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Separation Distances for Rocket Launch Operations

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An experimental permit issued by the Federal Aviation Administration's Office of Commercial Space Transportation (FAA/AST) authorizes reusable suborbital rockets to fly within a predefined operating area. Specifically, an operating area must contain a suborbital rocket's instantaneous impact point at all times. This paper will present a method for determining a buffer zone surrounding an operating area to mitigate the risks to non-participating aircraft from the hazards involving rocket operations. Determining the size of the buffer zone is a multi-step process. First, a principal operating area is established. Next, the risk to aircraft flying at the edge of the operating area is determined. Finally, the buffer zone size is established based on the additional distance beyond the edge of the operating area required to reduce the aircraft risk to acceptable levels. This paper will familiarize the reader with these proposed processes and the methodologies that support them.

Nomenclature

kft = thousands of feet
n. mi. = nautical miles
P_f = Probability of failure
P_I = Probability of impact
IIP = Instantaneous impact point

I. Introduction

Growth of the commercial reusable suborbital launch industry has increased the demand for experimental permits issued by the Federal Aviation Administration's Office of Commercial Space Transportation (FAA/AST). The experimental permit (permit) is an avenue for commercial space companies to receive authorization to flight test their technology in a rapid prototyping environment. Commercial space companies are eligible to apply for a permit for a reusable suborbital launch vehicle (RLV) by meeting one of three criteria. One criterion is that the company is performing research and development to test new design concepts, new equipment, or new operating techniques. Another criterion is that the company is showing compliance with requirements for obtaining a license. Lastly, a company may apply for a permit to train the crew of the RLV before obtaining a license.

In order to encourage and develop the commercial space transportation industry, Congressional guidance associated with the Commercial Space Launch Amendments Act of 2004 directed the FAA to develop a permit authorization process as a streamlined version of the license authorization process[1]. One of the key differences between permit and license applications resulting from this streamlining is that the FAA/AST does not require permit applicants to perform an expected casualty analysis to quantify the risks to the public. Instead, the permit applicant must identify and qualitatively characterize the risks of each of the potential hazards associated with its proposed operation and apply mitigation measures that lower high risks to public health and safety and the safety of property to acceptable levels. For a permitted flight transitioning through the National Airspace System (NAS) on its way to or from space, a potential hazard exists through which the RLV may explode or breakup causing falling debris to impact nearby aircraft. A permit applicant can mitigate the risk to these nonparticipating aircraft by entering into an agreement with the FAA Air Traffic Control to preemptively close the airspace through and below which the RLV operates. However, there is a potential for the falling debris to spread beyond the bounds of this operating area and this mitigation measure on its own would not prevent nonparticipating aircraft from flying at the

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edge of the operating area. The FAA/AST estimates the risk to the public on board aircraft flying at the edge of a proposed operating area. The FAA/AST reduces the risk to public on board nonparticipating aircraft to acceptable levels by imposing an additional separation distance for aircraft beyond the edge of the operating area. The designation of the additional area associated with this distance is the aircraft buffer zone. The extent of the aircraft buffer zone applied to the edge of the operating area is determined by first assessing the probability of an aircraft located at the edge of the operating area being impacted by debris capable of causing catastrophic damage. Next the computation is repeated at increasing radial distances from the edge of the operating area until the resulting probability is reduced to an acceptable level. Therefore, the size of the aircraft buffer zone directly relates to the threshold value for acceptable risk to the public.

By reducing the probability of impact of a debris fragment capable of causing catastrophic damage with a nonparticipating aircraft, an aircraft buffer zone protects the public on board aircraft during experimental permit operations. The extent of an aircraft buffer zone arises from the potential for debris to spread as it falls through the atmosphere following a vehicle failure and the vulnerability of aircraft to small pieces of debris. Given the speed at which aircraft travel, and the associated energy at impact with a piece of falling debris, aircraft are susceptible to catastrophic damage from impacts with smaller debris pieces that would generally not cause harm to a person on the ground; this is explained in detail in reference 2. This paper expands on the existing process of developing an aircraft hazard area as explained in reference 2 and will familiarize the reader with the proposed FAA processes and methodologies of determining the size of the aircraft buffer zone and aircraft hazard area.

