REQUIREMENTS FOR WARNING AIRCRAFT OF REENTERING DEBRIS

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ABSTRACT

Approximately 100 large, manmade objects reenter the Earth's atmosphere randomly every year. Reentry heating and loads disintegrates each object into a number of fragments that are spread over a long, narrow footprint. Some of these fragments, with mass totaling from 10 to 40% of the pre-reentry dry mass of each object, survive and are large enough to be a hazard to people and property. This paper considers the risk posed to aircraft by random reentries of space hardware, defines the airspace where falling debris might be encountered after such an event, and estimates the time available to develop and transmit a warning message to aircraft that might be affected. The results suggests that the risk from a random reentry is above the long term acceptable risk *for a flight exposed to such a risk*, but below the short term acceptable risk based on risk acceptability guidelines used by the FAA for other types of threats.

1. INTRODUCTION

The following story could be an interesting starting point for this paper:

> BEIJING, Dec 25, 1996 (Reuters)
>
> A Chinese passenger plane was forced to make an emergency landing after the exterior glass of the cockpit window was cracked by an unidentified flying object at 9,600-meters (31,500 feet), the Yangchen Evening News said.
>
> The object collided with the Boeing 757-200 passenger plane on December 19 on a flight from Beijing to Wuhan, capital of central Hubei province, an edition of the newspaper seen in Beijing on Wednesday said.
>
> The plane...made a successful emergency landing at Beijing's Capital International Airport.
>
> ©Reuters Limited 1996

The shiny object that fractured the windshield of the Boeing jet could have been a bit of debris that survived reentry of a spacecraft or launch stage. Fortunately, this accident occurred in a location where an airport was available for an emergency landing and not over a broad ocean area.

It is evident that events of this type—high-altitude strikes on aircraft by unknown objects—are very uncommon. But given the fact that there are approximately 70 reentries per year of objects over 800 kg worldwide and that from 10 to 40% of the mass of each object is expected to survive the event and fall through the airspace, the probability of an aircraft strike is not zero.

One thing that could be done to minimize the possibility of aircraft striking such debris is to send out a warning to aircraft that a reentry breakup will occur or is occurring and directing them to avoid the airspace where debris fragments are likely to fall. But what is the character of debris from a reentry breakup? Is the reentering object broken into very small, harmless fragments that wouldn't seriously damage an aircraft, or do larger, more dangerous objects survive? How much airspace would be affected by falling debris? What is the actual probability of an aircraft being struck by falling debris and how much warning would be possible and required? This paper provides answers to these questions.

2. SPACE HARDWARE REENTRY

2.1. Reentry Breakup Fundamentals

Most uncontrolled reentries result as the atmosphere slowly drags an orbiting object deeper into the atmosphere. Moving at over 7 km/sec, the object begins to heat as it encounters a steadily increasing atmospheric density. The heating increases as drag lowers the altitude and eventually low melting point materials reach the temperature where they fail. Items made from materials with relatively low melting points, such as composites and aluminum typically fail first, releasing fragments of the satellite to follow their own trajectories. Heating on the primary satellite and on released fragments continues to increase, and aerodynamic deceleration loads also begin to build. Major fragments such as electronics boxes, propellant and pressurization tanks, and other components are released. Deceleration loads build to seven or more times the acceleration of gravity, causing additional failures. Each object is further heated until its velocity drops and the heating and loads diminish. At this point, the original object has been broken into a number of smaller fragments, each falling independently. Much of the structure of the original object, typically aluminum, has melted away; objects made of high melting point materials like titanium, glass, and steel have survived, and even some objects made of low melting point materials have survived because they were released very early in the trajectory and decelerated quickly or they were shielded from much of the reentry heating by other objects. There are competing effects that complicate the prediction of whether a given object will survive to impact or demise. However, reentry heating rates are approximately proportional to the velocity cubed and inversely related to the radius of curvature. Thus, small objects released early in the disintegration process often demise, unless they have low enough density to slow down rapidly.

The major reentry breakup process takes place over a ~5 minute period. Objects that survive the reentry environment continue to decelerate and most will reach a terminal velocity proportional to the square root of their ballistic coefficient at about 18 km (60,000 ft). (Ballistic coefficient is defined as $\beta=W/(C_DA)$, where W is the weight of the object, C_D is its drag coefficient, and A its reference area). From this point, they fall nearly vertically, with their trajectory blown by winds.

