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FAA's Approach to Ground and NAS Separation Distances for Commercial Rocket Launches

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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 (RLVs) to fly within a predefined operating area. Specifically, an operating area must contain a suborbital rocket's vacuum instantaneous impact point. This paper will present an update of the work performed since the publishing of the AIAA conference paper titled "Separation Distances for Rocket Launch Operations" at the 2008 AIAA Atmospheric Flight Mechanics Conference. The focus of the above mentioned paper was on the necessary aircraft separation distances from rockets that launched into the national airspace system (NAS). This paper will include updates to the aircraft buffer zone size regarding probability of failure allocation, sensitivity to aircraft vulnerability, effects of wind conditions, and debris catalogue sensitivity, as well as adding information on ground buffer zones for reusable suborbital rockets. In the previously mentioned paper, it is recommended that the probability of failure for each point in time is equal to 1.0 for a reusable suborbital launch. More recent research examines the resulting aircraft buffer zone size if the probability of failure for the overall mission is equal to 1.0 and uniformly allocated to specific times of flight. The sensitivity of the aircraft buffer zone size to the commercial transport aircraft vulnerability model is also reported on in this paper. Day of launch wind conditions and debris catalogue development can significantly change the aircraft buffer zone size and it is important to characterize how these factors can affect the launch operations. The FAA/AST does not require an experimental permit applicant to perform a quantitative risk analysis to obtain a permit and instead has adopted the approach of determining a ground buffer zone around an operating area similar to the aircraft buffer zone. The ground buffer zone protects the public from reusable suborbital rocket explosions near the operating area boundary. Determining the size of the ground buffer zone is a multi step process. This paper will familiarize the reader with these processes and the methodologies that support them along with the results of the aircraft buffer zones in regard to the probability of failure allocation, aircraft vulnerability, wind effects, and debris catalogues.

Nomenclature

ft	=	feet
g	=	gram
lb	=	pound
n.mi.	=	nautical mile
P_f	=	probability of failure
P_I	=	probability of impact

I. Introduction

THE Federal Aviation Administration's Office of Commercial Space Transportation's (FAA/AST) mission is to ensure protection of the public, property, and the national security and foreign policy interests of the United

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States during commercial launch or reentry activities.[1] As part of this mission, the FAA issues experimental permits to the operators of suborbital reusable rockets who demonstrate compliance with FAA regulations. These regulations include the requirement for an operator to identify an operating area in which to conduct permitted flights of their vehicle. This paper addresses the protection of the public afforded by the addition of buffer zones beyond the boundary of an operating area that ensure no densely populated area or large concentration of public resides at the edge of an experimental permit operating area. Aircraft buffer zones and ground buffer zones are essential to protect the public from adverse effects of a vehicle impacting at or near the edge of the operating area during permitted commercial rocket launches. This paper is a continuation of the AIAA conference paper titled "Separation Distances for Rocket Launch Operations"[3] presented at the 2008 AIAA Atmospheric Flight Mechanics Conference. In addition to describing further work performed on aircraft buffer zones, it introduces two procedures for determining a ground buffer zone.

Part 437 of the Code of Federal Regulations, which codifies the regulations placed on experimental suborbital rocket launch operations, does not explicitly define or require buffer zones. However, computing a buffer zone addresses the prohibition of an operating area containing or being adjacent to densely populated areas or large concentrations of members of the public.[iii] The aircraft buffer zone serves the purpose of decreasing the risk to aircraft flying at or near the edge of the operating area by expanding the aircraft "keep out area" beyond the operating area. Similarly, the ground buffer zone decreases the risk to the public by increasing the distance from densely populated areas or large concentrations of the public to the edge of the operating area. One key difference between the aircraft and ground buffer zones is the aircraft buffer zone must be free of uninvolved aircraft in order for the permitted rocket launch to take place, while the ground buffer zone may contain members of the public during the flight. The difference in the location of the public, on the ground or in an aircraft, contributes to the acceptable risk levels used for determining each of the buffer zones. For aircraft flying near permitted operating areas, the FAA has chosen to limit the risk of the rocket or its debris impacting an aircraft to less than one in ten million, as described below. For people on the ground in and near a permit operating area, the FAA chosen to use the risk to an individual of greater than one in one million as an initial screening factor for further examination of the hazards posed to the public, including those posed to densely populated areas and large concentrations of members of the public adjacent to an operating area. The flight safety analysis tool utilized in this study is a Range Risk Analysis Tool (RRAT) developed by ACTA, Inc.[2] The RRAT software is also in use at other federal launch ranges including Cape Canaveral Air Force Station and the Navy's Pacific Missile Range Facility. The FAA does not require applicants applying for an experimental permit to possess a similar analysis tool, and therefore has taken on the responsibility of performing both the aircraft and ground hazard area analyses. The main focus of this paper is for the applicants applying for experimental permits as well as other interested parties to understand the proposed processes and methodologies that contribute to determining these hazard areas.

For these studies it is assumed that during the process of applying for an experimental permit an operator has provided the following information to the FAA/AST to determine both the ground hazard area and aircraft hazard areas. The example RLV will be propelled by a combination of liquid oxygen (LO_2) and rocket propellant (RP-1) and the operator plans to launch to an altitude of 300,000 ft from a location in the southwestern United States. The total propellant load at liftoff is 100,000 lbs, and the operator would like to launch the RLV on any given day and time throughout the year. Once the FAA/AST receives this information, the following analyses and sensitivity studies are conducted for the permit applicant.

