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UCRL-CONF-203793

An Approach to Estimate the Localized Effects of an Aircraft Crash on a Facility

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April, 2004

Energy Facility Contractors Group (EFCOG) Safety Analysis Workshop
San Fancisco Bay Area, California
May 1-6, 2004

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Auspices Statement

This work was performed under the auspices of the U.S. Department of Energy by University of California, Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

An Approach to Estimate the Localized Effects of an Aircraft Crash on a Facility

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Abstract

Aircraft crashes are an element of external events required to be analyzed and documented in facility Safety Analysis Reports (SARs) and Nuclear Explosive Safety Studies (NESSs). This paper discusses the localized effects of an aircraft crash impact into the Device Assembly Facility (DAF) located at the Nevada Test Site (NTS), given that the aircraft hits the facility. This was done to gain insight into the robustness of the DAF and to account for the special features of the DAF that enhance its ability to absorb the effects of an aircraft crash. For the purpose of this paper, localized effects are considered to be only perforation or scabbing of the facility. This paper presents an extension to the aircraft crash risk methodology of Department of Energy (DOE) Standard 3014.[1] This extension applies to facilities that may find it necessary or desirable to estimate the localized effects of an aircraft crash hit on a facility of nonuniform construction or one that is shielded in certain directions by surrounding terrain or buildings. This extension is not proposed as a replacement to the aircraft crash risk methodology of DOE Standard 3014[1] but rather as an alternate method to cover situations that were not considered.

Introduction

Aircraft crashes are an element of external events required to be analyzed and documented in facility Safety Analysis Reports (SARs) and Nuclear Explosive Safety Studies (NESSs). Aircraft crashes into DOE facilities are of concern because they can potentially lead to penetration of the facility, disruption of operations, and potential release of radioactive and/or hazardous materials. These effects may be caused either by the impact itself or by a fire resulting from the impact.

This paper discusses the localized effects of an aircraft crash impact into the Device Assembly Facility (DAF) located at the Nevada Test Site (NTS), given that the aircraft hits the facility. This was done to gain insight into the robustness of the DAF and to account for the special features of the DAF that enhance its ability to absorb the effects of an aircraft crash. For the purpose of this paper, localized effects are considered to be only perforation or scabbing of the facility. Global effects that could result in collapse of the facility structure are not considered in this discussion. Perforation is considered to be complete penetration of the facility structure from the outside surface to the inside surface. Scabbing is considered to be the ejection of bits and pieces from the inside surface of the facility structure caused by impact on the outside surface.

The analysis was performed for small and large military aircraft (i.e., >100,000 lb maximum takeoff weight [MTOW]). Because of the much greater number of small military aircraft flights, the results for these aircraft bound those for the large military aircraft. Consequently, only the small military aircraft results will be presented in the paper. All results will be normalized to an aircraft crash hit frequency of 1E-6/yr. The actual results of the DAF calculations will not be presented due to security considerations.

This paper is presented in the following sections. First, the methodology for estimating the localized effects of an aircraft crash impact on a building is discussed. Second, the results of the application of this methodology on the DAF is discussed. Finally, a summary of the results, and a final concluding discussion is presented.

Methodology

Aircraft Crash Hit Frequency

DOE Standard 3014-96[1] presents the generally accepted method for estimating the risk from an aircraft crash on a building with radioactive or hazardous materials within. The first step in this process is to estimate the frequency of the aircraft crash hitting the building. This step uses the standard 4-factor formula as shown below for facilities located in the airport flight environment :

$$F = N * P * f(x,y) * A_{eff} \qquad \text{Eq. 1}$$

where F = Aircraft crash hit frequency on to the facility (crash hit/year)
N = Number of relevant flight operations (operations/year)
P = Aircraft crash rate (/takeoff, /landing)
f(x,y) = Aircraft crash location conditional probability (/mi.^{2})

A_{eff} = Facility effective target area presented to aircraft during accident sequence (mi.^{2})

Because of the remoteness of the DAF in terms of its relative closeness to operating airports, the DAF is outside the airport flight environment and so Equation 1) cannot be applied. The flight environment applicable to the DAF is medium and high altitude overflights by military aircraft. Equation 1 must be modified to account for the specific aircraft flight environment that is applicable to the DAF. This was done in previous papers.[2,3]

