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Risk Considerations for the Random Reentry of Space Debris

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Congress granted the FAA the authority to license commercial launch or reentry to ensure protection of public, property, the national security and foreign policy interests of the United States and to encourage, facilitate, and promote U.S. Commercial Space Transportation. To meet this responsibility the FAA performs safety evaluations on applications to conduct commercial launches from the United States or outside the United States by a U.S. citizen or an entity organized under the laws of the United States. This paper discusses the risk analysis performed by the FAA, to determine the risk to the uninvolved public as a result of random reentering space debris. The FAA has not regulated the random reentry of Expendable Launch Vehicle upper stages due to their natural decay; however, the FAA has performed independent analysis on this subject discussed in this paper. This paper addresses considerations important to determine the risk to the uninvolved public. These include trajectory considerations, debris considerations, and population considerations. The FAA assessed the risk to the uninvolved public resulting from random reentry of space vehicles or debris. This paper shows that calculated risk is sensitive to casualty area and world population with time and that significant sized debris have reentered and impacted landmasses.

Nomenclature

E_c	=	Expected casualties
P_i	=	The probability of impact of debris at a point
lat	=	The latitude of impact
inc	=	The inclination of impact
R	=	The radius to the impact point at which the probability of impact is to be determined
Ec_i	=	The expected casualty for the ith grid
P_f	=	The probability of the random reentry (typically assumed to be 1)
N_i	=	The population density for the ith grid
A_i	=	The area associated with the population for the ith grid
i	=	Refers to the population grid point of interest.

I. Introduction

This paper addresses the risk to the public due to random reentering debris. Random reentry can occur as a result of several events, like spent stages which are put in orbits which will reenter over a period of time or objects which are placed in low earth orbits which will reenter given no orbit correction maneuvers.

