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Space and Air Traffic Management of Operational Space Vehicles

Daniel P. Murray[*]
Federal Aviation Administration, Washington, DC, 20591

The Federal Aviation Administration's Office of Commercial Space Transportation has developed a concept of operations describing commercial space launch and reentry operations that will occur in the National Airspace System (NAS). This concept also outlines a framework for safely integrating launch and reentry vehicles, on their way to and from space, with traditional air traffic operations. With consideration given to emerging experimental or research and development vehicles, it calls for assured separation between space and air traffic to mitigate the risks to aircraft from potential hazards resulting from space launch and reentry operations. Today, the FAA imposes flight restrictions on air traffic to allow space launch and reentry operations, which are infrequent, to occur. While this model may be well suited to accommodate the commercial space transportation industry in its current state, it may quickly become untenable as launch and reentry vehicle operators look to conduct higher frequency, more routine operations at a wider number of sites. The FAA is researching approaches to safely manage these vehicles in the NAS as they make the transition from research and development to operations. This paper provides an overview of this effort.

I. Introduction

IN 2004, as the FAA prepared to grant a reusable launch vehicle mission specific operator license to Scaled Composites to launch its *SpaceShipOne* launch vehicle from the Mojave Air and Space Port in Mojave, California, it developed an approach for addressing the risk to nonparticipating aircraft operating in the vicinity of the spaceport during those flights. The FAA identified a number of concerns which ultimately shaped its approach. First and foremost, the FAA considered the proposed *SpaceShipOne* launch operation to be "experimental" in nature since the program had completed just one relatively short duration rocket-powered flight prior to requiring a license to continue its flight tests. As such, its ability to successfully endure the combined inertial, aerodynamic, and thermal stresses of its entire proposed mission profile had not yet been demonstrated. The exclusive use of restricted airspace roughly 10 miles east of the airport to contain the rocket-powered ascent and ballistic portion of the reentry of the vehicle was implemented to effectively mitigate potential hazards to other aircraft associated with a vehicle failure during those phases of the flights. However, the FAA was concerned that latent effects of the vehicle's exposure to the spaceflight environment could manifest themselves later on, while the vehicle was gliding back to its landing site outside of the restricted airspace. The FAA assumed that a potential existed for these effects to cause a loss of control or in-flight breakup of *SpaceShipOne* at a time and location in which nonparticipating aircraft could be flying near or below its flight path.

Secondly, since *SpaceShipOne* was making an unpowered return to its landing site, the FAA wanted to avoid a situation in which a nonparticipating aircraft could be taking off from, landing on, or otherwise blocking the intended runway as *SpaceShipOne* made its final approach. It was thought that at low altitude in a gliding configuration, *SpaceShipOne* might have had few options available for avoiding a collision with the other aircraft and making a safe landing. Finally, the FAA wanted to prevent the presence of nonparticipating aircraft from distracting the *SpaceShipOne* pilot or obstructing his flight as he returned to the site. The potential for this hazard was not realized until after the second licensed flight, when a nonparticipating aircraft attempted to maneuver close enough to *SpaceShipOne* to follow and photograph its glide to landing.

As a result of these concerns, the FAA imposed temporary flight restrictions (TFRs) that closed the airport and surrounding airspace to all other air traffic. These restrictions were scheduled to be in effect during each mission for three hours, beginning roughly one half hour before *SpaceShipOne*'s carrier aircraft, the *WhiteKnight*, took off from

[*] Aerospace Engineer, Office of Commercial Space Transportation, AST-300, AIAA Member.

the spaceport and ending about an hour after *SpaceShipOne* returned and landed. As a result of this closure, other airport users were required to suspend their operations during this time. While the use of this approach was ultimately tolerable considering the limited number of flights of *SpaceShipOne* and their experimental nature, the FAA intends to safely manage the impact of non-mission related operations at spaceports during future operational spaceflights.

Few spaceports are envisioned to provide dedicated support to a single launch or reentry vehicle operator. On the contrary, most future spaceports will most likely operate in a manner similar to current operations at Mojave Air and Space Port, and the Oklahoma Spaceport near Burns Flat, Oklahoma. These sites support the operations of multiple launch and reentry vehicle developers and operators, as well as tenants representing other industries, including fixed based operators providing aircraft refueling and maintenance services, flight schools, charter services, and general aviation aircraft owners. Furthermore, as the commercial space industry continues to grow, the FAA expects launch and reentry vehicle operators to expand their operations to less remote locations and operate at higher rates that meet their business needs. In that environment, spaceport and vehicle operators will need to equitably balance their needs for airspace access and facility support with the airspace and facility support needs of other users.