As an example, for the 1997 reentry of a 920-kg Delta II 2nd Stage shown in Fig. 1, major breakup was estimated to occur at approximately 78 km altitude, and several fragments, shown in Fig. 2, were recovered. The debris from this reentry was contained within a footprint approximately 760 km long and 33 km wide. Details on this reentry event are given in [1].

Figure 3 shows the downrange and crossrange distributions for the debris recovered after the Space Shuttle *Columbia* accident, and Fig. 4 shows the size distribution. Considerable effort was expended to recover debris from *Columbia*, and approximately 40% of the original dry mass was found and cataloged. For any given reentry, surviving debris is expected to total between 10 and 40% of the original dry mass of the object. The presence of special materials used to shield against reentry heating and a major breakup altitude toward the end of the peak heating period are thought to have contributed to the survival of many small fragments from Columbia.

2.2. Characteristics of Debris Cloud

2.2.1. Launch Stage Reentry

As might be expected the quantity and type of debris surviving reentry depends on the type of body reentering. For example, a reentering rocket stage similar to that shown in Fig. 1 is essentially empty propellant tanks, with a low melting point aluminum framework plus some materials that can sustain high-temperatures. As illustrated in Fig. 2, items that survive reentry of rocket stages include empty propellant tanks, pressurization spheres and rocket motor components, if they are fabricated from higher melting point materials such as stainless steel or titanium, and small, low density fragments separated early in the trajectory, such as that held by the lady (it brushed her shoulder).

Table 1 presents an estimate of the numbers of each fragment type and the range of subsonic ballistic coefficients for debris from a reentry of a rocket stage similar to the Texas reentry event discussed earlier. The total footprint length was 760 km (410 nmi) for this case.

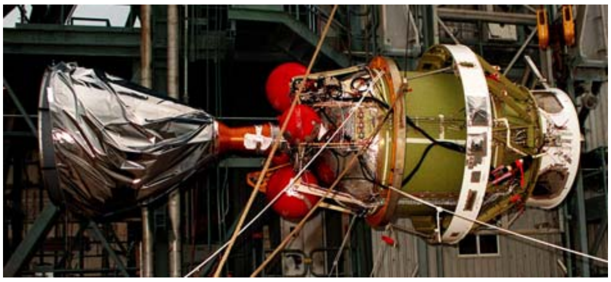

Figure 1. Delta II 2nd Stage prior to launch and reentry (Photo courtesy of NASA).

Figure 2. Debris from Delta II Second Stage reentry: from left: Lightweight fragment, propellant tank, sphere, thrust chamber. Photos courtesy Tulsa World (staff photo by Brandi Stafford), NASA, NASA, Aerojet, respectively).

2.2.2. Spacecraft Reentry

Spacecraft represent a different category as far as the quantity of surviving debris. Spacecraft are generally complex objects with solar panels, extensive internal equipment, mechanisms, electrical motors, batteries, complex fittings, pressurization bottles, and propellant tanks imbedded within a structure encased by an external skin and thermal blankets. Because some spacecraft utilize titanium bolts, fasteners, and structures, and may have instruments with glass and other high-melting-point materials, fragments of these might survive in hazardous sizes. It is also possible that solar panels and lightweight or flimsy elements that are separated early in the reentry might, as a result of their shape and density, largely survive.