II. Definitions

A. Operating Area and Safety Clear Zone

In the context of an experimental permit, an operating area is a volume of space that extends up from the surface of the Earth to the maximum planned altitude for permitted launch operations. 14 CFR §437.57[3] requires a permit applicant to propose an operating area of sufficient size to contain its proposed operations and then to prove that the RLV's vacuum instantaneous impact point (IIP) will not go beyond the edge of the operating area during both nominal and off-nominal flight conditions. Established within the boundaries of the operating area is a safety clear zone. The safety clear zone is the area that typically surrounds the launch and landing areas that is sized to contain the hazards associated with all pre- and post-flight activities per §437.53. In order to assure safety, a permittee must restrict public access to this area during hazardous operations. During flight, the launch operator rescinds the safety clear zone leaving a void that the operating area then envelops. The operating area may not contain nor be adjacent to densely populated areas or significant automobile, railway, and waterborne vessel traffic.

Once the permittee establishes the operating area and safety clear zone size the permittee must obtain a written agreement with the responsible Air Traffic Control authority having jurisdiction over the airspace through which a permitted launch or reentry is to take place. Among other things, agreements between air traffic control and the permittee reflect the amount of restricted airspace required to maintain acceptable levels of risk to nonparticipating aircraft.

B. Aircraft Buffer Zone and Aircraft Hazard Area

The aircraft buffer zone is the volume of space surrounding the operating area as shown in figure 1. The aircraft buffer zone, operating area, and safety clear zone combine to make up the aircraft hazard area. The aircraft buffer zone acts as the boundary between the aircraft and the edge of the operating area. The experimental permit allows the RLV to fly anywhere within the operating area. A failure of the RLV near the edge of the operating area increases the probability of debris exiting the operating area and impacting an aircraft flying parallel to its edge. Additional area is established between the operating area edge and neighboring aircraft because as will be shown below, an in-flight accident can disperse debris relatively great distances and a small piece of debris can cause a catastrophic aircraft accident. Keeping nonparticipating aircraft out of the aircraft

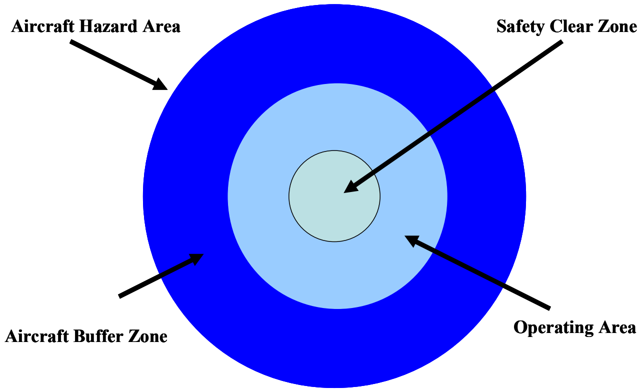

Figure 1. Drawing of an example Aircraft Hazard Area, Aircraft Buffer Zone, Operating Area, and Safety Clear Zone for an experimental permit.

hazard area prevents exposure of aircraft to unacceptable risk levels. Air Traffic Control maintains a clear flight hazard area by issuing a temporary flight restriction (TFR) for the launch or reentry window.

III. Procedure and Methodology Development

Determining the size of the aircraft buffer zone is a multi-step process and for that reason defining the key assumptions is an essential first step. There are five main underlying assumptions that contribute to the determination of the size of the aircraft buffer zone. The first assumption is that the vehicle utilizes a flight safety system capable of containing the IIP of the vehicle within the operating area regardless of the failure scenario. The effectiveness of a flight safety system is determined separately from the buffer zone analysis during a permit application evaluation and therefore it will not be discussed here, but will instead be assumed to be a sufficiently reliable method for containing the vehicle's IIP. The second assumption is a probability of failure of one for the mission (i.e. the vehicle is assumed to fail). The third assumption is that, unless restricted from doing so, nonparticipating aircraft will be flying parallel to the edge of the operating area during the permitted flight. The fourth assumption is that a vehicle failure is no less likely to occur at the operating area boundary than anywhere else in the operating area. The last assumption is that the risk to non-participating aircraft must be no greater than one in ten million (1.0E-7).

A. Probability of Failure

The assignment of probability of vehicle failure during flight is one of the determining criteria in sizing the aircraft buffer zone. A lack of flight history and operational experience of a vehicle generally leads the FAA to size the aircraft buffer zone minimum extent based on a maximum credible event. To accomplish this, the FAA assumes a probability of failure (P_f) equal to 1.0 at each point in time in the proposed trajectory of the vehicle, effectively assuming a failure at each trajectory time step. An examination of the collection of resulting failure scenarios then leads to the identification of the worst-case failure scenario, which is then designated the maximum credible event. Whereas intuition may suggest that other, less severe events may be more likely to occur, sufficient flight test data with which to rank the likelihood of occurrence of events relative to each other does not currently exist for most permitted vehicles. Consequently, sizing these aircraft hazard areas based on hazardous events other than the maximum credible event could provide inadequate protection to aircraft. Once sufficient experience has been gained and data has been collected, the FAA will consider more probabilistic or risk-based approaches to sizing these areas. But until that time, the FAA will continue to determine their minimum dimensions based on a maximum credible event.