To that end, the FAA has been researching potential approaches to more effectively integrate the operations of launch and reentry vehicles and traditional aircraft operations. At the same time, the FAA must retain its focus on public safety to ensure that the associated risks remain below the allowable levels established in Chapter 14, Part 400 of the Code of Federal Regulations. To date, this work has been conducted according to the FAA's current commercial space transportation concept of operations[1]. This framework outlined in the concept of operations calls for a space and air traffic management framework that assures separation of spacecraft and aircraft. The FAA anticipates a need for the definition of assured separation to evolve over time, away from its current manifestation that requires significant lateral spacing and absolute vertical spacing between aircraft and spacecraft to contain the potential hazards. This paper presents some of the potential approaches to accomplishing this evolution, relative to the hazards they address, highlighting their potential advantages and disadvantages as a means of conveying a direction toward future research and potential future policies.

II. Hazards to Aircraft from Launch and Reentry Operations

Spaceflight is inherently difficult and dangerous, and it will remain so for the foreseeable future. As in most other engineering endeavors, as new designs and operational concepts are proposed and tested, many will result in failure. But those that do not fail will continue to build upon the success and experience of *SpaceShipOne* and other vehicles that have charted the course for this new phase of commercial space transportation. The most successful companies in this industry will most likely be those whose business models are founded on the highest standards for safety and reliability. Their individual success and the overall success of the industry may one day cause historians to look back on this current period of spaceflight as the transition from experimental to operational spaceflight.

Ideally, to obtain the designation of "operational", launch and reentry vehicles will have clearly and convincingly demonstrated the ability to accomplish routine, safe operations. In this context, the idea of routine, safe operations may not correlate directly to the type and frequency of other seemingly related modes of transportation, such as aviation. As it matures to an industry that accomplishes hundreds of flights per year from one that currently accomplishes tens of flights per year, the capacity and commonness of the space transportation industry will still fall well short of an industry that safely accomplishes thousands of flights per day. Accordingly, routine launch and reentry operations may be more appropriately identified as repeatable activities that require a predictable, consistent level of effort to prepare for and safely conduct. In that regard, safety could be evidenced in multiple ways, but perhaps most easily through an accident rate commensurate with the historical rates of other forms of transportation at their corresponding levels of maturity.

The safety controls necessary to provide for operational launch and reentry in an integrated traffic environment will depend largely on the outcome of the hazard analysis of the vehicles and their intended operations. For nearly every launch or reentry operation currently envisioned, a hazard to nonparticipating aircraft exists in the form of a collision between the space vehicle and an aircraft. Furthermore, in the event of an in-flight failure of the space vehicle that generates falling debris, an additional hazard exists for any aircraft flying below. Studies have shown that an impact with a fragment weighing as little as one gram can inflict considerable damage on an aircraft[2]. With regard to public risk, both of these hazards are potentially quite severe, possibly resulting in the loss of the aircraft and those onboard, and if left unaddressed, potentially likely to occur. No feasible options for reducing the severity of these hazards have yet been contemplated, but mitigation measures can be applied to reduce their likelihood, as will be discussed below.

III. Mitigating the Collision Hazard

The collision hazard between a launching or reentering space vehicle and an aircraft is similar in nature in most circumstances to the collision hazard between two aircraft. In both cases, a loss of adequate separation between the two vehicles could occur for a number of reasons, including errant flight on the part of one or both vehicles or operational errors on the part of a controlling authority. Certainly the relatively high speed at which launch vehicles are anticipated to ascend through the airspace presents a unique problem with regard to maintaining adequate separation through either "see and avoid" or traditional air traffic control techniques. However, a launch vehicle will likely spend a minimal amount of time at typical aircraft altitudes. While *SpaceShipOne* began its mission at an altitude above most air traffic, most vertically launched vehicles and even vehicles that will take off from a runway under rocket power will look to climb quickly through the airspace to maximize their ability to reach space. Such a vertical or near-vertical ascent trajectory, if flown accurately, could be isolated to a volume of airspace, perhaps cylindrical in shape, oriented vertically and with a diameter of similar size to the width of a traditional jet route. Given its relatively small size and the short period of time for which it would need to be clear of other traffic, it could be easily activated and deactivated without presenting a significant impact to the capacity of the air traffic system.

