General Models for Assessing Hazards Aircraft Pose to Surface Facilities

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Abstract—*This paper derives formulas for estimating the frequency of accidental aircraft crashes into a surface facility. Objects unintentionally dropped from aircraft are also considered. The approach allows the facility to be well within a flight area; inside a flight area, but close to its edge; or completely outside a nearby flight area.*

I. INTRODUCTION

The surface facilities for the proposed Yucca Mountain repository are located beneath the restricted airspace of the Nevada Test Site (NTS). Just outside the boundaries NTS, and within several miles of the Yucca Mountain site, are portions of the Nevada Test and Training Range (NTTR), which the U.S. Air Force uses intensively for training and test flights. The Air Force also uses the airspace above the NTS to fly between the northern and southern portions of the NTTR. Commercial, military, and general-aviation aircraft fly within several miles to the southwest of Yucca Mountain on flight paths in a wide band that runs approximately parallel to U.S. Highway 95 and the Nevada-California border. These and other aircraft operations were identified and described in *Identification of Aircraft Hazards.*[1]

This paper derives formulas for estimating the frequency of accidental aircraft crashes into a surface facility. Objects unintentionally dropped from aircraft are also considered. Three different aircraft-crash cases are considered. In the first case, the flying time (aircraft hours per year) aircraft spend in the nearby flight area is known and it is assumed that the risk of crash initiation is distributed uniformly throughout the flight area. The time spent flying may not be known in the second case, but the frequency of flights must be known (numbers of aircraft per year) and the flights are assumed to be straight lines. The third case generalizes the NUREG-0800 model for airways[2] to take more credit for the decrease in crash risk as the distance from the center of the airway increases. The derivations owe their inspiration to the approach taken by Kimura et al.[3] Kimura et al. assume that the flight area completely surrounds the facility such that the flight area contains, at a minimum, all points from which an airplane destined to crash could reach the facility. In contrast, the present approach allows the facility to be well within the flight area; inside the flight area, but close to the edge; or completely outside the flight area.

II. WORK DESCRIPTION AND RESULTS

II.A. Randomly Oriented Flights

The NUREG-0800 airways model[2] is designed for conservatively estimating crash probabilities related to a nearby airway or aviation corridor. Other methods address point-to-point flights not restricted to airways[4] and randomly oriented flights in military operations areas.[3] This section develops methods for estimating the probability of an aircraft crash into a surface facility located near or within an airspace where flights are randomly distributed

The small dark shape near the center of Figure 1 represents the view from above a surface facility that may be damaged by an airplane crash. For the purposes of this paper, airspace volumes are defined by vertical extensions of areas on the ground. Therefore, for simplicity, they can be discussed in terms of the areas on the ground. The area A_f represents the airspace where aircraft crashes could originate. A small circle is drawn around the facility as a simplified representation of the facility's effective area with respect to plane crashes. The effective area is larger than the footprint of the facility to account for wingspan, skid, and shadow effects. To avoid clutter, the effective area, A_{eff}, is not labeled and its radius, r_{eff}, is not shown. The crash range, that is, the maximum horizontal distance an airplane destined to crash can travel before reaching ground level is shown as r_c. A crash-initiating event that occurs to an airplane while it is within the area A_d, which is defined as the intersection of the flight area A_f and a circle of radius r_c+r_{eff} centered at the

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facility, could cause the plane to crash into the facility. A typical crash-initiation point within area A_d is shown as a black dot. The surrounding area A_c in which the typical crashing plane could hit the ground is delimited by a dashed circle of radius r_c, centered at the crash-initiation point.

Although Figure 1 depicts the facility outside the flight area, the general models to be developed are applicable whether the facility is inside or outside the flight area. Special cases will be considered in which specific assumptions are made with respect to the location of the facility with respect to the flight area.