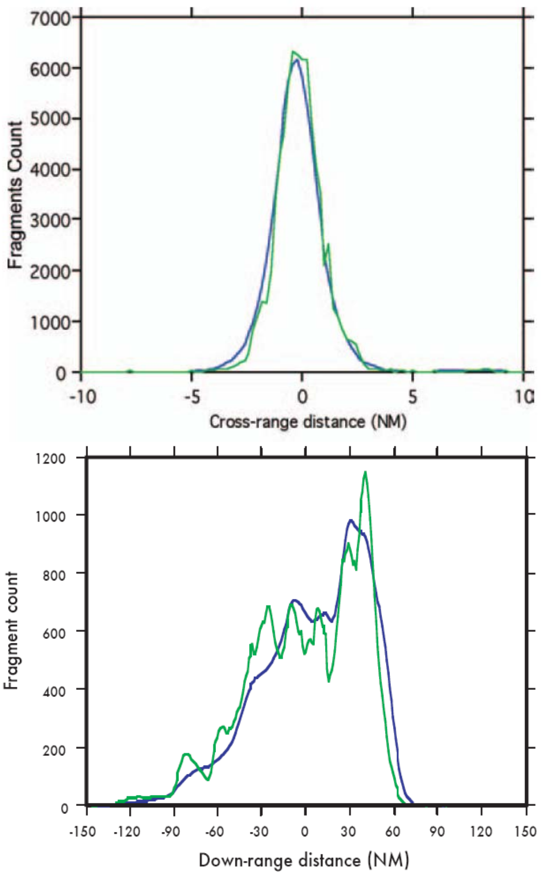

Figure 3. Downrange and crossrange distribution for debris from Columbia accident.

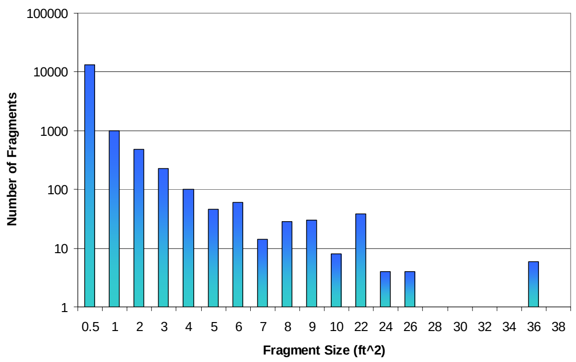

Figure 4. Size distribution of recovered Columbia Debris (note that x-axis is not uniform).

Table 1. Estimate of Number of Debris Items Surviving Reentry of Rocket Stage.

Item Size Range (largest dimension)	**Number of Fragments**	**Ballistic Coefficient Range (psf)**
<1 gm, solid spherical fragments (aluminum and steel droplets, titanium fragments, electrical connectors)	0-100	<25
<5 gm (fabric sheets)	5-20	1-2
<10 gm (miscellaneous fragments)	5	<25
Objects between 10g and 100kg (pressurization tanks, thrust chamber)	5	10-100
> 100 kg (propellant tank)	1-2	50
Total Significant Fragments	**10-30**	

Figures 5 and 6 show the distribution of objects along the ground track that were observed, tracked, and impacted following the reentry of two different spacecraft. Figure 5 includes 16 low ballistic coefficient fragments (ß<5 psf) believed to be remains of the vehicle's skin and internal components, but it is estimated that several orders of magnitude more than that number were actually observed and were significant, but not included on the figure. The figure shows that 29 objects with a higher ballistic coefficient were observed, but perhaps double that number were not included on the figure. The higher ballistic coefficient fragments were most likely remains of structural components, motors, mechanisms, instruments, pressurization spheres, and more dense payload elements.

The footprint length for the event pictured in Figure 5 is approximately 750 km (400 nmi), with very lightweight fragments typically, but not always, falling toward the heel of the footprint. The majority of the debris was observed within a footprint approximately 425km (230 nmi) long. The maximum off-track impact occurred about 6 km from the ground track. No information is available on the day-of-event winds.

Figure 6 also records actual surviving and impacting debris following a spacecraft reentry, and the footprint length for this case, 1960 km (1060 nmi), is somewhat longer, possibly due to the shallower entry angle (closer to an orbit decay type of entry angle) for this case. Once again, the number of surviving objects shown on the figure is much less than what was observed and known to have survived. Since this event is a closer approximation of an actual orbit decay reentry, the nominal length of airspace affected by a randomly reentering object with mass exceeding 800 kg will be assumed to be 2000 km (~1080 nmi).

The observed reentries of Figs 5 and 6 are believed to be representative of what might be expected for any spacecraft not designed to survive reentry. The number of fragments would depend on the materials used for various components, the complexity of the spacecraft (e.g., the components of a more complex spacecraft might shield other components from some fraction of the reentry heating, increasing the likelihood of survival), and the total dry mass of the spacecraft—a heavier spacecraft would yield more fragments (for the purpose of this study, it is assumed that any spacecraft with a dry mass of 800 kg or more would have the fragment distribution given in Table 2). The table includes examples of surviving fragments.