II. Aircraft Buffer Zone

An aircraft buffer zone can be relatively large, having a radius on an order of magnitude of tens of nautical miles. Its size is dependent on the vehicle class, propellant type and quantities, and flight altitudes. For an explanation of the process involved with creating an aircraft buffer zone, see Reference 3. This paper examines the sensitivity to the aircraft buffer zone size with changes in the probability of failure, commercial transport aircraft vulnerability model, and wind conditions at the launch site, and development of the debris fragment catalogue for RLVs.

A. Probability of Failure Allocation

The effect on the aircraft buffer zone size when allocating a probability of failure (P_f) over the entire flight is a contentious topic in the flight safety community. Past studies on this subject applied a probability of failure equal to one to each state vector, effectively representing one hundred percent failure throughout the mission.[3] While

iii §437.57(b)(3)

sometimes viewed as being overly pessimistic, this approach speaks to the nature of research and development by characterizing a maximum credible event. The new effort utilizes the same assumption of one hundred percent failure of the mission, but instead allocates a fraction of the total P_f to each state vector. In this example, a total failure probability equal to one is uniformly allocated over the failure time span of the vehicle's flight.[4] The vehicle's failure time span for this problem is the period of time spanning from liftoff to the end of powered flight; therefore the P_f for each second in flight is equal to one divided by the failure time span. The risk analysis tool applies a P_f to each state vector of a vehicle's trajectory when determining the risk to aircraft. From a series of modeled debris-generating events, a set of probability of impact (P_I) contours are formed by grouping all of the locations that have the same P_I magnitude.

When a P_f equal to one for each state vector is applied, the results from all state vectors are combined with a union operation, where as, when a P_f equal to one is applied per mission, then the results from all state vectors are summed. The expected result is a significant decrease in the buffer zone size compared to that which is computed by applying a P_f of one to each vector. The outcome of this study will lead to either an investigation of an alternative method to decrease the aircraft buffer zone size or provide additional motivation to ongoing efforts investigating a systematic approach to allocating P_f for RLV flights.

B. Commercial Transport Aircraft Vulnerability Model

In order to reduce the likelihood that an aircraft not associated with the launch operation of an experimental vehicle will not be impacted from hazardous debris, a containment area or "keep out zone" is established. As the FAA currently does not have a published standard for aircraft risk, it has chosen to determine the size of this area based on the risk threshold for aircraft of no more than one in ten million ($1\text{x}10^{-7}$) established in the Range Commanders Council Common Risk Criteria Standards for National Test Ranges (RCC 321-07) supplement.

Previous work investigated the aircraft buffer zone size of a commercial transport aircraft vulnerability model defined a 1 gram impact as capable of causing a catastrophic accident.[3] This aircraft vulnerability model resulted in a large containment area which was viewed as both overly conservative and impractical considering the current airspace capacity demands of commercial air traffic.[5] The current study applies an improved vulnerability model for debris impacting commercial transport aircraft. This updated vulnerability model is taken from the RCC 321-07 criterion[6] which defines the vulnerability of commercial transport aircraft by a quadratic relationship between the mass of the impacting debris fragment and the projected vulnerable area of the aircraft. Prior to the institution of this model, the entire area of an aircraft was assumed to be vulnerable to debris as small as 1 gram. By allowing a subset of the area of the aircraft that is vulnerable to the impacting debris fragment to be identified by the previously mentioned quadratic equation, the vulnerability of the aircraft is more realistically represented. The factors determining the consequences of an impact to an aircraft include the fragment mass, shape and material, impact velocity magnitude and direction, aircraft type, aircraft velocity vector, location, and geometry of the impact.[6] Additional research on the impact of debris fragments of aircraft will improve the understanding of the associated consequences. Equation 1 below describes the relationship between the mass (m) of an impacting debris fragment (in grams) and the projected vulnerable area[iv] of a commercial transport aircraft (in ft^2) that could result in a catastrophic event (i.e. an occurrence resulting in multiple casualties, usually with the loss of the aircraft).

$$A_{CAT}^{PROJ} = 0.025m^2 + 4m \tag{1}$$

Equation 1 is valid for impacting debris fragments up to 300 g. For a detailed explanation of the commercial transport aircraft vulnerability model, see references 6 and 14. The risk analysis tool is utilized to determine the probability of an aircraft with projected vulnerable area computed using equation 1 above impacting falling debris, thus creating a set of probability of impact contours. The impact contours are then translated into the aircraft buffer zone by adding the largest distance measured from the launch point to the $1\text{x}10^{-7}$ contour and then to the edge of the operating area. The 1 gram aircraft vulnerability model baseline results for the radius of the commercial transport aircraft buffer zone example are on the order of 40 n.mi. radius. It is expected that the results of the aircraft buffer zone radius for the commercial transport aircraft will decrease with the new vulnerability criterion in place.

[iv] Projected area is in square feet and the mass (m) of the fragment is in units of grams.

