Paper Session I-C - Launch Safety Principles for Reusable Launch Vehicles

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Launch Safety Principles for Reusable Launch Vehicles
Safety will be a major consideration in the operation of Reusable Launch Vehicles (RLVs), regardless of the location of the launch facility. While frequently it is asserted that RLVs will be operated in a manner more similar to aircraft than Expendable Launch Vehicles (ELVs), RLVs potentially are at least as hazardous as ELVs. However, RLVs will have aspects, features, and capabilities which may alter approaches to meeting safety requirements.

**Basic Launch Safety Principles**

Launch safety is sometimes called "Range Safety" or even "Flight Safety". Launch safety includes protection from not only the actual launch, but encompasses orbital and re-entry flight modes and ground-based processing, testing, and recovery. All of these issues require the watchful eye of an accountable and responsible range operator.

Launch of rocket powered vehicles is inherently a hazardous undertaking. The explosive potential of the vehicles is enormous; this is complicated by the fact that the vehicles move very quickly and could theoretically reach any place in the world literally in a matter of minutes. The basis for determining what is and is not acceptable in terms of public safety is very simple. In Public Law 60 the 81st Congress specified that the public will not be exposed to dangers greater than that from conventional aircraft flying overhead. This equates to a risk of 30 X 10^-6, or one death in the general public every 1,000 years for a rate of 33 launches a year. The situation becomes more complex as risks for ground-based operations also must be accounted for as well as the unique RLV post-launch risks.

While RLVs differ in a number of aspects from ELVs, during ascent they present essentially the same level of hazard. A representative single stage to orbit liquid hydrogen/liquid oxygen fueled RLV weighing 2 million pounds at liftoff represents an explosive potential approximately equivalent to 1000 tons of TNT. One frequently heard argument is that RLVs will have reliabilities similar to commercial aircraft and therefore can be operated in a similar manner. This is unproved at best. Even if RLV reliabilities eventually prove to be that high, it will take some time to demonstrate them and probably will require at least dozens and probably even hundreds of flights. And in any case, the potential hazard presented during at least the early portions of the flight will exceed those for any commercial aircraft due to the considerable explosive potentials as noted above. Also, the fact remains that even commercial aircraft of demonstrated reliability are limited as to where and how they can operate. For such aircraft, the Federal Aviation Administration (FAA) imposes standards and limitations on such factors as runway lengths, glide paths, and cruising altitudes. For experimental aircraft, including those of limited performance and possessing relatively little potential hazard, the standards are even stricter. Even for the most proven operational aircraft, stringent FAA regulations apply should significant quantities of hazardous materials be carried (as will inevitably be the case for launch propellants of the launch vehicle and its payload).

In summary, we can state with near-certainty that RLVs will not be allowed to present a greater danger to the public than do ELVs. Both types of vehicles will be allowed to kill the same number of people: zero!

**Traditional Risk Mitigation Approaches**
Recognizing the substantial risks inherent in space boosters and ballistic missiles, the Air Force and NASA have developed approaches to reduce the risk to an acceptable level. The risk is mitigated by:

a. Location of launch complexes in uninhabited areas.

b. Limiting allowed trajectories to reduce exposure to the population.

c. Requiring risk mitigation systems, such as commanded destruct systems (Flight Termination Systems, abbreviated as FTS) and Inadvertent Separation Systems (ISS) to destroy the vehicle should it wander off course or break up in flight. Typically, these systems use explosive destruction of the vehicle.

d. Limiting acceptable weather conditions, both to protect FTS and ISS from hazards such as lightning and to reduce the population's exposure to hazards in the event of a failure.

Generally speaking, these same approaches will be appropriate for RLVs. However, RLVs present both new safety challenges as well as some potential new opportunities for addressing risk mitigation.