The methodology used to estimate the aircraft crash hit frequency on to the DAF generally follows the procedure given by the DOE-STD-3014-96 on Aircraft Crash Analysis[1], and its supporting technical support documents.[4,5] However, certain modifications were made to the formulas to account for those flight characteristics relevant to medium altitude flights by military aviation aircraft over the NTS. Equation 2 below gives the final form of Equation 1 as modified to account for medium and high altitude flights over the NTS.

$$F = N_t / A_t * A_{eff} * \lambda * (4/\pi) * (R_{eff} + R_c) \qquad \text{Eq. 2}$$

where N_t = Total number of flights over the NTS (operations/year)
A_t = Total area of the NTS (mi.^{2})
λ = crash rate per unit distance (accident/mi.)
R_{eff} = Radius of the area of the facility effective target area, A_{eff} , when modeled as a circle (mi.)
R_c = The radius of the crash area affected by a distressed aircraft (mi.)
all other terms as defined in Equation 1

Only the facility effective target area, A_{eff} , and the related radius of the effective target area, R_{eff}, are dependent on facility characteristics, all other terms of Equations 1 and 2 are dependent on the aircraft flight parameters. The area presented by a facility to an aircraft during an accident sequence represents a proportionality with the aircraft crash location conditional probability. Normally, the area presented by a facility consists of a fly-in area and a skid-in area. These represent the probability that an aircraft will fly directly into the facility, and the probability that an aircraft will hit the ground first, then skid into the facility, respectively. The facility effective target area, A_t , is equal to the fly-in area, A_f , plus the skid-in area, A_s .

$$A_t = A_f + A_s \qquad \text{Eq. 3}$$

The fly-in area, A_f , is

$$A_f = [(WS + R) * H * \cot \phi] + [(2 * L * W * WS)/R] + (L * W) \qquad \text{Eq. 4}$$

and the skid-in area, A_s , is

$$A_s = (WS + R) *S \qquad \text{Eq. 5}$$

where WS = aircraft wingspan

L = facility length
W = facility width
R = diagonal dimension of the facility = $(L^2 + W^2)^{1/2}$
H = facility height
$\cot \phi$ = mean cotangent of aircraft impact angle
S = mean aircraft skid length

Figure 1 shows the subregions used to develop Equations 4 and 5.[1,4]