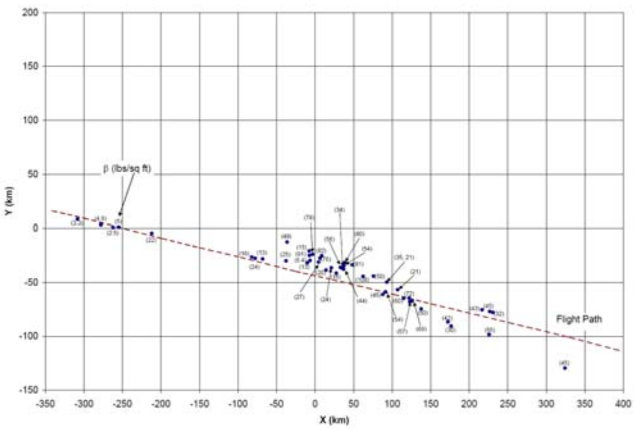

Figure 5. Ground distribution of debris after reentry breakup, Object 1.

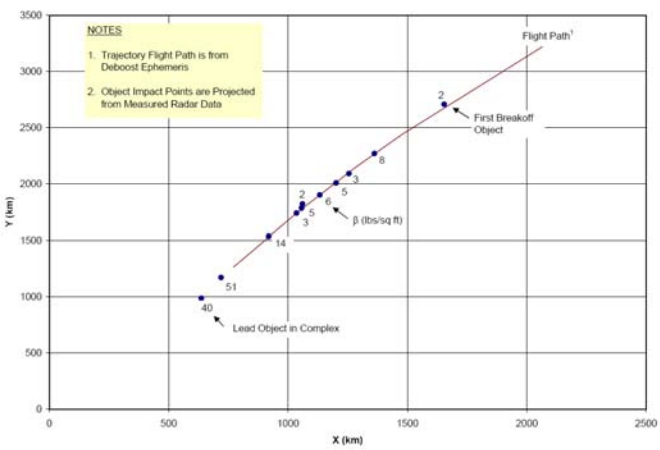

Figure 6. Ground distribution of debris after reentry breakup, Object 2.

Table 2. Debris catalog for reentry of generic spacecraft.

Item Size Range (largest dimension)	**Number of Fragments**	**Ballistic Coefficient Range (psf)**
<1 gm (Aluminum, titanium, beryllium, and steel droplets, electrical connectors and components, etc.)	>1000	1-5
<10 gm (Small aluminum fragments; thin, flat plates; glass fragments, electrical components, batteries, etc.)	100-200	5 to 25
>10 gm (Structural components; pressurization spheres; fragments of higher melting point materials; more dense materials; fragments of mechanisms and protected payload elements)	20-60	25 to 100
Total Significant Fragments	**120-300**	

Using the observed reentry as a model for this study, it is assumed that a reentering spacecraft weighing 800 kg or more will be fragmented into a debris field containing as many as 300 significant fragments. Of course, this assumption relates to the common, unmanned spacecraft. The reentry of the Russian Mir space station likely produced many times this number.

2.2.3. Effect of Winds

The horizontal component of velocity is generally dominated by the winds encountered as the object falls, although lift can produce significant horizontal dispersion. Note that that the 250-kg propellant tank from the Delta II reentry was blown 8 km (4 nmi) from the ground track by winds. In this case, the tank fell through the jet stream on the way down, giving the maximum crossrange dispersion that might be expected for an object of this size and mass. For this study, the width of the airspace potentially including reentering debris will be assumed to be 35 km (20 nmi) on each side of the reentering vehicle's ground track.

2.2.4. Summary: Characteristics of Hazard Zone

Summarizing, the hazard zone for a reentering spacecraft of 800 kg or more is approximately 2000 km (1080 nmi) long, 70 km wide and 18 km high as Fig. 7 illustrates. For a reentering launch stage, the hazard zone length is 1000 km (540 nmi).