In the *SpaceShipOne* example above, the FAA addressed the potential for a collision with a nonparticipating aircraft during the rocket-powered portion of the mission by confining that portion of the mission to existing, active restricted airspace. This was a relatively large amount of airspace, measuring roughly 50 miles by 25 miles and spanning from the surface to an unlimited altitude, which is normally used by the U.S. Air Force to conduct test flights and training missions of its high performance aircraft. Given the experimental nature of *SpaceShipOne*, such a volume of dedicated airspace in which to contain the ascent was deemed appropriate. Indeed, the rocket-powered ascents of several of *SpaceShipOne's* flights required the full extent of the restricted airspace in which they were intended to be contained. However, an operational launch vehicle, having consistently demonstrated trajectory control sufficient to accurately fly along an intended ascent trajectory, could be assigned a much smaller area.

To prevent space vehicles from making surprise appearances to fellow pilots or air traffic controllers when they descend from higher altitudes down through aircraft altitudes, advanced communications, navigation, and surveillance (CNS) technologies will most likely be required. Knowledge of the space vehicle's flight plan and a downlink of voice and tracking information could provide air traffic controllers with the situational awareness to maintain adequate separation between the vehicle and the aircraft under their control. In addition, future automatic dependent surveillance-broadcast (ADS-B) technology may enable the pilots of any equipped aircraft to receive and display broadcast space vehicle information in the cockpit, providing them with increased situational awareness with which to take the most appropriate action[3].

The potential maneuverability of both the space vehicle and the aircraft during the final phases of the mission in which the two might share airspace, including approach and landing, could serve to further reduce the likelihood of a collision. Given the effectiveness of air traffic control and see-and-avoid techniques at lower speeds, the potential for a mid-air collision or runway incursion between a space vehicle and a nonparticipating aircraft may not be any more likely than the same potential shared by any two aircraft performing similar operations. Support for this assertion may lie in the data characterizing the potential for occurrence of these types of accidents at airports that support aircraft conducting flight tests and aircraft that make unpowered landings. Two such airports include the Mojave Air and Space Port (KMHV) described above and Frederick Municipal Airport (KFDK) in Frederick, Maryland. KMHV hosts an average of 48 daily operations[4], including those of the National Civilian Test Pilot School. In addition to *SpaceShipOne*, it has also hosted the flight tests of a variety of aircraft types, including rocket-powered aircraft like the XCOR Aerospace *EZ-Rocket* and the Rocket Racing League racer prototype, all of which glide to a landing. While flight test may not be a common occurrence at KFDK, on a daily basis it supports an average of 444 operations[5],

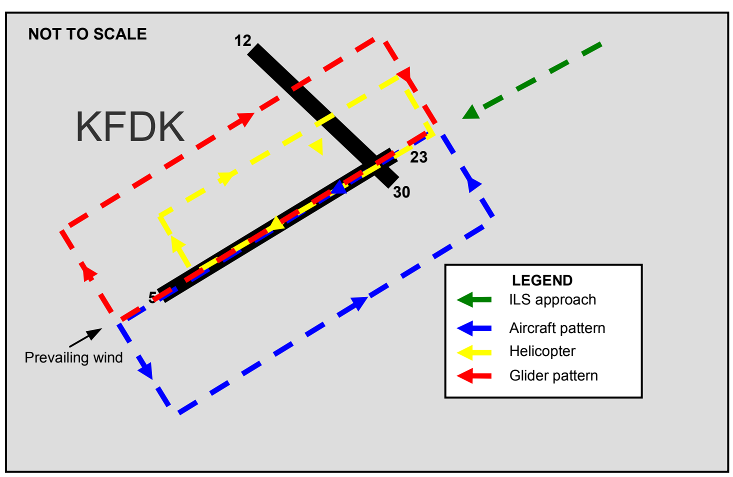

Figure 1: KFDK Pattern with Runway 23 Active

including those of gliders, helicopters, corporate jets, and single and multiengine aircraft, many of which are piloted by student pilots. Figure 1 depicts the pattern at KFDK that supports this traffic. KFDK does not have a control tower, which points to the important fact that the traffic management at the airport is totally dependent on voluntary, mutual see and avoid, rather than air traffic control instructions.