C. Wind Conditions at the Launch Site

The wind conditions at the launch site can dramatically affect the aircraft buffer zone size and consequently the flight plan for the proposed rocket launch. As the aircraft buffer zone is sized to protect aircraft against rocket debris that could impact it in the event of a vehicle explosion or breakup, it is important where and when the explosion or breakup occurs. Buffer zones resulting from explosions or breakups occurring at high altitudes that produce large amounts of small fragments can be very large due to the amount of time it takes for the debris to return to the Earth. During this fall time, these fragments can be spread many miles and cause the aircraft buffer zone to increase in size as the wind disperses the debris. If the vehicle explodes or breaks up at a lower altitude, the wind has less time to act on the falling debris, reducing its effects.

The aircraft hazard area computation normally uses the historical average monthly wind conditions obtained from the Global Gridded Upper Atmosphere Statistics (GGUAS). The GGUAS wind data is based on measurements taken over a 15-year time span. The variability of both wind speed and direction across an entire month is relatively large. Accordingly, the uncertainty applied to the GGUAS data in the risk analysis tool is much larger than the measurement uncertainty applied to the day-of-launch observed winds. The risk analysis tool applies both uncertainties using Monte Carlo sampling across three-sigma bounds. Even though the historical average wind speeds may be lower than those observed on the day of launch, the addition of the monthly variability to the GGUAS data produces more conservative winds. The four months chosen for review and comparison are February, July, October, and December. The day of launch wind observations were obtained from the NOAA/ESRL Radiosonde Database website[v] at a location near the proposed launch site and used to replace the monthly averaged winds in the analysis. The aircraft hazard area results for an inland launch site using local day of launch observed wind data in comparison with the historical average monthly wind data are discussed in section 4 of this report.

D. Debris Size

The final study regarding the aircraft hazard area size is the sensitivity to the mass of the debris fragments impacting aircraft. In order to see the sensitivity to the aircraft hazard area size, the debris catalogue that is input into the risk analysis tool was modified for three separate cases and the hazard area was recomputed. For case 1, all debris fragments smaller than 1,000 g were removed from the catalogue. The catalogue for case 2 contained only debris fragments larger than 200 g in mass. And lastly, the debris catalogue for case 3 contained only debris fragments larger than 20 g. Each of these cases modified the original baseline debris catalogue but they are identical in all other aspects. By removing smaller sizes of debris fragments from the catalogue, the aircraft buffer zone size is expected to decrease. The results of this analysis are compared to the baseline case, which contained the original debris catalogue are discussed in section 4 of this report.

III. Ground Buffer Zone

The purpose of a ground buffer zone is to protect densely populated areas and large concentrations of public and property on the ground that are not associated with the launch operation from explosions occurring at or near the operating area boundary. Experimental permit operating areas must be large enough to contain each planned trajectory and all expected vehicle dispersions, but they are not required to contain hazardous fragments generated by a vehicle failure.[vi] During launch, an errant vehicle trajectory can cause the vehicle to impact or breakup at the edge of the operating area, sending debris fragments well outside of the operating area. The ground buffer zone is the additional area outside of the operating area that protects the

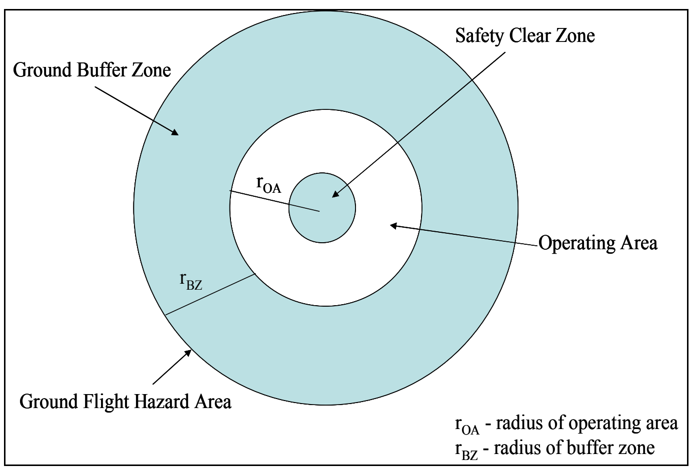

Figure 1. Ground flight hazard area centered on launch point.

[v] http://www.esrl.noaa.gov/raobs

public during these mishaps where large concentrations of people could be at risk of a serious injury or death.

The ground flight hazard area is made up of the safety clear zone, operating area, and ground buffer zone as shown in Figure 1. The radius of the ground flight hazard area is computed as the sum of the distance from the launch point to the edge of the operating area and the distance from the edge of the operating area to the edge of the ground buffer zone. In some rocket launch operations, the safety clear zone is the same size as the operating area, but this does not affect the size of the ground buffer zone as it is still added to the edge of the operating area. Figure 1 shows one representation of a ground flight hazard area, while Figure 2 represents a nonsymmetrical ground flight hazard area.