2.3. Detection Time vs. Warning Time

The US Air Force maintains a catalog of objects in Earth orbit that is updated periodically with new radar and optical observations and can be used to estimate when an object will reenter (defined as when the object will intersect the entry interface, the top of sensible atmosphere, generally defined to be at an altitude of 120 km or 400,000 ft). Because of uncertainties in the atmospheric density and the orientation and dynamics of the reentering body, reentry prediction using this tracking data have an error of approximately 10 percent in time; that is, if an object is observed and an accurate orbit based on that observation is computed one hour prior to reentry, there is a ±6 minute error in that prediction. Since this object is traveling at orbital speed (~4.1 nmi/sec or ~7.6 km/second), this error translates to an uncertainty in the reentry point of approximately ±1480 nmi (±2740 km), as Fig. 8 illustrates (this is likely an optimistic scenario—without special tasking, good estimates of final orbits are generally not computed within one hour of reentry).

Figure 9 shows the ground locations of possible impact points for debris from an object in a high-inclination orbit based on a prediction made 1 hour before reentry using orbit data updated 1.15 hours before the prediction. The figure assumes an uncertainty in the predicted reentry time of ± 30 minutes; with each tic mark representing a 5-minute shift in the impact point.

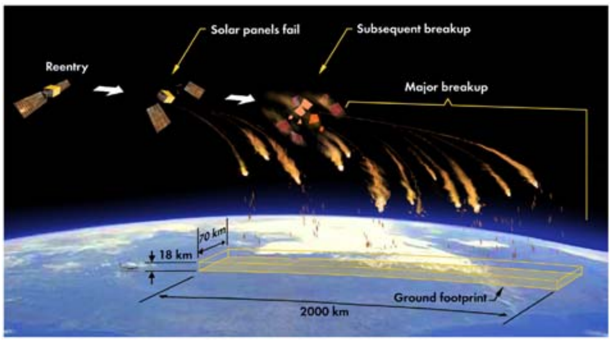

Figure 7. Dimensions of airspace affected by a spacecraft reentry event.

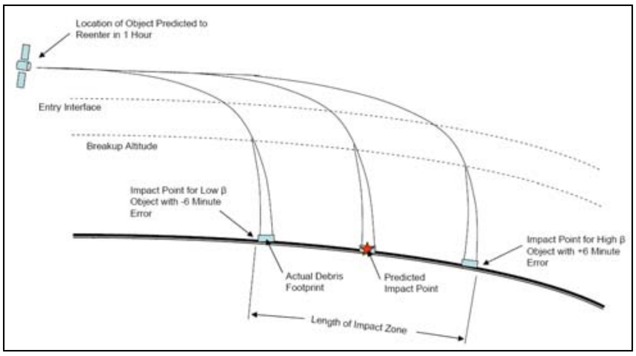

Figure 8. Possible downrange impact points from observation prior to breakup.

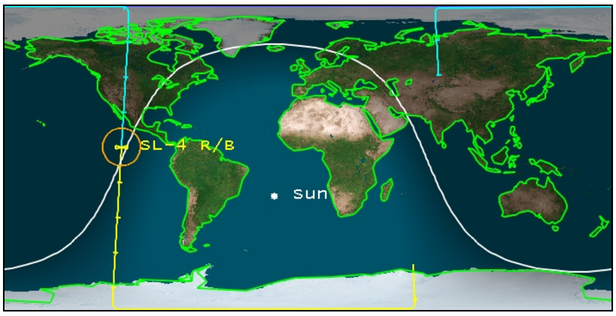

Figure 9. Impact points predicted 1 hour ahead of predicted reentry time (the sinusoidal line marks the day-night boundary; the circle indicates the predicted impact point; the blue line is the ground track before the nominal impact point, the yellow line after).

The uncertainty in the impact zone can be reduced substantially if the object is observed at the primary breakup altitude, as Fig. 10 illustrates. If an object is observed before breakup, no major debris has yet been released, so the predicted impact zone must include uncertainties in the atmosphere, vehicle dynamics, etc., for the remaining time before breakup. After breakup, there is uncertainty as to whether the observed object is at the toe or heel of the debris footprint, and since the objective is to produce a ground impact zone that will contain the debris with a high level of confidence, the possible ground area affected is larger than the actual debris footprint. For these reasons, the observation altitude that produces an affected area that is closest to the actual debris footprint length is the altitude where the object experiences the primary breakup event.

