

Aircraft Protection Standards and Implementation Guidelines for Range Safety

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The US range safety community has published consensus standards designed to protect aircraft from potential launch and reentry vehicle debris impacts. Specifically, the current Range Commanders Council (RCC) 321 Standard and Supplement includes requirements to defined aircraft hazard areas to protect aircraft from harmful impacts of debris, planned or unintended, as well as practical guidelines for implementation. This paper provides details on the development and intended application of recent updates to RCC 321, including probabilistic vulnerability models and threshold masses for compact metal fragments capable of causing casualties or a catastrophe on-board commercial transport or transoceanic business jets. This paper also provides insight into the rationale for launch and reentry safety standards intended to protect aircraft occupants from excessive individual and collective risks, as well as catastrophe aversion criteria.

Nomenclature

A_{CAS}^{PROJ}	= projected area of an aircraft vulnerable to a casualty producing event (ft ²)
A_{CAT}^{PROJ}	= projected area of an aircraft vulnerable to a catastrophe producing event (ft ²)
m	= mass of the projectile (Kg unless otherwise noted)
θ	= obliquity: angle between projectile velocity and outward pointing normal to impacted surface (radians)
C_S	= empirically determined shear constant (Pa)
L	= perimeter of the subtended presented area (m)
t	= thickness of the impacted material (m)
V_{50}	= classically defined as the impact velocity with a 50% probability of penetration
ψ	= approach angle of debris: between projectile velocity relative to aircraft and horizontal (radians)
ρ	= density of projectile material (Kg/m ³)

I. Introduction

THE Federal Aviation Administration (FAA) requires (in 14 CFR 417.107(b)) that a launch operator to “establish aircraft hazard areas that provide an equivalent level of safety to that provided by aircraft hazard areas implemented for launch from a Federal launch range.”¹ The FAA treats the requirements and guidelines for aircraft protection published by the Range Commanders Council (RCC) in the consensus based 321-07 Standard and Supplement on “Common Risk Criteria Standards for National Test Ranges”² as the best available expression of how to “provide an equivalent level of safety to that provided by aircraft hazard areas implemented for launch from a Federal launch range.” The aircraft protection measures put forward in RCC 321-07 include probability of impact limits for “debris capable of causing a casualty,” as well as individual, collective, and catastrophic risk acceptability criteria for launch and reentry vehicle operations.² Since RCC 321-07 requires that individuals in aircraft (ships and other vehicles) be accounted for in the computation of the collective risk from a mission, the vulnerability and hazard areas (i.e. keep-out zones) established for aircraft are best viewed as vital elements of “a

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common set of range safety policies, risk criteria, and guidelines for managing risk to people and assets during manned and unmanned flight operations”² that include explicit quantitative risk acceptability criteria for both the general public and mission essential personnel, debris injury thresholds for unprotected people, vulnerability models for large commercial transport aircraft, and debris hazard thresholds for various classes of aircraft and ships.

The FAA’s Office of Commercial Space Transportation (AST) was established, at least in part, to facilitate safe and efficient sharing of the National Air Space (NAS) by launch and reentry vehicles as well as aircraft. AST recognizes four major elements of the approach to aircraft protection from launch and reentry vehicle hazards:

1. Risk acceptability criteria to establish an appropriate level of protection for aircraft potentially threatened by launch or reentry vehicle debris impacts.
2. Aircraft vulnerability models to quantify the areas of aircraft expected to produce an undesirable outcome given debris impact, such as a casualty due to penetration of the fuselage or an uncontrolled landing following a ruptured fuel tank,
3. Launch or reentry debris dispersion models to quantify the probability of a debris impact on aircraft flying in the vicinity of a launch or reentry, and
4. A system to alert aircraft to launch or reentry vehicle debris hazards and rapidly clear threatened airspace in real-time.

This paper focuses on the development and application of the first two of these elements, with some discussion of how these influence the last two. Aircraft protection during launch and reentry is currently accomplished primarily by activation of special use airspace associated with federal ranges, such as the large Special Use Airspaces activated during a Space Shuttle launch, and issuance of Altitude Reservations (ALTRVs) or Notices to Airmen (NoTAMs) that “encompass the volume and duration necessary to protect from each planned debris release[‡] capable of causing an aircraft accident.” (Quote is from paragraph 3.3.3 of Ref. 2.) In the event of a mishap, current practice² includes notification to the FAA of the region potentially threatened by debris. In response to the *Columbia* accident, the FAA implemented a system to clear aircraft from airspace threatened in the event of a Space Shuttle break-up during reentry. The FAA may expand the current real-time aircraft warning system, which applies strictly to Space Shuttle reentries and is based on containment for debris that exceeds the certain aircraft vulnerability thresholds, to more efficiently integrate launch and reentry vehicles into the NAS³ without compromising safety by activating aircraft hazard areas based on a probabilistic analysis of debris fields in near real time.⁴ Whether aircraft protection from launch or reentry vehicle hazards is achieved through current means or using a system to rapidly clear threatened airspace based on a near real-time probabilistic analysis,⁵ the risk acceptability criteria and aircraft vulnerability models described below are essential building blocks.⁴

II. Aircraft Protection Standards for Launch and Reentry

The FAA formally identified two policy goals regarding risk acceptability criteria and aircraft protection during the rulemaking for Title 14 Code of Federal Regulations (CFR) Part 431:⁶

- 1) the requirements “accomplish the regulatory objective of ensuring that persons in the vicinity of a reentry site or designated landing location for an RLV or reentry vehicle are not exposed to greater than normal background risk,” and
- 2) “consistent application to RLVs of FAA safety requirements would also ensure that launch concepts involving multi-stage vehicles, comprised of wholly or partially reusable stages, would not expose the public to greater risk than that defined as acceptable by the FAA in other commercial space transportation regulations.”

To meet these regulatory objectives, the FAA may formally adopt risk acceptability criteria and aircraft protection requirements that are (1) commensurate with the background risks voluntarily accepted by people in flight, and (2) equally applicable to launch and reentry vehicles that are expendable or reusable. It is important to note that the RCC 321-07 requirements express essentially the same policy objective in terms of background risks: that “the general public should not be exposed, individually or collectively, to a risk level greater than the background risk in comparable involuntary activities, and the risk of a catastrophic mishap should be mitigated.” (Quote is from paragraph 2.2.1 of Ref. 2.)

The aircraft protection standards in RCC 321-07 appear to be commensurate with the background risks associated with aircraft flight based on the currently available data. For example, RCC 321-07 (paragraph 3.3.1 in Ref. 2) requires that non-mission aircraft (i.e. those not operated in direct support of the launch or reentry) must be restricted “from hazard volumes of airspace where the cumulative probability of impact of debris capable of causing

[‡] Planned debris releases includes intercept debris, jettisons stages, nozzle covers, fairings, inter-stage hardware, etc

a casualty on an aircraft exceeds $0.1E-6$ ($1E-7$).” Data from the NTSB aviation accident database indicated an average of eight fatal accidents for every ten million departures of US air carriers (operated under 14 CFR Part 121 or scheduled flights under Part 135) during the 20-year period from 1984 to 2003.⁷ The data behind these estimates intentionally excludes incidents involving sabotage or suicide, since these are not considered accidental, even though those incident do contribute to the background risk for aircraft occupants. The “background risk” accepted by occupants of US general aviation aircraft appear to be significantly higher than commercial passengers. Data from the NTSB aviation accident database indicates that the probability of a fatal accident per departure of aircraft operated under Part 91 was about $8E-6$, or about ten times higher than that for commercial aircraft passengers during the same 20-year period. However, the estimated background risk for general aviation is more uncertain due to the relatively uncertain data on the number of general aviation departures compared to commercial flights. Since “casualties” is used in the range safety community to refer to serious injuries or worse (including fatalities), the background risks of approximately $8E-7$ and $8E-6$ fatal accidents per departure of commercial transport and general aviation aircraft, respectively, both of which exclude incidents involving sabotage or suicide, appear commensurate with the RCC 321-07 requirement to protect aircraft to no more than $1E-7$ cumulative probability of impact of debris capable of causing a casualty on an aircraft. Thus, the aircraft protection requirements in RCC 321-07 are commensurate with the background risks voluntarily accepted by members of the flying public.

Not surprisingly, the available data also show that the “background risk” accepted by a passenger on a commercial transport flight appears to fall between the long and short term acceptable risk levels identified in an FAA guideline intended “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 commercial transport aircraft.⁸ Specifically, AC 39-8 is aimed at the assessment of the risk of unsafe conditions associated with the power

plant or Auxiliary Power Unit (APU) installations on transport category airplanes. However, the general concepts, safety goals, and definitions (especially for the consequences of concern) presented in AC 39-8 are considered relevant to the development of standards for protection of the flying public from launch and reentry vehicle hazards. For example, AC 39-8 recognizes “that acceptable risk levels should be regarded as upper limits, to be allowed only when reducing the risk further would result in undue burden.” This FAA guideline appears to be equivalent to the general preference for complete containment or elimination of hazards reflected in RCC 321-07 policy also: “all ranges must strive to achieve complete containment of hazards resulting from both normal and malfunctioning flights.”⁸ AC 39-8 also provides short term acceptable risk levels that equate to where “the malfunction is beginning to contribute more risk than the aggregate risk from all other causes, including contributions from the crew.” Specifically, AC 39-8 identifies the probability of no greater than $4E-6$ for a “level 4 event” as a short term acceptable risk for each flight. Level 4 events defined in AC 39-8 include serious injuries or worse (i.e. casualties), hull loss when occupants were on-board, and forced landings. AC 39-8 uses the NTSB definition of serious injuries; however, “the level 4 risk guidelines are intended to cover exposures to the most severe of ‘serious injuries’ (i.e., life-threatening injuries).” Therefore, the level 4 event guideline may be relaxed if only non-life threatening injuries are involved, such as simple bone fractures. AC 39-8 identifies a probability of no greater than $1E-9$ for a “level 4 event” as the long term acceptable risk for each flight. Clearly, compliance with the $1E-7$ probability of impact criterion given in the RCC 321-07 Standard will ensure that no aircraft are exposed to unacceptable short term risks as defined in AC 39-8. Furthermore, exposures to risks from launch or reentry debris hazards are rare and fleeting events, lasting only a matter of minutes for a relatively small number of flights.⁶ Therefore, limiting non-mission