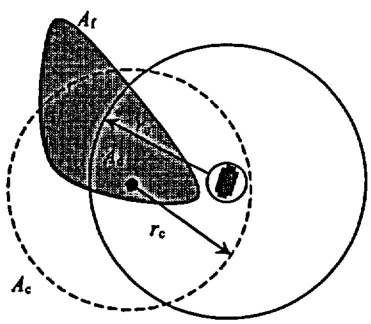

Figure 1. Surface Facility Near a Convex Flight Area

II.A.1. Known Time in Flight

Let T be the expected total annual flight time in h/y of all flights in flight area A_f. If β is the mean crash rate per hour of flight, then the expected annual frequency of crashes initiated in the flight area is $T\beta$. Only those crashes that are initiated within range of the facility (that is, in the area A_d, which is a subset of the flight area A_f as shown in Figure 1) pose any hazard to the facility. On the assumption that crash-initiation events are uniformly distributed throughout the flight area, the frequency of crashes that may hit the facility is given by $T\beta(A_d / A_f)$. Finally, assume that crashes are uniformly distributed throughout the circular area defined by the crash range. Using the full effective area of the facility even when part of the facility is out of reach, the frequency of crashes into the facility (y^{-1}) depends on the effective area of the facility A_{eff} and the size of the potential crash area A_c as follows:

$$F = T\beta \frac{A_d}{A_f} \frac{A_{eff}}{A_c} \quad . \qquad \text{(Eq. 1)}$$

A special case emerges when the flight area completely surrounds the facility and includes the entire area that is within crash range of the facility. In that case, $A_d = \pi(r_{eff} + r_c)^2$ and $A_c = \pi(r_c)^2$. If the facility is small compared to the crash range, that is, $r_{eff} << r_c$, then $(A_d / A_c) \cong 1$ and

$$F = \frac{T\beta}{A_f} A_{eff} \quad . \qquad \text{(Eq. 2)}$$

Note that the crash range r_c does not appear in the formula for the special case. The formula may be regarded as the product of two factors: (1) the uniform areal crash-initiation density per year associated with the flight area and (2) the effective area of the facility. Three additional special cases are worth mentioning for the insight they provide.

The first additional special case demonstrates a pure edge effect. If the facility is located right on the edge of a large rectangular flight area (and far from any corner) then the area A_d is a semicircle and the potential crash area A_c is a circle of approximately the same radius. The ratio of the two areas, A_d / A_c, is one-half. So the pure edge effect reduces the crash probability by one-half.

The second additional special case demonstrates a pure 90-degree corner effect. If the facility is located right on a corner of a large rectangular flight area, then the area A_d is a quarter circle and the potential crash area A_c is a circle of approximately the same radius. The ratio of the two, A_d / A_c, is one-quarter. So the pure 90-degree corner effect reduces the crash probability by three-quarters.

The third case applies when the crash range completely encompasses the flight area. Then $A_d = A_f$, and $F = T\beta A_{eff} / (\pi r_c^2)$. Note that, in this special case, a greater crash range implies a lower frequency of crashes into the facility. When, as in the first two additional special cases, the crash range partially extends outside the flight area, an edge effect appears. In this special case, edge effects occur throughout the flight area.

II.A.2. Straight-Line Flights

Now assume that the total flight time in the flight area is not known, but the frequency of flights is known and the flight paths can be considered straight lines. Let N be the annual frequency of flights (y^{-1}) passing through the flight area, and λ be the crash frequency per kilometer of flight (km^{-1}). The expected frequency of crashes initiated in the flight area is given by $N\lambda l_m$, where l_m is the mean length of flights through the flight area (km). The areal density of crashes initiated in the flight area is $N\lambda l_m / A_f$.

For a convex area, the mean length of a chord intersecting the area is

$$l_m = \frac{\pi A}{L}, \qquad \text{(Eq. 3)}$$

where A is the surface area and L is the length of the perimeter.[5] Thus, the areal density of crashes originating in the flight area is $N\lambda l_m / A_f = N\lambda\pi / L_f$. Only those crashes that occur within the crash range (that is, in the area A_d, which is a subset of the flight area A_f as shown in Figure 1) pose any hazard to the facility. On the assumption that crash-initiation events are uniformly distributed throughout the flight area, the frequency of crashes that may hit the facility is given by $(N\lambda\pi / L_f)A_d$ Finally, assume that crashes are uniformly distributed throughout the circular area defined by the crash range. Using the full effective area of the facility even when part of the facility is out of reach, the frequency of crashes into the facility (y^{-1}) depends on the effective area of the facility, A_{eff}, and the size of the potential crash area A_c as follows:

$$F = \frac{N\lambda\pi}{L_f}\frac{A_d}{A_c}A_{eff} \quad . \qquad \text{(Eq. 4)}$$

Again, a special case emerges when the flight area completely surrounds the facility and includes the entire area that is within crash range of the facility. In that case, $A_d = \pi(r_{eff} + r_c)^2$ and $A_c = \pi r_c^2$. If the facility is small compared to the crash range, that is, $r_{eff} << r_c$, then $(A_d / A_c) \cong 1$ and

$$F = \frac{N\lambda\pi}{L_f}A_{eff} \quad . \qquad \text{(Eq. 5)}$$

Note again that the crash range does not appear in the formula for the special case. The right-hand side of Equation 5 makes intuitive sense if it is regarded as the product of two factors: the uniform areal crash-initiation density per year associated with the flight area and the effective area of the facility.