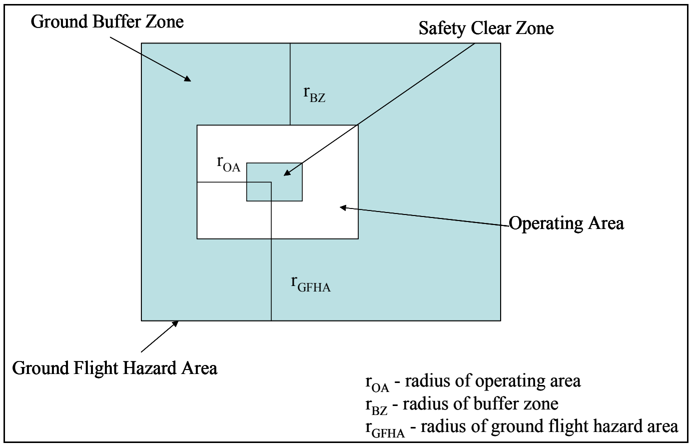

Figure 2. Ground flight hazard area with varying buffer radius.

This section discusses the limitations of two methods used to compute the additional area needed to protect the public. The first method utilizes the Department of Defense Ammunition and Explosive Safety Standards[11] and the second method assumes that the probability of a hazardous debris fragment[vi] impacting a person is no greater than one in a million.

E. Ground Buffer Zone Example Calculation Using DoD Safety Standards

The Department of Defense established uniform safety standards (DoD 6055.9) for the safety of ammunition and explosives during their development, manufacturing, testing, transportation, handling, storage, maintenance, demilitarization, and disposal[11]. The DoD 6055.9 safety standard cautions that the standards represent minimum protection criteria for personnel and property and do not imply full protection from hazards. Additionally, the DoD safety standards for accidental explosions pertain to static systems, and do not directly apply to launch vehicles in flight. Likewise, the DoD safety standards do not directly account the for the type and size of debris generated by a launch vehicle breakup when determining the fragment throw.[7] In the past, the FAA/AST has employed relevant sections of these safety standards when establishing safety clear zones for ground operations. This approach could also be used to compute an additional ground buffer zone outside of a vehicle's operating area for low altitude amateur and permitted flights (below 1,000 ft). As the commercial space flight industry grows, specifically vehicles flying under an experimental permit, larger vehicles flying to near orbital altitudes will increase in number. As will be shown below, for low altitude flights, the DoD safety standards produce conservative ground buffer zones.

The computation of a ground buffer zone using the DoD safety standards has four parts; determine the amount of propellant left as the vehicle impacts the ground at the edge of the operating area, choose the yield factor associated with the vehicle's impact speed, calculate the peak incident overpressure distance (D) and hazardous fragment distance (HFD), and finally define the ground flight hazard area by choosing the larger of the peak incident overpressure distance or the hazardous fragment distance.

1. *Net Equivalent Weight and Yield Factor*

The net equivalent weight (W) is the weight of trinitrotoluene (TNT) that would produce the same explosive yield as the weight of the explosive material being analyzed. Obtaining the W requires the amount of propellant available during the explosive event multiplied by the yield factor. The liquid propellant explosive yield factor is the percentage of the total available explosive material used to compute its net explosive weight of TNT. The value of this parameter depends upon a number of factors, including the types of explosive materials present and the amount of mixing that may occur between the fuels and oxidizers. Test data provides a relationship between the impact speed of the rocket and the yield factor, as shown in the curves in Figure 3 for the appropriate propellant. This example uses RP-1 as the fuel and LO_2 as the oxidizer, totaling 100,000 lb at liftoff.

[vi] FAA regulations define a hazardous debris fragment as having a kinetic energy of 11 ft-lb or greater.

The most conservative estimate of remaining propellant is a full load; thereby giving the largest peak incident overpressure and hazardous fragment distances. For a less conservative and more realistic approach, the remaining amount of propellant is estimated by multiplying the mass flow rate of propellant by the amount of burn time and subtracting this new value from the total propellant load. The burn time is subject to the vehicle's modeled thrust profile, as represented in the permit application. The vehicle is assumed to fly toward the operating area boundary in a manner that would require activation of the flight safety system, terminating the thrust before the vehicle's instantaneous impact point would exit the operating area. The speed at which the vehicle falls and impacts the ground once the flight is terminated correlates to a liquid explosive yield factor (YF) found in Figure 3. The total available propellant weight is then multiplied by the yield factor to compute *W*.

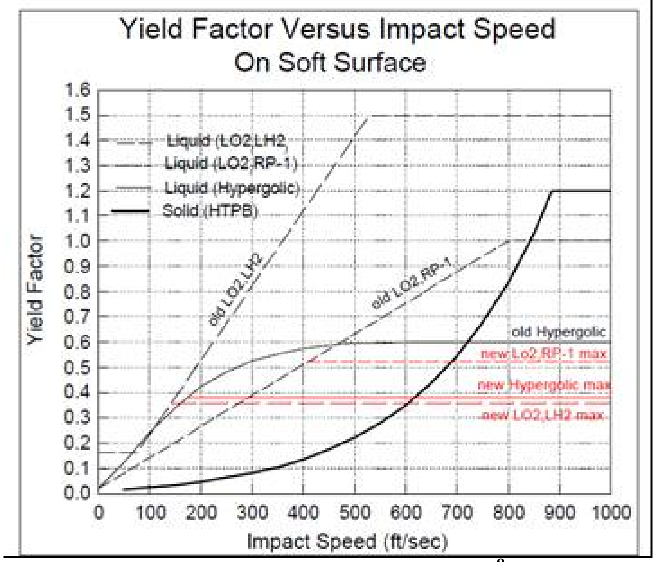

Figure 3. Liquid Propellant Yield Factors.[8]