An examination of FAA Accident/Incident Database (AID)[6], National Transportation Safety Board (NTSB)[7], and Aviation Safety Reporting System (ASRS)[8] data covering the past five years for both of these airports reveals eleven recorded instances (eight at KFDK and three at KMHV) in which a runway could have been temporarily blocked because of an accident or incident involving an aircraft. These accidents or incidents include four losses of control on landing, two hard landings, and three landing gear extension failures. In each of these instances, if a gliding aircraft were on approach to land when these events occurred, the glider may have been forced to choose an alternate runway or make a contingency landing in order to avoid a collision. For this same time period, the ASRS database contains 31 voluntary safety reports for these two airports, eleven of which involved a loss of adequate separation between two aircraft when one or both were on approach to land. In one case, a glider making a landing at KFDK was forced to land on the grass adjacent to the runway when an aircraft taxied onto the intended runway in preparation for takeoff[9]. During the time period analyzed, only one collision between aircraft was recorded at either site, which occurred on the ground while both aircraft were maneuvering along taxiways[10].

As some of this data is voluntarily provided, largely anecdotal, and of a limited sample set, caution should probably be exercised in any attempt to use it to glean a statistical representation of the potential for a vehicle to encounter a runway incursion or loss of separation on landing. However, the lack of collisions between aircraft at these airports, either on approach, landing, or rollout, may be viewed as a demonstration of the ability of piloted aircraft, even those in a gliding configuration, to use existing controls to avoid accidents when unforeseen circumstances present themselves during these phases of flight. These controls include the publishing of Notices to Airmen (NOTAMs) to alert pilots of special circumstances and activities, active radio communications between all vehicles in the traffic pattern, the ability to see other vehicles and maneuver to avoid them along established patterns[11] and right-of-way rules (§91.113)[12], the general proficiency developed among pilots to safety conduct go-around landing maneuvers, and the ability for gliding vehicles to safely land in pre-planned alternate areas adjacent to their intended runway. More generally, common aviation safety practices stemming from proper notification, communications, training, and planning are equally important in the conduct of launch and reentry vehicle operations. Once an operator has adopted these practices and consistently demonstrated the capability to maneuver its vehicle in a similar manner, each of these controls could be applied to a launch or reentry vehicle.

Overall, traditional air traffic control techniques, perhaps slightly modified to account for the dynamics of the rocket-powered portion of flight and combined with increased situational awareness of the plans and progress of all parties involved, could serve to adequately mitigate collision hazards between space vehicles and aircraft throughout all phases of the space vehicle flight.

IV. Mitigating the Debris Hazard

Although aircraft are certainly capable of failing in such a way as to create falling debris that could strike other aircraft, the rarity of such a failure to date among aircraft makes the debris hazard somewhat unique to spaceflight. As the Space Shuttle *Columbia* accident demonstrated, the high performance required to travel to and from space, the complexity of the systems required to provide that performance, and the environments that a vehicle must endure in transit make space vehicles somewhat susceptible to these types of failures. In addition, the impact of the hazard produced by such a failure can be considerable. Analysis has shown that an in-flight explosion of a space vehicle at high altitude, where the low density of the air does little to reduce the velocity imparted on the resulting fragments produced by the explosion, can spread debris great distances[13]. Even debris generated by a non-explosive breakup, such as an aerodynamic or thermal load failure, can become entrained in the wind as it falls and scatter over a wide area. In many cases, the extent of the hazarded area could be so large that it encompasses the launch or landing site, exposing aircraft taking off from or landing at these sites to unacceptable risk. In these situations, the collision hazard described above may become a secondary concern.

The risk containment approach that the FAA applied to the *SpaceShipOne* flights represents one means of reducing the likelihood of debris striking a nonparticipating aircraft in the event of an in-flight space vehicle failure. Isolating the space vehicle from other traffic based on a maximum credible hazardous event requires some amount of analysis, planning and scheduling, but is procedurally straightforward once implemented. This method may be the most appropriate method to apply to experimental vehicles, where a lack of flight history limits confidence in the vehicle's ability to operate in a predictable manner during both nominal and off-nominal situations. But, as mentioned above, the extent of the restricted airspace necessary for containment approach to be effective can create substantial impacts to both air and space traffic capacity. Therefore, as a space vehicle transitions from experimental to operational status, alternative approaches should be identified and employed. The FAA has identified one such approach that it currently uses during the reentries of the NASA Space Shuttle orbiters.