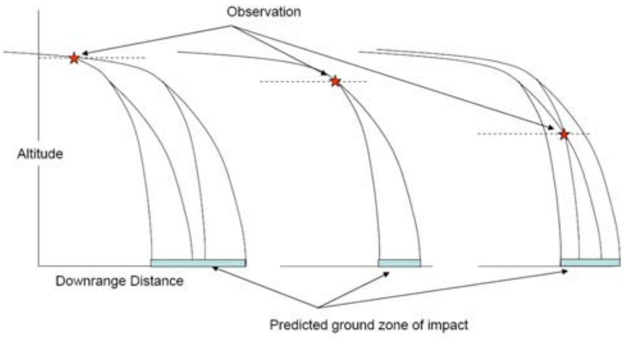

Figure 10. Illustration of effect of altitude of reentering object at observation on the length of the predicted impact zone.

Thus, the best predictions of the airspace to be affected by debris are made if the object is observed during the actual reentry and the prediction is based on trajectory data obtained at the breakup altitude. For example,

Figure 11 shows the footprint for the same reentering object shown in Fig. 11, but based on conditions at a representative breakup altitude of 78 km (42 nmi) [2].

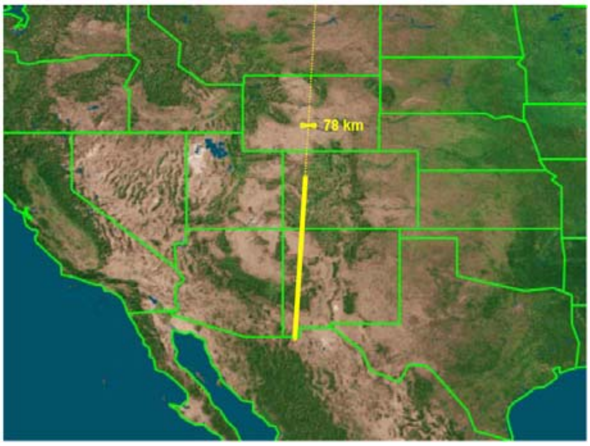

Figure 11. Footprint predicted based on observation at 78 km (42 nmi).

Assuming that the object is observed at 78 km (42 nmi), how long will it take for debris to reach the top of the airspace used by commercial aircraft (18 km or 60,000 ft)? Or said another way: how much time is available in which to determine the impact zone and send out a warning? Figure 12 shows how the time to the top of the airspace varies for the typical ballistic coefficient range considered here. The "pre-breakup" β in the figure refers to that for the reentering object before breakup; the "post breakup" β represents ballistic coefficients of debris fragments. Given a prediction based on an observation of a launch stage (pre-reentry hypersonic continuum β_1=45 psf) at the breakup altitude (78 km, 42 nmi), the time for the first fragment to reach 60,000 ft is 13 minutes from the prediction point. The last fragment (β_2=1 psf) would reach that altitude ~19 minutes from the prediction point. Summarizing, if predicted based on an observation when the object reaches 78 km (42 nmi), threatening fragments could reach the airspace anywhere from 13 to 19 minutes later.

Based on aircraft vulnerabilities, 1 gm cubes of aluminum and stainless steel will be used as a threshold for fatal damage to aircraft. Ballistic coefficients for these cubes would be in the range of 10 to 20 psf or greater, and fragments in this ballistic coefficient range would reach the airspace approximately 10 minutes after breakup, with lower ballistic coefficient fragments that may also threaten aircraft generally arriving over the next 9 minutes or so.

It should be noted that a reasonable range for pre-reentry ballistic coefficients for satellites as well as launch stages is 50 to 400 kg/m^2 (10 to 80 psf). As noted earlier, the Delta II second stage that reentered into Texas had a pre-reentry ballistic coefficient of 220 kg/ m^2 (~45 psf). Many spacecraft have large solar panels, which give the vehicles a much larger reference area and hence, lower β, as the orbit decays. These solar panels will likely fail early in the reentry, and the ballistic coefficient will increase as a result.