**Characteristics of RLVs**

RLVs do have some characteristics which set them apart from ELVs and may alter the risk mitigation requirements and approaches. These are:

a. Single stage to orbit (SSTO) RLVs do not have stages, thereby limiting the vehicle's inherent ability to break up and distribute itself over larger areas.

b. SSTO RLVs may be significantly larger than any single stage or component of any other previous launch vehicle.

c. RLVs will require both launch and landing operations, presenting an additional safety and support challenge over ELVs.

d. RLVs may have an ascent abort capability, which offers a potential alternative to commanded destruction. Aborts could be to the area of the launch facility, to a downrange site, or to a "disposal" site in the ocean or another suitably deserted area.

e. RLVs may have an engine-out capability which could increase their reliability and decrease the risk they present.

f. RLVs probably will be liquid fueled only, most likely with only cryogenic propellants, and therefore will be relatively inert until a few hours before launch.

**Overall Risk Mitigation Approaches**

Taking traditional safety requirements into account along with unique RLV characteristics, we can reach some conclusions.

a. Launch areas should still be located in remote areas, just as has been done for ELVs.

b. Toxic material hazards may be reduced substantially over current ELVs but there will be new factors in this area that must be taken into account, including re-entry and recovery of the vehicle.

c. Trajectory restrictions currently used for ELV launches from Cape Canaveral Air Station (CCAS) and the Kennedy Space Center (KSC) should be sufficient to handle the risks presented by RLVs for the traditionally approved launch azimuths.
d. New approaches will be needed to enable RLVs to fly trajectories outside the limits currently used for ELVs.

e. Risk mitigation systems will have to take into account the ability of RLVs to abort flight during ascent.

f. Explosive destruction should be avoided if at all possible for SSTO RLVs, since it spreads the debris over a larger area. Also, for SSTO RLVs, ISS installations are not required.

g. RLVs using gliding, unpowered approaches do not appear to be likely to present serious safety challenges; it may be possible to reduce safety oversight significantly during the landing phase in manner similar to the approach used for the Space Shuttle. However, they also will require extensive meteorological forecasting support in order to address both safety concerns and vehicle limitations.

h. Current techniques used to protect launch crews and other essential personnel during ELV and the Space Shuttle operations should continue to be used. RLVs do not appear to present any special challenges in this regard.

The most significant portions of these areas are discussed in following sections.

**Location of Launch Complexes**

The location of launch complexes and landing fields in relatively remote and unpopulated areas is standard practice at Cape Canaveral Air Station (CCAS) and the Kennedy Space Center (KSC). A typical limit on inhabited buildings near the launch complex for large RLVs would be approximately 3500 ft using current standards. This Quantity Distance (QD) requirement is substantial but should not be particularly difficult to achieve on CCAS and KSC, depending on the number of launch facilities required. However, the stationary QD is small in comparison to the Flight Hazard Area (FHA), which will be highly dependent on the characteristics of the vehicle and the specific mission trajectory. Given the geographic layout of CCAS and KSC and the predicted total launch activity, it is likely that some personnel evacuations will be required during launch operations as well as limited restrictions placed on non-launch test operations.

It is preferable that RLV launch complexes be located relatively close to landing areas; this is not only more convenient but may obviate the need for specialized handling and transportation equipment. The SLC-48 site which has been identified on CCAS can meet these requirements, although there will be some impact on SLC-36 Atlas, SLC-17 Delta, and SLC-46 operations on launch days. Routing of taxiways from the CCAS Skid Strip to the SLC-48 site does not appear to present any significant problems in regards to surface traffic, but some minor alteration of utility systems would be required.

On Kennedy Space Center (KSC), it does not appear to be feasible to locate the RLV launch pads in very close proximity to the Shuttle Landing Facility (SLF). The required Flight Hazard Area for such a siting would force evacuations of areas such as the VAB and possibly LC-39A and LC-39B as well; these will likely be unacceptable to NASA. The best locations for new RLV pads on KSC is North of the current Space Shuttle launch facilities. This will entail the construction of significant new taxiways but may be very compatible with the construction of a new runway, which would in turn improve availability of the runway relative to vehicle weather restrictions.