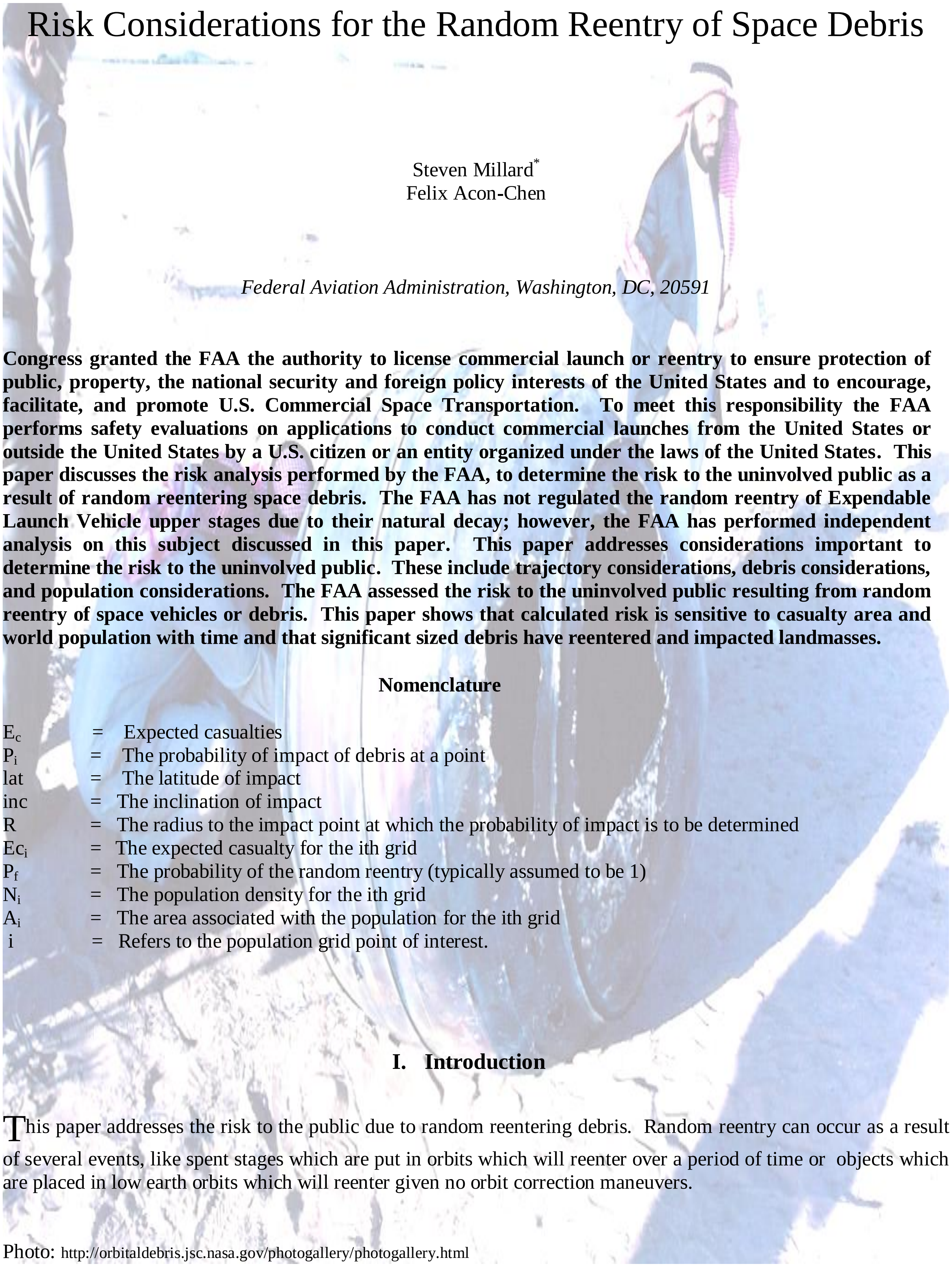

Photo: http://orbitaldebris.jsc.nasa.gov/photogallery/photogallery.html

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II. Objective

To determine the risk to the public of the random reentering space debris and to determine if reentered debris that has been catalogued poses a significant risk to the public.

III. Authority

The FAA's authority to regulate commercial space launches is given by Title 49 of the U.S. Code as summarized.

TITLE 49--TRANSPORTATION

SUBTITLE IX--COMMERCIAL SPACE TRANSPORTATION

CHAPTER 701--COMMERCIAL SPACE LAUNCH ACTIVITIES

Sec. 70103. General authority

(a) General.--The Secretary of Transportation shall carry out this chapter.
(b) Facilitating Commercial Launches and Reentries.--In carrying out this chapter, the Secretary shall--
(1) encourage, facilitate, and promote commercial space launches and reentries by the private sector, including those involving space flight participants; and
(2) take actions to facilitate private sector involvement in commercial space transportation activity, and to promote public-private partnerships involving the United States Government, State governments, and the private sector to build, expand, modernize, or operate a space launch and reentry infrastructure.
(c) Safety.--In carrying out the responsibilities under subsection (b), the Secretary shall encourage, facilitate, and promote the continuous improvement of the safety of launch vehicles designed to carry humans, and the Secretary may, consistent with this chapter, promulgate regulations to carry out this subsection.

IV. Definitions

"Citizen of the United States" means--
(A) an individual who is a citizen of the United States;
(B) an entity organized or existing under the laws of the United States or a State; or
(C) an entity organized or existing under the laws of a foreign country if the controlling interest (as defined by the Secretary of Transportation) is held by an individual or entity described in subclause (A) or (B) of this clause.

"Reentry vehicle" means--
A vehicle designed to return from Earth orbit or outer space to Earth substantially intact. A reusable vehicle that is designed to return from Earth orbit or outer space to Earth substantially intact is a reentry vehicle.

"United States" means the States of the United States,
the District of Columbia, and the territories and possessions of the United States.

"Public safety" means, for a particular licensed launch, the safety of people and property that are not involved in supporting the launch and includes those people and property that may be located within the boundary of a launch site, such as visitors, individuals providing goods or services not related to launch processing or flight, and any other launch operator and its personnel.

V. Method of Analysis

A. Probability of Impact of Random Debris

The probability of random reentering debris impacting at any point on the earth has been characterized by Patera[1] of the Aerospace Corporation and Johnson[2] of NASA JSC in similar studies on this subject. This is expressed in the following equation.

$$P_i(lat,inc) = 1/(2\ \ ^2*R^2(\sin^2(inc)-\sin^2(lat))^{1/2}) \qquad (1)$$

Where P_i is the probability of impact, lat is the latitude of impact, inc is the inclination of impact, R is the radius to the impact point at which the probability of impact is to be determined. In addition, knowing the population at an impact point of interest the risk can be calculated per unit casualty area. The expected casualty per unit area of casualty area is calculated using the equation below

$$Ec_i=P_f*P_i(lat,inc)_i*N_i*A_i \qquad (2)$$

Where Ec_i is the expected casualty for the ith grid, P_f is the probability of the random reentry (typically assumed to be 1), N_i is the population density for the ith grid, A_i is the area associated with the population for the ith grid, and i refers to the population grid point of interest.

