TS

NOT MEASUREMENT SENSITIVE

DOE-STD-3014-2006
October 1996

Reaffirmation
May 2006

DOE STANDARD

ACCIDENT ANALYSIS FOR AIRCRAFT CRASH INTO HAZARDOUS FACILITIES

U.S. Department of Energy
Washington, DC 20585

AREA SAFT

5. METHODOLOGY FOR EVALUATING AIRCRAFT CRASH IMPACT AND RELEASE FREQUENCY

5.1 Introduction. This chapter establishes a set of guidelines and methods for calculating and analyzing the impact frequency of aircraft crashes into a facility and the release frequency for radioactive and/or hazardous materials. The approach to analyzing frequency is divided into three parts:

a. Impact Frequency Evaluation: The fundamental analysis, based on estimating the frequency of aircraft crashes into a facility. This provides basic frequencies for subsequent screening and evaluation analyses.

b. Release Frequency Screening: An analysis based on including the structural response evaluation in the impact frequency evaluation.

c. Release Frequency Evaluation: An analysis based on developing release scenarios from the time of an aircraft crash until the time exposure occurs due to the release of hazardous material.

The method used to estimate the frequency in each part is based on the same technical principle; however, each part consists of varying degrees of complexity and conservatism. After each part is completed, the results are compared with the guideline value given in Chapter 4. If the result exceeds the guideline value, then additional analyses are performed; otherwise, no further work is required beyond documenting the analysis.

The technical information provided in this chapter covers only the basic guidelines for implementing the three parts, along with a description of the frequency estimation models and the corresponding important input parameters for each model. Further technical information required to perform the analysis is provided in Appendix B.

Detailed technical evaluations that support the development of each frequency model are provided in the modeling and data technical support documents (References 1 and 2). These support documents should be consulted if additional information on the specifics of

each method is needed. Neither this standard nor the modeling and data technical support documents contain site-specific information; rather, they provide guidance on what site-specific information is necessary and how to develop it.

Aircraft crash frequencies are estimated using a "four-factor formula" which considers (1) the number of operations, (2) the probability that an aircraft will crash, (3) given a crash, the probability that the aircraft crashes into a 1-square-mile area where the facility is located, and (4) the size of the facility. In this standard, the four-factor formula is implemented in two different ways, depending on the flight phase:

a. For near-airport activities, which consist of takeoffs (*i=1*) and landings (*i=3)*, the four-factor formula is implemented through a combination of site-specific information and data obtained by the user of the standard, and a set of tables (whose origins are discussed in Reference 2) provided in Appendix B of this standard.

b. For nonairport activities (*i=2*), DOE site-specific values, as well as reasonable estimates applicable throughout the continental United States, for the expected number of crashes per square mile per year in the vicinity of the sites (i.e., the value of the product NPf(x,y)) are provided in Appendix B of this standard; the four-factor formula is implemented by combining these with the facility effective areas to assess frequencies.

Mathematically, the four-factor formula is:

$$F = \sum_{i,j,k} N_{ijk} \cdot P_{ijk} \cdot f_{ijk}(x,y) \cdot A_{ij} \qquad (5\text{-}1)$$

where:

F = estimated annual aircraft crash impact frequency for the facility of interest (no./y);

N_{ijk} = estimated annual number of site-specific aircraft operations (i.e., takeoffs, landings, and in-flights) for each applicable summation parameter (no./y);

P_{ijk} = aircraft crash rate (per takeoff or landing for near-airport phases and per flight for the in-flight (nonairport) phase of operation for each applicable summation parameter;

$f_{ijk}(x,y)$ = aircraft crash location conditional probability (per square mile) given a crash evaluated at the facility location for each applicable summation parameter;

A_{ij} = the site-specific effective area for the facility of interest that includes skid and fly-in effective areas (square miles) for each applicable summation parameter, aircraft category or subcategory, and flight phase for military aviation (see Appendix B);

i = (index for flight phases): i=1, 2, and 3 (takeoff, in-flight, and landing);

j = (index for aircraft category or subcategory): j=1, 2,..., 11;

k = (index for flight source): k=1, 2,..., K (there could be multiple runways, and nonairport operations);

Σ_{ijk} = $\Sigma_k\ \Sigma_j\ \Sigma_i$; site-specific summation over flight phase, i; aircraft category or subcategory, j; and flight source, k.