The pure edge and corner effects discussed in Section II.A.1 for known time in flight apply to straight-line flights as well. A similar special case also emerges when the crash range completely encompasses the flight area. Then $A_d = A_f$, and the term A_d / A_c in Equation 4 becomes $A_f / (\pi r_c^2)$, so that a greater crash range implies a lower frequency of crashes into the facility.

II.B. Extension of the NUREG-0800 Model for Airways

The *Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants*[2] provides the following formula for calculating the frequency F of aircraft crashes into the facility when an airway or aviation corridor passes near the site.

$$F = \frac{N\lambda}{w}A_{eff} \quad , \qquad \text{(Eq. 6)}$$

where N is the annual frequency of flights (y^{-1}) passing through the aviation corridor, λ is the crash frequency per kilometer (km^{-1}), and w is the width of the aviation corridor plus twice the distance from the edge of the corridor to the facility when the facility is outside the corridor (km). The formula may be regarded as the product of two factors: (1) the uniform areal crash-initiation density per year associated with a band that includes the aviation corridor and extends out the distance to the facility on either side, and (2) the effective area of the facility.

One feature of the NUREG-0800 model that restricts its applicability to the proposed Yucca Mountain surface facility is its treatment of edge effects. Note that the crash-rate density assigned to the center of an airway is the same as that near the edge or beyond it. Considering the simple treatment of edge effects in the NUREG-0800 model, it is understandable that the U.S. Nuclear Regulatory Commission implied a range of applicability of the model of 3.2 km (2 miles) from the edge of an airway.[2] The proposed Yucca Mountain facility will be more than 3.2 km (2 miles) from the edge of an aviation corridor, so edge effects may be significant, and the standard NUREG-0800 model may be too conservative.

A straightforward extension of the NUREG-0800 model to take more credit for edge effects is possible. Consider an airway with flight paths running along the length l of an arbitrarily long section of the airway (Figure 2). In keeping with assumptions of the previous sections, assume that the effective radius of the facility is very small compared to the crash range: $r_{eff} << r_c$. Further assume that flight paths are uniformly distributed across the width of the airway w_f. Aircraft in flight farther away than the crash range, r_c, from the facility are not considered a threat. The annual frequency of crash initiation in the area A_f is $N\lambda l$. Only the fraction A_d / A_f of the total crash frequency represents a hazard to the facility. Therefore, the crash frequency of concern to the facility is $N\lambda l A_d / (l w_f) = (N\lambda / w_f)A_d$. As in Figure 1, A_c denotes the area surrounding the crash-initiation point in which a crashing plane could hit the ground. Assuming that the crash-impact points are distributed uniformly throughout the area within reach of the crashing aircraft A_c, the fraction of the crashes in the area A_d that are expected to hit the facility is A_{eff} / A_c. Therefore, the total crash frequency into the facility is

$$F = \frac{N\lambda}{w_f}\frac{A_d}{A_c}A_{eff} \quad . \qquad \text{(Eq. 7)}$$

Note that the NUREG-0800 formula (Equation 6) and the formula just developed (Equation 7) are the same except for the width variable and the ratio A_d / A_c. For the special case in which the facility is exactly on the edge of the airway, the definitions of the width variable are the same and the ratio A_d / A_c is one-half, independent of the crash range. Thus, the edge-effect adjustment is one-half when the facility is located on the edge of the airway.