Since the *Columbia* accident, the FAA and NASA have developed a strategy to address the risk to aircraft in the event of another Shuttle orbiter breakup during reentry[14]. Given the extent of the National Airspace System that the orbiter can potentially overfly on its way from orbit to landing, a risk containment approach could affect hundreds of aircraft and a large number of major airports. Therefore, other than the restricted airspace in the immediate vicinity of the landing site, no airspace is closed in advance of a Shuttle landing. Rather, NASA provides the FAA with critical information, in the form of data and verbal communications, to increase the FAA's situational awareness and speed of reaction during an event. In particular, NASA provides the FAA with a collection of potential predicted reentry trajectories several days prior to each landing, allowing the FAA to identify the potentially affected airspace underlying each trajectory and to publish NOTAMs and advisories alerting the air travelling community of the times and general locations. The FAA also uses these planning trajectories to predict the extent of the airspace that could contain falling debris hazardous to aircraft at various points along each path[15]. The example in Figure 2 depicts a series of rectangular shaped hazard areas that bound the affected airspace at simulated failure times along the predicted trajectory.

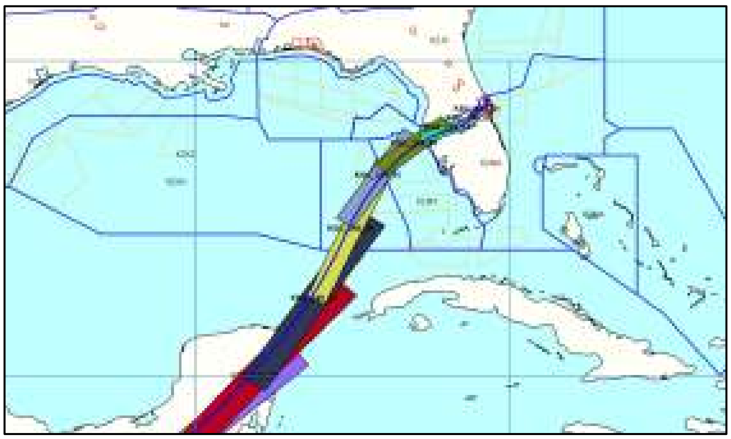

Figure 2: Example Predicted Shuttle Reentry Hazard Areas

During the reentry event itself, NASA provides the FAA with access to a secure website that displays downlinked telemetry from the orbiter describing its actual trajectory. In addition, an open, direct line of communication with a NASA representative in its Mission Control Center is established to provide the FAA with periodic updates on the orbiter's progress and health status. This line also provides the FAA with a means of receiving confirmation of an orbiter breakup and the accompanying information that can assist the FAA in computing a single, updated hazard area that identifies the best estimate of the extent of the affected airspace and the aircraft at risk[16]. Using this information, the FAA can determine the most appropriate course of action, which may include reroutes of airborne traffic, ground stops at underlying or adjacent airports, and closures of airspace.

In the past, arguments have been waged over whether or not the Shuttle should be considered an operational vehicle[17]. The FAA does not intend for this paper to be used to argue for or against that position. However, NASA's ability to accurately predict the orbiter's trajectory in advance of a reentry and the orbiter's demonstrated ability to accurately follow that trajectory are key elements to success of this approach. Any variations or uncertainties in both of these key factors must be accounted for in the prediction of the location and extent of the affected airspace, in order for the FAA to plan its contingency operations and successfully identify all of the aircraft at risk. While the FAA has noted some differences in the orbiter's actual path versus its predicted path, a sufficient amount of flight history has been accumulated over the life of the Shuttle program in order to allow the FAA, with NASA's assistance, to characterize the extent of the orbiter's trajectory control and account for these differences in its predictions[15].

The FAA could look to this approach as a model for safely and efficiently managing future space traffic involving operational launch and reentry vehicles in the NAS. Mitigations that the FAA has put into place to address the debris hazard to aircraft for Shuttle orbiter reentries include NOTAMs and advisories, direct lines of communication established prior to and during the flight, and the sharing of predicted and realtime trajectory data. Once a commercial operator has consistently demonstrated the capability to accurately predict and fly along its intended launch or reentry trajectory, all of these mitigations could be applied to produce correspondent increases in situational awareness and speed of response. The benefit of such an approach would be a minimal impact to air and space traffic capacity, as airspace would only be closed in the event of a confirmed failure of the space vehicle.