It should be noted that there is uncertainty associated with the frequency estimates produced using the four-factor formula, caused by the need to model complex physical processes using parameters that are based upon limited historical data. Experience-based judgements have been made as needed to supplement historical data, introducing additional uncertainties. This standard does not provide a quantitative estimate of the uncertainties involved; rather, the mathematical formulations and supporting parameter estimates have been made so as to provide a reasonable point estimate of the frequency of aircraft crash impacts into specified facilities.

5.2 Methodology for Impact Frequency Screening. Although the desirability of a simple impact frequency screen based on the number of operations at nearby airfields was

recognized, the high value of the maximum expected frequency of an in-flight mishap resulting in an aircraft impacting an arbitrary square mile in the continental United States precluded the development of a useable impact frequency screening methodology.

5.3 Methodology for Impact Frequency Evaluation. This section describes the approach for implementing the impact frequency evaluation, using the four-factor formula as given in Equation 5-1. The following guidance provides a set of steps for calculating impact frequency. Steps 1 through 6 are for determining the impact frequency from airport operations; Steps 7 through 19 are for determining the impact frequency from nonairport operations (Steps 7-8 for general aviation, Steps 9-12 for commercial aviation, Steps 13-16 for military aviation; and Steps 17-19 for helicopters); and Steps 20 and 21 are for comparing the results with the guidelines.

An example of the use of these steps is included as Section B.5 of Appendix B.

5.3.1 Impact Frequency from Airport Operations.

Step 1. Identify the flight sources affecting the facility. To do this, identify any airports that can be located within the boundaries of the aircraft crash location probabilities (Tables B-2 through B-13). Contact these airports to get an estimate of the annual number of takeoffs and landings, N, for each aircraft category or subcategory. This information can usually be provided by the airport on a category basis. If the airport can only provide total operations and is not able to discriminate between operation activities, assume that one-half (50 percent) of the operations are takeoffs and one-half (50 percent) are landings. This assumption will result in very conservative numbers because total operations include activities other than takeoff and landing, such as an aircraft contacting the tower for a change of vector. Finally, have the airport identify the pattern side of the runway for military aviation, if applicable.

Step 2. For each flight source, determine the orthonormal distance (Cartesian distance, both x and y coordinates) from the facility, measured from the facility's closest point, to the center of each runway at the flight source (for guidance on determining the orthonormal distance see Appendix B, Section B.3.1, and the example in Section B.5).

Step 3. Given the orthonormal distance of the facility from each flight source, obtain the generic aircraft crash location probability per square mile, i.e., f(x,y), for takeoff and landing for each aircraft category/subcategory. This information is included in Appendix B as Tables B-2 through B-13. If the orthonormal distance of a facility falls outside the boundaries of these tables, the corresponding f(x,y) is assumed to be zero (a noncontributor).

Step 4. Obtain the aircraft takeoff and landing crash rates, P, for each aircraft category or subcategory. This information is provided in Table B-1 of Appendix B.

Step 5. Calculate the effective area, A, for each aircraft category or subcategory. The calculation of the effective area consists of two components: the aircraft can crash into the structure either by skidding or by flying directly into it. To calculate the effective area, assume that the aircraft skids or flies into the structure in the direction that produces the largest area, i.e., crashing in a direction perpendicular to the largest diagonal of the building. The formula for calculating the skid- and fly-in areas of an aircraft crashing into a facility are provided as Equations B-3 through B-5 in Section B.4 of Appendix B. The effective area is a function of the cotangent of the impact angle, wingspan, and skid distance of the crashing aircraft. Values of these parameters are given in Section B.4 of Appendix B.

Step 6. Multiply the values for N, P, f(x,y), and A for each combination of flight source, flight phase, and aircraft category/subcategory. Sum over flight sources and flight phases to calculate an impact frequency for each aircraft category/subcategory. (Do not sum the categories yet; this will be included in a later step.)