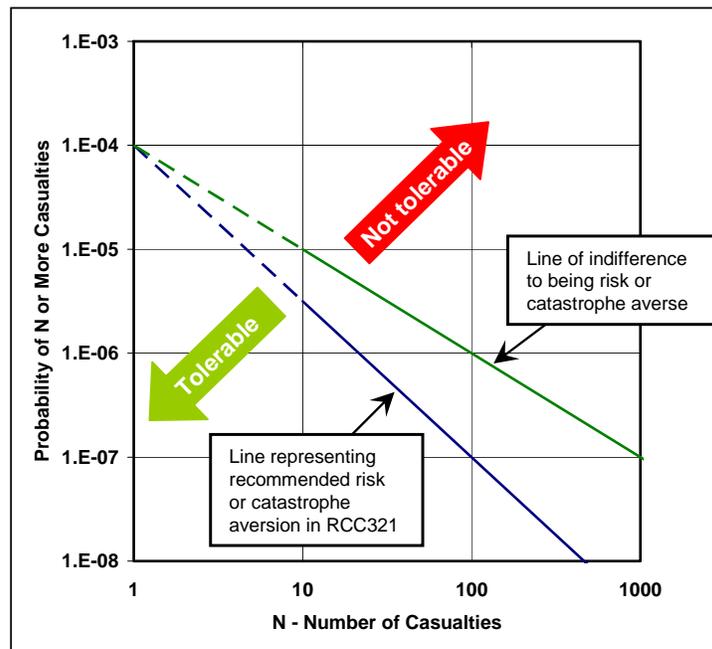


Figure 1. Risk Profile for Catastrophe Aversion.

aircraft to regions where the probability of impact with debris capable of producing a casualty on an aircraft does not exceed $1E-7$ appears to ensure reasonable aircraft risks based on the FAA guidelines given in AC 39-8.

RCC 321-07 included a provisional requirement to limit the probability of high consequence events (also referred to as catastrophic events): an occurrence resulting in multiple casualties, usually with the loss of the aircraft as defined in AC 39-8. RCC 321-07 also included a policy objective that “the risk of a catastrophic mishap should be mitigated.” RCC 321-07 recommended catastrophic risk aversion[§] to protect against incidents involving multiple casualties, for example loss of a bus, ship, or aircraft and demonstrate that the risk of a catastrophe is sufficiently mitigated. Specifically, RCC 321-07 presented a risk profile to identify progressively lower risk levels as acceptable for events associated with increasing numbers of casualties as shown in the Fig. 1: a “catastrophe averse” line to define acceptable risks for events expected to cause multiple casualties. RCC 321-07 did not formally define a catastrophic accident. However, OSHA promulgated a formal definition of catastrophe in 29 CFR 1960.2: “an accident resulting in five or more agency and/or non-agency people being hospitalized for inpatient care.” Santa Barbara County, CA uses a minimum number of 10 people to define a catastrophe, which explains why the RCC 321-07 Standard showed a dashed line for 10 or less casualties in the acceptable catastrophe risk profile in Fig.1.

The risk profile shown in Fig. 1, which identifies potentially acceptable risk levels for high consequence events, was put forward in RCC 321-07 on a provisional because (1) catastrophe aversion is not yet commonplace at U.S. ranges, (2) the RCC wanted to allow time to experiment with catastrophe aversion before adopting a permanent requirement, and (3) it would be better to have additional rationale for permanent catastrophe aversion requirements. Even so, compliance with the catastrophe protection requirements of RCC 321-07 also appears to ensure reasonable aircraft risks based on FAA guidelines given in AC 39-8.

III. Aircraft Vulnerability Modeling for Launch and Reentry Debris Impact Hazards

The FAA-AST co-sponsored the development of vulnerability models for debris impacts on civilian aircraft along with DoD partners. These efforts produced greatly refined Aircraft Vulnerability Models (AVMs) for Commercial Transport (CT) and long range Business Jet (BJ) aircraft compared to the one gram steel fragment threshold adopted in the early versions of RCC 321.¹⁰ The present CT and BJ class AVMs, which are intended for range safety use, are based on the best available information, methods, and reasonably conservative assumptions made in areas where there was no conventional approach or un-quantified uncertainty. For example, the impacting object is assumed to be a compact metal fragment such as a solid sphere, solid cube, or a solid cylinder with a small aspect ratio. Also, these AVMs assume that fragments are falling at speeds near the terminal velocity at aircraft altitudes, which may be twice the terminal velocity at ground level, and that the exposed aircraft are operating near their maximum cruise airspeeds. The methods used to develop these AVMs were subject to independent review by recognized experts.¹¹ Thus, these AVMs are considered valid for use in the development of aircraft hazard areas designed to comply with the RCC 321 Standard.² However, there remains considerable uncertainty about the AVM results because of the lack of test data on impacts at highly oblique angles, which are clearly important to the vulnerability of CT and BJ aircraft. Thus, the FAA-AST has sponsored a series of impact tests aimed at improving the penetration equations that underlay these AVMs. Furthermore, these AVMs make conservative assumptions with respect to the consequence of a debris penetration due to a lack of detailed information about the location and vulnerability of critical systems, etc, which are also described below. Thus, there appears to be some potential to leverage past work done for military aircraft vulnerability assessments to refine the estimated consequences of a given debris impact on various types of civilian aircraft.

The FAA-AST has engaged the DoD’s aircraft vulnerability community and other elements of the FAA with the intent to learn from experts in the field, and apply/adapt their tools and analyses to better determine the vulnerability of civilian aircraft to debris impact. There are relatively sophisticated and mature methods available to perform impact vulnerability assessments for the military, and some of those assessments have been performed for military equivalents of civilian aircraft. For example, the US Navy has performed such an assessment for the P8, which is essentially a militarized B737. Unfortunately, the military’s vulnerability assessments cannot be applied directly to ensure aircraft protection from launch and reentry vehicle debris, whether generated intentionally such as jettisoned components or unintentionally, because they treat the impacts of bullets or warhead fragments: shaped projectiles

[§] In academic literature,⁹ the term *risk averse* is almost equivalent to the term *catastrophe averse*. In both cases resistance to accepting multiple casualties grows non-linearly with the number of potential casualties. The difference between the two is that risk averse is for all N for $N \geq 2$ and catastrophe averse is for all N above a higher starting number such as 5 or 10. Catastrophe averse is a subset of risk averse. The background for the criteria by the RCC can be found in Section 5.5 of Ref.2.

that generally impact at rather high velocity. Whereas a typical irregular shaped debris impact from a launch or reentry vehicle would be expected to occur at a velocity near 800 fps relative to a CT aircraft, the military threats impact at a much higher relative velocity. Thus, military aircraft vulnerability assessments use penetration equations that are likely inappropriate for impacts by irregular shaped debris at relatively low velocities. Also, the input data necessary to characterize the location and vulnerability of critical systems, which were already developed for several militarized versions of CT aircraft, appear to be unavailable without approval from the aircraft manufacturers.

Several previously published papers also have described various aspects of the development and application of the AVMs intended for range safety use. For example, Ref. 12 presented event trees and flow charts that were foundational to these efforts, as well as evidence showing that mitigation of the hazard posed to aircraft by launch debris is often possible because there is a delay of several minutes following an accident before impacts with aircraft are possible. Also, Ref. 5 identified the nature of the threat to aircraft posed by debris from reentries, suggesting that the risks to aircraft are lower than the threshold for short term acceptable events, but exceed the threshold for long term risks for aircraft in the hazarded areas. Ailor and Wilde⁵ estimated that the annual world wide risk that a commercial aircraft will strike a reentering debris fragment is on the order of $1E-4$ and the probability that a single commercial aircraft will strike a debris object is on the order of $1E-9$. Very significant to the following discussion was that finding published in Ref. 13 about the importance of substantially oblique impacts to the AVMs developed for range safety use. Specifically, Draper and Wilde found that impacts to the fuselage and top of the wing fuel tanks by fragment masses in the range of greatest interest, which are at the heart of the predicted vulnerability to casualty and catastrophe producing events as described below, are predicted to occur at obliquities between 70 and 80 degrees.

The AVMs developed for range safety use a modified form of a penetration equation developed by the FAA to assess the threat posed by fragment from an uncontained engine failure, such as turbine blades. The FAA's Aircraft Catastrophic Failure Prevention Program (ACFPP) was created after the 1989 Sioux City Accident.^{**} The mission of the ACFPP is to conduct research that will reduce the risk of catastrophic aircraft accidents and fatalities, and their primary focus has been on uncontained engine failure research. The FAA also sponsored the development of the Uncontained Engine Debris Damage Assessment Model (UEDDAM). The UEDDAM software was developed to address an industry-FAA need for an analytical tool capable of conducting rotor burst assessment that incorporates fragment penetration, system level hazard assessment, and multiple debris fragments. UEDDAM was developed as a design tool capable of conducting aircraft configuration trade studies and as certification tool to show compliance with 14 CFR 25.903(d)(1). UEDDAM is based on vulnerability assessment codes used in industry during aircraft design and development to minimize the vulnerability of military aircraft to ballistic threats. The FAA published the results of a study of generic commercial transport aircraft using UEDDAM,¹⁴ as well as an assessment of the potential consequences of the impact and penetration of fuel tanks by debris from uncontained engine failures on commercial jet aircraft.¹⁵ Those studies were instrumental in the development of the AVMs published in RCC 321-07.^{2,11} However, they were not entirely sufficient because uncontained engine fragments threaten a relatively limited region of the aircraft (e.g. near the plane where the turbine blades rotate) and impact with a different geometry as described below.