When determining the maximum planned weight of propellant present during flight operations, it is assumed that the total amount of propellant on the vehicle, not including inert pressurant, corresponds to the maximum propellant load of the vehicle (the combined capacity of the fuel and oxidizer tanks). In this example, the propellant burned during a low altitude flight (assume 25% consumption) is subtracted from the total propellant weight. This approach assumes that during a low altitude flight, the wind effects and imparted velocity on debris fragments generated by an in-flight explosion or breakup are small. Therefore, by modeling an impact of the vehicle on the ground following a successful thrust termination with the resulting fragment throw and overpressure, the DoD 6055.9 safety standards provide a conservative estimate for a ground buffer zone in these conditions. The total propellant weight at impact is 75,000 lb.

To apply additional conservatism, a yield factor characteristic of the worst conceivable accident that may occur during flight operations is chosen from the graph shown in Figure 3. Figure 3 is from a report produced by RTI International that updated the previous work on liquid explosive yield factors completed in 1991.[9] The curves represented in red are the updated values for the liquid explosive yield factors. The curve labeled "LO2/RP-1 max" indicates a maximum yield factor of approximately 0.52 (52%). The next assumption is the use of the maximum yield factor because the impact speed of the vehicle can vary widely based on the circumstances under which the thrust is terminated and can credibly reach speeds above 400 ft/s. After identifying the yield factor and total propellant weight, the net equivalent weight (*W*) is 39,000 lb as shown in the equation (2) below.

$$\begin{aligned} W &= W_{propellant} * YF \\ W &= 75{,}000\, lb * 0.52 \\ W &= 39{,}000\, lb \end{aligned} \tag{2}$$

2. Peak Incident Overpressure Distance

The peak incident overpressure distance (*D*) is the distance measured from the point of explosion at which the resulting overpressure has decreased to the point where people in the open are not expected to be seriously injured. FAA/AST regulations define the threshold overpressure capable of causing serious injury as 1.0 psi. This threshold of 1.0 psi corresponds to a K=45 ft/lb$^{1/3}$ (17.85 m/kg$^{1/3}$). The *K* represents the K-factor and is a scaling factor used to compute the distance corresponding to a particular overpressure, based on the Kingery-Bulmash relationship.[10]

In this example, the vehicle uses propellants classified as hazard division (HD) 1.1. When subjected to a 1.0 psi overpressure generated by a HD 1.1 explosion, unstrengthened buildings can be expected to sustain: (1) damage that approximates less than 5% of their replacement cost, (2) people in buildings are provided a high degree of protection from death or serious injury, and (3) people in the open are not expected to be injured seriously by blast effects, as described in DoD 6055-9. Equation C9.4-3 from DoD 6055-9 is used to compute the peak incident pressure distance for the vehicle and is shown in equation 3 below. The peak incident overpressure distance of 1,526 ft.

$$D = K * W^{1/3}$$
$$D = \left(45 \, ft / lb^{1/3} \right) * (39{,}000 lb)^{1/3} \tag{3}$$
$$D = 1{,}526 ft$$

3. Hazardous Fragment Distance

The hazardous fragment distance (*HFD*) is measured from the point of explosion to the point at which the density of hazardous fragments generated by the explosion has decreased to a level where people in the open are not expected to be seriously injured. FAA/AST regulations do not define an acceptable hazardous fragment density; however the DoD safety standard[11] establishes a hazardous fragment density of 1 hazardous fragment per 600 ft^2 (55.7 m^2).[vii, 7] Equation C9.T2-2 of DoD 6055-9[11] computes the minimum *HFD* to protect the public from primary and secondary hazardous fragments, as shown in equation 4 below. The *W* represents the net equivalent weight in lbs of the propellant at the time of the explosion, and the *HFD* is expressed in units of feet.

$$HFD = -1133.9 + [389 * \ln(W)]$$
$$HFD = -1133.9 + [389 * \ln(39{,}000 lb)] \tag{4}$$
$$HFD = 2{,}978 ft$$

4. Ground Buffer Zone Distance

Lastly, the larger of the hazardous fragment distance (*HFD*) and the explosive overpressure distance (*D*) is chosen as the minimum dimension for the ground buffer zone. For this case, the peak incident overpressure distance is 1,526 ft and the hazardous fragment distance is 2,978 ft. Based on these results, the distance from the edge of the operating area to the edge of the nearest densely populated area or large concentration of members of the public should be no less than 2,978 ft for flights of this vehicle. Likewise, the distance from the launch point to the edge of the ground flight hazard area should be no less than 29,378 ft for this operation; where the distance from the launch point to the edge of the operating area is 5 mi (26,400 ft) and this is added to the 2,978 ft for the minimum dimension of the ground hazard area.