5.3.2 Impact Frequency from Nonairport Operations. Even though the expected frequency of aircraft crashes into a facility due to mishaps occurring during the in-flight phase of operation, is expected to be lower than the frequency associated with airport operations, the expected frequency cannot be shown to be a noncontributor to the overall frequency for all facilities. Thus, nonairport operations must be considered in the impact frequency analysis.

The analysis of the nonairport operations impact frequency for all categories of aircraft is based on the same four-factor formula (Equation 5-1) as is used for airport operations; i.e., the frequency, F_j, for the class of aircraft, j, is

$$F_j = N_j \cdot P_j \cdot f_j\,(x,y) \cdot A_j \qquad (5\text{-}2)$$

where the product NP represents the expected number of in-flight crashes per year; f(x,y) is the probability, given a crash, that the crash occurs in a 1-square-mile area surrounding the facility of interest; and A is the effective area of the facility. Ideally, values for NP and f(x,y) would be provided for any location within the continental United States (CONUS), similar to those provided for airport operations. However, this is impractical because of the large area of the CONUS. For this standard, values of the product NPf(x,y) applicable to selected DOE sites are provided in Tables B-14 and B-15. Also included are minimum, U.S. average, and maximum values, which can be used for facilities at other locations within the CONUS, for each category of aircraft.

Development of the values in the tables is based on an analysis of the locations of past aircraft crashes within the CONUS. For general aviation, this record is substantial (over 1000 crashes) while the available data for other aircraft categories/subcategories, e.g., air carrier and large military, are very limited. Discussion of the bases of the values in Tables B-14 and B-15 and an outline of the analysis steps follow.

a. General Aviation. The distribution of general aviation (GA) aircraft crashes throughout the CONUS is based on GA aircraft flying under both VFR and IFR conditions. Except for certain restrictions, e.g., restricted airspace, a GA aircraft can fly almost anywhere in the CONUS. In addition, once an in-flight mishap does occur, with an eventual loss of control, there is nothing to prevent a disabled aircraft from crashing into any location, even within a restricted airspace area. Thus, it is

reasonable to assume that GA aircraft can crash anywhere in the CONUS.

Crash location probabilities for GA aircraft are based on the assumption that future levels of GA aircraft activity and flight patterns will be similar to the historical record. The model for estimating the distribution of GA aircraft crash locations uses historical locations as the most likely but assumes that future locations will deviate within some area about the historical locations.

Several models of the variation of future crash locations based on different hypotheses formed the basis for conducting a parametric study of the product NPf(x,y). The models and the associated sensitivity studies are discussed in Reference 1. The DOE site-specific values provided in Table B-14 of Appendix B represent reasonably conservative estimates obtained through a collective consideration of the sensitivity study results.

Step 7. Refer to Appendix B, Table B-14, and obtain the appropriate site-specific or generic value for NPf(x,y).

Step 8. Multiply the value of NPf(x,y) by the corresponding value for A determined in Step 5. This is the estimated GA nonairport impact frequency.

b. Commercial and Military Aviation. Nonairport commercial and military impact frequency calculations are based on the assumption that the aircraft will fly point to point under the new FAA regulations rather than in specific airways. The values of NPf(x,y) in Table B-15 are derived from values developed for the ARTCC spanning the CONUS. The model assumes that the traffic density within an ARTCC is uniform and, given a crash in the ARTCC, the location of the crash is random.

For commercial and large military aviation, crashes are assumed to occur at random throughout the CONUS, and the variation in traffic volume is reflected by the variation in the number of aircraft handled in each ARTCC. For small military aviation, the number of crashes varies among the ARTCCs. Thus, the expected number of crashes per year is estimated for each ARTCC based on the distribution of crash locations in the historical record.

Table B-15 in Appendix B provides reasonable estimates of NPf(x,y) for selected DOE sites, as well as estimates of a minimum, average, and maximum value applicable for facilities at other locations within the CONUS.