B. Penetration Equation

The FAA penetration equation "probably originated from the formula for calculating the force required to punch a round hole in a sheet of metal" but the exact origin of this equation "is not fully known".¹⁶ Even so, a derivation with the assumptions apparently implicit in this equation can be explained as follows based on the complete description provided in Ref. 16. The FAA penetration equation uses a combination of physics, an empirically derived constant, and the following two assumptions:

- 1) The minimum energy required for penetration is equivalent to the energy required to shear a out a "plug" of the impacted material as illustrated in Fig. 2, and

^{**} The 1989 Sioux City accident involved a DC-10 flight (United 232) from Denver to Chicago on July 19, 1989. Fragments generated from the failure of the tail engine damaged all three hydraulic systems and some of the tail control surfaces. The accident produced 100 fatalities because the crew was unable to move any of the control surfaces and had only the engine power of the left and right engines to control the aircraft. The crew managed to touch down near the beginning of a runway centerline. However, a wingtip hit the ground just prior to the landing gear, pulling the aircraft sideways. The excess airspeed and high sink rate on approach caused the aircraft to break up on impact, igniting a huge fire. Despite high speed break-up and fire, 185 people survived the accident.

- 2) The normal component of the impact velocity is the only source of kinetic energy relevant to the minimum energy required for penetration, which is the energy required to shear out a “plug” of the impacted material as illustrated in Fig. 2.

These assumptions lead to the following equation:

$$\frac{1}{2}m(V_{50} \cos \theta)^2 = C_s L t^2 \quad (1)$$

where the left hand side represents the kinetic energy associated with the component of the projectile velocity normal to the target surface and the right hand side represents the mechanical work necessary to shear out a plug of the target material. Thus, the FAA equation for the ballistic limit, V_{50} , defined as the minimum velocity where a penetration occurs is:

$$V_{50} = \sqrt{\frac{2LC_s t^2}{m \cos^2 \theta}} \quad (2)$$

where

m = the mass of the projectile (kg);

θ = the obliquity (radians): the angle between the projectile velocity and the outward pointing normal to the impacted surface;

C_s = an empirically determined shear constant (Pa), which is roughly correlated with classical material properties as described most recently in Ref. 16 and Ref. 17^{††};

L = the perimeter of the subtended presented area of the projectile (m): in the case of impacts with obliquity this is the area of the projectile normal to the velocity at impact and projected onto the target (e.g. roughly the perimeter of the hole in the target as discussed below);

t = the thickness of the target material (m).

V_{50} is classically defined as the velocity where there is a 50% probability of penetration. However, the FAA penetration equation is deterministic and intended to provide a conservative estimate such that no penetration is predicted for impacts at velocities less than V_{50} , and penetration is predicted for impact velocities greater than V_{50} .

The FAA penetration equation as presented above uses the perimeter of the subtended presented area of the projectile. The perimeter of the subtended presented area of the projectile can be visualized as the shadow the projectile would cast on the target given a beam of light aligned with the path of the projectile. For a spherical projectile, the perimeter of the subtended presented area increases as follows with obliquity.

$$L = 2d \left(\frac{1}{\cos \theta} - 1 \right) + \pi d \quad (3)$$

Thus, the use of the perimeter of the subtended presented area of the projectile infers that the energy required for penetration increases with obliquity.

The AVMs developed for range safety are based on modified form of the FAA-JTCG penetration equation that conservatively uses:

- 1) a shear constant equal to 210 MPa that was empirically derived for impacts thin plate made of aircraft aluminum only,¹⁸ although thicker plate impact tests conducted later led to a revised value of 276 MPa for this parameter,¹⁶
- 2) the minimum perimeter of the projectile presented area, regardless of obliquity, instead of the perimeter of the subtended presented area of the projectile, and
- 3) an important modification to the obliquity term as explained below.

The AVMs appropriately use the more conservative value for the shear constant because the most vulnerable parts of CT and BJ class aircraft (e.g. the fuselage) are covered by skin with thicknesses that measurement showed¹¹ are often even less than the plates impacted in the tests.¹⁸ The modifications to the FAA penetration equation were made in light of scant data available from tests with impacts at significant obliquity as described below. The available data appeared insufficient to justify the potential non-conservatism associated with the use of the perimeter of the subtended presented area of the projectile. However, the data justified the modification to the obliquity term explained below.

^{††} The most recent analysis of the test data¹⁶ determined that it is better to refer to a shear constant (s) rather than a dynamic shear modulus (G_d) as previously reported in Ref. 18.

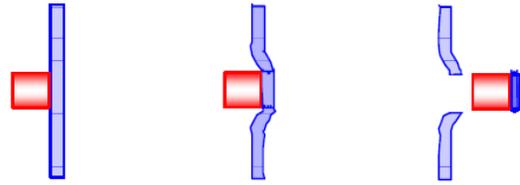


Figure 2. “Plug” Penetration of a Flat Plate.

One of the primary assumptions associated with the FAA penetration equation, and commonly accepted in the impact analysis community, is that “the normal component of the impact velocity is the only source of kinetic energy relevant to the minimum energy required for penetration”.¹⁶ If this assumption were always true, then the ballistic limit would always vary as the cosine of the obliquity angle. However, this relationship is not always true for all impacts as shown in Fig. 3 and explained below.

While relevant data at high obliquities are limited, there are some highly relevant data to show the influence of obliquity on the ballistic limit for 1g steel sphere impacts on 1/16th inch aluminum plates.^{19,20} If the ballistic limit varied only as a function of the cosine of the obliquity, the perpendicular component of the impact velocity at the ballistic limit for a high obliquity impact should be equal to the ballistic limit of a normal impact. Figure 3 shows this is not true based on the data presented in Refs. 19 and 20.

In Fig. 3, the dashed line identifies the impact velocity of a normal impact, while the red ticks along the red line identify the perpendicular component of the impact velocity at the ballistic limit for each obliquity based on the available test data. The assumption of a direct relationship between velocity at the ballistic limit and the cosine of the obliquity is non-conservative where the normal component of the impact velocity at the ballistic limit derived by test data is below the ballistic limit of a perpendicular impact. When this condition exists, the data indicates that

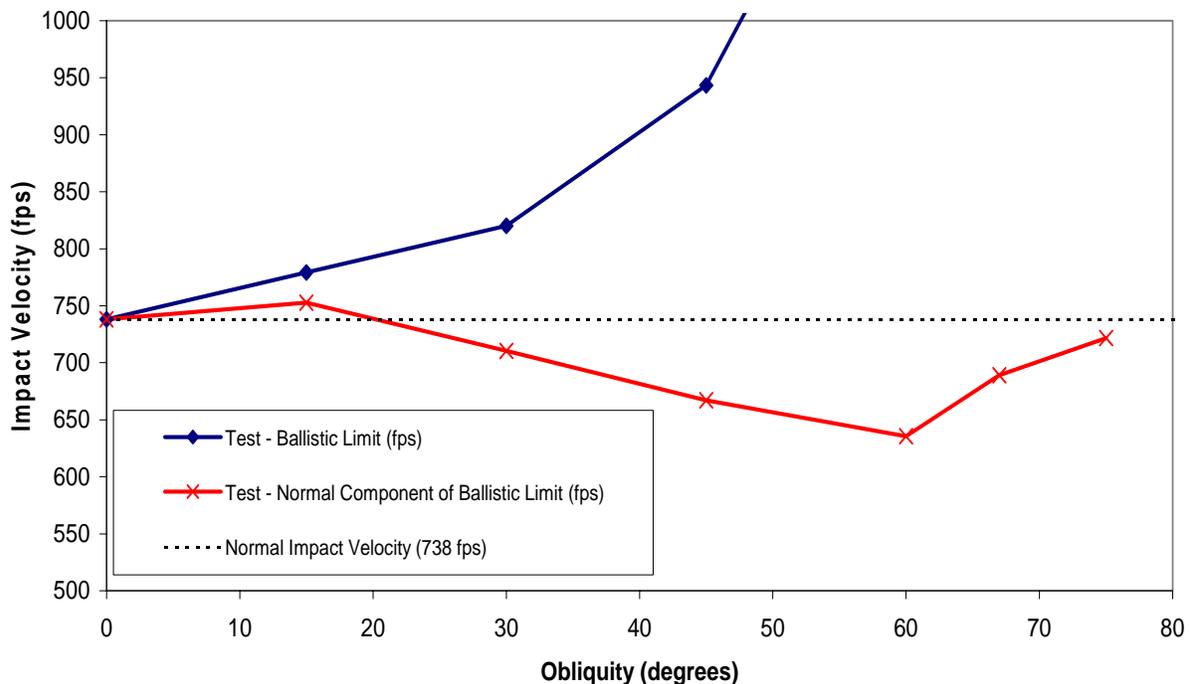


Figure 3. Ballistic Limit and Normal Velocity Component at Various Values of Obliquity.

penetration would occur at a velocity lower than that predicted by a model that assumes a direct relationship between the ballistic limit and the cosine of the obliquity. In other words, when this condition exists, such a model would predict no penetration under conditions for which the data indicates penetration. Because of this non-conservatism when using a direct relationship between the ballistic limit and the cosine of the obliquity, the FAA penetration equation was modified to ensure that the ballistic limit at high obliquities does not cause non-conservatism relative to results obtained for perpendicular impacts. The conservatism of the FAA penetration equation compared to test data for low obliquity impacts (shown below) is a separate issue from the non-conservatism inherent in the treatment of obliquity without the modification made for use in the AVMs. A conservative relationship between ballistic limit and impact obliquity is necessary to ensure reasonable conservatism for impacts at every obliquity.

