crowd or launch points based on current wind or other weather conditions.

2.2. The Spectator View.

Because rocket launches are invariably spectacular events, with great public interest, government and private launch operators generally provide viewing stands for spectators. However, the needs of the spectator are always secondary to the needs of the launch mission. Spectators can be removed altogether if necessary to complete the mission successfully.

At a rocket show, on the other hand, the enjoyment of the spectator is the primary reason for the launches. This should not be allowed to compromise safety, of course, but there is inherent tension between affording the spectators a close-up view and protecting the spectators by conducting launches a safe distance away. There is no reason to hold a rocket show if the spectators can not see any launches.

2.3. Experimental Nature of Launches.

Because one of the purposes of a rocket show is to support competitions, the vehicles in those competitions are often experimental. All lunar lander challenge vehicles proposed in the past have been one-of-a kind vehicles designed primarily for the lunar lander challenge. The same is true for the vehicles preparing for this year's competition. Because of this, the reliability of these vehicles is unknown with any great certainty. The behavior of the vehicles in a non-nominal situation is also hard to predict.

2.4. Multiple Launch Operators.

The show can include multiple launch operators launching close to one another in time and space. On the second day of the 2006 X Prize Cup, approximately 7 launches, 4 static motor firings, and 2 rocket belt flights occurred within 6 hours of each other. All launch operations took place in relatively close proximity to one another.

2.5. Mix of Rocket and Aircraft Operations.

The past two X Prize Cup events have been held at Las Cruces International Airport. This has allowed for aircraft operations such as F-18 flyovers, rocket powered airplanes, and skydivers. A rocket launch can be hazardous to aircraft in flight, and an aircraft in flight can be hazardous to launch operators directly below who are preparing rockets for launch.

2.6. Spectrum Use.

The running of a rocket show involves the use of a number of electronic devices, presenting the opportunity for radio frequency interference. Multiple radiating devices exist at a show to include radio communication, a Webcast, streaming video, and launch operator command, control, telemetry.[4] Some of this interference can have safety implications, such as if a launch operator loses a control link with the vehicle, or if central flight operations communications is compromised.

2.7. Strict Timelines.

Entertainment shows are usually scheduled down to the minute. The organizers of a show have a legitimate interest in keeping the crowd entertained. Unfortunately, a strict timeline is not necessarily compatible with rocket launches. Most rocket launches work with launch "windows" that ideally leave some

[3] The 2006 X Prize Cup spectator area was approximately 366 m (1200 ft) by 122 m (400 ft).

[4] In X Prize Cup 2007, a "Space Elevator" competition was held that included the use of microwave beams.

opportunity to delay launch due to vehicle or launch support equipment problems, or weather issues.

2.8. Non-Optimum Times.

Being a day long event, launches may be scheduled during times that are not necessarily ideal for rocket launching. In particular, late afternoon can see increased winds and an increase chance of thunderstorms.

3. SAFETY MEASURES FOR A ROCKET SHOW

Given the unique characteristics of a rocket show, the following discussion of safety measures reflect the experience of the FAA during the past two X Prize Cup events.

3.1 Spectator Distance.

Putting distance between a rocket and the spectator is perhaps the most important safety measure of all. An appropriate distance will keep all hazards away from the spectators while, hopefully, affording an exciting view for the spectator.

Two types of vehicles are addressed below – guided lunar-lander type vehicles and amateur sounding rockets. With the exception of the rocket belt, these were the only two types of rockets flown at past X Prize Cup events.

3.1.1 Guided launch vehicles.

The low altitude, long duration flights of the lunar lander challenge vehicles make an ideal launch from the spectator's perspective. However, these vehicles are deceptive in that although they nominally hover at low altitude and only traverse 100 meters (328 feet), they have the energy to reach great distances.

To authorize a launch by the private sector, the FAA has two authorization mechanisms – a license and an experimental permit. The experimental permit is designed for the launch of a reusable suborbital rocket for, among other things, research and development to test new design concepts, new equipment, or new operating techniques [4]. All lunar lander challenge contestants have applied to the FAA for an experimental permit.

Under an experimental permit, a launch operator proposes an operating area, and must demonstrate to the FAA that it will contain the vehicle's instantaneous impact point (IIP)[5] within it. An applicant must demonstrate that the likelihood of any hazardous condition that may cause death or serious injury to the public is extremely remote. To do this, an applicant performs a hazard analysis, and presents measurable evidence that any safety measure derived from the hazard analysis is effective and properly implemented, and will reduce risk to an acceptable level. Once permitted, a launch operator must track and resolve anomalies, and comply with a number of operating requirements.