It is important to recognize that the in-flight analysis for military aviation given below only applies to normal in-flight operations outside military operations areas and low level flight ranges. For facilities at or near these latter types of areas, it is necessary to perform a site-specific assessment of the impact frequencies associated with activities in these areas.

The analyses for each of the commercial and military subcategories are as follows:

1. Commercial Aviation Air Carrier.

Step 9. Refer to Appendix B, Table B-15, and obtain the appropriate site-specific or generic value of NPf(x,y).

Step 10. Multiply the value of NPf(x,y) by the A value determined for air carriers in Step 5.

2. Commercial Aviation Air Taxi.

Step 11. Refer to Appendix B, Table B-15, and obtain the appropriate site-specific or generic value for NPf(x,y).

Step 12. Multiply the value NPf(x,y) by the A value determined for air taxis in Step 5.

3. Large Military Aviation.

Step 13. Refer to Appendix B, Table B-15, and obtain the appropriate site-specific or generic value for NPf(x,y).

Step 14. Multiply the value NPf(x,y) by the takeoff effective area value, A, determined for large military takeoff in Step 5. The takeoff effective area, A, is used because it more closely represents in-flight crashes.

4. Small Military Aviation.

Step 15. Refer to Appendix B, Table B-15, and obtain the appropriate site-specific or generic value for NPf(x,y).

Step 16. Multiply the value NPf(x,y) by the takeoff effective area value, A, determined for small military takeoff in Step 5. The takeoff effective area, A, is used because it more closely represents in-flight crashes.

c. Helicopter Aviation. Based on an analysis of historical helicopter crash data, the contribution to impact frequencies associated with nonlocal helicopter overflights is insignificant and need not be considered in the impact frequency calculations. However, it is necessary to consider local overflights, either planned overflights associated with the facility operations, e.g., security flights, or flights associated with area operations, e.g., spraying flights. Thus, the calculation of in-flight helicopter impact frequencies is a site-specific calculation. For

application of this standard, each facility needs to obtain (1) the expected number, N, of helicopter local overflights per year; (2) the average length, L, in miles, of the flights corresponding to the site-specific overflights; and (3) the effective area for helicopter in-flight crashes, using Equation B-4, assuming an impact angle of 60 degrees, i.e., cotϕ = 0.58 (note skid length is assumed to be 0). For these calculations, as shown in Equation 5-3, the lateral variations in crash locations for a helicopter are conservatively assumed to be one-quarter a mile on the average from the centerline of its flight path.

The analysis for helicopter impact frequency calculations is as follows:

Step 17. Obtain N_H, the expected number of local helicopter overflights per year, and L_H, the average length of a flight.

Step 18. Compute the effective area, A_H, using Equation B-4.

Step 19. Using the values of the probability of a helicopter crash per flight, P_H, in Table B-1 in Appendix B, compute the helicopter impact frequency, F_H.

$$F_H = N_H \cdot P_H \cdot \frac{2}{L_H} \cdot A_H \tag{5-3}$$

5.3.3 Calculated Impact Frequency.

Step 20. Sum the calculated impact frequency for airport and nonairport operations for each aircraft category or subcategory. For example, add up all the general aviation impact frequencies calculated in Steps 6 and 8. Rank the impact frequencies for all aircraft categories/subcategories in decreasing order. Sum the impact frequencies over the aircraft categories/subcategories to get the total impact frequency for the facility of interest.

Step 21. If the total impact frequency is below the guideline value, the safety risk is below the level of concern; stop the analysis and document the results. If the total impact frequency is greater than the guideline value, it is necessary to identify the aircraft categories/subcategories to be used for the structural response and release frequency analyses. A certain amount of judgment is required in making this selection. It is recommended that the analyst interact with the facility structural engineers and/or analysts to identify a subset of those aircraft categories/subcategories that are significant contributors to the impact frequencies.