Figure 13 shows the amount of time fragments remain within the hazard zone as a function of their ballistic coefficient. As seen, objects with subsonic ballistic coefficients of 10 psf that survive reentry require about 400 seconds to fall from an altitude of 60,000 feet to the Earth's surface. Items with lower ballistic coefficients can take considerably longer.

3. RISK TO AIRCRAFT

Range Commanders Council (RCC) policies and criteria are intended to apply to launch and reentry hazards generated by all aspects of developmental tests, operational tests, and commercial military, and civil flights. All RCC documents are advisory in nature; however, RCC 321 has been cited worldwide in the development of safety policies for civilian [3,4] and military [5] launches. More specifically, the FAA cited RCC 321 in the development of regulations to protect aircraft from commercial launch activities.

The updated version of RCC 321-07[6] includes improved means to quantify the vulnerability of commercial transport aircraft [*] to potential debris impacts[†]. Assuming that the risks to people in aircraft scale linearly with the number of debris pieces and assuming each piece of recovered debris after the *Columbia* accident was capable of producing a catastrophe such as an uncontrolled landing with about 100 casualties, 27 pieces from a random reentry under similar conditions would produce a probability of catastrophe equal to the acceptable limit given by RCC 321-07. Specifically, the roughly 80,000 pieces of *Columbia* produced an estimated 0.3 expected casualties on commercial aircraft only, so 27 pieces from a random reentry under similar conditions (i.e., continental U.S. during a weekend morning) would correspond to a casualty expectation equal to the acceptable limit of 1x10^{-4} given by RCC 321-07, even if only commercial air traffic is considered. The *Columbia* experience indicates that accounting for Visual Flight Rule traffic may lead to at least ten times higher probability of impact on any aircraft. This simple scaling analysis of the data from *Columbia* is

[*] Commercial transport aircraft refers to aircraft that are certified under 14 CFR Parts 23 or 25 and operate in compliance with 14 CFR Part 121 or 135.

[†] RCC 321-07 clearly states that the threshold masses listed in Table 2 continue to apply to all other types of aircraft.

intended to demonstrate that the casualty expectation due to aircraft in the vicinity of a random reentry can be substantial; much more sophisticated methods are necessary (and available) to identify the risk presented by a given reentry [7].

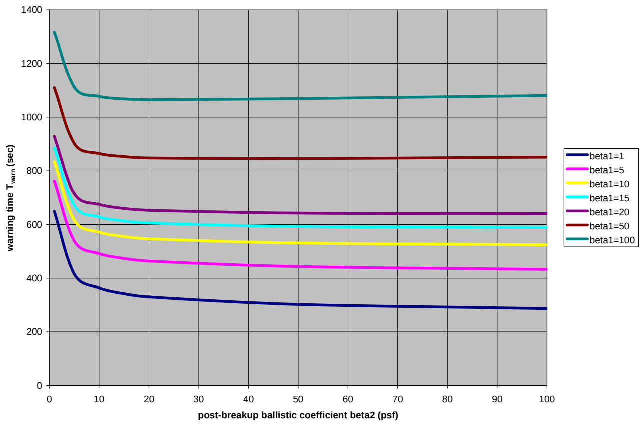

Figure 12. Time from breakup at 42nmi to 60,000 ft (hypersonic ballistic coefficients.

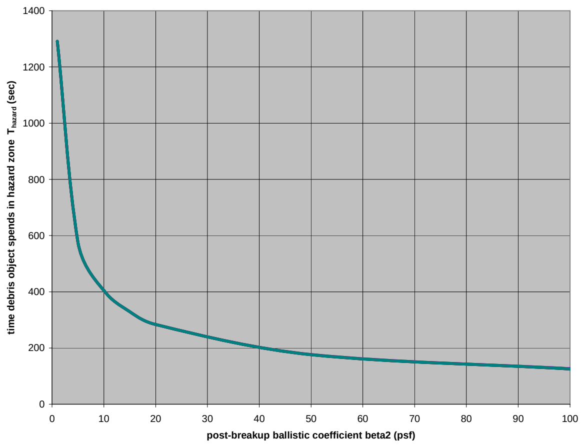

Figure 13. Time objects spend in hazard zone as a function of subsonic ballistic coefficient.