The total expected casualties for an inclination band of interest is given by the equation below.

$$Ec = \ \ Ec_i, \qquad (3)$$

Where i = 1 to N, where N is the number of population grids within an inclination band of interest.

B. Population Considerations for Random Reentering Debris

Once the probability of impact of the random debris has been determined, the next step is to address the population at risk. The population data base was obtained from the Gridded Population of the World[3] for the years from 1995 to 2015. Given the trends in population over time, which are well documented, the FAA was able to predict risk as far as 2050. This is an important requirement since NASA standards require objects placed into low earth orbit to have a lifetime before reentry of less than 25 years from the date of release. Debris from middle earth orbit and geosynchronous orbit do not pose a random reentry issue.

VI. Results

A. Physical and Material Properties

The physical properties of the reentering objects greatly affect the risk of random reentries. Large, spherical metal objects, such as the tanks and stage motor cones, tend to survive reentry. Aerodynamic deceleration and aerothermal heating experienced during the object's fall through the atmosphere cause the object to break up. Different materials absorb and shed heat differently. Those materials that can re-radiate heat effectively or have a high enough melting temperature (so they can store the majority of the heat non-destructively) are more likely to survive intact. Materials with low melting points, low vaporization temperatures, and poor re-radiation properties like aluminum have a greater probability of shedding the majority of their mass in the atmosphere before impact.

Geometry can also affect the ability to disperse heat. Spheres are the most likely to impact the ground with the majority of their mass intact. Titanium spheres are generally considered as the worst case due to their higher melting temparautre[2]. These properties must be taken into account to determine what percentage of mass will actually contribute to the total casualty area.

The majority of reentry debris recovered and identified so far has consisted of spherical pressure vessels and rocket motor cones. A small, lightweight piece of charred woven material (10 x 13 cm) struck a woman[4], but did not cause significant injury. This material is believed to be part of a Delta II 2nd stage whose propellant tank and combustion chamber landed in Texas. The tank is shown in Figure 1 courtesy of the NASA website.

Figure 1. Delta II Second Stage reentered in Georgetown Texas on January 22, 1997

The Aerospace Corporation Center for Orbital and Reentry Debris Studies has identified 60 pieces of space debris found throughout the world from 1960 to 2008. Figure 2 summarizes this data, which contains debris pieces classified as skins, plates, cylinders, and spheres. The data shows that the largest piece of debris found to date measured about 5 m^2 to 6 m^2 in area. The largest piece of debris was a skin/flat plate while the second largest piece of debris was a cylindrical tank as shown in Figure 1. Figure 2 illustrates the size and weight of the debris catalogued by the Aerospace Corporation [4].