5.4 Methodology for Aircraft Crash Release Frequency Screening. The assessment of impact frequency, as evaluated above, assumes that all impacts will lead to facility damage and a possible release of radioactive or hazardous chemical material. This assumption is due to the lack of information about the response of the structure to impact during the impact frequency stage of the analysis. Following completion of the structural analysis, as described in Chapter 6, it is possible to determine the initial release frequency, which is the total impact frequency minus the impact frequencies of the aircraft categories/subcategories shown to have little or no effect on the facility, i.e., will not lead to a release. This section explains the process of calculating the initial release frequency using results from the structural analysis.

The approach for the initial release frequency analysis is to exclude those aircraft categories/subcategories that are known and/or shown by the structural response analysis to inflict little or no damage should they impact the facility. The major assumption in this analysis is that if any of the impact locations analyzed in the structural response analysis for a particular aircraft category/subcategory can be shown to cause sufficient damage to lead to release, then all impact locations will lead to a release. This simplifies the analysis. The screening is performed in the following steps:

Step 1. From the structural response analysis results, identify the aircraft categories/subcategories whose impact into the facility would result in little or no damage to the facility, i.e., would not result in a release.

Step 2. From the list of impact frequencies compiled for the impact frequency evaluation, delete the impact frequencies corresponding to the aircraft categories/subcategories identified in Step 1.

Step 3. Sum the impact frequencies for the remaining aircraft categories/subcategories. The calculated sum is the release frequency screening value.

Step 4. Compare the release frequency screening value to the guideline. If the guideline is met, the safety risk associated with aircraft impact is below the level of concern and no further analysis is needed; document the results. If the guideline is exceeded, proceed to the release frequency evaluation (Section 5.5).

5.5 Methodology for Aircraft Crash Release Frequency Evaluation. The release frequency screening does not take into account the fact that, even if a particular aircraft category or subcategory can cause damage that could potentially lead to a release, only certain impact locations will have that effect. By making better use of the structural analysis and the impact frequency calculations, the analyst can define specific release scenarios and estimate the frequency associated with those scenarios. This makes it possible to determine the extent to which the actual release frequency may be lower than the initial release frequency. This section addresses the evaluation process for making this determination.

For each impact location which is determined in the structural response analysis to exceed the structural response guideline, a release scenario associated with the level of damage resulting from the impact should be developed. The intent is to specify the most realistic conditions that can be justified. The scenario selected should be physically possible and rational within the physical constraints of the level of damage incurred (including the occurrence of process accidents as a result of system failures). Once it has been determined that a release can occur, the overall facility dimensions used to assess the impact frequency are replaced with a partial facility dimension representing the impact location (a new effective area) for the specific release scenario. The new effective area is input into the four-factor formula (Equation 5-1) for the appropriate aircraft subcategory, resulting in a revised impact frequency specific to the impact location being evaluated.

This process is performed on each of the impact locations that exceeds the structural response guidelines, following the steps listed below.

Step 1. From the results of the structural analysis, take the description of the level of damage. This description will provide a conservative estimate of the structural damage that has occurred, including the path and location of penetrators; the damage state of walls, barriers, and equipment; the location of the aircraft fuel; and other pertinent information, as described in Chapter 6.

Step 2. Assume that all available fuel burns, as well as any other combustibles that are in the path of the penetrators. Assume also that any high explosive material undergoes a high explosive violent reaction (HEVR). High explosive material includes such things as TNT, ion exchange resins, and the like, but not highly flammable materials that are subject to burning (i.e., prompt thermal releases) rather than true explosion (e.g., aircraft fuel, hydrogen gas). Note that this assumption pertains only to combustibles and explosives that are directly affected by the penetrators; that is, they are in areas or compartments that are actually breached by the penetrators.

Step 3. Evaluate the extent to which secondary effects cause the scenario to spread beyond the area directly damaged by the crash. Comprehensive guidance cannot be provided for this step because situations will vary greatly from facility to facility. However, these are some questions to consider:

- Is there sufficient combustible material to breach additional barriers and spread further through the facility? Remember that fire can also spread through ducts and along wiring conduits. Credit can be taken for the existence of fire barriers and breaks, if they have not been damaged by the crash. The basis for taking credit (e.g., short duration of the fire) should be documented. Therefore, a characterization of fire duration will almost certainly be required, although the level of detail will depend on how much sophistication is required to determine the duration of the fire relative to the capability of the fire barriers. Due to the difficulty of demonstrating that active systems can function following a crash, credit should

not be allowed for fire suppression systems unless an explicit analysis shows that they will remain effective.