Given the current PAVM assumption that launch and reentry debris is best modeled as a compact steel fragment, specifically a cubic projectile with an edge length (d) that impacts a locally flat surface, the perimeter of the minimum presented area equals $4d$. Substituting this into the FAA penetration equation, it can be shown that the minimum mass of a projectile with density ρ to penetrate at a velocity V may be estimated using the modified form of the FAA penetration equation as:

$$m = \frac{t^3 (8C_s)^{3/2}}{\rho^{1/2} V^3 (\cos \theta)^{3\gamma}} \quad (4)$$

This equation incorporates the obliquity modification denoted as gamma, γ . The value of gamma was empirically derived to ensure reasonable conservatism for range safety use as described below.

The effect of the gamma term is illustrated in Fig. 4 for an impact at 35 degrees obliquity. Modifying the FAA penetration equation with the gamma term means that the modified equation assumes that more than just the normal component of the impact velocity contributes to the kinetic energy required to penetrate the impacted material. A value of zero for gamma would treat every impact as perpendicular, which would be overly conservative given the available test data.

A gamma value was derived based on the data provided in Refs. 19 and 20 to ensure that the empirical component of the impact velocity relevant to the ballistic limit is no less than the ballistic limit for perpendicular impacts determined from test data. The optimal value for γ is the maximum value that ensures conservatism for impact data at all obliquities, where conservatism is indicated by non-negative values for the following expression:

$$\xi(\gamma) = \frac{V_{50,\theta>0} \cos^\gamma(\theta)}{V_{50,\theta=0}} - 100\% \quad (5)$$

<i>Gamma Value</i>	1.0	0.0	0.7
<i>Effective Impact Angle (deg)</i>	35.0	0.0	29.6

and $V_{50,\theta=0}$ is the ballistic limit for perpendicular impacts determined

from test data, and $V_{50,\theta>0}$ is the velocity magnitude of the fragment at the ballistic limit for the oblique impacts also based on test data, both of which were reported in Refs. 19 and 20. The numerator in Equation 5 is the component of the experimentally determined impact velocity that the

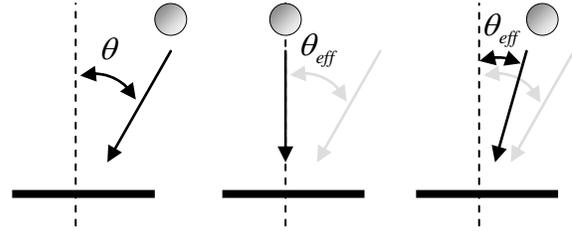


Figure 4. Influence of Gamma on Effective Obliquity.

modified FAA equation requires to predict penetration; the denominator is the minimum velocity for a perpendicular impact that is required to satisfy the fundamental “plug” assumption intrinsic in the FAA equation. The ratio identified in Equation 5 was computed with the available data to determine that the optimum value of γ is 0.707: the maximum value of gamma that produced non-negative values for the ratio for all available test data. The values of $\xi(\gamma)$ are shown for different possible values of gamma in Table 1. Although the optimized value of 0.707 is the least conservative value required to ensure the modified FAA equation is conservative, the AVMs developed for range safety use are based on a gamma value of 0.6. This value was implemented to allow for an estimated uncertainty of up to 5 fps in the ballistic limits presented in available test data. Thus, the gamma value of 0.6 is the least conservative choice that accounts for the estimated uncertainty in the ballistic limits determined by the limited test data available.

Table 1. Conservatism, $\xi(\gamma)$, of Modified Penetration Equation Compared to Test Data

<i>Obliquity (deg)</i>	$\gamma = 1.0$	$\gamma = 0.707$	$\gamma = 0.6$
0	0.0%	0.0%	0.0%
15	2.0%	3.0%	3.4%
30	-3.8%	0.4%	1.9%
45	-9.6%	0.0%	3.8%
60	-13.9%	5.5%	13.6%
67	-6.7%	22.9%	35.9%
75	-2.2%	45.2%	67.9%

Figure 5 compares the residual velocities, which are only non-zero after a predicted penetration, derived from three empirical penetration equations with test data for essentially normal (i.e. zero obliquity) impacts of engine fragments with masses from 25 to about 200 grams.²¹ These tests involved simulated and actual impacts against various thicknesses of aluminum plates and aircraft skin structures (primarily made of 2024-T3) by irregular shaped fragments of a jet engine fan, turbine, and compressor, all of which were solid titanium except the steel blade fragments. As evident in the plot, the modified FAA penetration equation leads to estimates of the residual velocity that exceed the measured residual velocity (i.e. the yellow points are above the Predicted = Actual line), with some exceptions for conditions that produce residual velocities in excess of 100 m/s. Most importantly for the AVMs used for range safety, since penetration occurs only when the residual velocity is greater than zero, the FAA penetration equation never predicted no penetration (i.e. zero residual velocity) in any cases where the tests produced penetrations. These data demonstrate that the FAA penetration equation produces conservative predictions for a range of fragment masses of directly relevant to the AVMs, particularly near the ballistic limit.

The results shown in Fig. 5 are as expected because the FAA penetration equation assumes plugging is the only deformation mode. The test results depicted in Fig. 5 that show lower residual velocities measured than predicted by the FAA penetration equation indicate that some of the kinetic energy of the projectile was transformed into forms of energy beyond the mechanical work related to simple shear plug described above; the test results often reveal a larger hole in the target than the presented area of the fragment at impact, and evidence of target deformation known as “petaling” or “dishing.” Petaling is the “formation of petals caused by radial cracking from the point of impact” and dishing refers to “the flexural and stretching deformation of an annular region of the plate surrounding the projectile impact point, where the dished region is displaced normal to the surface of the plate”²²

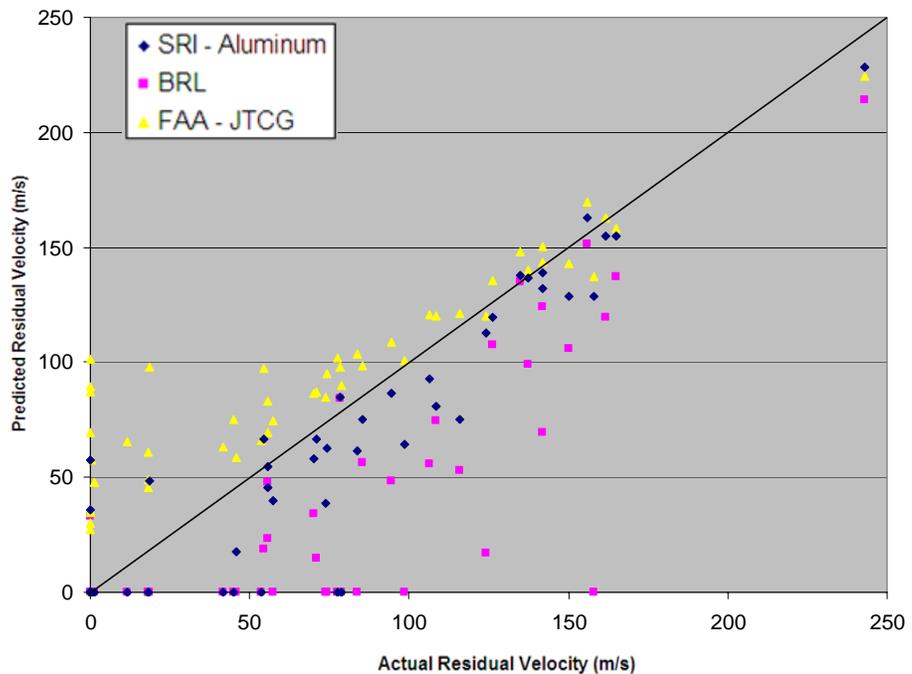


Figure 5. Comparison of Empirical Impact Models with Test Results.

C. Penetration Consequence Analysis

Figure 6 summarizes the results and logic of the penetration consequence analysis for the development of the currently available AVMs.¹¹ This section summarizes evidence to suggest that the currently available AVMs, such as those published in 321-07 and presented below, make reasonably conservative assumptions with respect to the consequence of debris penetrations.

1. Consequence of a 300 gram Fragment Impact

The current AVMs make the clearly conservative assumption that any impact by a fragment with a weight of at least 300 grams produces a catastrophic consequence, regardless of the impact location. This assumption was made after consideration of the following: (1) results from empirical tests (sponsored by the FAA and reported in Ref. 18) demonstrated that fuselage ribs and other primary structural elements can be defeated when impacted in an effectively normal manner by 300 gram engine fragments at velocities ranging from about 700 fps to 800 fps, (2) AC25.571-1C (Ref. 23) defines a principle structural element as one that “contributes significantly to the carrying of flight, ground, or pressurization loads, and whose integrity is essential in maintaining the overall structural integrity of the airplane,” (3) AC25.571-1C specifically identifies skin-stringer combinations in the wing, circumferential frames (ribs) and adjacent skin in the fuselage as examples of a principle structural element, (4) launch or reentry

vehicle fragments with a weight of at least 300 grams are expected to approach CT and BJ aircraft at relative velocities that exceed 800 fps. This assumption is considered reasonable because the consequences of defeating a principle structural element (or defeat of “redundant structure”) were deemed catastrophic in a UEDDAM study of generic commercial transport aircraft sponsored by the FAA.¹⁴ This assumption is considered conservative because (1) it requires more energy for a highly oblique impact to penetrate compared to a normal manner, (2) there is a relatively high likelihood of highly oblique launch or reentry vehicle debris, and (3) past experience with uncontained engine failures and other aircraft incident indicates that critical damage from fragment impacts has often been sustained without producing casualties.

Of course, it is reasonable and prudent to be cautious when attempting to predict what type of fragment impact damage may produce a catastrophe, which would involve multiple casualties and potential loss of the aircraft. However, past experience and FAA guidance indicate that modern commercial transport aircraft are rather robust with respect to fragment impact damage. Past experience shows that this class of aircraft can not only land safely after sustaining substantial damage from uncontained engine fragment impacts, but conditions exist where these aircraft can even land safely after sustaining more severe damage, such as a missile strike, even during the take-off phase of flight. Even if a fragment damages or even destroys critical components, limited experience and FAA guidance indicates that a catastrophic outcome may be very unlikely. For example, Ref.13 presented evidence from events where commercial transport sustained extensive damage without loss of the aircraft. Although the damage and outcomes experienced in such incidents represent only a few events, the available statistical data also suggests that Commercial Transport (CT) aircraft can sustain major damage without a catastrophic outcome, which is summarized below in the section on engine impact consequences.