B. Nonparticipating Aircraft

Permit applicants are required to obtain an agreement with the local Air Traffic Control (ATC) to coordinate use of the airspace through which the permitted flight will take place. In the absence of available, existing special use airspace, ATC uses a TFR to keep nonparticipating aircraft out of the potentially hazarded airspace during permitted flight operations. As there is no restriction on the permitted operation that would prevent the vehicle from operating anywhere within its proposed operating area, the closed volume of airspace must be at a minimum no smaller than the operating area. With no other restrictions in place, aircraft would tend to fly at the edge of the operating area during hazardous operations to increase efficiency and minimize impacts to the system's capacity. Since hazards exist through which an in-flight failure of the vehicle within the operating area can spread debris beyond the bounds of the operating area, an aircraft buffer zone moves aircraft further from the operating area boundary thereby lowering the risk to aircraft. With the closed volume of airspace in place, it is prudent to next analyze the probability of debris impacting aircraft at the edge of the operating area, as well as the aircraft's vulnerability to debris impacts. This project employed a probabilistic risk analysis for modeling the risk to aircraft from debris impacts.[2, 11] The probabilistic risk analysis approach is summarized below.

> "In probabilistic risk analysis we employ a probability density distribution of debris. The full set of debris is separated into fragment groups, each of which is represented by a single debris cloud. Then the probability of impact P^i_1, from a single fragment of the i^{th} fragment group, is the probability density of the debris cloud integrated over the volume swept out by the aircraft."[11]

For the detailed equations used in the probabilistic risk analysis approach please refer to reference 11.

Aircraft location, size, and speed are key factors in the determination of the probability of impact (P_I) of debris on aircraft. The analysis of aircraft susceptibility also depends on several other factors, including aircraft direction when debris impacts, location on the aircraft of the impact, and the composition of the impacting fragment, and the velocity imparted on the fragment as a result of the failure[2]. FAA/AST contracted ACTA, Inc. of Torrance, CA to research the process of creating an aircraft hazard area. The resulting report[2] uses the Range Commanders' Council

(RCC) standard 321-07[4] threshold limit of debris heavier than one gram impacting an aircraft being able to cause a catastrophic accident. Recent advances in aircraft vulnerability modeling for commercial transport aircraft were not included in this analysis[2]. Currently the FAA/AST abides by the "one gram" standard; a future reevaluation of the standard will determine the level of conservatism necessary for aircraft protection.[12, 13]

C. Flight Operations and Threshold Risk Limit

The basis for the fourth assumption stems from the experimental permit regulation allowing an RLV to fly anywhere within the operating area as long as the IIP is contained. If the vehicle can operate at any location then the probability of failure is independent of failure location within the operating area. The most conservative failure scenario to be considered is one that occurs at the edge of the operating area (which has the possibility to be the "expected" flight plan for a given launch, because the permit does not require submission of individual mission plans).

Limiting the risk to nonparticipating aircraft to no more than one in ten million is a standard threshold risk limit from the RCC 321-07[4]. A license requires an applicant to meet the same risk probability or to provide an equivalent level of safety to methods in use at the Federal ranges. The FAA has chosen to use the same level of risk in an experimental permit.

D. Vehicle Breakup

With the previous five assumptions in place, the determination of the aircraft buffer zone size depends on when and where the failure occurs, the worst-case debris generation due to explosive potential or aerodynamic breakup at time of failure, and what type of aircraft could be at the operating area edge. Deciding when and where the maximum credible event can occur requires a trajectory analysis. Applicants are not required to submit a specific trajectory analysis in the permit application. However, the operating area size, a limited set of vehicle characteristics, and the planned maximum altitude are required in the application. Modeling of the trajectory requires the maximum altitude, engine performance data, propellant loads, and vehicle gross liftoff weight. Using a trajectory analysis program[5], the state vectors describing a proposed flight path can be approximated. The input of the state vectors into the flight safety analysis program describes the initial conditions at each state time at which the program will model the effects of a vehicle failure. The aircraft buffer zone size varies directly with the nature of the maximum credible event. Earlier in flight the vehicle has more propellant capable of producing a larger explosion, but has not entered the NAS where aircraft are affected by an in-flight failure. Later in flight the vehicle has less propellant, but is above the NAS where aircraft will be affected by an in-flight failure, the debris is exposed to the effects of winds for a longer period of time, and the atmospheric density is less capable of limiting the distance that the debris may be propelled by an explosion.