- Is the force of any explosion capable of causing further barriers to be damaged or destroyed? Can it cause additional fires and/or explosions in the facility? Again, credit can be taken for the dissipation of explosive energy by existing barriers, if they have not been damaged by the crash. Credit can also be taken for diversion of the explosive force through breaches caused by the crash, thus reducing the shock to intact barriers. The basis for taking credit should be documented. Again, characterization of the explosive force generated relative to barrier strength and the force transmitted to collocated explosives is required to justify the credit.

Step 4. Based on the findings of the previous step, determine if a release could occur, given the scenario as defined. Again, specific guidance cannot be provided, but the following questions should guide the analyst's thinking:

- Could any of the material at risk in the facility be impacted by any release mechanism (e.g., shock, fire, explosion) as a result of the scenario? The answer to this question should be "yes" if there is any material that is not separated from the energy available from the release mechanism by an intact barrier capable of dissipating that energy.

- Could the primary confinement around any of that material be breached as a result of the scenario? The answer to this question should be "yes" if the structural integrity of the primary confinement is degraded below that required under accident conditions and if there is a driving force capable of causing the material to migrate through the breach.

- Could a path to the atmosphere result from the scenario? The answer to this question should be "yes" if there are no longer any intact barriers between the material and the atmosphere, assuming that the primary confinement is failed and that there is a driving force capable of causing the material to migrate along the path.

In this context, the word "could" should be taken to mean "is it mechanistically possible, given the level of damage." The possibility that failures occurring away from the material could cause system failures resulting in process accidents should also be considered. Therefore, intersystem dependencies and support system interactions should be explicitly evaluated. If there is any doubt about the answer to any of the three questions listed in this step, the answer should be assumed to be “yes.” If, for the given crash location, the answer to any of these questions is “no,” the scenario can be designated as a nonrelease scenario and eliminated from further consideration.

Step 5. If the scenario has not been eliminated (i.e., the analysis has shown that it could lead to a release), calculate the impact frequency by rerunning the four-factor formula for the appropriate aircraft subcategory, using facility dimensions specific to the impact location associated with the scenario. The analyst will need to better define the location as an area (rather than just a single point) where impact could result in the release scenario. This requires judgement and consultation with the analyst(s) who conducted the structural response evaluation. Use this information to develop a set of "scenario facility dimensions" that represents what the target would look like if it encompassed an area equal to the target area associated with the release scenario being evaluated. Credit should be taken for shielding effects from other facilities to further reduce the scenario facility dimensions (Appendix B, Section B-4). The development of the scenario facility dimensions should be well justified and documented in detail. Once these dimensions have been established, run the appropriate four-factor formula to calculate the scenario release frequency.

Step 6. Repeat Steps 1 through 5 for all of the impact locations that exceed the structural response guidelines. Adding together the scenario release frequencies from each pass through Step 5 gives the final release frequency for the evaluation step.

Step 7. Compare the final release frequency value to the guideline. If the guideline is met, no additional analysis of aircraft impact is required. If the guideline is not met, a more detailed analysis of the exposure associated with each release scenario needs to be performed in accordance with Section 7.3 of this standard. For the purpose of that

analysis, each scenario that contributes to the release frequency exceeding the guideline should be fully documented. In particular, a full description of the damage state of the facility should be provided, including details about what parts of the facility are subject to each of the release mechanisms considered (e.g., fire, explosion, and crush/impact).

5.6 References.

1. Sanzo, D. et al. *ACRAM Modeling Technical Support Document*. LA-UR-95-X, TSA-11-95-R112. Los Alamos National Laboratory, 1996.
2. Kimura, C.Y. et al. *Data Development Technical Support Document for the Aircraft Crash Risk Analysis Methodology (ACRAM) Standard*. UCRL-ID-124837. Lawrence Livermore National Laboratory, 1996.