A quantitative risk analysis is not required under an experimental permit. The lack of flight data with experimental vehicles such as lunar lander-type vehicles makes it impossible to quantitatively estimate risk with any great certainty.

As applied to the X Prize Cup, three important considerations are the sizing of the operating area, vehicle containment within the operating area, and the placement of the operating area in relation to the spectator area. Details of any specific approach used by permit applicants are beyond the scope of this paper, but a general approach can be described.

Because the lunar lander-type vehicles have the energy to reach the public, some active flight safety system is necessary to contain the vehicle's IIP within the operating area. To determine the minimum size of the operating area, a launch operator must take into account a worst case trajectory away from the nominal, and the reaction time for any flight safety system, to include hardware and any human reaction time. Estimating the worst case trajectory is challenging from both a technical perspective, and in terms of what can reasonably be expected to occur. Using a three degree of freedom trajectory program, the FAA has found that using a vehicle pitch rate that causes the vehicle to obtain a zero flight path angle condition near thrust termination maximizes horizontal velocity at that point. This, in turn, maximizes range. Whether this type of trajectory can be reasonably expected to occur is uncertain, but this approach provides a conservative approach to estimating the size of an operating area.

A number of approaches are available to a launch operator to contain the vehicle within the operating area. For example, one approach would be to have the on-

[5] The instantaneous impact point is the impact point, following thrust termination of a launch vehicle, calculated in the absence of atmospheric drag effects. 14 CFR § 401.5.

board guidance system abort the flight if the vehicle's IIP reached the edge of the operating area. Another approach is to have a separate, independent system abort the flight in the same manner. Manual abort systems are also possible, with humans in the loop to directly terminate thrust. The FAA expects to see the use of multiple approaches to contain the vehicle within the operating area due to the experimental nature and low demonstrated reliability of these vehicles. Moreover, each approach to containment has inherent weaknesses (e.g. the human in human-in-the-loop), and a layered approach is not vulnerable to any particular weakness. A layered approach combined with the inherent instability of these vehicles provides assurance that these vehicles will be contained.

Because the operating area only contains the vehicle IIP, and not vehicle hazards, the operating area must be placed away from the spectator area to account for winds and the explosive capability of the vehicle upon impact. To determine this distance, an applicant should assume a wind that blows toward the crowd at the maximum magnitude the applicant will launch in.[6] Upon impact, a distance must be estimated to contain peak overpressure and debris scatter hazards. These distances would be based on the maximum estimated propellant remaining at impact and an estimated explosive yield factor based on the propellant combination. Using equations found in such documents as Department of Defense standard 6055.9 [5], a safe distance based on overpressure and debris scatter can be calculated. The FAA uses a peak incident overpressure of 1 psi as a safe limit [6].

3.1.2 Unguided suborbital launch vehicles.

At X Prize Cup 2006, 6 small sounding rockets were launched. These rockets ranged in take-off weight from 30 kg (80 lbs) to 150 kg (402 lbs), and reached altitudes ranging from 1800 m (5906 ft) to 6100 m (20,010 ft). Each were powered by one or more composite propellant solid rocket motors. The rockets were unguided, fin-stabilized, rail-launched rockets. All rockets were recovered by parachute, typically deploying a drogue parachute at apogee and then a main parachute at a lower altitude. This staged recovery approach is designed to reduce drift.

Launches such as these are considered amateur rocket activities by the FAA. Similar launches are conducted by hobbyists across the United States all year long, and are not normally given regulatory scrutiny other than the clearance of aircraft. However, due to the large crowd in close proximity to these launches, these rocket launches require safety measures more akin to professional sounding rockets.

As with professional sounding rockets, the primary measure to protect spectators is to launch the rockets at an elevation angle away from the crowd sufficient to reduce the chance of impact into the crowd to an acceptable level. In this case, the FAA used a probability of impact less than 1×10^{-6}. Determining the appropriate elevation setting involves first determining a nominal, no-wind elevation angle that will provide the acceptable probability of impact. This provides a nominal impact point for the rocket. Then, on day of launch, the launch team uses a technique called wind weighting to adjust the launcher elevation angle to produce the nominal impact point under the current wind conditions.[7]

The rockets at X Prize Cup 2006 were launched 610 m (2000 ft) from the crowd. To determine the appropriate nominal, no-wind elevation angle, the FAA conducted an independent monte carlo dispersion analysis. Trajectory variations due to unmeasured winds and system dispersions were first determined. The resulting probability density function was integrated over the spectator area to obtain the probability of impact. To determine the appropriate elevation angle, the rocket impact point was displaced until the probability of impact into the crowd was less than 1×10^{-6}. A launch elevation angle was determined based on the resulting impact point. The FAA considered two scenarios – a nominal flight and one where neither parachute deploys.