For horizontal take off RLVs, the existing runways at CCAS and KSC cause some safety concerns. The KSC SLF is 15,000 ft long, has a concrete surface, and it's Northwest end is located in a remote area suitable for a propellant loading area's QD, all
major advantages for RLV use. However, for easterly launches the ascent trajectory would take the vehicle over or near the Space Shuttle processing facilities, the KSC Industrial Area and the CCAS Industrial Area. Depending on the size of the RLV evacuations of these areas might be required. For polar orbit missions it is likely that departures from the SLF would be to the Northwest and over flight of Titusville and other communities in that area would be a limitation.

The CCAS Skid Strip is asphalt and 10,000 ft long. It's Northwest end is near payload processing areas, so evacuations may be required for the fueling of horizontal take off RLVs. This may be feasible if required, since the time required for fueling should not be more than a few hours. Thanks to the Southeastern end of the Skid Strip's proximity to the ocean, ascent trajectory considerations for equatorial orbits should be minimal. Trajectories to polar orbits departing the Skid Strip to the Northwest would have to take into account flight of the CCAS and KSC Industrial Areas.

For horizontal takeoff RLV's the use of a concrete runway would be preferable to reduce the hazard associated with a propellant spill or an accident. Further studies of the mission requirements will be required to determine if the Skid Strip can handle horizontal take off RLVs. Resurfacing of the Skid Strip with concrete is technically feasible. In any case, the runway load capability will also be a factor and may drive the requirement for resurfacing in any case.

**Ascent Trajectory Considerations**

ELVs and the Space Shuttle are trajectory-limited due to safety considerations. During the initial portion of the trajectory, the vehicles cannot overfly populated areas; this is handled by limiting flight to over the open oceans and by warning water and air traffic to stay away. During the later portions of the trajectory, some land overflight is allowed, since the vehicle's reduced explosive yield, higher velocity, and very high altitude reduces the threat to populations. For launches from Cape Canaveral Air Station (CCAS) and the Kennedy Space Center (KSC) launch azimuths are limited from approximately 37 degrees to about 114 degrees. These equate to direct-injection orbital inclinations of approximately 57 degrees to 28 degrees.

Orbital inclinations of greater than 57 degrees have not been flown from CCAS or KSC due to range safety considerations. A trajectory to achieve direct injection sun-synchronous polar orbits has been proposed and involves a northwesterly trajectory which crosses the Georgia coastline and continues over central South Carolina. Such trajectories will require new risk mitigation approaches but may be possible given the unique characteristics of RLVs.

**Toxic Hazards**

Toxic hazards are associated with the exhaust plumes of vehicles during ascent, from venting of propellants, and from the spread and combustion of propellants and structural materials associated with explosive destruction of the vehicle.

Most RLVs intend to utilize either LOX/Liquid Hydrogen or LOX/Kerosene propulsion systems. This will limit but not eliminate the hazards associated with exhaust plumes. However, for horizontal take-off RLVs, during ascent the vehicles will remain relatively close to the ground during a longer period, so the toxic hazard presented will be somewhat greater than with comparable vertical launch vehicles.
During either normal operations or emergencies, such as aborts during ascent, RLVs may need to vent propellants in flight prior to landing. Venting of hydrogen in the area of the Ozone Layer is a concern and will likely require that venting be restricted in some manner.

RLVs will likely use substantial amounts of composite materials. Some of these materials can produce toxic vapors and electrostatic hazards in the event of destruction of the vehicle. This possibility must be taken into account and may affect ascent and recovery trajectory design.