The next component of the aircraft buffer zone size is the debris cloud expected to be generated based on maximum explosive potential and aerodynamic breakup properties of the vehicle. The maximum explosive potential is dependant on the amount of propellant in the vehicle, which changes throughout the flight. The likelihood of an aerodynamic breakup depends on the flight dynamics of the vehicle at the time of failure. An explosive or aerodynamic failure will cause two different aircraft buffer zone sizes, the larger of which is chosen for conservatism when a potential for the occurrence of both failure modes exists. As the example model will show later, the explosive failure causes larger aircraft buffer zones at higher altitudes. The reason explosive failures are more detrimental to aircraft than aerodynamic breakups is two-fold. Explosive failures have more energy to impart on the vehicle fragments than an aerodynamic vehicle breakup, thus spreading the hazardous debris pieces farther. Explosive failures also create a larger number of small debris pieces. Similar to large debris pieces, small pieces of debris impacting aircraft can also cause catastrophic accidents. Due to differences in vehicle configurations, propellant types, failure modes, and modeling limitations, a considerable amount of uncertainty exists in the estimated magnitude of the imparted velocity on each fragment. ACTA uses a proprietary modeling technique to predict vehicle break up characteristics[10]. Data from these models, applied to the available configurations of two expendable launch vehicles, were used to construct the fragment model and respective imparted velocities discussed later in the example.

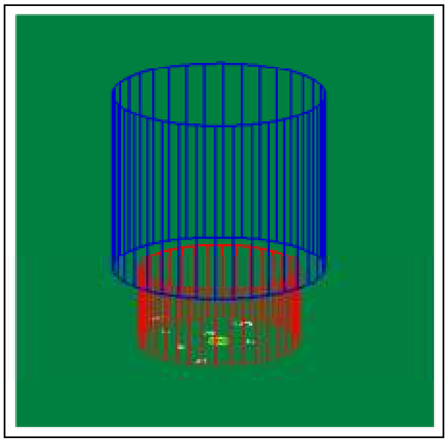

Figure 2. Tiered Aircraft Hazard areas

E. Aircraft Types

The last element in sizing the aircraft buffer zone is the type of aircraft flying at the operating area edge. The classification and altitude of the aircraft are dependent on the maximum planned altitude of the RLV. For example, a planned maximum altitude of 500 ft requires analysis of only general aviation aircraft because en route commercial aircraft fly at higher altitudes. RLV flights penetrating both the general aviation aircraft and commercial aircraft airspace may have aircraft buffer zone sizes that vary with altitude. Figure 2 shows two aircraft hazard areas for two different types of aircraft flying at different altitudes. The bottom tier is the aircraft buffer zone for smaller, slower general aviation aircraft whereas the top tier is for commercial aircraft. For each aircraft buffer zone evaluation the most conservative (largest) aircraft and flight altitude are chosen. Choosing the aircraft type to use for the analysis can depend on a local air traffic analysis. If a proposed operating area does not encroach on commercial air traffic routes, only general aviation aircraft will be used to calculate the probability of impacting an aircraft. However, for all proposed operating areas the most conservative aircraft that can potentially penetrate the operating area's airspace will be used for the analysis.

F. Sizing the Aircraft Buffer Zone

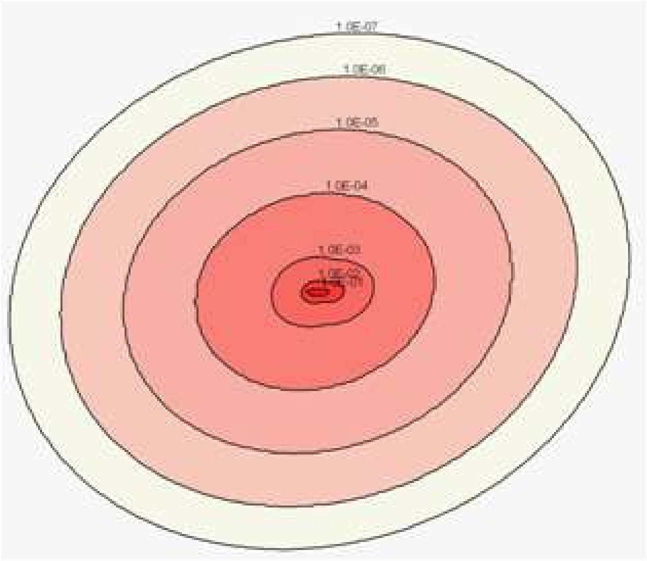

Figure 3. Aircraft Probability of Impact Contours.