F. Ground Buffer Zone Example Calculation Using Probability of Impact Contour

The second method of computing the ground hazard area and buffer zone uses probability of impact contours, computed assuming that the vehicle explodes or breaks up in flight, to determine the individual risk to people on the ground. This method is based on the report prepared for the FAA/AST by its contractor ACTA Inc.[12] These contours represent the probability of a hazardous debris fragment (a fragment with a kinetic energy of 11 ft-lb[viii] or greater) impacting a person in the open on the ground. The person is represented by an area on the ground of 3 ft^2. The probability of impact contours computed for people on the ground are similar in shape to the aircraft hazard area contours. The $1x10^{-6}$ contour describes the area where a person has a probability of one in one million of being impacted by a hazardous debris fragment assuming the vehicle fails in flight in such a manner that generates falling debris. For high altitude flights and vehicles with large operating areas, this method provides a more appropriate ground hazard area as it accounts for the wind effects and velocities imparted on fragments from the breakup event that can disperse the debris as it falls to the surface.

Similar to the aircraft buffer zones, the experimental permit regulation did not intend for applicants to initially possess the expertise and tools required to compute the additional area needed to protect the public outside of the operating area boundary. The development of these contours requires knowledge of the characteristics of the debris

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[vii] Hazardous fragments according to DoD 6055.9 are those fragments having an impact energy of 58 ft-lb (79 Joules) or greater.

[viii] § 417.107 (c)

fragments generated by a vehicle breakup, the altitude at which the breakup occurs, and the wind conditions post breakup. None of this information is specifically required of a permit applicant in the permit application. For this study, the same debris catalogue used in the aircraft probability of impact contours is applied to the ground probability of impact contours with the exception that the debris pieces are now propagated to the ground. Likewise, the same physics based propagation model of the debris fragments is also utilized for the ground impact contours.

Another unknown is the time in flight that the vehicle breaks up, sending the debris fragments in all directions. Previous research has shown that the higher the altitude at which the breakup occurs, the more extensive the buffer zone becomes in order to protect the public; with the caveat that above 150,000 ft the wind conditions become insignificant in affecting the dispersion of the debris fragments and are instead affected by the additional fall time.[3] Therefore, in order to be conservative, probability of impact contours computed from breakups modeled at a series of different altitudes, with the corresponding debris models, were developed and combined to obtain the set of contours representing the entire flight. The final input needed to develop the probability of impact contours is the wind conditions present during launch. The wind conditions are important to this process because as debris fragments begin to fall back to Earth, the pieces with high lift-to-drag (L/D) ratios can drift further from the explosion centerline. The longer the allowed fall time, the greater the dispersions. The ground buffer zone size sensitivity to different wind conditions is the topic of the next section.

In this study, the sensitivity of the ground buffer zone size to the historical monthly averaged wind conditions versus the observed day of launch wind conditions was examined. Four months of historical data (February, July, October, and December) were sampled in this study. For each month, the GGUAS[13] monthly averaged wind conditions were input into the risk analysis tool to obtain a set of probability of impact contours. In order to produce the probability of impact contours for a specific day of launch, the daily wind conditions are needed. A single day from each of the four months listed above was chosen and the observed wind conditions from that day were acquired from the NOAA/ESRL Radiosonde Database website. Typically, unless the launch site is located at a federal launch range or near a NOAA[ix] weather facility, the radiosonde (weather balloon) data does not extend to altitudes above 30,000 or 40,000 ft. Since the majority of experimental permitted vehicles launch from remote locations across the United States, a southwest weather station was chosen to provide the day of launch wind conditions. As expected, the balloon data received from the weather facility ended at 35,000 ft and the GGUAS monthly averaged winds above 35,000 ft were concatenated onto the observed wind data. Finally, the risk analysis tool produced a new set of probability of impact contours for the four specific days.

IV. Results

G. Aircraft Buffer Zone Results

5. Results on the Allocation of Probability of Failure Study

The results of the study on the sensitivity of the aircraft hazard area to the allocation of P_f showed the expected decrease in radius. By reducing the probability of failure for each state vector from one to one divided by the failure time span, the aircraft buffer zone decreased by approximately 45%. Given the difference between the way in which the probabilities are applied (union combine vs. sum, as described above), the resulting buffer zone radius becomes a complex function of failure probability, making it difficult to estimate. For that reason, further analysis is recommended.

6. Commercial Transport Aircraft Vulnerability Results

The updated version of the aircraft vulnerability model is expected to decrease the aircraft buffer zone due to the fact that the aircraft are assumed to tolerate the impacts of debris fragments larger than 1 gram without causing catastrophic events. The example case utilized the same assumptions and debris catalogue as the previous work with the 1-gram vulnerability model. The aircraft buffer zone decreased in radius as expected by nearly one quarter of the distance, from 43 n.mi. down to approximately 30 n.mi. Each of these cases assumed historical average monthly wind conditions.

[ix] National Oceanic and Atmospheric Administration

7. Results on the Sensitivity to Wind Conditions

The aircraft buffer zone sensitivity to wind conditions was thought to vary more in direction than magnitude as the historical wind data itself tends to vary more in direction than magnitude. The results from this study show that generally this trend holds true. However it is noted that the trend could dramatically change depending on the location of the launch point. An analyst determining the aircraft hazard area must take into account locations prone to severe weather conditions where the day of launch conditions might fall well outside a nominal deviation from