The amateur nature of these rockets brought about two challenges in this analysis. First, the FAA did not have sufficient data to estimate the vehicle dispersion parameters to any accuracy. These include thrust misalignment, axial and normal force coefficients, and center of gravity.[8] Second, the FAA did not have sufficient data to estimate the probability of different failure scenarios. For example, what is the probability that the recovery system will fail? The normal solution to a lack of data is to use conservative assumptions, and that is what the FAA did. Fortunately, enough

[6] The launch operator would then include that wind constraint in its flight rules.

[7] Normally, the launcher azimuth must also be adjusted. However, for the X Prize Cup event, azimuth error was not critical because the spectators were directly behind the launcher, and a wide, unpopulated downrange area was available for recovery.

[8] Others include mass, moment of inertia, center of pressure, fin cant, total impulse, propellant weight, launch rail azimuth, and launch rail elevation.

unpopulated area existed downrange to allow for conservatively low launch elevation angles.

Wind weighting, used on the day of launch, is a technique used to predict launch azimuth and elevation settings for unguided launch vehicles such that a rocket's flight through a forecasted wind field will produce the predicted nominal impact point for the rocket. The system is designed to compensate the rocket's trajectory for the day of launch winds and contain the impact area in the pre-planned recovery area. The system consists of four main components: 1) weather balloons that measure wind speed and direction, 2) a wind tower for measuring wind speed and direction near the surface,[9] 3) wind weighting trajectory software, and 4) a means to align the launcher.

The amateur nature of these rockets provided a number of challenges on the day of launch as well. The launch rails used were not designed to be adjusted to any great accuracy. The launch operators were also not accustom to using wind weighting in launch operations. The wind weighting software used, although commercially available, did not have the capability that is typically available on government launch ranges. Given these constraints, the launch team at the X Prize Cup 2006 conducted all sounding rocket launches safely.

3.2 Other Safety Measures.

Although distance between launches and spectators is important, other safety measures must also be considered.

3.2.1 No Envelope Expansion.

As noted above, the rockets being launched at a rocket show will be experimental. The lunar lander-type vehicles are reusable, and are normally subject to a flight test program with gradual envelope expansion. Ideally, no envelope expansion should occur at the show itself. Launch vehicles with the energy to reach the spectator area should not be flying in a new flight regime in front of a large crowd.

[9] The wind tower used at past X Prize Cup events was over 36 meters (117 feet) tall. Because a tall tower is dangerous to the aircraft involved in the show, the location of this type of tower and its raising and lowering must be scheduled so as not to endanger aircraft.

3.2.2. Non-Spectator Members of the "Public."

Protecting the general public that attends the show in the spectator area is not the only safety concern. From the FAA's perspective, for any given launch, the public to be protected is anyone not associated with the launch. At a rocket show, with multiple activities going on at once, many people could be outside the spectator area. For any particular launch, it must be clearly documented exactly who must be present around the vehicle during hazardous activities. Entrance to the hazard area must also be strictly controlled. Before a launch can proceed, neighboring launch operators, show personnel, photographers, and anybody else that does not have a job to do must be located in a safe area.

3.2.3. Communications.

As noted above, a rocket show involves multiple launch operators launching close to one another in time and space, as well as a mix of rocket and aircraft operations to include skydivers, civilian and military aircraft, and weather balloons. Many activities on the ground and in the air can be hazardous to show participants. Communications is important between show organizers, within launch teams themselves, and perhaps most importantly, between the flight director and each launch operator. All activities in the flight area must be closely coordinated so that show participants remain clear of preflight and fight hazard areas. Situational awareness is also needed for all show participants. Thus, a robust communication system and procedures is vital.

A rocket show has many different elements, to include individual launch operators, emergency response personnel, the team running the non-flight entertainment parts of the show, airport personnel, pad managers, and safety observers. The communication system design should allow for communication within each element, as well as centralized control of all flight and ground operations and emergency response. In practice, this may require each launch team to have two radios, one for team communication, and one for coordinating with a flight director. The flight director controls all movement in the flight area, and gives go/no-go commands at pre-coordinated times in individual launch operations.