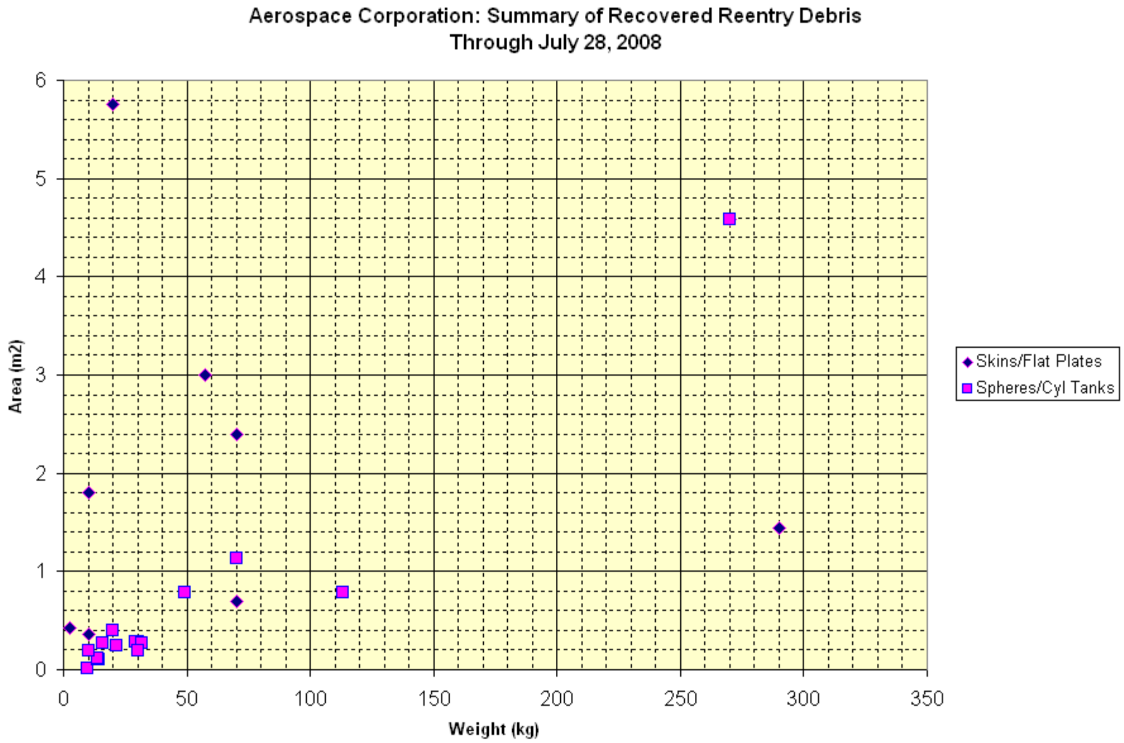

Figure 2. Recovered Reentry Debris

B. Random Reentry Risk

Random reentries are reentries that are allowed to occur naturally as orbits decay. No steps are taken to target specific impact points. In previous rulemaking the FAA stated, "it is generally expected that reentering space objects burn up upon reentry into the Earth's atmosphere. As a result, they do not present a threat to public safety" (NPRM 431 Vol. 64, No. 76 pg 19627). In the absence of sufficient empirical data or analyses to the contrary, the existence of large oceans, sparsely populated regions, and significant demise during reentry provided support for this statement. However, additional debris recovered from larger satellites and rocket bodies that use more heat tolerant metals, as well as the results of a number of analyses that have been conducted, show that the debris and risks associated with random reentries can present a significant threat to public safety. As illustrated in Figure 2, debris of greater than 5 meters squared from random reentries have been found and catalogued.

To determine the risk to the population, the inclination of the object's orbit and the Earth's geography must be taken into account. In general, the Earth is 70% water with most of the land mass concentrated in the Northern Hemisphere. Large expanses of the land mass are sparsely populated. The analysis that follows does not consider the risk presented by reentering debris to ships and aircraft. Analysis done by the Aerospace Corporation[5] shows the risk to aircraft is on the order of one in one billion and is well below the Range Commanders Council guideline of one in ten million. At this time, the risk to ships is not quantified but it is assumed to be comparable to or less than the risk to aircraft. Because of the irregular population distribution on Earth, certain orbital inclinations present more risk. Figure 3 shows an example of year 2005 population of the world. As can be seen by this figure most of the significant populations are located in the Northern Hemisphere. To be consistent with NASA guidelines[6] for reentering debris this analysis chose to set the threshold for risk requirement to one hundred in a million.