It was concluded earlier that random reentries of satellites larger than 800 kg can yield as many as 300 potentially hazardous fragments and reentering rocket stages and platforms will yield as many as 30 potentially hazardous objects. Based on the discussion above, both reentries could produce enough potentially hazardous fragments to exceed the risk limit given by RCC 321-07 if an aircraft is exposed to the debris field.

Advisory Circular (AC) 39-8 [8] is an FAA guideline used "to identify unsafe conditions and determine when an 'unsafe condition is likely to exist or develop in other products of the same type design' before prescribing corrective action" for transport aircraft. Extrapolation from *Columbia* risk analyses suggests that the risk from a random reentry is above the long-term acceptable risk *for a flight exposed to such a risk*, but below the short-term acceptable risk for a level 4 event defined in AC 39-8 (level 4 guidelines are intended to cover "exposures to the most severe of 'serious injuries' (i.e., life-threatening injuries)"). It should be noted that the FAA has developed and implemented measures to mitigate the risk to aircraft from Shuttle reentries after the Columbia accident [9]. In addition, the FAA has sponsored the development of aircraft vulnerability models necessary to define aircraft hazard areas appropriate for space vehicle debris [10].

A recent analysis [11] estimates that the annual world wide risk of a commercial aircraft being struck with a piece of reentering space debris is on the order of 3 x 10^{-4}. The associated mean time between occurrences of a world wide accident is about 3,300 years. The referenced analysis assumes 100 reentries worldwide per year and 100 hazardous fragments per reentry, roughly the same as predicted here (as a point of reference, [11] quotes a study concluding that the likelihood of a meteor striking an aircraft is between 1.3×10^{-5} and 1.7×10^{-5}).

4. SUMMARY

The purpose of this analysis is to discuss the characteristics of the hazard zone created by falling debris after reentry of a space object. It was found that the typical hazard zone would have minimal dimensions of 70 km wide by 18 km high, and would extend along the reentering object's ground track for approximately 1000 km if the object is a reentering launch stage and 2000 km if the object is a spacecraft. In both cases, a pre-reentry dry mass of the object of 800 kg was assumed as the lower limit for the hazard analysis.

Predictions of the airspace to be affected by the debris would be limited to these minimal lengths (the width and height are unchanged) only if based on observation of the actual breakup, assumed to be at an altitude of approximately 78 km (42 nmi). After breakup, the first hazardous debris will reach the top of the airspace approximately 10 minutes after breakup is observed, so a warning to aircraft should be issued prior to this time. Hazardous debris will be falling through the airspace for approximately 16 minutes after entry of the first fragment into the airspace, so aircraft must avoid this area for approximately 16 minutes.

Many airlines currently have essentially instant message capabilities that could be useful for providing warnings to aircraft. In addition, the FAA is considering possible research into communication, navigation, and surveillance infrastructure that can accommodate spacecraft and other new types of vehicles as an integrated part of the next generation national airspace management system, which could also facilitate rapid warnings related to reentry debris [12].

If a warning system is to be developed, it must have the following characteristics:

1) It must be able to track a reentering object, make a prediction of the hazard zone based on trajectory information developed as close as possible to the object's breakup altitude, and provide a warning to air traffic control of the location of the boundaries of the hazard zone and the start and end times of the hazard period. Depending on the capabilities of the air traffic control system, this information must be generated within minutes of the breakup event. If the reentry is observed, but a specific breakup event is not observed, the prediction should be based on tracking data when the object reaches 78 km (42 nmi).

2) The warning must be sent to aircraft that might be affected by the debris within approximately 10 minutes after the time of the breakup event (or when the object reaches 78 km (42 nmi)).

3) Aircraft must be directed to avoid that hazard zone for approximately 16 minutes.

Comparison with hazards estimated for the Space Shuttle *Columbia* indicate that the general hazards to aircraft are lower than the threshold for short term acceptable events, but exceed the threshold for long term risks for aircraft in hazard areas. The estimated annual world wide risk that a commercial aircraft will strike a reentering debris fragment is on the order of $1x10^{-4}$ and the probability that a single commercial aircraft will strike a debris object is on the order of 10^{-9}.

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