It should be noted that NASA has committed to a relatively low flight rate for the Shuttle program and a limited number of flights remain. These facts contribute to the acceptability of the residual risk. In that regard, future commercial launches and reentries that are planned to occur at much higher rates may require additional mitigation to produce similarly acceptable risks. The FAA is currently researching the applicability of additional potential mitigations, such as the broadcast of space vehicle safety data directly to aircraft and other benefits of the advanced CNS technologies mentioned in the context of collision hazards above[3]. These approaches look to apply additional controls from a different direction, sending information directly to aircraft to enable their pilots to enact appropriate procedures and make informed risk decisions.

V. Making the Transition from Experimental to Operational

The attainment of "operational" status for a space vehicle is obviously a key element of this discussion, in that it can lead to the availability of lower impact and less burdensome approaches to safety. Returning then to the definition of routine, safe operations proposed above (repeatable activities that require a predictable, consistent level of effort to prepare for and safely conduct), the obvious questions then become, how repeatable, predictable, and consistent must these operations be and how would a typical launch or reentry vehicle clearly and convincingly demonstrate this level of reliability? These are questions that the FAA and other members of the safety community have been working to answer for some time. Unfortunately, no threshold limits or approach to their demonstration that can be universally applied across vehicle types and programs yet exists. However, the FAA is continuing to work toward the definition of a tangible, consistent, and technically credible process.

A wide variety of approaches successfully applied to other endeavors, including both top-down and bottom-up approaches to determining and demonstrating reliability, are being considered. Using a top-down approach, the reliability of the entire launch or reentry vehicle system is estimated, most often through the examination of flight test results. During flight test, successes and failures are tallied as the vehicle is systematically exposed to an expanding envelope of significant flight regimes. These include ranges in Mach numbers, angles of attack, dynamic pressures, altitudes, accelerations, and wind and thermal conditions that correspond to the anticipated environments of operational flight. When examining the data collected, the definition of success and failure used to categorize the results and the mode by which a failure occurs are important. If a vehicle malfunctions in such as way that causes it to fail to achieve its mission or test objectives but does not endanger the public, its future operations may not be considered to be more hazardous as a result. For example, a vehicle employing redundancy in a safety-critical system may suffer a failure in flight that causes it to switch to the use of a backup system. If the backup system is just as capable of performing the critical function as the primary system, then the safety measures worked as planned and risks to the public were maintained at allowable levels.

For the hazard described in the previous section, the potential for the vehicle to fail in such a way as to generate falling debris hazardous to aircraft characterizes the likelihood of the failure in question. Additionally, an underlying factor of the operational approach to safety described above was the ability of the vehicle to control its trajectory to the extent necessary to allow air traffic managers to depend upon predicted hazard areas to identify affected airspace in the event that debris is generated. Therefore, failures resulting in a loss of trajectory control should also be considered in the vehicle probability of failure estimate. Since an off-course trajectory does not necessarily culminate in an explosion or breakup of the vehicle, as there may be a potential to perform a successful abort along a planned abort trajectory, its probability of occurrence must be assessed separately. Consequently, only a subset of all of the flights that end in failure, of all those that are considered, would apply to the estimate of the likelihood of this type of failure.

Uncertainty based on sample size, homogeneity of the available data, and other factors also must be accounted for. The application of methods to handle these uncertainties prevents the user from concluding that a vehicle will not fail on a future flight, even though the vehicle has rarely or never failed. Likewise, it allows the user to assume that a vehicle may not fail on a future flight when many or all of the previous flights have failed. With the help of the U.S. Air Force, the FAA addressed these and other scenarios through the use of both statistical and probabilistic principles in its guide for determining probability of failure estimates for new expendable launch vehicles (ELVs)[18]. This guide provides a consistent, mathematically sound method for determining the probability that a new ELV will fail on its next flight, based on a binomial distribution of failure percentages and the application of two-sided, 60% confidence intervals to the statistical outcomes of all of its previous flights. Using the method described in this guide and depicted in Figure 3, an example vehicle that has failed once in three opportunities would have a reference value for its likelihood of failing on its next (fourth) flight of 0.39 (39%). Given the uncertainties addressed by the confidence bounds, this likelihood could vary between 0.71 (71%) and 0.07 (7%). Considerations regarding the circumstances under which the failure was experienced, the steps taken to prevent its recurrence, and other potential factors could shift the estimate of failure on the next flight away from the reference value toward the upper or lower bound. For the special cases of zero failures or all failures, the reference values are equal to the midpoints between the 80%, one-sided confidence limit of the binomial distribution and zero or one, respectively. So a vehicle that has not failed in six opportunities would have a reference value for its likelihood of failing on its next (seventh) flight of 0.12 (12%). Given the uncertainties addressed by the confidence bounds, this likelihood could vary between 0.24 (24%) and 0.00 (0%).