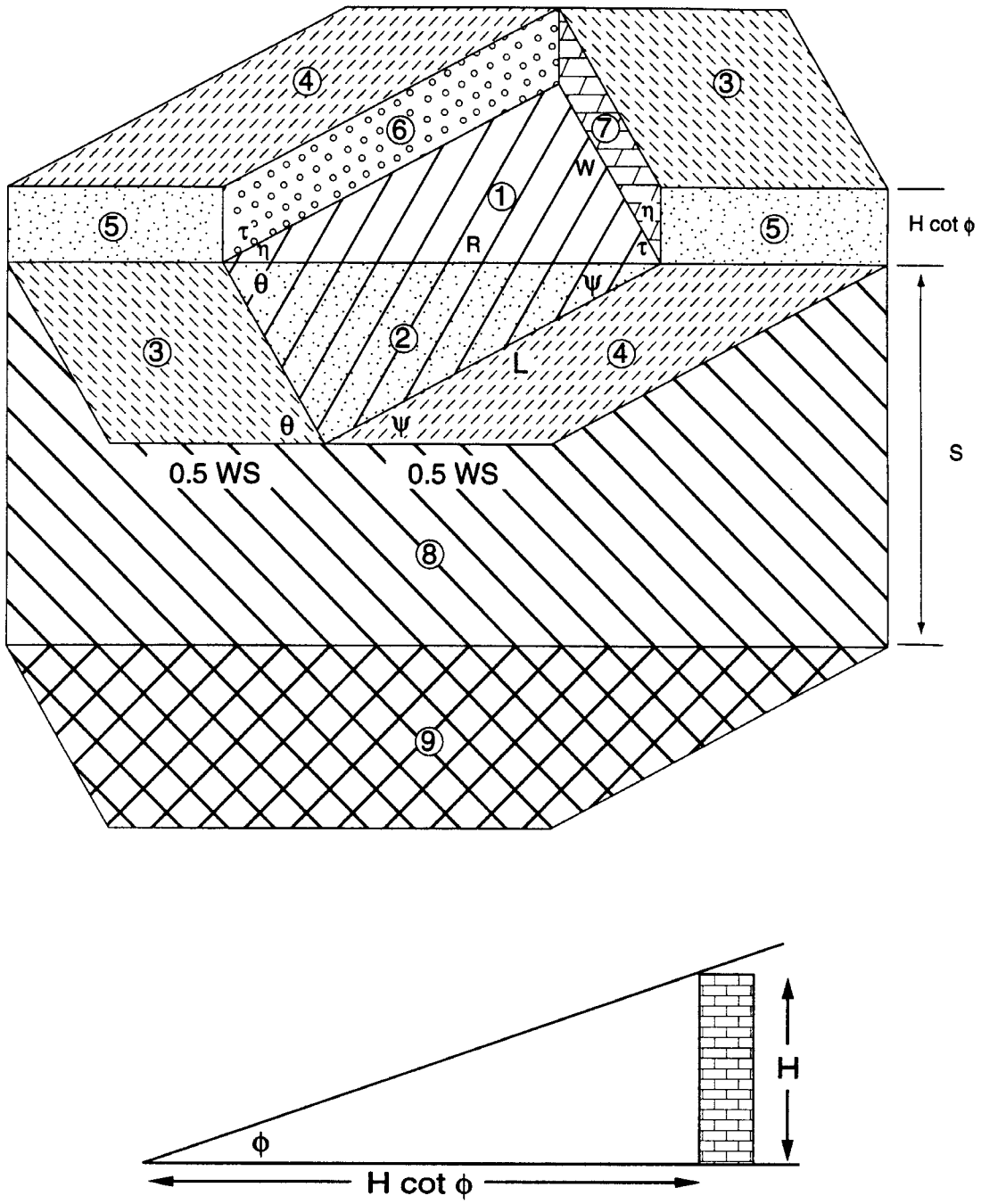

Figure 1

Geometry used to derive Effective Area, A_{eff} [4]

Effective Area Modification

If the facility is uniform in construction in all directions and is not surrounded by any topography or buildings that might serve as shielding to the facility, then the effective area formulas, Equations 3, 4, and 5, as given by the Solomon model[1,4] may be used to calculate a conservative value of the effective area of the facility. Where a bounding estimate of the facility effective target area is all that is desired, this formula works acceptably well. However, when it is necessary to determine the effective area of a facility that may be affected by aircraft heading in certain directions due to shielding by surrounding terrain or by nonuniform building construction, then the Solomon Effective Area needs to be modified to account for directionality of the aircraft. The DAF is partly covered with only one face exposed to the outside environment. Additionally, the construction of the DAF is very nonuniform directionally. For these reasons, the effective area formula of the Solomon model was modified to account for directionality of the aircraft crash.

A facility footprint is modeled by a bounding rectangle of length L, width W, and height H. The heading of the crashing aircraft is taken to be perpendicular to the side of the facility. Figure 2 shows the subregions used to develop the modified facility effective area, A_{eff} derivation.

The total effective area of the facility is the sum of the effective areas generated by aircraft crashing in all directions multiplied by the probability of an aircraft crashing in that direction.

$$A_{eff} = \Sigma dir\ P\ (dir) * A_{eff}\ (dir) \qquad \text{Eq. 6}$$

For convenience, we will associate an aircraft in the northward (or southward) direction to be flying in the L side of the facility. Likewise, an aircraft in the eastward (or westward) direction will be associated with the W side of the facility. The total effective area of the facility is the sum of the product of the probability of the aircraft crashing in northward, southward, westward and eastward direction times the effective areas when the aircraft is heading in the northward, southward, westward, and eastward direction, respectively:

$$A_{eff} = P_N * A_{eff\ N} + P_S * A_{eff\ S} + P_E * A_{eff\ E} + P_W * A_{eff\ W} \qquad \text{Eq. 7}$$

where $A_{effN,S,E,W}$ = effective area of the facility to an aircraft crashing in that direction,
$P_{N,S,E,W}$ = probability of the aircraft crashing in that direction.