2. Consequence of a Fuel Tank Penetration

Based on FAA design requirements, guidelines, expert input, past analyses and experience, the current AVMs assume that *any* debris that penetrates a wing fuel tank produces a catastrophic event, even though it appears that it might be reasonable to treat a penetration of a wing fuel tank less than two square inches as a potentially casualty producing, but non-catastrophic. For example, AC 20-128A states that *the fuel reserves should be isolatable such that damage from a disc fragment will not result in loss of fuel required to complete the flight or a safe diversion.*²⁴ AC 20-128A states that the effects of fuel loss, and the resultant shift of center of gravity or lateral imbalance on airplane controllability should also be considered in the aircraft design. AC 20-128A describes design practices presumably in use by the aviation industry to prevent an uncontrolled fire due to uncontained engine fragment impacts, including provision of a minimum 10 inch drip clearance from potential ignition sources (such as the engine) and areas potentially penetrated by an engine fragment. These design measures include consideration of the fact that an uncontained fragment could produce damage to adjacent systems, wiring, etc. and thus create both an ignition source and a fuel source. Furthermore, current design practices intend to provide the ability to extinguish a fire in the event of an uncontained rotor failure means that “flammable liquid shutoff valves should be located outside the uncontained rotor impact area,” and that any shutoff actuation controls routed through the impact area “should be redundant and appropriately separated in relation to the one-third disk maximum dimension.”²⁴

There is some evidence that suggests that it may be reasonable to assume that catastrophic consequences are unlikely due to a small penetration (i.e. less than two square inches) of a single wing fuel tank on a commercial transport aircraft built to comply with FAA requirements. For instance, AC 39-8 defines “Level 3- Serious Consequences” so as to include “substantial damage to the aircraft or second unrelated system,” which in this context means “damage or structural failure that adversely affects the limit loads capability of a Primary Structural Element or the performance or flight characteristics of the aircraft.”⁸ AC 39-8 specifically states that “*small penetrations of aircraft fuel lines or aircraft fuel tanks, where the combined penetration areas exceed two square inches, is a level 3a classification (The concern is exhaustion of fuel reserves.)* Hence, AC 39-8 implies that a fuel

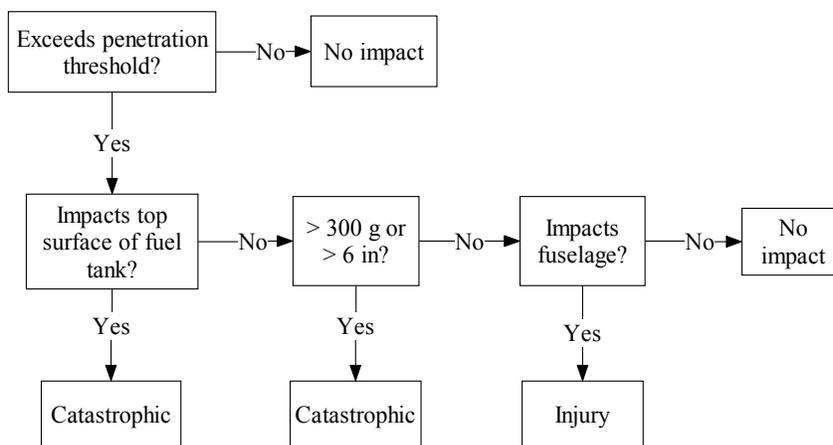


Figure 6. Penetration Consequence Analysis Results and Logic.

tank penetration of less than two square inches might not be deemed a “serious consequence.” Note that although real debris would most likely be an irregular shape with a larger presented area, an aluminum cube that weighs 300 grams is less than two inches on a side. Furthermore, the FAA study on “*The Potential for Fuel Tank Fire and Hydrodynamic Ram From Uncontained Aircraft Engine Debris*” included “a brief review of accident data and of the pertinent technical literature, a detailed analysis of in-tank ignition by hot fragments, and parametric calculations using a computer code for hydrodynamic ram.”¹⁵ The results of that study suggest that “in-tank fire and hydrodynamic ram can be produced by engine debris, though their expected probability of occurrence is very low.”¹⁵ The review of historical accidents involving fragments from engine failures penetrating fuel tanks in Ref. 15 found “reports on fuel tank ruptures and the outpouring of fuel from the tank, as well as fuel tank fires and explosions.” However, the two specific scenarios of interest: “uncontained engine failure, penetration of the fuel tank by engine debris, ignition of the fuel inside the tank or hydrodynamic ram (pressure rise inside the tank), and tank rupture” have “not been reported in any particular accident,” but “some of these events have been reported singly or in various combinations.” Ref. 15 concluded that “a definitive resolution of this issue cannot be achieved from our quick review of accident data.” In addition, there are data from a bird strike event (on 21 February 2002) that produced a rapid fuel leak without any casualties. Thus, a more comprehensive review of bird strike and other accident data could help clarify the likelihood of a catastrophe due to penetration of a fuel tank by debris.

Never-the-less, the safety analysis requirements in AC 20-128A clearly acknowledge the potential for fragment impact to produce an uncontrolled fire, and a fuel tank penetration from a launch vehicle debris impact would almost certainly be distinct from any of those planned for in protecting against uncontained engine or APU failures given the differences between geometries involved in those impacts. Figure 7 shows that region potentially threatened by uncontained engine debris courtesy of Ref. 14. Note that the uncontained engine debris fragments follow trajectories that are generally perpendicular to the fuselage, while launch and reentry debris fragments will tend to follow trajectories parallel to the fuselage.

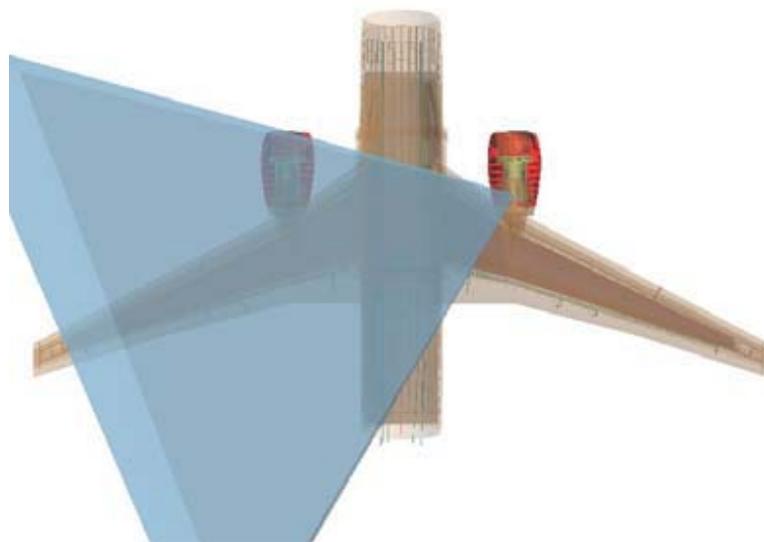


Figure 7. Region Potentially Threatened by Uncontained Engine Debris.¹⁴

The decision to assume that any fuel tank penetration by launch or reentry vehicle debris would be modeled as catastrophic in the AVMS was heavily influenced by the fact that an FAA study of a generic twin-engine commercial transport jet and a generic twin-engine business jet using UEDDAM showed that fuel system impact was a serious threat.¹⁴ Specifically, the analysis in Ref. 14 found that the potential for a severed fuel supply and fuel motive lines (resulting in fire) was a dominant source of potential catastrophic damage from uncontained engine fragment impacts. Specifically, page 4-8 of Ref. 14 noted that the wing fuel tanks of a generic twin engine jet are considered critical components, and page 3-8 stated that all critical components, except larger structural components, were assigned a conditional probability of a catastrophic hazard equal to one given an impact.

Another previously performed FAA study “identified that damage to the fuel tank can produce fuel leakage resulting in other adverse impacts to the aircraft.”¹⁵ For example, Ref. 15 found that “fuel can leak into dry bays and engine nacelles, be ingested by an engine...the fires resulting from such leakage can pose great danger to an aircraft structure.” Furthermore, Ref. 15 found that “those scenarios have occurred in the past (such as the Manchester accident in 1985) and may be more important than those examined in this study.” Thus, it is important to recognize that there is some chance, which is difficult to quantify, that fuel could splash or pool in an area where an ignition source exists. Foreseeable ignition sources include areas near an engine, APU, de-icing system, or severed electrical line. Previously, the RCC found that a penetration of the wing leading edge is a major safety concern only “if a fragment actually penetrates the front wing spar which normally forms one wall of a fuel tank.”¹⁰

3. *Consequence of a Fuselage or Cockpit Penetration*

The currently available AVMs appear to make reasonably conservative assumptions with respect to the consequence of a debris penetration of the fuselage. The penetration consequence analysis considered that a fuselage penetration could cause (1) a direct casualty due to impact with an occupant, or (2) a depressurization event, which is likely to lead to an injury, and may cause a catastrophic accident if depressurization is very rapid. Note that rapid depressurization of the cabin was one of the explicit “Level 3- Serious Consequences” identified in AC 39-8. A study of commercial aircraft vulnerability to firearm discharge acknowledged that the cabin pressurization system can fail in such a way that the cabin pressure fluctuates rapidly, but concluded that “this is a non-issue as the pilot can descend and turn off cabin pressurization.”²⁵ Furthermore, modern aircraft fuselage have re-enforcements designed to prevent a small puncture from growing into a hole large enough to produce rapid depressurization, as well as controlled area breakaway zones designed to maintain the integrity of the fuselage structure in the event of a small skin penetration. The present AVMs calculate the capability of debris to penetrate the fuselage based on the minimum skin thickness measured on actual aircraft, and neglect any ballistic resistance of interior wall panels, insulation, etc. Based on the FAA penetration equation, the residual kinetic energy for a fragment capable of penetrating the fuselage remains well above the 11 ft-lb threshold for causing casualties due to blunt trauma established in 14 CFR 417.107(b).¹ The FAA has not established a threshold for lacerating injuries, but these fragments also appear capable of producing penetration injuries based on the penetration injury threshold level of 8 foot-pounds per inch squared published by the Air Force Space Command.²⁶

Similarly, the penetration consequence analysis performed during the development of the CT and BJ AVMs concluded that a penetration of the cockpit (or fuselage) by a fragment that weighs less than 300 grams should be expected to produce a casualty, but not a catastrophe. The penetration consequence analysis considered that a penetration of the cockpit could cause (1) a direct casualty due to impact with a crew member, (2) damage to a control system, or (3) a depressurization event. The present AVMs assume that penetration of the cockpit by a fragment less than 300 grams would not produce a rapid depressurization based on the same evidence cited for the fuselage penetration consequence analysis.