Since it was constructed for use on new ELVs, the method described in this guide may not be directly applicable to the outcomes of flight tests of an RLV. Key differences between ELVs and RLVs, such as the ability of an RLV to successfully abort, the existence of additional RLV mission phases beyond ascent, and the potential for RLV failures due to stresses or latent effects of repeated operations, would need to be addressed. The consideration of the use of alternate values lying between the confidence bounds may provide a means to address these differences. Further, the method described in this guide assumes that all of the previous flights applied are sufficiently similar to be considered representative of future flights. In that regard, significant variations in vehicle configuration and flight profile from flight-to-flight have the potential to reduce the available data describing previous flights, increasing the probability of failure estimate for the next flight. Consequently, as the FAA continues to research the application of this method to broader classes of vehicles, it continues to seek alternate methods for computing likelihood of failure estimates that could be used to inform and perhaps supplement the values computed using this top-down approach.

<-------- Success   Failure -------->

Next Launch											
3	0.55	0.89	1.00								
	0.28	**0.50**	**0.72**								
	0.00	0.11	0.45								
4	0.42	0.71	0.93	1.00							
	0.21	**0.39**	**0.61**	**0.79**							
	0.00	0.07	0.29	0.58							
5	0.33	0.58	0.79	0.95	1.00						
	0.17	**0.32**	**0.50**	**0.68**	**0.83**						
	0.00	0.05	0.21	0.42	0.67						
6	0.28	0.49	0.67	0.83	0.96	1.00					
	0.14	**0.27**	**0.42**	**0.58**	**0.73**	**0.86**					
	0.00	0.04	0.17	0.33	0.51	0.72					
7	0.24	0.42	0.59	0.73	0.86	0.96	1.00				
	0.12	**0.23**	**0.36**	**0.50**	**0.64**	**0.77**	**0.88**				
	0.00	0.04	0.14	0.27	0.41	0.58	0.76				
8	0.21	0.37	0.52	0.65	0.77	0.88	0.97	1.00			
	0.10	**0.20**	**0.32**	**0.44**	**0.56**	**0.68**	**0.80**	**0.90**			
	0.00	0.03	0.12	0.23	0.35	0.48	0.63	0.79			
9	0.18	0.33	0.46	0.58	0.70	0.80	0.90	0.97	1.00		
	0.09	**0.18**	**0.28**	**0.39**	**0.50**	**0.61**	**0.72**	**0.82**	**0.91**		
	0.00	0.03	0.10	0.20	0.30	0.42	0.54	0.67	0.82		
10	0.16	0.30	0.42	0.53	0.63	0.73	0.82	0.91	0.98	1.00	
	0.08	**0.16**	**0.26**	**0.35**	**0.45**	**0.55**	**0.65**	**0.74**	**0.84**	**0.92**	
	0.00	0.02	0.09	0.18	0.27	0.37	0.47	0.58	0.70	0.84	
11	0.16	0.27	0.38	0.48	0.58	0.67	0.76	0.84	0.92	0.98	1.00
	0.07	**0.15**	**0.23**	**0.32**	**0.41**	**0.50**	**0.59**	**0.68**	**0.77**	**0.85**	**0.93**
	0.00	0.02	0.08	0.16	0.24	0.33	0.42	0.52	0.62	0.73	0.85