Another aspect of communication system design is that it must be fail-safe. With hazardous activities taking place, the loss of communications could create hazardous situations. If the primary communication system goes down, at least one back-up system is needed to, at minimum, close the show down in an orderly manner.

Besides design, training for all participants is critical. Unlike air shows, where the participants are pilots with experience using radios, rocket show participants may not have much experience. Thus, training on the appropriate use of the radio system, frequency discipline, and the use of appropriate radio terminology is a must.

One aspect that can not be overlooked is frequency management. The potential for radio frequency interference is not unique to rocket shows. At air shows, for example, aviation event radio communication frequencies are coordinated. However, the environment at a rocket show is particularly prone to problems. With each launch operator having its own radio communication system, as well as vehicle telemetry and control links, show organizers may not necessarily have the same level of control.

As an example, at the 2006 X Prize Cup event, the X Prize Foundation planned to use a relatively sophisticated system that included three different communication loops for flight operations, safety, and overall command. Radio interference made it inoperable. Fortunately, the X Prize Foundation had a back-up system that was used successfully to control the show. Frequency management must be taken seriously, and strictly enforced.

3.2.4. Avoid Launch Fever.

Launch fever occurs when the desire to get a rocket off the ground hinders sound judgment. This phenomenon is something every launch manager needs to be aware of. At a rocket show, individual launch operators are prone to launch fever, especially if prize money is at stake. And, as noted above, a rocket show is entertainment, and the organizers of the rocket show have an interest in keeping the crowd entertained. Compounding this concern is that being a day long event, launches may be scheduled during times that are not necessarily optimum, weatherwise, for rocket launching. The 2006 X Prize Cup event was held from 7:00 am to 3:00 pm. Ending the show early to avoid late afternoon weather helps to some extent, but will not solve all weather concerns.

The remedy for all of this is that the launch operators and show organizers have to, at a minimum, allow for flexibility in launch schedules. Launch times cannot be scheduled down to the last minute.

More importantly, launch operators and show personnel must also be willing to scrub a launch all together. This may be a difficult reality for people with a vested interest in a launch, particularly at an annual event. But limited time, weather, and other conditions may combine to make a safe launch impossible. All participants must understand that conducting a launch at the show is not a guarantee.

3.2.5. Mishap Response.

Mishaps can occur for all launches and air shows alike, and an emergency response team is necessary. The emergency response team for past X Prize Cups included local police and fire departments. Emergency services included emergency medical technician, fire suppression and control, police, emergency room, and propellant spill control.

The unique aspect at rocket shows is that there are many different launch vehicles presenting unique hazards and fuels. Thus, an important aspect of emergency planning for a rocket show, with such a varied operations environment, is pre-event planning. For X Prize Cup 2006, weeks before the event, the emergency response personnel were briefed by each team. Included were points of contact, the types of fuel and oxidizer used, normal operations, the beginning and end of hazardous operations, and conditions for the declaration of an emergency. The emergency response team was prepared for each vehicle’s unique hazards. An operations readiness review was also held prior to the event.

4. THE FUTURE OF ROCKET SHOWS

It is difficult to predict the future of rocket shows. The X Prize Foundation calls the X Prize Cup an annual event, so one can expect more in the future. For 2007, the X Prize Foundation has partnered with the Air Force to hold the Wirefly X Prize Cup at Holloman Air Force Base, Alamogordo, New Mexico. The event is billed as the world’s largest “Air and Space Flight Demonstration,” and is expected to include up to 8 lunar lander challenge vehicles [7]. Aircraft demonstrations will include F-16, F-22, and F-117 aircraft. The crowds are expected to exceed 100,000 people, much greater than past X Prize Cup events. The event will also feature more performances, presentations, and displays than past events [7].

Rocket shows in the future may grow even larger, with larger crowds, larger launch vehicles, and a greater numbers of launches. Keeping the spectators safe while affording them a show worth viewing will prove a challenge for both the organizers of such events and the government.

5. SUMMARY

Rocket shows involve a careful balance between the needs of putting on a good show for spectators and the need to protect the spectators from launch vehicle hazards. Organizers, participants, and government regulators need to recognize the unique characteristics of a rocket show compared to more traditional launches, and traditional air shows. The most important consideration for safety is to contain rocket hazards away from the spectator area. Other considerations include not allowing envelope expansion, restricting hazard areas to only necessary personnel, having a robust communications system and training, avoiding launch fever, and having a good mishap response plan. The continued success of rocket shows depends on a robust focus on safety for all involved.

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