

**APPROVED METHODS AND ALGORITHMS FOR  
DOD RISK-BASED EXPLOSIVES SITING**



**Approved for public release; distribution is unlimited.**

**Department of Defense Explosives Safety Board  
Alexandria, VA  
21 July 2009**

### ***Foreword***

Technical Paper (TP) 14 provides Department of Defense Explosives Safety Board (DDESB) approved methodologies for calculating the risk associated with explosives operations and storage. The three elements of the methodology are the probability of event, probability of fatality given an event, and exposed personnel. This document will be kept current and will be updated as new methodologies are developed. The latest version of the document can be found on the DDESB Web-Page:

<http://www.ddesb.pentagon.mil>

The information in this document was based on the work of the DDESB-chartered Risk-Based Explosives Safety Criteria Team (RBESCT).

This TP has been reviewed by the DDESB Staff.

A handwritten signature in black ink, appearing to read 'C. M. BOWLING', is positioned above the printed name.

CURTIS M. BOWLING  
Chairman  
DDESB

### ***Disclaimer***

The principles and techniques presented in this document are in the opinion of the Department of Defense Explosives Safety Board (DDESB), the best available at the time of publication. Adherence to these principles should provide an acceptable level of safety during ammunition and explosives operations; however, use of this approach cannot ensure or guarantee a risk-free operation or address every situation that could be encountered. Because of the inherent danger in handling ammunition and explosives, neither the DDESB nor the contractors involved in the software development can be held responsible for any mishap or accident resulting from the use of this document.

The use of SAFER Version 3.1 has been approved by the Department of Defense (DoD) Services and will be incorporated in DoD 6055.09-STD in the next revision. The SAFER model is based on accident experiences, explosion effects, and structural response, and is for DoD application only.

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- Attachment 3:** “Input Section,” Tech Memo CE1-16200, A-P-T Research, Inc., Huntsville, AL, May 2009.
- Attachment 4:** “SAFER 3 Pressure and Impulse Branch,” Tech Memo CE1-15800, A-P-T Research, Inc., Huntsville, AL, May 2009.
- Attachment 5:** “SAFER Injury Algorithms,” Tech Memo CE1-16400, A-P-T Research, Inc., Huntsville, Alabama, May 2009.
- Attachment 6:** “SAFER 3.1 Glass Methodology,” Tech Memo CE1-16000, A-P-T Research, Inc., Huntsville, AL, May 2009.
- Attachment 7:** “SAFER 3.1 Structural Response Methodology,” Tech Memo CE1-15700, A-P-T Research, Inc., Huntsville, AL, May 2009.
- Attachment 8:** “SAFER 3.1 Debris Methodology,” Tech Memo CE1-15900, A-P-T Research, Inc., Huntsville, AL, May 2009.
- Attachment 9:** “An Analytical Approach for Treating Uncertainty in Probabilistic Risk Assessments,” Mensing, Dr. R.W., presented to the 31<sup>st</sup> Explosives Safety Seminar, 24-26 August 2004.
- Attachment 10:** “SAFER 3 P(e) Matrix,” Tech Memo CE1-01000, A-P-T Research, Inc., Huntsville, Alabama, May 2009.
- Attachment 11:** “RBESCT Bibliography,” Tech Memo CC1-02700, A-P-T Research, Inc., Huntsville, Alabama, May 2009.
- Attachment 12:** “Universal Risk Scale,” 1<sup>st</sup> presented to the ’99 Explosives Safety Seminar in Parari, then presented a 2<sup>nd</sup> time Updated to the 31<sup>st</sup> Explosives Safety Seminar, 24-26 August 2004.
- Attachment 13:** “Public Traffic Route Methodology,” Tech Memo CC1-03600, A-P-T Research, Inc., Huntsville, Alabama, May 2009.
- Attachment 14:** “Comparison of Individual Risk Criterion to Risk at IBD,” Tech Memo CC8-04900, A-P-T Research, Inc., Huntsville, Alabama, July 2007.

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### ***Acronyms and Abbreviations***