The effective area is the sum of the fly-in area into the side of the facility, and the fly-in area of the facility roof and the skid area for the direction that the aircraft is heading:

$$A_{eff\text{-}dir} = A_{fly\text{-}in\text{-}dir\text{-}side} + A_{fly\text{-}in\text{-}dir\text{-}roof} + A_{skid\text{-}dir}. \qquad \text{Eq. 8}$$

Expanding for the definition of effective areas for each direction that the aircraft is heading by substituting Equation 8 into Equation 7 and separating the effective areas for the roof from the effective areas for the sides of the facility yields:

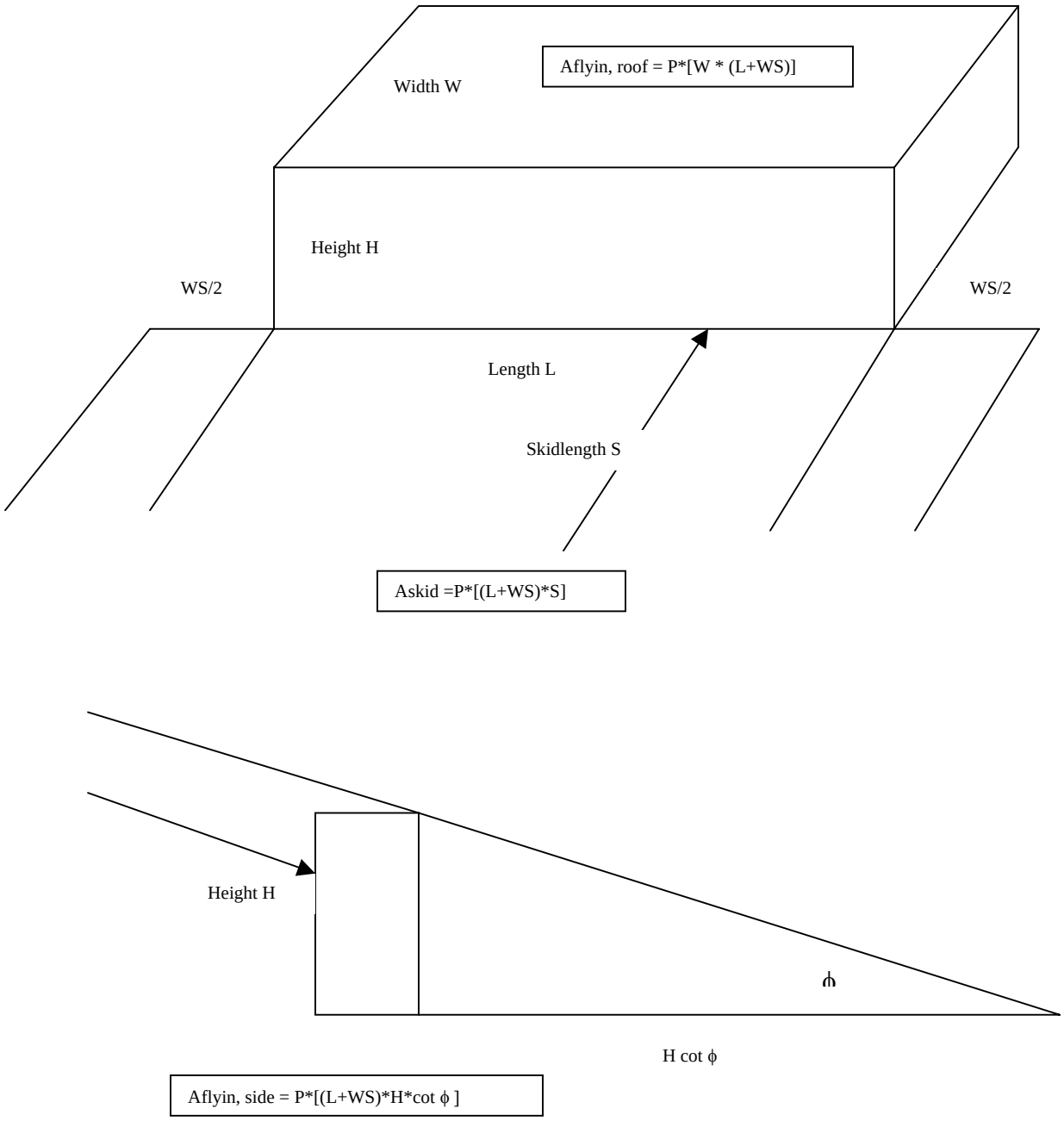

Figure 2
Geometry used to derive modified Effective Area

$$A_{eff} = P_N * [A_{fly\text{-}inNside} + A_{skidN}] + P_N * A_{fly\text{-}inNroof} + P_S * [A_{fly\text{-}inSside} + A_{skidS}] + P_S * A_{fly\text{-}inSroof} + P_E * [A_{fly\text{-}inEside} + A_{skidE}] + P_E * A_{fly\text{-}inEroof} + P_W * [A_{fly\text{-}inWside} + A_{skidW}] + P_W * A_{fly\text{-}inWroof}. \quad \text{Eq. 9}$$