The current AVMs also assume that there are sufficiently redundant control systems in the cockpit to continue safe flight following penetration with a fragment less than 300 grams. This assumption was made in light of the FAA requirements that certified commercial aircraft must be able to continue safe flight and landing following failure or jamming of any flight control system element. Specifically, §25.671(c) requires that “the airplane must be shown by analysis, tests, or both, to be capable of continued safe flight and landing after any of the following failures or jamming in the flight control system and surfaces (including trim, lift, drag, and feel systems), within the normal flight envelope, without requiring exceptional piloting skill or strength.” Also, a previous analysis performed to assess the vulnerability of the cockpit to firearm discharges treated the “loss of hydraulic power to flight controls [as] not catastrophic- [because the] ailerons/elevators can be controlled manually.”²⁵ The same study stated that the hydraulic controls are triple redundant (system A, system B, and a standby system), the flight instruments are triple redundant (pilot, co-pilot, and standby), and the brakes and landing gear should be operable despite loss of hydraulics. Lastly, the same study stated that if all three systems flight instrument systems were defeated, the pilot can fly using a visual approach and landing, with the airspeed indicator as the only exception (which is also triple redundant). So the current AVMs apply only to aircraft flown with two pilots on-board, and assume that penetration of the cockpit with a fragment less than 300 grams would not incapacitate both pilots.

Furthermore, FAA regulations (specifically § 23.775(h)(2)) require windshield panels be redundant to the extent that loss of visibility through one panel does not preclude continued safe flight and landing. However, the impact resistance requirements for commercial aircraft windshields are less strict than the four or eight pound bird impact resistance for other parts of the airplane. Specifically, § 23.775(h)(1) requires that “windshield panes directly in front of the pilots in the normal conduct of their duties, and the supporting structures for these panes, must withstand, without penetration, the impact of a two-pound bird when the velocity of the airplane (relative to the bird along the airplane’s flight path) is equal to the airplane’s maximum approach flap speed.” The AVMs for the CT and BJ class aircraft models the cockpit vulnerability to penetration based on the minimum measured skin thickness in the cockpit region, and the assumption that the windscreen ballistic resistance is equivalent to a 0.125 inch thick aluminum plate. The assumption that the windscreen ballistic resistance is equivalent to a 0.125 inch thick aluminum plate produced a minimum weight for a steel fragment capable of penetration near the two gram value published in RCC 321-02,¹⁰ which used entirely difference penetration equations and accounted for the Lexan material used in typical windcreens (although approximately and ignored the complex multilayer construction).²⁷ Given the criticality of any windscreen penetration, and the potential importance to general aviation aircraft vulnerability also, we recommend pursuit of test data on the ballistic resistance of typical windcreens also.

4. *Consequence of an Engine Impact*

The currently available AVMs make reasonably conservative assumptions with respect to the consequence of an engine impact with debris less than 300 grams. The penetration consequence analysis considered that an engine impact of a single piece of debris less than 300 grams could lead to failure of the engine (i.e. loss of thrust) and might produce additional fragment impacts due to uncontained engine debris. The analysis assumed that the potential for multiple impacts by launch or reentry vehicle debris to an aircraft are negligible because aircraft are restricted from regions where the probability of impact with debris capable of causing a casualty exceeds 1E-7. Therefore, the probability of multiple impacts by launch or reentry vehicle debris should be truly tiny.

The consequence analysis for an engine impact performed during the development of the current AVMs led to three important findings:

- 1) certified CT and BJ aircraft are able to continue safe flight after the loss of thrust from any single engine,
- 2) uncontained engine debris impacts are unlikely to generate a potentially catastrophic condition, and
- 3) even total loss of thrust (from all engines) is not expected to produce a catastrophe, except during the period from initial flight to the first power reduction, or for transoceanic flights.²⁴

The first finding is that certified commercial aircraft must be able to continue safe flight following the loss of thrust from any single engine. Specifically, 14 CFR §25.903(b) requires that “the power plants must be arranged and isolated from each other to allow operation, in at least one configuration, so that the failure or malfunction of any engine, or of any system that can affect the engine, will not - (1) prevent the continued safe operation of the remaining engines; nor (2) require immediate action by any crewmember for continued safe operation.” Therefore, current federal law for commercial transport aircraft requires designs that enable continued safe operation following any single engine loss. Even so, experience shows that there is still some chance of a catastrophic consequence given an engine loss due to crew errors during the engine shutdown sequence, etc. FAA experts reported that the empirical data indicates about one out of a thousand engine losses results in a catastrophic outcome.²⁸

The second finding based on input from FAA experts and guidelines is that debris ingestions into commercial aircraft engines are unlikely to generate a potentially catastrophic condition due to engine fragment throw. Specifically, the experts reported that (1) engine ingestion of a fragment less than 300 grams is unlikely to produce uncontained impacts other than perhaps some fan blade fragments,²⁹ (2) experience shows that uncontained fan blade impacts have the potential to impact the fuselage, causing injury, significant damage to the plane, or decompression, but (3) this is less than a 1 in 100 occurrence.^{28,29}

Historical experience indicates that fragment impacts from uncontained gas turbine failures often produce “significant damage” without casualty or other serious consequences, even prior to the implementation of FAA design guidelines intended to reduce this threat. Specifically, even prior to implementation of Advisory Circular 20-128A, fragment impacts from uncontained gas turbine engine failures were about six times more likely to produce “significant damage” without casualty than an outcome involving casualties, hull loss, or a crash landing.²⁴ AC 20-128A presents results based on a total of 676 uncontained gas turbine engine rotor failure events occurring in fixed wing aircraft during the 28 year period prior to the Sioux City accident, from 1962 to 1989. This data suggests that about 2% of the uncontained gas turbine engine rotor failure events resulted in crash landing, critical injuries, fatalities or hull loss (i.e. a catastrophe) in the 28 year period prior to the Sioux City accident. The empirical data from this 28 year period suggests that multiple fragment penetrations due uncontained gas turbine engine rotor failure events were about six times more likely to produce significant damage without an outcome involving casualties, hull loss, or a crash landing. These events were caused by a wide variety of influences classed as environmental (bird ingestion, corrosion/erosion, foreign object damage), manufacturing and material defects, mechanical, and human factors (maintenance and overhaul, inspection error and operational procedures). These statistical inferences are made only to convey that CT aircraft (1) have demonstrated significant capability to sustain fragment impacts without casualties, and (2) casualties or worse are not the expected outcomes of uncontained engine failures. However, given the evolution of design and construction techniques for aircraft during the 28 year period for these data, and the variability of conditions during each of these events, these statistical inferences must be considered weak and unsuitable for quantitative predictions. Furthermore, in the absence of detailed data on the location and vulnerability of critical systems, including principle structural elements, it appears reasonable and prudent to assume that a 300 gram or heavier fragment impact to an engine will produce a catastrophic outcome.

D. Aircraft Vulnerability Model Geometry

The present AVMs use a greatly simplified geometry compare to the detailed finite element models available for the exterior of many types of commercial transport aircraft. Instead of using thousands of finite elements contained in a typical model of the exterior shape of an aircraft, each Probabilistic Aircraft Vulnerability Model (PAVM) of a particular aircraft type (e.g. the B747) consists of basically 12 flat panels as shown in Fig. 8: (1) the nose cone, (2) a

half-cylinder fuselage top, (3) two trapezoidal wing top surfaces, (4) two trapezoidal wing leading edge surfaces, (5) two trapezoidal horizontal stabilizer top surfaces, (6) two trapezoidal horizontal stabilizer leading edge surfaces, (7) a trapezoidal vertical stabilizer leading edge, (8) rectangular vertical stabilizer top edge surface. Figure 8 is an exploded view of the simple geometric shapes that each PAVM uses to model these 12 major sections.

The geometry model used by each PAVM made the following simplifying assumptions.

- 1) The top surface of each wing, including the skin above the fuel tank, is entirely in the horizontal plane.
- 2) The top surface of each horizontal stabilizer in the tail is entirely in the horizontal plane.
- 3) The leading edge surface of each wing is entirely in the vertical plane and swept back.
- 4) The leading edge surfaces of the empennage are entirely in the vertical plane.

The PAVMs evaluate the threat posed by each fragment mass by:

- 1) Computing the terminal velocity of the debris assuming it is a steel cube falling at altitude,
- 2) Computing the approach angle of the fragment relative to the aircraft using the upper end of the aircraft cruising velocity,
- 3) Computing the impact angles for the 12 major sections shown in Fig. 8. Note that for the curved sections, such as the fuselage and cockpit, there are multiple impact angles computed.
- 4) Computing if a penetration is predicted for each major section based on the modified FAA equation presented above.
- 5) Computing the projected area of each panel (or portion there of for the curved sections) where penetration is expected
- 6) Aggregating the projected area for a given consequence (e.g. casualty or catastrophe).