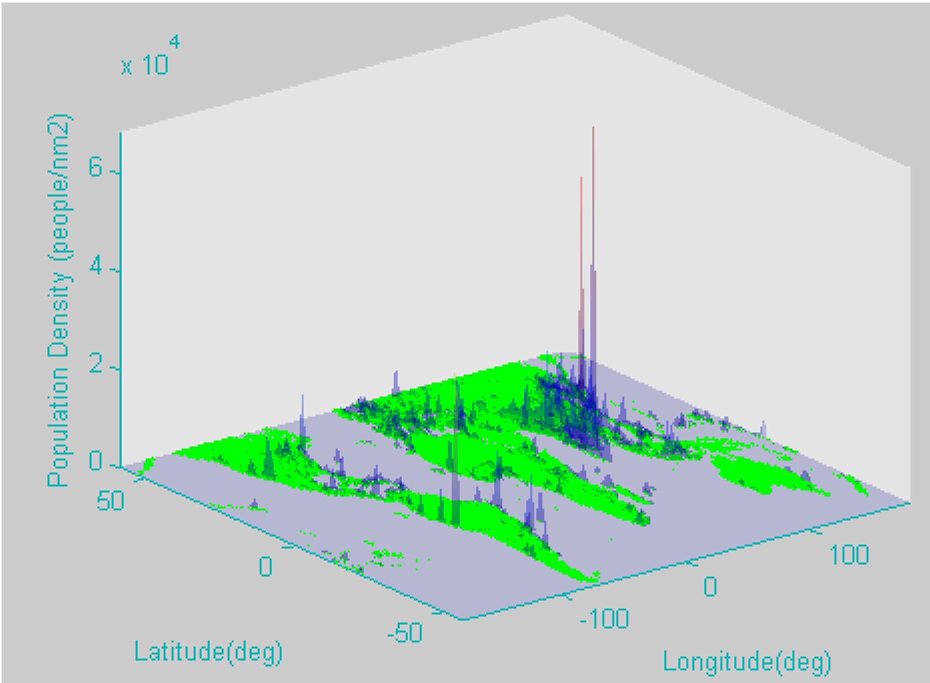

Figure 3. Gridded Population of the World for Year 2005

Figure 4 shows how the expected casualty per square meter varies by the inclination of the reentering debris. This figure illustrates the increase in collective risk from 1995 to 2015 per unit casualty area (in square meters) using the Gridded Population of the World database. It also shows the casualty area (in square meters) which results in a collective risk of one hundred in a million. Results obtained from Dr. Russell Patera of Aerospace Corporation for the year 2005 population are also shown. As the Earth's population grows so will the collective risk to the public. The number of random reentries will also increase as current and future space debris reenters the atmosphere. It is important to note that for the current population the debris size is about 5 m^2 or about 54 ft^2 at the worst inclination of 35 degrees considering the 2005 population database. The average casualty area for all inclinations is shown to be 8.3 meters squared for the year 2005. Figure 5 shows the average size of the debris that results in a risk of one hundred in a million as the population is expanded to the year 2050 assuming a 1.2%[7] growth rate from 2015 to 2050. As seen by this figure the debris average casualty area drops to about 4.5 m^2 for the year 2050 compared to 8.3 m^2 for the year 2005.