The fly-in area of an aircraft heading Northward into the side of the facility is the area of the facility side along the projected flightpath of aircraft. Defining ϕ as the aircraft impact angle (or the flightpath angle of the aircraft), then an aircraft flying Northward into the South side of the facility would fly into the area defined by facility length, L, plus the aircraft wingspan, WS, times the facility height, H, times the cotangent of ϕ or:

$$A_{fly\text{-}inNside} = (L + WS) * H * \cot \phi \quad \text{Eq. 10}$$

The skid-in area of an aircraft heading Northward into the facility of length, L is the area of the facility length, L, plus the aircraft wingspan, WS, times the aircraft skid distance, S, or:

$$A_{skidN} = (L + WS) * S \quad \text{Eq. 11}$$

The fly-in area of an aircraft heading Northward into the roof of the facility is the length of the facility, L, plus the aircraft wingspan, WS, times the width of the building, W, or:

$$A_{fly\text{-}inNroof} = W * (L + WS) \quad \text{Eq. 12}$$

The fly-in area for the side and roof and skid-in area for an aircraft heading Southward into the facility are similar. The fly-in area for the side and roof and skid-in area for an aircraft heading Eastward or Westward into the facility are similar except that W is substituted for L inside the parenthesis of Equations 10, 11, and 12.

Substituting Equations 10, 11, and 12 into Equation 9 yields:

$$A_{eff} = P_N * [(L + WS) * H * \cot \phi + (L + WS) * S]_N + P_N * W * (L + WS)_N + P_S * [(L + WS) * H * \cot \phi + (L + WS) * S]_S + P_S * W * (L + WS)_S + P_E * [(W + WS) * H * \cot \phi + (W + WS) * S]_E + P_E * L * (W + WS)_E + P_W * [(W + WS) * H * \cot \phi + (W + WS) * S]_W + P_W * L * (W + WS)_W. \quad \text{Eq. 13}$$

To calculate the effective area, it is necessary to have the height of the facility, H; the dimensions, L and W, of the bounding rectangle; the wingspan, WS, of the crashing aircraft; and two representative crash parameters: skid length, S, and impact angle, ϕ. Representative values of WS, S, and ϕ are provided in Appendix B of DOE Standard 3014.[1] Mean values of the distribution of S and ϕ are recommended.

The effective area for the South side of the facility for an aircraft heading in the Northward direction is:

$$A_{eff,N} = P_N * [(L + WS) * H * \cot \phi + (L + WS) * S]_N \quad \text{Eq. 14}$$

Similarly, for an aircraft heading in the Southward, Eastward, and Westward directions respectively:

$$A_{eff,S} = P_S * [(L + WS) * H * \cot \phi + (L + WS) * S]_S \quad \text{Eq. 15}$$

$$A_{eff,E} = P_E * [(W + WS) * H * \cot \phi + (W + WS) * S]_E \quad \text{Eq. 16}$$

$$A_{eff,W} = P_W * [(W + WS) * H * \cot \phi + (W + WS) * S]_W \quad \text{Eq. 17}$$

The effective area for the roof is the summation of the roof fly-in areas over all directions or:

$$A_{eff,\ roof} = P_N*W*(L + WS)_N + P_S*W*(L + WS)_S + P_E*L*(W + WS)_E + P_W*L*(W + WS)_W. \quad \text{Eq. 18}$$

Localized Effects

After modifying the likelihood of the aircraft crash by direction, it was desired to estimate the effect of the aircraft crash hit on the facility. Because of the nonuniformity of the facility construction and the protection afforded by local overburden, the likelihood of localized effects had to be considered on a facility-face by facility-face basis. Localized effects included scabbing and perforation. Global effects on the facility were not considered but may be considered in the future. The scabbing and perforation formulas[1,6] were applied by using the dimensions of the DAF to backcalculate the required aircraft impact velocity needed to perforate or scab the facility structure. Using this velocity, the likelihood of the aircraft crash can be reduced using the aircraft crash velocity distributions.[5] These distributions considered both the probability of penetrating the facility and the velocity required for penetration.