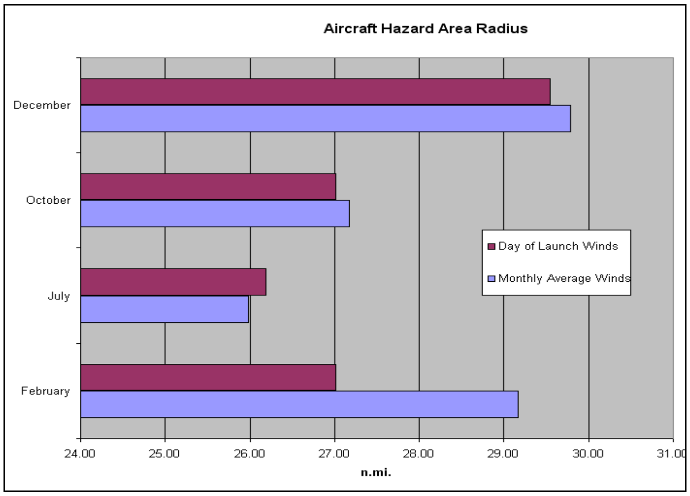

Figure 4. Aircraft Hazard Area Radius for Monthly Average Winds and Day of Launch Winds.

the monthly averages. At the same time, such conditions could violate launch commit criteria imposed for other reasons, such as concerns over vehicle integrity or performance, creating a situation in which the operator would not launch anyway. With these exceptions noted, the results for a southwest launch location indicated the observed day of launch wind conditions did not significantly deviate from the monthly average wind conditions as shown in Figure 4.

Figure 5 displays the second trend when comparing the monthly averaged wind conditions versus the day of launch wind conditions. The figure on the left shows the aircraft hazard area for the historical October monthly averaged wind conditions. The picture on the right is the aircraft hazard area for conditions observed on October 15th. As seen in Figure 5, the day of launch hazard area is smaller in size yet similar in shape. Similar results occurred for each of the other three months.

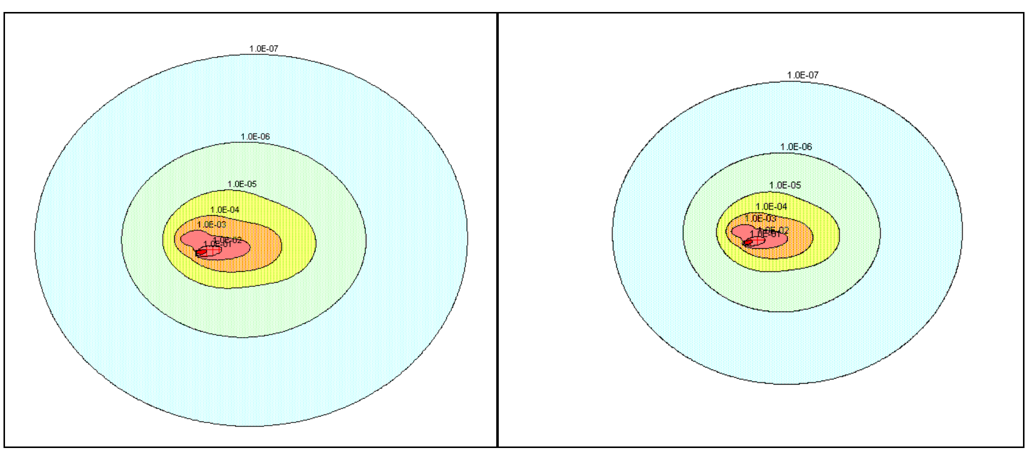

Figure 5. Aircraft Hazard Area with Average Monthly Winds (Left) and Day of Launch Winds (Right).

8. *Results of Sensitivity to Debris Mass Size*

The aircraft hazard area is sensitive to the fragment debris catalogue used in the risk analysis tool. As Figure 7 indicates, a debris catalogue that contains a larger number of smaller pieces generally leads to a larger aircraft hazard area. In Figure 7, the y-axis starts at '1', which corresponds to a debris catalogue containing only debris fragments 1,000 g or larger in mass, and ends at '4', which corresponds to the full debris catalogue that contains both large and small pieces. The aircraft hazard area at different altitudes for the Boeing 747, Cessna Citation X, and Cessna 172 are shown in this figure. The Boeing 747 shows no decrease in aircraft hazard area when the debris catalogue is stripped of all pieces smaller than 20 g. This result is expected as the 747 is analyzed with the updated aircraft vulnerability model for commercial transports which considers pieces larger than 30 g as significant impacts. The Cessna Citation X has the steepest increase in aircraft hazard area from a debris catalogue with only pieces larger than 1,000 g to the full debris catalogue – the percent change is approximately 52%. Of the three aircraft examined, the Cessna 172 is the least sensitive to a changing debris catalogue with a 36% change in aircraft hazard area radius. The general trend for all three aircraft is for the aircraft hazard area to decrease as smaller fragment pieces are removed from the debris catalogue.