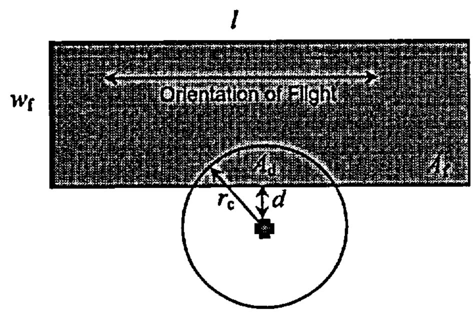

Figure 2. Surface Facility and Nearby Airway

When the facility is located some distance d away from the edge of the airway, the computation of the ratio A_d / A_c is more complicated. The area A_d as a function of the radius r_c and the distance d is given[6] by:

$$A_d = r_c^2 \cos^{-1}(\frac{d}{r_c}) - d\sqrt{r_c^2 - d^2} \quad . \qquad \text{(Eq. 8)}$$

The effect of increasing distance from the airway (as determined with the help of Equation 8) is illustrated in Table I. The crash frequency depends on the crash range. However, if the crash range is not known, a conservative edge adjustment of 0.5 can be used whenever the facility lies outside the edge of the airway.

Equation 8 may also be used with Equation 7 to account for the edge effect inside an airway, but near the edge. The distance from the edge of the airway is negative whenever the facility is inside the airway. Note that when $d = -r_c$ (such that there is no edge effect), Equation 8 gives $A_d = \pi r_c^2$. Then, $A_d / A_c = 1$ in Equation 7 and the resulting special case is identical to the NUREG-0800 model as applied to a facility inside an airway.

II.C. Objects Dropped from Aircraft

Consider a facility that is located within a convex area A, for which the annual frequency of over-flights N is known. Let α be the average rate at which objects are unintentionally dropped per sortie, D be the average distance traveled per sortie, and A_{eff} be the effective area of the facility with respect to dropped objects. While the aircraft is within area A, its flight path is assumed to be a straight line. Much of the distance traveled on each sortie may be flown outside the area A. Therefore, while the total drop frequency for the flights that pass over area A is $N\alpha$, only a fraction of the drops will occur within area A.

Conservatively assuming that the distribution of dropped objects along the flight path is uniform, the fraction that occur in area A is the ratio of the mean chord l_m through area A to the average distance per sortie, D, that is, l_m / D. A uniform distribution is conservative because there are reasons to expect that the drop rate per unit distance traveled would peak on or near the runway and fall with distance away from the runway. For example, objects falling from the landing gear would fall before the gear is withdrawn after takeoff or after it is extended before landing. Objects loosely attached or not attached at all would fall soon after the acceleration, vibration, and wind pressure associated with takeoff began.

Table I Edge Adjustment for the Modified Airways Model

Distance d Outside Airway	Edge Adjustment (A_d / A_c)
$0.0r_c$	0.500
$0.1r_c$	0.436
$0.2r_c$	0.374
$0.3r_c$	0.312
$0.4r_c$	0.252
$0.5r_c$	0.196
$0.6r_c$	0.142
$0.7r_c$	0.094
$0.8r_c$	0.052
$0.9r_c$	0.019
$1.0r_c$	0.000

According to Equation 3 the mean length of a chord through A is $\pi A / L$, where L is the perimeter of area A. Thus, the fraction of drops that occur over area A is $\pi A / (LD)$ and the frequency of drops over area A is $N\alpha\pi A / (LD)$. Of those, the fraction expected to hit the facility is A_{eff} / A. The frequency of objects expected to hit the facility, F, is the product of the frequency of drops over area A and the fraction expected to hit the facility. The area A cancels, giving:

$$F = \frac{N\alpha\pi}{LD} A_{eff} \quad . \qquad \text{(Eq. 9)}$$

III. DISCUSSION AND CONCLUSIONS

Equations 1 and 4 may be used to estimate accidental crash frequencies for the proposed Yucca Mountain surface facility when the facility is not directly below a flight area where randomly oriented flight occurs (as is the case for nearby NTTR airspace) and when the facility is near the edge of the flight area (as is the case for NTS airspace). The special cases represented by Equations 2 and 5 may be used when the flight area completely surrounds the facility and includes the entire area that is within crash range of the facility. Equation 7 may be used when the facility is near an aviation corridor (such as the one to the southwest of Yucca Mountain) in preference to the more conservative NUREG-0800 model. Equation 9 provides a conservative assessment of the frequency of hits from objects unintentionally dropped from aircraft.

If a flight area is used by different kinds of aircraft with different characteristics, the formulas may be applied separately for each aircraft type, and the frequency results summed to get the total crash frequency from aircraft of all types. Similarly, if the flight area is used by aircraft over a broad altitude range, and none of the special cases in which the crash range cancels out apply, Equations 1, 4, and 7 may be applied for each of several altitude bands, allowing greater crash ranges for higher altitudes.

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