Figure 3: Failure Probability Reference Values and Confidence Limits

For example, analyses of the type described in the FAA's guide to RLV reliability analysis[19] employ both top-down and bottom-up approaches that can assist in the defining of operational, test, and safety requirements. These include both reliability allocation and probabilistic risk assessment approaches, which can be used to provide consideration for the ability of an RLV to abort and to employ redundant systems and other means of obtaining high fault tolerances. More generally, techniques for identifying safety critical systems, performing system and subsystem hazard analyses to identify failure modes, subsequent risks, and potential controls, and validation and verification to determine the effectiveness of these controls are elements of the system safety process. All of these techniques are required of RLV launch license applicants in the FAA's Part 431 requirements, and to a lesser degree of experimental permit applicants in Part 437. Given their place as an intrinsic part of the approach to safety that the FAA has continued to advocate, the FAA continues to work to identify an appropriate means for using the test and analysis data collected during the validation and verification process of system and subsystem hazard analyses to produce an estimation of a vehicle's overall reliability (or probability of failure). Complications typically arise due to the potential for the accumulation of system and subsystem level reliability estimates to create overly optimistic total vehicle reliability estimates compared to those produced using other approaches, such as the top-down approach described above. Additional limitations stem from the lack of a direct means of accounting for the use of less tangible but equally important safety practices in the design, development, and test of a vehicle, such as requirements traceability, quality assurance, anomaly reporting, and the use of dedicated and independent safety organizations. The FAA continues to research methods for addressing all of these factors.

Once an appropriate method of demonstrating reliability has been identified, a threshold level for operational reliability must be set. In practice, it may not be appropriate to impose a one-size-fits-all criterion, as differences in vehicle types and operational practices may lend themselves better to a case-by-case assessment. However, as the FAA continues to research potential limits, it can look to the experience gained during the reentries of the Space Shuttle orbiter, described above, as potential guidance. Using the top-down approach to determining an estimate of the probability of the orbiter failing on reentry in a way that produces falling debris, one such failure in the 122 Shuttle reentries completed to date gives a reference value of probability of failure on the 123rd reentry of 0.013 (1.3%), with an upper bound of 0.024 (2.4%) and a lower bound of 0.002 (0.2%). NASA has used probabilistic risk assessment techniques to estimate the probability of a loss of control on reentry that could lead to an immediate or delayed breakup of roughly 0.01 (1%)[20]. Given the relatively good agreement between the results of these two approaches, there is some confidence that the probability of a failure producing falling debris on reentry is about 1%. This probability of failure, combined with the orbiter's demonstrated ability to fly along its predicted trajectory and the other controls in place during reentries described above, has allowed the FAA to treat the orbiter in a more operational manner, leaving the airspace below it open to air traffic unless a failure is confirmed. If a similar probability of failure can be demonstrated and similar controls exist, the FAA may be able to treat other future vehicles in this manner.

VI. Conclusions

The FAA is researching alternative approaches to safely manage operational launch and reentry vehicle operations in the NAS. These alternative approaches, if successful implemented, will provide for more seamless operations, lessoning the impact of space launch operations on other NAS users. As discussed above, the nature of the potential hazards lends their mitigation to a number of controls. Using existing controls, the hazard due to a collision of a space vehicle and an aircraft may not be any more likely than the potential for a collision between two aircraft. Common aviation safety practices stemming from proper notification, communications, training, and planning are equally important in the conduct of launch and reentry vehicle operations. In addition, experience gained during Space Shuttle orbiter reentries has shown that NOTAMs and advisories, direct lines of communication established prior to and during a flight, and the sharing of predicted and realtime trajectory data could all be applied to commercial launch and reentry vehicles to effectively mitigate the hazards to aircraft posed by falling space vehicle debris.

Reliability, in the form of low failure rates and accurate trajectory control, will be essential to the success of these approaches and must be adequately demonstrated. A threshold value of reliability remains to be identified, and it may ultimately be determined based on the unique characteristics of the vehicles themselves and their proposed operations. However, the use of both top-down and bottom-up methods of demonstrating reliability, through a combination of flight test, subsystem verification, and analytical means, continues to be researched as a candidate tangible, consistent, and technically credible process.

A potential exists for a less restrictive treatment of launch and reentry vehicles to be successfully applied to those vehicles capable of conducting repeatable activities that require a predictable, consistent level of effort to prepare for and conduct. These approaches may become essential to the long term success of the commercial space industry. While additional work remains, the FAA continues to address the issues identified in this paper in preparation for the accommodation of the growing industry.

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