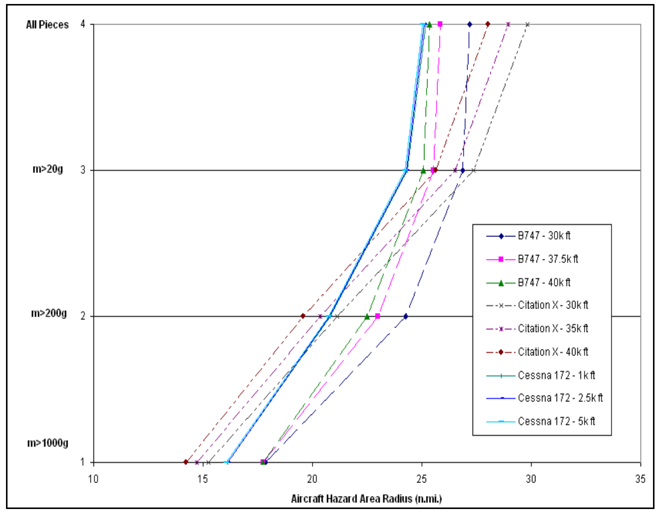

Figure 7. Aircraft Hazard Area Sensitivity Results with Varying Mass Size of Fragments in Debris Catalogue.

H. Ground Buffer Zone Results

Figure 6 shows the ground buffer zone minimum distances for each of the four months analyzed that were computed using the probability of impact contours. February produced the largest distance when observed winds from a single day that month were input into the model. When the monthly averaged winds were input into the model, December produced the largest distance. However, it is noted that all the ground buffer zone distances are within the same order of magnitude and are relatively close in size. Figure 6 shows the graphical effects of the different wind conditions. At the bottom of Figure 6, the ground hazard area for the monthly averaged February wind conditions is displayed. The top displays the same result is shown but with the day of launch wind conditions. The day of launch wind conditions only elongates the already asymmetrical ground hazard area produced by the monthly averaged wind conditions.

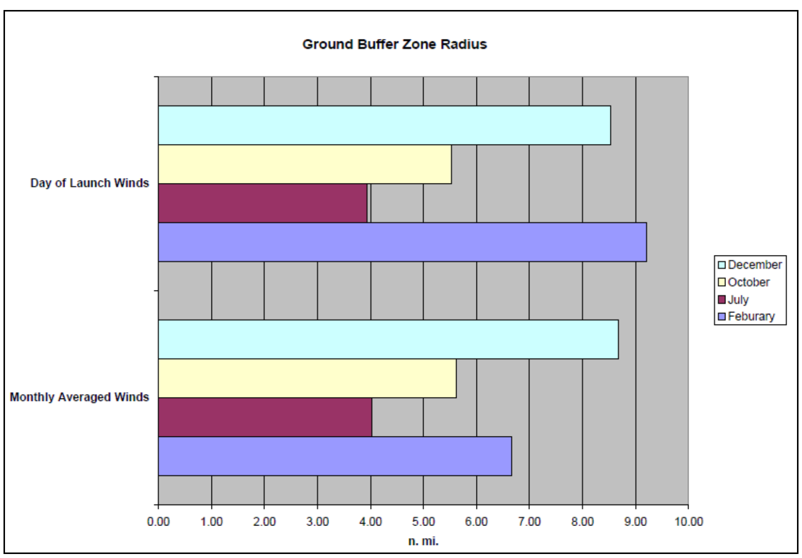

Figure 6. Ground Buffer Zone Radius for Varying Wind Conditions.

To obtain the ground hazard area distance, the ground buffer zone distance is added to the distance from the launch point to the edge of the operating area. However, it is appropriate to extend the buffer only in the direction that the results show that it is in.

V. Conclusion

The probability of failure allocation for an experimental reusable launch vehicle remains contentious. Reducing the P_f of each state vector from one to one over the failure time span decreased the aircraft hazard distance by a factor of 0.45. It is recommended that research on generating credible probability of failure values for new reusable launch vehicles continue so as to better inform the analysis.

As expected, the updated aircraft vulnerability model resulted in a smaller aircraft hazard area. For future aircraft hazard area determinations, the updated model should be used for commercial transport aircraft instead of the overly conservative 1-gram model. This paper also recommends further testing of the vulnerability of aircraft to impacts from rocket debris fragments at various angles of impact to supplement the theoretical work that has been accomplished on this subject.[14]

The sensitivity study on the effects of the wind conditions at the southwest launch site produced two significant results. The first is that the aircraft hazard area size does not significantly change when the day of launch wind conditions are input into the analysis instead of the historical average monthly wind conditions. The second is that the probabilities of impact contours are similar in shape and direction for the day of launch winds and monthly averaged winds. These two outcomes lead to the conclusion that using the historical average monthly wind conditions, with a large uncertainty factor applied to account for their monthly variability, for the aircraft hazard area analysis is a reasonably conservative assumption.

The development of the debris fragment catalogue, a process similar to the development of P_f for an RLV, also contains a substantial number of unknown variables that can affect the number and size of debris fragments. An applicant developing a debris catalogue could assume for its vehicle that it will only break up into large pieces, thereby reducing the aircraft hazard area. This approach, however, is under-conservative and analysts should be wary of debris catalogues without small pieces which could be an indication that the operator is overly optimistic regarding the consequences of vehicles failure modes. The sensitivity of the aircraft hazard area to the number of small pieces in the debris catalogue is considerably smaller than expected. It likely does not produce an order of magnitude change in the final hazard area, but analyses of additional scenarios would be necessary to reach a more definitive conclusion.

Finally, the study on the methodologies for computing a ground hazard area resulted in a proposal for future low altitude and high altitude flights for experimental permitted vehicles. For low altitude flights, the ground hazard area is conservatively computed using the DoD safety standards; however, for high altitude flights, the probability of impact contour method is recommended.

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