Upon completion of the assumption definitions and initial analyses, the data are input into the flight safety analysis tool[6]. The model of the RLV trajectory is the baseline trajectory for the flight safety analysis tool. The fragment model from either the explosive or aerodynamic break up failure is input into the flight safety analysis tool. The last input in the flight safety analysis tool is the type, speed, and altitude of the chosen aircraft. With these inputs, the flight safety analysis tool displays separate probability of impact contours for each aircraft type as shown in figure 3. The contour labeled one in ten million (1.0E-7) represents the boundary at which aircraft of the type analyzed can fly with an acceptable level of risk. Centered on the launch pad is the probability of impact contours. Shifting the center of these contours to the edge of the operating area represents the aircraft buffer zone required for a failure at the edge of the operating area. The aircraft buffer zone radius is determined by choosing the largest 1.0E -7 probability of impact contour from the all the aircraft failure scenarios, measuring its radius, and adding the operating area radius to this value.

IV. Implementation

Upon completing the development of the procedure, a test case was used to examine the application of the process for determining aircraft buffer zones for experimental permits. The hypothetical suborbital RLV used for the test case is vertically launched and has a gross lift-off weight of 100,000 lb and a maximum planned altitude of 350,000 ft. The nominal flight profile for the RLV is broken up into three segments. From launch the RLV accelerates full throttle until main engine cut-off time occurs at which time it then coasts to the apogee. Once the RLV reaches apogee, it begins the descent stage returning to Earth and landing on a pad adjacent to the launch pad. The operating area is set to a circle with a radius of 5 nautical miles, centered on the launch pad. With a nominal apogee of 350,000 ft the RLV flies through and over the NAS requiring analysis of both general aviation aircraft and commercial aircraft for the aircraft buffer zone size.

The next step in the procedure is to define possible trajectories for the RLV using a trajectory analysis tool[5]. Eight separate nominal trajectories are modeled. Each trajectory originates from the same launch point, using the 100,000 lb gross liftoff weight, and flies along the same vertical profile at maximum thrust. However, different burnout times are employed to produce incrementally increasing apogee altitudes, ranging from 25,000 ft to 350,000 ft. The state vectors output from the tool are input into a flight safety analysis tool[6] thus defining the initial conditions from which this tool will model the effects of the failure. The flight safety analysis tool propagates each of the debris fragments associated with the vehicle failure to their impact with the surface, accounting for any velocity imparted on them as a result of the failure, the size and shape of the fragment, and the effects of winds and other atmospheric variations.

Creating a fragment catalogue is the next step in the procedure. Several fragment catalogues were considered before selecting the final version. The first few versions contain a small number of large pieces, corresponding mainly to the vehicle components. The later versions represent a more realistic model of the expected fragments based on preexisting fragment databases from similarly designed expendable launch vehicles. For the baseline RLV test case, the chosen vehicle fragment catalogue consists of 1,116 fragments. These fragments are created by dividing the components of the vehicle, such as the engines, propellant tanks, skin, and fins, into smaller pieces. Each component was broken up into fragments of relatively equal size. The vehicle components expected to fracture into the largest number of fragments are the propellant tanks, avionics, wiring, plumbing, and airframe. Imparted velocity quantities are assigned to each fragment upon completion of the debris catalogue. The chosen imparted velocities are established with the aid of previous analyses from similarly designed expendable launch vehicles. For simplicity, the same fragment catalogue as the explosive case study, sans the imparted velocity, is used in the modeling of the aerodynamic breakup of the RLV. This generally produces conservative results since the explosive catalogue contains a larger number of small pieces than would be expected from an aerodynamic breakup and these smaller pieces tend to drift greater distances than larger pieces as a result of winds. Wind is the primary factor in buffer zone size for aerodynamic breakups.

Examining the aircraft density and what types of aircraft are most common in the region of the RLV flight path is the next step in the procedure. The test case identifies an inland region of the United State where a variety of commercial and general aviation aircraft are flown. This region is assumed to be sufficiently far away from major airports to support the assumption that all commercial aircraft in the vicinity are flying at cruising altitudes. Based on the conservatism provided from its larger size, the Boeing 747 was selected to represent these commercial aircraft. The Cessna 172 was used to represent the general aviation aircraft operating in this region at lower altitudes, based on its wide use and the availability of data describing its dimensions. The frontal and top areas of the Boeing 747 are 1613 ft^2 and 10812 ft^2 respectively. The altitude and average cruising speed of the Boeing 747 is 37,500 ft and 831 ft/s respectively. The frontal and top areas of the Cessna 172 are 52 ft^2 and 281 ft^2 respectively. The altitude and average cruising speed of the Cessna 172 is 2,500 ft and 165 ft/s. As stated above, an impact of debris weighing one gram or more counts as an impact to the aircraft that can cause a catastrophic accident.