For example, a penetration of any orange “panel” in the aircraft representation shown in Fig. 8 contributes to the area susceptible to a casualty producing event. As described in detail in the previous section, these casualties are assumed to be caused by (a) direct impact of a crew member for penetrations of the cockpit skin or windscreen, (b) direct impact of a passenger or crew member for penetrations of the fuselage, or (c)

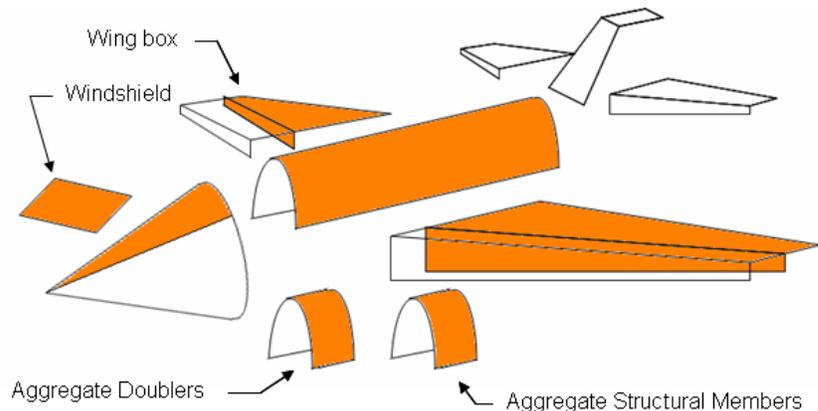


Figure 8. Exploded View of Simplified Geometry Model Surfaces.

a catastrophic event for penetrations of the section of the wing containing fuel or the structural portions of the fuselage. The two partial sections of the fuselage represent the aggregate area where (1) doublers or other non-structural members are located that create a significant portion of the fuselage that is thicker than the outer skin but not as thick as a location backed by a primary structural member and (2) primary structural elements are located. These partial sections are portions of the fuselage and are neither continuous nor located in a specific location. For example, the non-structural section could represent fraction of the fuselage composed of stringers and doublers that do not constitute a “primary structural element” as defined by AC 25.571-1C: a structural member is one that “contributes significantly to the carrying of flight, ground, or pressurization loads, and whose integrity is essential in maintaining the overall structural integrity of the airplane.”²³ Also, a separate rectangular area is used to represent the windscreen.

We investigated the viability of using the simplified geometry for the PAVMs by performing several comparisons with the complex Finite Element Model (FEM) mesh. One set of penetration analyses was performed using the complex geometry captured in a FEM mesh of the outer surface of a 757 aircraft, and compared to the results of another set of performed using the simplified geometry described above. However, in these comparisons both models used a uniform skin thickness of about 0.05 inches for all surfaces. The uniform thickness simplification was necessary to avoid excessively time consuming work on the complex geometry model. The results of these comparisons showed that the simplified geometry produced estimated areas susceptible to penetration within a few percent of those based on the high fidelity geometry model, except for impacts by masses near the threshold values. Therefore, the curve fits to the PAVM results used as the CT and BJ class AVMs reported below were designed to be conservative for fragment masses below 10 grams. The present AVMs for the CT and BJ classes of aircraft are also believed conservative because LS-DYNA runs indicate that a curved surface such as the

top of a wing is less susceptible to penetration than a flat plate. By ignoring the curvature of various surfaces such as the upper surface and leading edges of the wings and horizontal stabilizers, the AVMs add some conservatism.

E. Results for Commercial Transports and Long Range Business Jets

This section summarizes the results of the AVMs currently available for range safety use. The commercial transport class AVM shown below was adopted in 321-07 on a provisional basis, and the next version of RCC 321 will include the same AVM for CT aircraft, but the provisional caveat removed and with the threshold masses identified as below. This section also presents vulnerability thresholds for the CT and BJ classes that were previously unpublished and the best available AVMs for the BJ class. The authors consider rapid publication of the BJ class AVM especially important in light of the potential need for larger aircraft hazard areas to protect BJ class aircraft compared to CT class aircraft. The threshold masses and AVMs reported in this section were based on the penetration equation and consequence analysis presented above, which was documented in more detail in Ref. 11. All of the results presented below apply only to debris impacts by fragments composed of materials with a maximum density of 8100 Kg/m³.

The CT aircraft results presented here apply only to commercial transport aircraft class with all the following characteristics:

- 1) Aluminum skin (composite skin aircraft have not been studied),
- 2) Multiple turbofan engines, and
- 3) Governed by the FAA certification requirements of 14 CFR Part 23/25.

The BJ Class includes all multi-engine, jet propelled aircraft that have the capability to carry no more than 20 passengers for hire. All aircraft within the BJ class primarily exhibit:

- 1) Aluminum skin and structural members,
- 2) Two pilots during operation, and
- 3) Design and maintenance requirements defined by the FAA certification requirements of 14 CFR Part 23/25.

The BJ class excludes:

- 4) Single pilot versions of otherwise BJ class aircraft,
- 5) Emerging “very light jets” with composite skins or structures, or
- 6) Aircraft that rely on propeller-based propulsion.

Therefore, the same consequence analysis assumptions used for the CT class were also applied to the BJ class.³⁰

5. Threshold Masses for Tier 1

Table 2 lists threshold masses for the vulnerability of CT, BJ, and other classes of aircraft to launch vehicle debris impacts. The thresholds listed equate to conservative estimates the minimum mass of a compact metal fragment, which consists entirely of materials with a density of no more than 8100 Kg/m³, predicted to have just less than a 1% conditional probability of causing a casualty given an impact. The values listed in Table 2 were derived as described above and their proper application is summarized below.

Table 2. Tier 1 Thresholds for Aircraft

<i>Aircraft Class</i>	<i>Threshold mass (g)</i>
<i>Commercial passenger transport jets</i>	<i>2.1</i>
<i>Business jets</i>	<i>0.6</i>
<i>All other aircraft</i>	<i>1.0</i>

To provide protection of aircraft in compliance with the probability of impact requirements in paragraph 3.3.1 of the RCC 321-07 Standard, hazard volumes may be based on the maximum projected area of the aircraft potentially exposed to all debris fragments above the Tier 1 threshold masses given in Table 2. For example, a valid Tier 1 approach to demonstrate compliance the RCC 321-07 Standard is to restrict non-mission aircraft from volumes of airspace where the cumulative probability of impact of debris above the threshold masses exceeds 1E-7, using the maximum projected area of the aircraft. The maximum projected area is the two-dimensional projection of the aircraft in the plane that is perpendicular to the fragment velocity vector (relative to the aircraft) of the largest aircraft potentially exposed. In terms of plan and front areas and assuming an aircraft flying horizontally and debris falling vertically, the maximum projected area may be computed based on

$$A^{proj} = A^{front} \sin(\psi) + A^{top} \cos(\psi) \tag{6}$$

and

$$\psi = \tan^{-1} (V_{AIRCRAFT} / V_{DEBRIS}) \tag{7}$$

where the aircraft velocity and debris velocities are relative to the ground.

It is important to emphasize that there exists a potential for adverse consequences to occur from impacts to aircraft with masses below the Tier 1 thresholds shown in Table 2. For example, the more detailed AVMs, which underlay the CT class vulnerability model presented below, indicate that there is a very small chance of a casualty if a fragment between 0.4 and 2.1 grams impacts the cockpit. Specifically, according to the present model for a cockpit, which is considered the least well developed element of the current AVMs for range safety use, an impact with a compact steel fragment below the 2.1 gram threshold could penetrate the aircraft skin and potentially produce a penetration injury of a crew member. Therefore, the only intended use of the threshold masses presented in Table 2 is as a Tier 1 model: accounting for all impacts above the threshold anywhere on the aircraft as producing an adverse consequence. In addition, it is important to emphasize that the thresholds list in Table 2 apply only to fragments composed of materials with a density of no more than 8100 Kg/m³.

6. Aircraft Vulnerability Models for Tier 2

Figure 9 compares the best available CT class AVMs for range safety use with those presented in RCC 321-07 (which did not include explicit threshold masses) as well as the underlying Probabilistic Aircraft Vulnerability Model (PAVM) for the B747. The Tier 2 AVMs presented in Fig. 9 are intended to facilitate evaluation of the risk of an event that produced an on-board casualty and the risk of a catastrophic event. The AVMs recommended for