Risk Mitigation Systems

Risk Mitigation Systems are used to reduce the hazard presented by launch vehicles. Aside from remote location of the launch complexes, evacuations, and trajectory shaping, the most common risk mitigation approach now used for ELVs is deliberate explosive destruction of errant vehicles. For U.S. launch vehicles this takes two forms: commanded destruction and destruction by the vehicle's Inadvertent Separation System (ISS). In commanded destruction, a UHF radio signal is initiated by the Missile Flight Control Officer when tracking sources reveal the vehicle is determined to be crossing predetermined destruct lines or that the vehicle is obviously out of control. The ISS activates and destroys the vehicle if the system indicates that the stages are separating. In either case, the destruct signal initiates an explosive destruction of the vehicle, terminates thrust, and ensures burning and/or intermixing of liquid propellants. The range safety trajectory requirements and other safety design requirements ensure that should the vehicle spontaneously explode or be commanded to destruct, any debris will not fall in a manner which endangers life and property.

Explosive destruct systems are the standard technique for current ELVs and have been such for over 50 years, but are somewhat undesirable for RLV's, particularly large SSTO vehicles. Such RLV's do not have the separable stages which tend to increase the risk, but as a consequence are much larger than any other single component ever launched. Explosive destruction would produce a large debris pattern and endanger a wider area. While this is not particularly significant for over-water trajectories, it is a problem for land over flight. On the other hand, impact of the entire vehicle in the open ocean is not a problem for over-water flights, either. What is needed is a single approach which will satisfy all missions and trajectories. The ability of RLVs to abort offers one alternative to explosive destruction.

RLVs now being planned will be autonomous vehicles and will not normally receive guidance instructions from the ground, but will likely use the Global Positioning System (GPS), probably with Differential GPS (DGPS) augmentation from ground stations during the landing phase. RLV on-board guidance and health management systems presumably will be capable of recognizing when the vehicle is unable to achieve orbit and take the required action, including maneuvering as required, thrust termination, dumping of propellants, and selecting an appropriate landing site.

While on-board autonomous risk mitigation systems may be redundant and robust, they are not likely to be judged adequate by and of themselves to ensure safety. The capability for direct intervention will almost certainly be required. A tiered approach to risk mitigation is a possible way to handle this issue. For example:

1. A vehicle is tracked by the launch range, determined to be errant, and is allowed a period to correct it's flight path. If it does not, then:
2. A signal is uplinked to command an abort sequence. If this fails, then:
3. The vehicle is commanded to terminate thrust. If this fails:
4. The vehicle is commanded to dispose of itself in a suitable area.

This represents a significant difference from the current approach but should present no insurmountable technical challenges. If unable to conduct an autonomous abort, the hazard presented by the vehicle can be reduced to an acceptable level by commanding it to terminate thrust and "go ballistic" and/or to dive into the ocean. This is the approach is planned for the X-34 program, in conjunction with the restriction of flight operations to over unpopulated areas. The X-34 also has a limited autonomous in-flight abort capability which allows an unpowered glide-to-landing in some phases of the flight.

For flights within the 28 to 57 degree range normally approved for launches from CCAS and KSC, disposal can take place in the open ocean and normal Flight Hazard Area safety procedures should apply (i.e, warning notices to ships and aircraft and launch area evacuations). However, operators of RLVs would prefer to recover the vehicle, so suitable emergency landing sites will be required. In order to facilitate transport of the vehicle back to the launch site, such locations should have ready access to water transportation; RLVs such as the VentureStar will be too large to enable air transport to be used. Some potentially suitable emergency landing sites for high inclination missions have been identified but will require further evaluation. These include Mayport Naval Air Station at Jacksonville, Florida., Marine Corps Air Station Beaufort in South Carolina, Marine Corps Air Station Cherry Point in North Carolina, and NASA's Wallops Flight Facility in Virginia. For lower inclination missions Homestead Air Force Base in Florida may be useful, but for those missions the over water nature of the flight enables a huge variety of "disposal" options.