Scabbing is the local damage that results when the missile causes material to peel or break off (become ejected) from the backside of the target. An empirical formula by Chang[1] applicable to missile with impact velocity less than 500 ft./sec. (152 m./sec.) calculates the mean scabbing thickness for reinforced concrete targets by cylindrical rigid (nondeformable) missiles as:

$$t_s = [1.84 * (U / V)^{0.13}] * \{(M* V^2)^{0.4} / [D^{0.2} * (f'_c)^{0.4}]\} \quad \text{Eq. 19}$$

where U = reference velocity = 200 ft/sec
V = missile impact velocity (ft/sec)
M = mass of missile = W/g
Where W = missile weight (lb) and g = 32.2 ft/sec^2
D = effective missile diameter (ft)
f'_c = ultimate compressive strength of concrete (lb/ft^2)
t_s = scabbing thickness (ft)

Rearranging Equation 19 to solve for V yields:

$$V = [(t_s * D^{0.2} * (f'_c)^{0.4}) / (1.84 * U^{0.13} * M^{0.4})]^{1.5} \quad \text{Eq. 20}$$

For reinforced concrete f'_c = ultimate compressive strength of concrete[6] = 3000 lb/in^2 or 432,000 lb/ft^2. Missile mass M and diameter D for the F-16 Falcon F110-GE-129 engine is 3920 lbs. and 46 in., respectively. Scabbing thickness, t_s, is set equal to the reinforced concrete thickness of the DAF.

Perforation is the local damage that results to a target when the missile fully penetrates the target or passes through the target. An empirical formula from DOE-STD-3014[1] calculates the perforation thickness for reinforced concrete targets by cylindrical rigid (nondeformable) missiles as:

$$t_p = (U / V)^{0.25} * (M * V^2 / D * f_c)^{0.5} \quad \text{Eq. 21}$$

where U = reference velocity = 200 ft/sec
V = missile impact velocity (ft/sec)
M = mass of missile = W/g
where W = missile weight (lb) and g = 32.2 ft/sec^2
D = effective missile diameter (ft)
f_c = ultimate compressive strength of concrete (lb/ft^2)
t_p = perforation thickness (ft)

Rearranging Equation 21 to solve for V yields:

$$V = [(t_p * D^{0.5} * f_c^{0.5}) / (U^{0.25} * M^{0.5})]^{1.333} \quad \text{Eq. 22}$$

All terms are as for Equation 21. Perforation thickness, t_p, is set equal to the reinforced concrete thickness of the DAF.

Event Tree Development

The final step of this calculation was to apply the results of the effective area modification and the localized effects to the DAF within the framework of a logic event tree. A logic event tree is a convenient way to model the sequence of events that occur during the course of an aircraft crashing into a facility. Figure 3 shows the logic event tree developed for the DAF for a small military aircraft hitting the facility and perforating or scabbing the walls or roof. The first event considered is that the aircraft hits the facility. The second event is the aircraft hitting a particular side or the roof of the facility. Aircraft hitting a combination of sides or a combination of a side and roof were not included because such an event would require the aircraft to hit exactly on the edge of a facility side or roof. The likelihood of such an event was considered extremely small and thus ignored. The third event was an aircraft hitting a particular part of the South face of the DAF. This is the exposed face of the facility and different sections of the South face are constructed very differently from each other. Some sections of the DAF are covered by overburden. Other sections are reinforced concrete, while the doors which provide