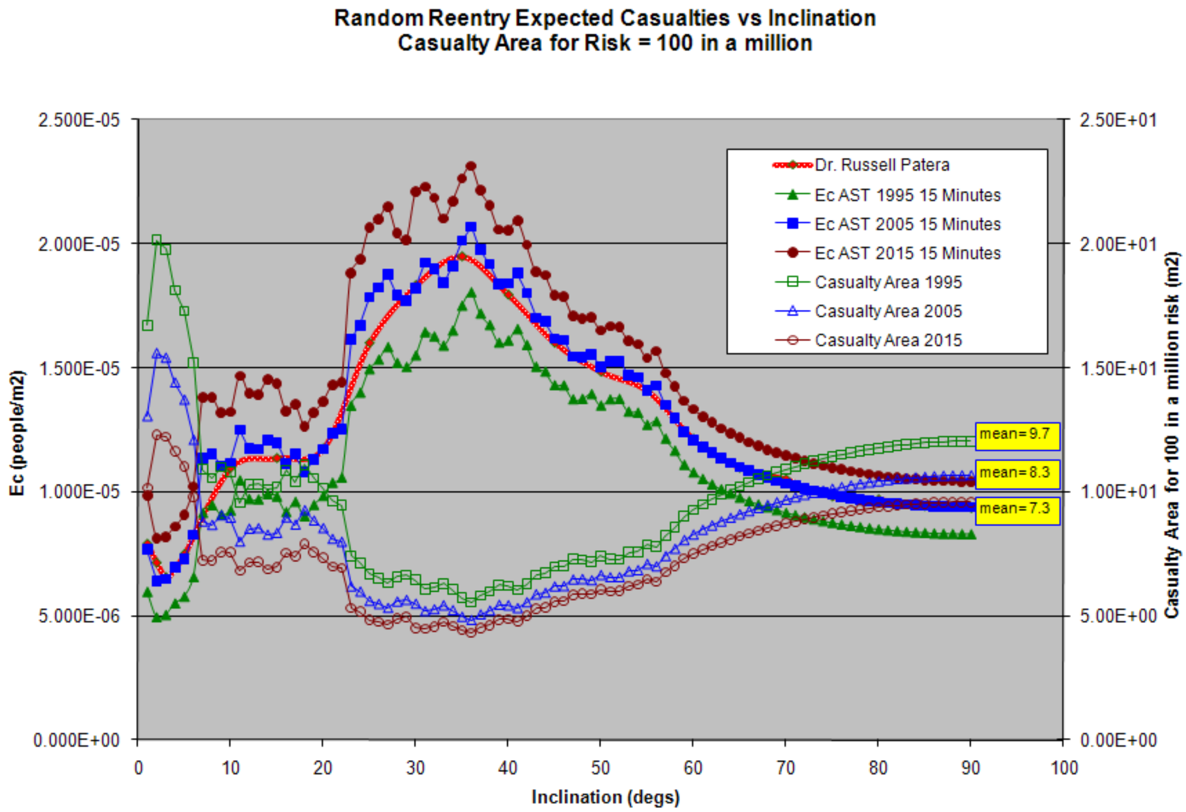

Figure 4. Random Reentry Collective Risk vs. Orbital Inclination

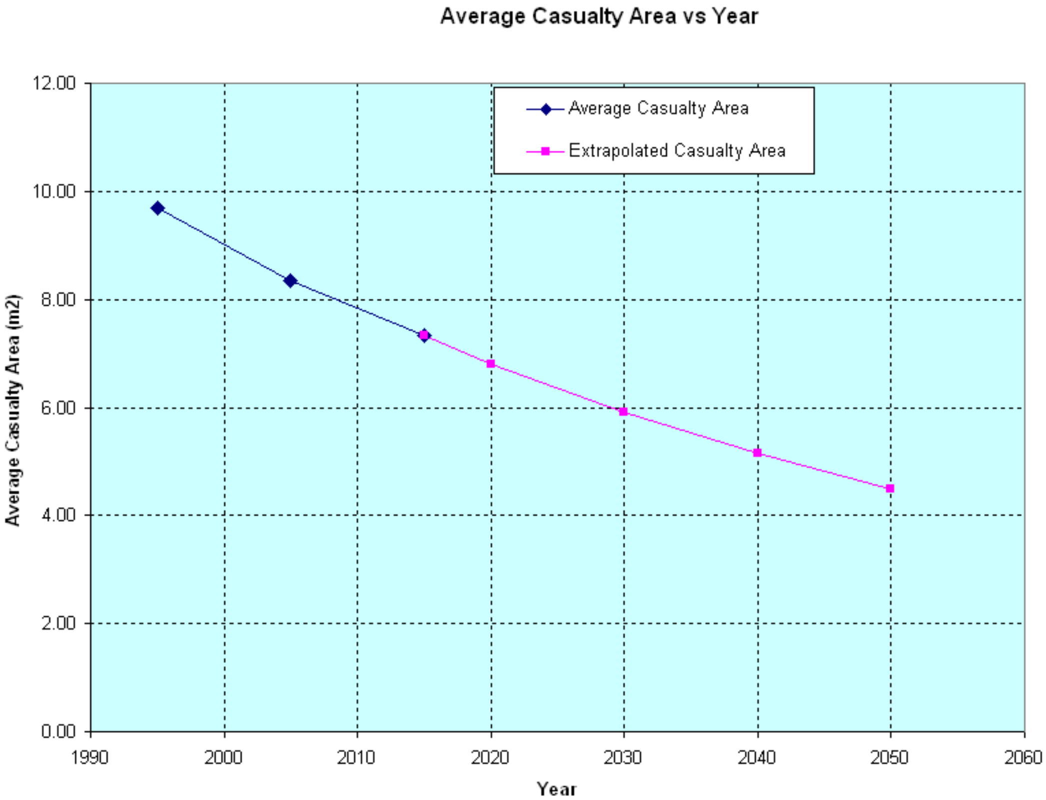

Figure 5. Average Casualty Area versus year to meet 100 in a million risk requirement

VII. Conclusion

The analysis performed shows that risk due to random reentering debris is sensitive to the inclination of the random debris and the world population at the time of random reentry. The analysis shows that for a 2005 population the average size of debris that meets a NASA risk criterion of 100 in a million is about 8.3 square meters. In addition, for this population database, the minimum size of debris that meets the 100 in a million risk requirement considering any inclination was found to be 5 meters squared occurring at an inclination of about 35 degrees. If one considers population growth out to the year 2050, then the minimum average casualty area meeting the risk criterion of 100 in a million drops to about 4.5 meters squared. This analysis shows that significant pieces of random debris, in excess of 5 square meters, have impacted a landmass of the earth. For this size of debris the risk to the public approaches 100 in a million when considering the year 2005 Gridded Population of the World and exceeds 100 in a million when considering a world population expanded to the year 2050.

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VIII. Acronyms

CFR – Code of Federal Regulation
FAA – Federal Aviation Administration
AST – Commercial Space Transportation Office
RLV – Reusable launch vehicle
ELV – Expendable launch vehicle
GPW – Gridded Population of the World

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X. References

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