The flight safety analysis tool requires the RLV trajectory, fragment catalogue, and aircraft data to generate the impact probability contours for nonparticipating aircraft. To accomplish this, the tool established a grid of user-defined resolution that covers the estimated area at risk. The tool places an aircraft of one of the two types described above at each node on the grid at its corresponding altitude. At each state vector time in the RLV trajectory, the tool computes the probability of impact at each grid node. Nodes with probabilities of impact of similar order of magnitude are then collected into contours. The tool then examines the resulting collection of contours, one set for each state vector time, to identify the largest set. This set represents the worst credible event associated with that aircraft type. The process is then repeated for the other aircraft type. An atmospheric model associated with the month of October and the geographical region containing the launch pad was used for the test case. The database used for the atmospheric model is the Global Gridded Upper Atmosphere Statistics (GGUAS[7]) which models atmospheric conditions from data obtained over a 15 year time span from all over the world. The GGUAS database contains average wind, wind variation, average air temperature, and average air density for each month. The effect on the aircraft buffer zone size for launching during various months was also examined.

V. Results

The RLV modeled in this example has several aircraft hazard areas related to the altitude of the failure, failure mode, and the type of aircraft in the failure region. The two failure modes analyzed for this test case are the explosive and aerodynamic breakups of the RLV. The results shown in figures 4 and 5 are for the month of October. Figures 6 and 7 represent change in size for the aircraft hazard areas depending on the average atmospheric conditions of the month the launch occurs. The nonparticipating aircraft considered in this analysis are the Cessna 172 and Boeing 747 flying at altitudes of 2,500 ft and 37,500 ft respectively.

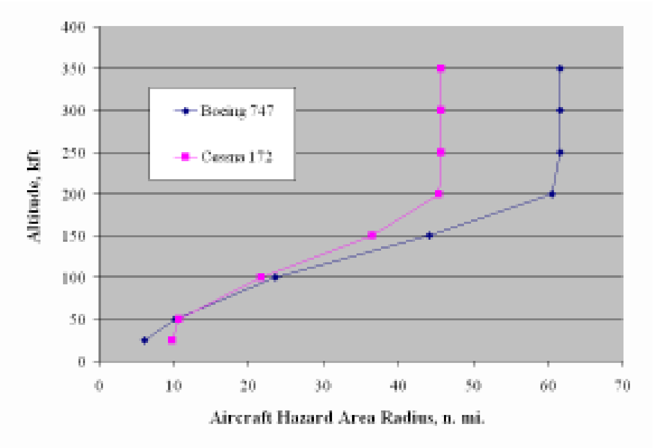

Figure 4. Explosive Breakup Aircraft Hazard Area Radius

Figure 4 shows the Boeing 747 and Cessna 172 aircraft hazard area radius for an operating area radius of 5 n.mi. These aircraft hazard areas are from the explosive breakup failure mode of the test case RLV. For the trajectories flown to lower apogee altitudes (below 50,000 ft), the aircraft hazard areas for the Cessna 172 and the Boeing 747 are nearly equal. For higher altitude flights of the RLV (above 50,000 ft), the aircraft hazard area is larger for the Boeing 747. This difference is due to the size and flight altitude differences of the two aircraft[2]. The atmospheric density is lower at higher altitudes, leading to additional dispersion of debris from the explosion altitude. The added dispersion in debris increases the extent of the aircraft hazard area and lowers the overall density of the debris. Near the edge of the hazard area (45-60 miles out), the debris density has reduced to the point that the likelihood of the smaller Cessna being impacted by debris is lower than the likelihood of the larger 747. These results also illustrate the potential to use the “tiered aircraft hazard area” approach discussed in the procedure and methodology development section. At altitudes above 200,000 ft, where the density of the atmosphere becomes too small to effectively slow the horizontal velocity of the fragments, the hazard area radius becomes nearly constant.