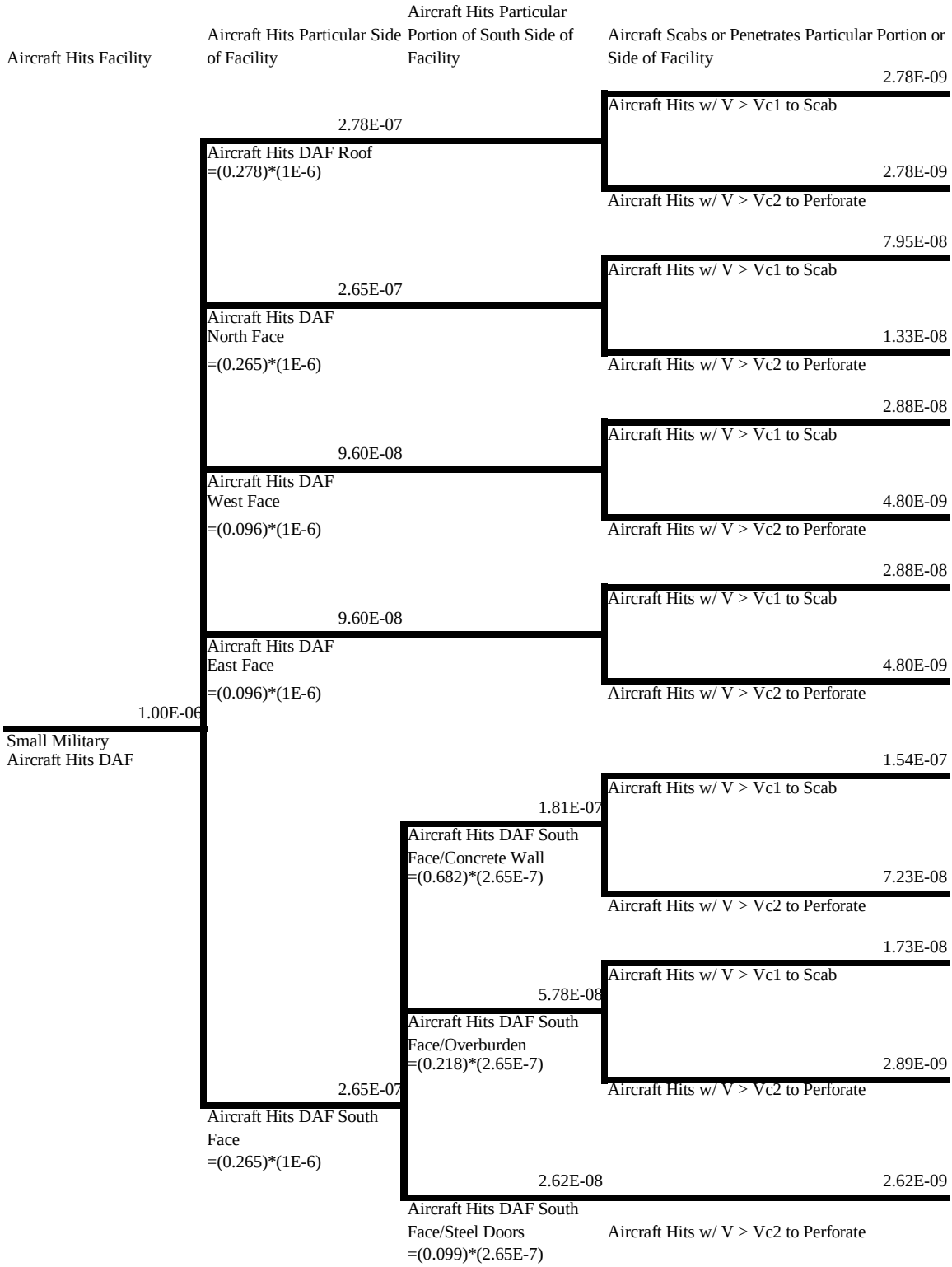

Figure 3
Aircraft Hit Logic Event Tree

access to the DAF, are steel. Each section required separate perforation and scabbing calculations as well as separate aircraft hit frequency estimates. The last event of Figure 3 is the aircraft crash hit resulting in the scabbing or perforating of the particular facility wall or roof.

Results

As can be seen from Figure 3, the frequency of a small military aircraft hitting and perforating or scabbing a side or roof of the DAF is largest for the South face; smaller for the North, East and West faces; and smallest for the roof. All results are normalized to an aircraft crash hit frequency of 1E-6/yr. It should be noted that the normalized value of an aircraft crash hit frequency on the DAF of 1E-6/yr. is larger than the actual values calculated.[2,3] This analysis was performed strictly for the purpose of illustrating this methodology and is not intended to convey any information on the actual estimated aircraft crash hit frequency on the DAF.

Summary and Conclusion

This paper has presented an extension to the aircraft crash risk methodology of the DOE Standard 3014.[1] This extension applies to facilities that may find it necessary or desirable to estimate the localized effects of an aircraft crash hit on a facility of nonuniform construction or one that is shielded in certain directions by surrounding terrain or buildings. This extension is not proposed as a replacement to the aircraft crash risk methodology of the DOE Standard 3014[1] but rather as an alternate method to cover situations that were not considered. Certainly, if only a bounding aircraft crash hit estimate is all that is required, then the effective area formulas, Equations 3), 4) and 5) from the Solomon model[1,5], are adequate.

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