For inclinations above 57 degrees such as sun-synchronous missions, launches from CCAS or KSC will require a new approach to risk mitigation. During the early portion of the trajectory, the vehicle is over the ocean and can either abort back to the launch base or dispose of itself in the open water. Normal Flight Hazard Area safety procedures should apply. During the later portions of the flight the vehicle can either abort to orbit or have the performance to reach a suitable landing area or a water disposal area. The primary concern is during that portion of the flight just after the vehicle crosses the Georgia coastline. In the event the vehicle cannot reach the other principle emergency landing sites, suitable sites for emergency landing should be identified. Such sites should have long runways and offer approaches over relatively unpopulated areas. Military bases are preferred due to ready availability of emergency response capabilities, airspace control, and security. Possible choices include North Field, S.C., Myrtle Beach Jetport, S.C. and the former Donaldson Air Force Base near Greenville, S.C. Due to the difficulty in recovering large RLVs from these sites, they should be used for emergency flight termination use only, as an alternative to destruction of the vehicle.

**Landing and Recovery Operations**

During normal landing operations, the allowable flight paths and associated safety precautions will depend upon the hazard presented by the vehicle. RLVs making unpowered landings, such as gliding recoveries, should be able to use either the CCAS Skid Strip or KSC Shuttle Landing Facility (SLF) with a relatively little impact to other activities in a manner similar to the Space Shuttle. RLVs making powered, vertical landings will presumably have more explosive potential and probably will require precautions similar to the launch phase, including the creation of a landing Flight Hazard Area with associated evacuations.
For recovery of horizontal landing RLVs a suitable runway will be required. Potentially, either the CCAS Skid Strip or the KSC SLF could be utilized. The SLF is concrete and is suitable for contact with cryogenics or hypergols. The Skid Strip is asphalt and is not suitable for such contact. From the safety standpoint, the runway material should not be a limiting factor, since with proper planning and procedures it would require a catastrophic event to cause propellants to impact the runway. Should an RLV land on the Skid Strip and require post-landing defueling operations, it would be best done at a concrete pad to one side of the Skid Strip, probably on the dedicated taxiway to the launch pad.

In terms of other hazards, if the vehicle or support equipment has the potential to spill more than one pint of hypergolic fuels (such as Hydrazine), Toxic Hazard Corridors will have to be established and provisions made for access to protective equipment for the ground crew.

### Implications for Range Instrumentation

If a multi-tiered approach to commanded risk mitigation is adopted, range instrumentation systems must be modified. This does not appear to be particularly challenging in terms of technology, but will require revised approaches to depicting the vehicle status. Close integration of vehicle control and range safety functions will be vital and may require changes to the Range Operations Control Center.

Support of trajectories outside of the standard Eastern Range limits likely will require additional range instrumentation. It is very likely that some instrumentation will be required at any emergency landing sites. Space-based instrumentation may offer one solution to these requirements but analyses will be required to confirm the ability to communicate with the vehicle during re-entry.

### Summary and Conclusion

RLVs, regardless of their specific design characteristics, present potentially significant hazards to launch area personnel and the general public. The risks presented by these hazards must be mitigated.

The traditional approaches developed to handle expendable launch vehicles and the Space Shuttle are appropriate for application to RLVs, with some modification. For operation within established launch azimuths RLVs during ascent look essentially identical to ELVs and safety issues can be dealt with in much the same manner. However, the ability of RLVs to possess a credible abort capability requires changes in the range safety approach to risk mitigation.

Due to their abort capability and lack of expendable stages, RLVs potentially can utilize trajectories which would not be allowable for ELVs. A key to realizing such additional capabilities will be the development of suitable disposal techniques in the event of a failure during ascent during a period which precludes either achieving orbit or reaching a primary recovery site. Realistically, such trajectories will not be allowed before the vehicle has demonstrated a relatively high degree of reliability.
Most other safety aspects of RLV operation are simpler and less risky than ELV operations, but new factors such as possible differences in toxic hazards presented must be taken into account.

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