Figure 5 displays the aircraft hazard areas for an aerodynamic breakup failure mode for the test case RLV. With only the effects of the wind to disperse the debris, the extent of the hazard area is nearly three times smaller than the explosive hazard area. Unlike the aircraft hazard areas for the explosive breakup failure mode, the aircraft hazard areas for the Cessna 172 and the Boeing 747 are nearly equal at all apogee altitudes. This arises because there is no explosive velocity, so the remaining two most significant effects defining the buffer work in opposite directions for the two aircraft. The Cessna is smaller, but it is lower, so there is more debris spread before it reaches the Cessna altitude. The next series of results provides an additional representation of how the explosive breakup case is the dominant element in aircraft hazard area analysis.

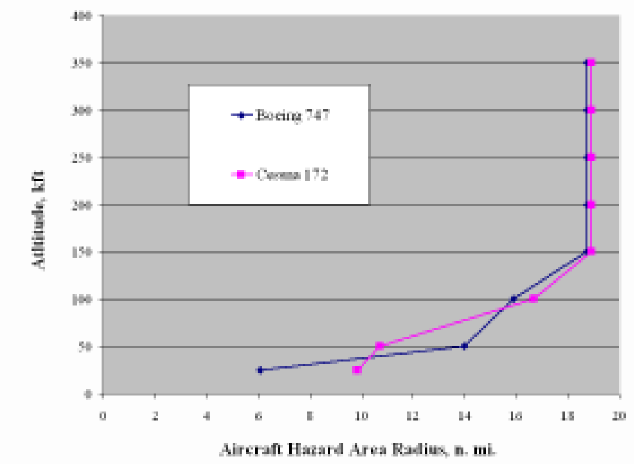

Figure 5. Aerodynamic Breakup Aircraft Hazard Area.

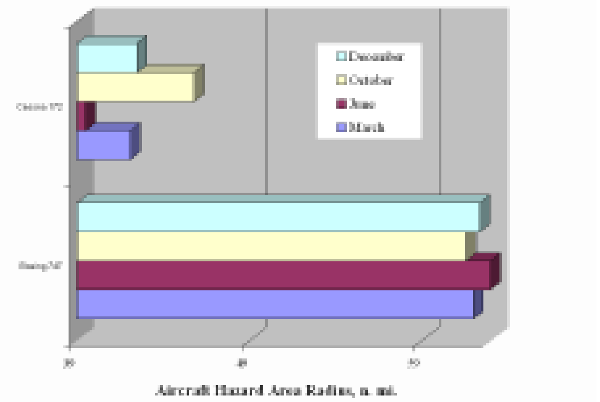

Figure 6. Explosive Breakup Aircraft Hazard Area Radius for the Months of March, June, October, and December.

Figures 6 and 7 illustrate the effects of local atmospheric conditions on the size of the aircraft hazard area. Figure 6 displays the explosive breakup test case results for four months, whereas figure 7 displays the results for the aerodynamic breakup test case. In the explosive breakup test case, the aircraft hazard area for the Cessna 172 is largest in October, and for the Boeing 747, the month of June. The Boeing 747 aircraft hazard areas range in size from 59 to 62 n. mi., which includes the operating area radius of 5 n. mi. The Cessna 172 aircraft hazard areas range from 39 to 45 n. mi. for the same operating area radius. The Boeing has a larger hazard area because it is larger and moving faster and most debris spread occurs above the altitude where the aircraft are flying (due to the explosion velocity).

However, the risk to the Cessna is much more significantly affected by the wind conditions. This is because the wind effects are significant below 37,500 ft, and winds are typically stronger—especially in the jet stream--in October than June.

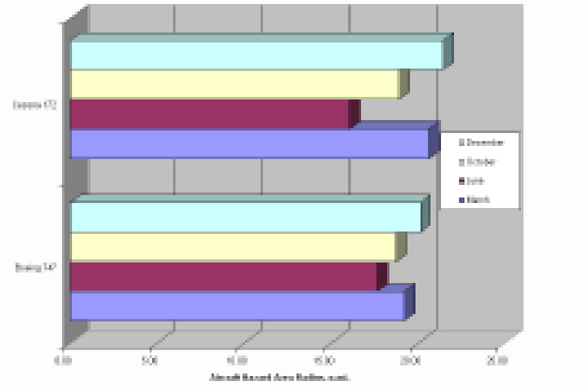

Figure 7. Aerodynamic Breakup Aircraft Hazard Area Radius for the Months of March, June, October, and December.

Figure 7 reveals the effect of atmospheric conditions on the aircraft hazard areas for both the Boeing 747 and Cessna 172 in the case of aerodynamic breakup. The Boeing 747's range of aircraft hazard areas is 15 to 19 n. mi., and the Cessna 172's range is 12 to 20 n. mi. For the aerodynamic breakup test case, the probability of impact contours indicate a minor difference in the two aircraft's hazard areas. Since aerodynamic breakup assumes no imparted velocity on debris, atmospheric conditions are the sole contributors to spreading the debris after the breakup.