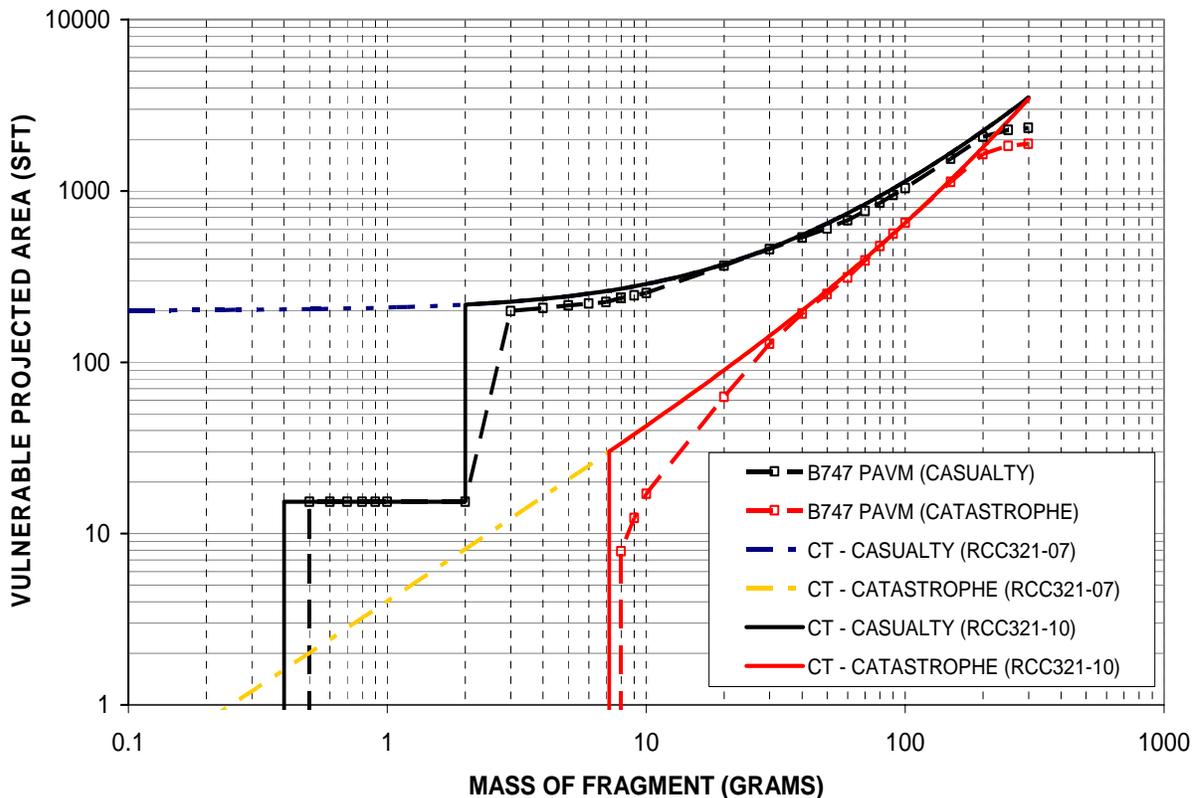


Figure 9. Comparison of AVMs for Commercial Transport Class Aircraft.

range safety use to protect CT and BJ class aircraft are smoothed versions of ACTA’s Probabilistic Aircraft Vulnerability Models (PAVMs) developed for a variety of aircraft types that fit within those classes.^{11,30} For fragment masses between 30 and 300 grams, the CT and BJ class AVMs are curve fits to the discrete simulation results of the PAVMs. The CT class AVMs use simple functions listed in Table 3 and Table 4 to conservatively fit the results of the PAVMs and make their application in launch and reentry safety analysis relatively straightforward. As described above, all PAVMs currently assume fragments above 300 grams impacting anywhere on an aircraft are catastrophic: an occurrence resulting in multiple casualties, usually with the loss of the aircraft. Commercial transport aircraft are typically passenger jets, which have a high priority for protection. Their size results in a bigger “target” making the probability of impacting them generally higher than for many other planes, although there is evidence presented below that business jets present a larger area susceptible to a casualty producing event for fragments between about 2 to 30 grams. Moreover, CT aircraft carry many passengers so that the consequence of a

catastrophe impact may be very high. Table 3 and Table 4 show the functional relationships between the mass of an impacting fragment, m (in grams), and the projected area (in ft^2) of a CT class aircraft vulnerable to a casualty producing event (i.e., a single casualty regardless of the occupancy of the aircraft), A_{CAS}^{PROJ} , and a catastrophic event, A_{CAT}^{PROJ} , respectively.

Table 3. Tier 2 AVM for Casualty of Person on a Commercial Passenger Transport Jet

Fragment mass (g)	A_{CAS}^{PROJ} (ft^2)
<0.4	0
0.4 to 2	15.3
2 to 300	$0.0085 m^2 + 8.5m + 200$
> 300	$(\sqrt{A_{PROJ}} + \sqrt{A_{FRAG}})^2$

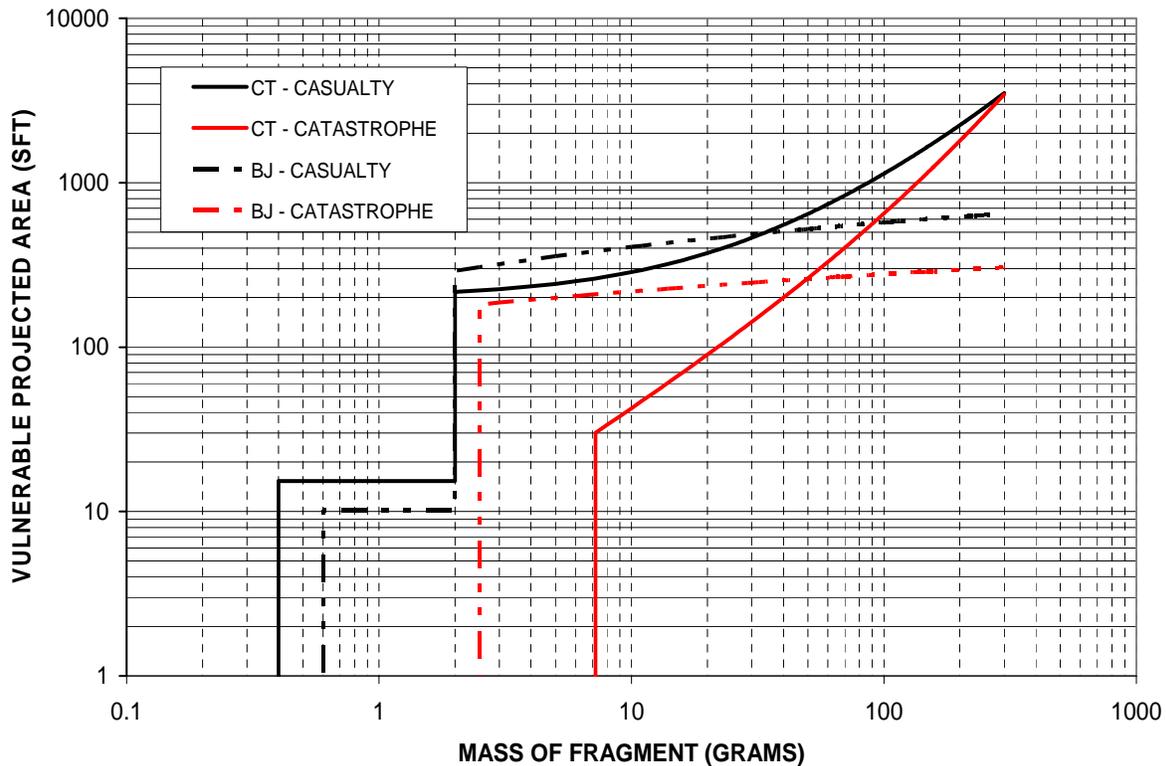


Figure 10. Comparison of AVMs for Commercial Transport Class Aircraft.

Table 4. Tier 2 AVM for Catastrophe on a Commercial Passenger Transport Jet

Fragment mass (g)	A_{CAT}^{PROJ} (ft^2)
<7.2	0
7.2 to 300	$0.025m^2 + 4m$
> 300	$(\sqrt{A_{PROJ}} + \sqrt{A_{FRAG}})^2$

Regardless of the vulnerability model or hazard threshold levels used, aircraft hazard areas should be based on the largest aircraft in common use (which is currently the B747 in the CT class) because, (1) they present the largest

vulnerable area of any commercial transport, and thus will define hazard areas that are reasonably expected to provide adequate protection for all other types of commercial transport aircraft, and (2) the best available probabilistic aircraft vulnerability model results indicate that other common types of aircraft (the B757 in particular) can exhibit a higher conditional probability of adverse consequences (given an impact) than the B747, but the total area susceptible to adverse consequences is always larger for the B747 than those associated with other commercial transport aircraft examined (B737-800, B757m and B767). *No attempt should be made to scale the vulnerability models presented here for application to other commercial transport aircraft.* Instead, it is recommended that the equations be applied directly to all planes in the CT class as defined at the beginning of this section.

Figure 10 compares the best available AVMs for range safety use that apply to CT and BJ class aircraft. It is evident in Fig. 10 that BJ class aircraft present larger areas susceptible to casualty and catastrophe producing impacts by fragments between about 2 to 30 grams. This result was attributed to differences in the design of the wing top surfaces between typical BJ and CT class aircraft: the thickness of typical CT wing top surfaces taper from root to tip, but BJ class aircraft often use essentially constant thickness of the wing top surface over the fuel tank.

Table 5 and Table 6 show the functional relationships between the mass of an impacting fragment, m (in grams), and the projected area (in ft^2) of a BJ class aircraft vulnerable to a casualty producing event (i.e., a single casualty regardless of the occupancy of the aircraft), A_{CAS}^{PROJ} , and a catastrophic event, A_{CAT}^{PROJ} , respectively.

Table 5. Tier 2 AVM for Casualty of Person on a Business Jet

Fragment mass (g)	A_{CAS}^{PROJ} (ft^2)
<0.6	0
0.6 to 2	10.2
2 to 300	$72 \ln(m) + 241$
> 300	$(\sqrt{A_{PROJ}} + \sqrt{A_{FRAG}})^2$

Table 6. Tier 2 AVM for Catastrophe on a Business Jet

Fragment mass (g)	A_{CAT}^{PROJ} (ft^2)
<2.5	0
2.5 to 300	$36 \ln(m) + 158$
> 300	$(\sqrt{A_{PROJ}} + \sqrt{A_{FRAG}})^2$

IV. Conclusion

This paper presents risk acceptability criteria that establish an appropriate level of protection for aircraft potentially threatened by launch or reentry vehicle debris impacts. Specifically, the aircraft protection requirements published in RCC 321-07 were shown to (1) be commensurate with the background risks accepted by occupants of US air carrier and general aviation aircraft and (2) ensure that aircraft risks from launch or reentry debris hazards fall well below the short term acceptable risk levels identified in an FAA guideline intended “to identify unsafe conditions” and determine when to take “corrective action” for commercial transport aircraft. This paper describes the development of Aircraft Vulnerability Models (AVMs) that quantify the areas of aircraft expected to produce an undesirable outcome given debris impact, such as a casualty due to penetration of the fuselage or an uncontrolled landing following a ruptured fuel tank. This paper includes evidence to demonstrate that the present AVMs for Commercial Transport (CT) and Business Jet (BJ) classes of aircraft are based on a penetration equation and penetration consequence analysis that used the best available information, methods, and reasonably conservative assumptions.

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