With the above results, the aircraft buffer zone radius is chosen by selecting the largest radius from the above analysis. For the RLV's maximum altitude of 350,000 ft the aircraft buffer zone radius is 57 n. mi. and thus the aircraft hazard area radius is 62 n. mi. The maximum aircraft buffer zone radius produced by the Cessna 172 is 45 n. mi. and is therefore smaller than the radius produced by the Boeing 747. In this test case the Boeing 747 aircraft hazard area radius must be used if the RLV plans to operate with a maximum planned altitude of 350,000 ft. These distances could be reduced if the RLV's maximum altitude was below 200,000 ft. For example, from Figure 4, the size of the aircraft hazard area is approximately 40 n.mi. if the maximum altitude of the example RLV is not above 150,000 ft.

VI. Future Work

The FAA/AST procedure for determining the size of an aircraft buffer zone for each experimental permit applicant is a continually improving process. An aircraft hazard area with a radius of 62 n. mi. would create a problem in most regions of the United States' air traffic routes. In order for aircraft to avoid a potential aircraft hazard area of 124 n. mi. diameter, the route would need to be altered far in advanced of the restricted airspace. Consequently altering aircraft flight routes adds to the over all flight time and fuel usage. Another potential problem of closing an extensive amount of airspace is the interruption of operations for smaller municipal airports that may lie underneath the restricted airspace. Decreasing the size of the aircraft buffer zone size in order to decrease the aircraft hazard area is the major concern for high altitude inland RLV launches. This paper recommends for future work the following studies in order to decrease the aircraft buffer zone radius.

1. Continue examining the vulnerability of different class and aircraft type to debris.
2. Determine a failure probability reference and confidence bounds table for RLVs or an equivalent means of assigning probability of failures to new RLVs.
3. Identify operational approaches to implementing safety in the current air traffic system to support frequent rocket launches into the NAS.
4. Create fragment catalogues for various RLVs to use for future analyses.

Examining various types and classes of aircraft will help the FAA to learn more of the vulnerability to impacts from debris. Preliminary research has shown that larger aircraft, such as the Boeing 747, can withstand an impact from debris larger than 1 gram and not suffer a catastrophic accident[8]. Future research will show if aircraft buffer zones can be reduced by allowing the analysis to discard smaller pieces of debris or by reducing the amount of the total area of the aircraft used in the analysis that is considered to be vulnerable to debris.

The aircraft buffer zones could be reduced in size if a smaller probability of failure is applied during the analysis. Decreasing the P_f requires constructing a justification for a more reliable vehicle. Providing a rationale that the vehicle has a smaller probability of exploding or demonstrating that fuel is depleted are two possibilities to decrease the P_f. Decreasing the P_f by 10% would effectively allow the acceptable risk criterion to be set at one in a million probability of impact (1.0E-6)[2] instead of the current one in ten million criterion, since P_f is a multiplicative factor in the computation of probability of impact. This would further reduce the aircraft buffer zone radius. In particular, investigate how to bound the probability of in-flight explosions (and likewise, examine closely applicants methods to reduce the probability of such events).

The third recommendation for future work is improving the current air traffic system's ability to address the risks from rocket operations in a more operational manner[9]. The current program for managing air traffic together with rocket operations is already in place, but is not operational. The future work would include improving the operational response for rerouting aircraft around aircraft hazard areas.

Lastly it is recommended to create fragment catalogues for different RLVs in order to more accurately capture the potential fragment pieces from an explosion or aerodynamic breakup. At the time of this study similar RLV fragment catalogues were not available for comparison, and it would have been beneficial to the study to compare the created test case fragment list with preexisting RLV fragment databases.

VII. Conclusion

The commercial space transportation industry is another form of transportation that must coordinate with the commercial aircraft transportation sector. The space industry's need to share the National Airspace System (NAS) with aircraft triggered the origination of the aircraft buffer zone. Protection of non-participating aircraft is the responsibility of the FAA as RLVs fly through the NAS. Likewise, the determination of the buffer zone size is also a duty of the FAA.

This paper explains and demonstrates the proposed procedure for determining the aircraft buffer zone size for experimental permit applications, as well as the results from testing this procedure on a RLV. The generic RLV used as the model to test the procedure produced an aircraft buffer zone radius of approximately 62 nautical miles from an explosive event. A viable solution to reduce the aircraft buffer zone area is necessary to be able to sustain demanding launch schedules of the future.

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