|         |                                                                                 |
|---------|---------------------------------------------------------------------------------|
| AASTP-4 | Allied Ammunition Storage & Transport Publication 4 (NATO Risk Analysis Manual) |
| AGBS    | Aboveground Brick Structure                                                     |
| CG      | Compatibility Group                                                             |
| DDESB   | Department of Defense Explosives Safety Board                                   |
| DoD     | Department of Defense                                                           |
| DTRA    | Defense Threat Reduction Agency                                                 |
| ECM     | Earth-Covered Magazine                                                          |
| ES      | Exposed Site                                                                    |
| HAS     | Hardened Aircraft Shelter                                                       |
| HD      | Hazard Division                                                                 |
| IBD     | Inhabited Building Distance                                                     |
| ICT     | Integrated Combat Turn                                                          |
| IR      | Individual Risk                                                                 |
| KE      | Kinetic Energy                                                                  |
| LAP     | Load-Assemble-Pack                                                              |
| MOW     | Model of the World                                                              |
| NATO    | North Atlantic Treaty Organization                                              |
| NEWQD   | Net Explosive Weight For Quantity Distance                                      |
| OCONUS  | Outside Continental United States                                               |
| PEMB    | Pre-Engineered Metal Building                                                   |
| PES     | Potential Explosion Site                                                        |
| P-I     | Pressure-impulse                                                                |
| PTR     | Public Traffic Route                                                            |
| QD      | Quantity-Distance                                                               |
| R/C     | Reinforced Concrete                                                             |
| RBESCT  | Risk-Based Explosives Safety Criteria Team                                      |
| RCC     | Range Commanders Council                                                        |
| SAFER   | Safety Assessment For Explosives Risk                                           |
| SCD     | SAFER Calculated Distance                                                       |
| TDY     | Temporary Duty                                                                  |



### Variable Names and Symbols

| Term                    | Type         | Variable Name/Explanation                                                                                                                                                          |
|-------------------------|--------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| % $ES_{Hrs\ explosive}$ | User Input   | The percentage of hours that the group spends at the ES that explosives are also present at the PES. [Eq. (6)]                                                                     |
| % $ES_{roof\ damaged}$  | Variable     | Percentage of ES roof damaged. [Eq. (94), Eq. (138)]                                                                                                                               |
| % $ES_{roof\ intact}$   | Variable     | Percentage of ES roof intact. [Eq.(94), Eq. (139), Eq. (140), Eq. (142)]                                                                                                           |
| % $ES_{wall\ damaged}$  | Variable     | Percentage of ES walls damaged. [Eq. (92), Eq. (93)]                                                                                                                               |
| % $ES_{wall\ intact}$   | Variable     | Percentage of ES wall intact. [Eq. (93), Eq. (143), Eq. (146), Eq. (147)]                                                                                                          |
| % $glass$               | User Input   | Percentage of glass on ES. [Eq. (146), Eq. (147)]                                                                                                                                  |
| % $glass\ breakage$     | Variable     | Percentage of ES glass breakage. [Eq. (61), Eq. (66)]                                                                                                                              |
| $2IBD$                  | Variable     | Attachment 13.                                                                                                                                                                     |
| $a$                     | Variable     | Parameter used in calculating PES component damage ( $PES_{damage(i)}$ ). [Eq. (30)]                                                                                               |
| A                       | Stored Value | The first-order parameter used in calculating the effective yield (Y). [Table A-2, Eq. (19)]                                                                                       |
|                         | Stored Value | The first-order parameter used in calculating the unmodified pressure (P). [Table A-3, Eq. (22)]                                                                                   |
|                         | Stored Value | The first-order parameter used in calculating the unmodified impulse (I). [Table A-4, Eq. (23)]                                                                                    |
|                         | Stored Value | The first-order parameter used in calculating the adjusted weight ( $W_a$ ). [Table A-5, Eq. (25)]                                                                                 |
|                         | Stored Value | Parameter used in calculating the <i>Yield adjustment</i> for glass. [Table A-13, Eq. (62)]                                                                                        |
|                         | Stored Value | Parameter used in calculating Probability of fatality due to glass ( $P_{f(g)2}$ ) (at the boundary between the “transition region” and the “normal region”). [Table 11, Eq. (82)] |
|                         | Stored Value | Pressure asymptote. Parameter used to calculate the hyperbola defining a curve on a pressure and impulse diagram. [Table A-10, Table A-17, Table A-19, Eq. (85)]                   |
|                         | Stored Value | Parameter used to calculate region boundary ( $R_2$ ). [Table A-16, Eq. (87)]                                                                                                      |
|                         | Stored Value | Parameter used in calculating the mass of crater ejecta thrown ( <i>Crater ejecta mass</i> ). [Table 20, Eq.(119)]                                                                 |
|                         | Stored Value | Parameter used in calculating final velocity (FV). [Table 25, Eq. (135)]                                                                                                           |
| $Adj. P_{maji(bc)}$     | Variable     | “Adjusted probability of major injury due to building collapse”. [Eq.(89)]                                                                                                         |
| $Adj. P_{mini(bc)}$     | Variable     | “Adjusted probability of minor injury due to building collapse”. [Eq. (91)]                                                                                                        |

| Term                                  | Type         | Variable Name/Explanation                                                                                                                                                          |
|---------------------------------------|--------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| $AHrs\ at\ ES_{group}$                | User Input   | The number of hours per year that a group is at the ES. [Eq. (6)]                                                                                                                  |
| $AIAR$                                | Variable     | Adjusted Invulnerable Area for the ES Roof. [Eq. (140), Eq. (141)]                                                                                                                 |
| $AIAW$                                | Variable     | Adjusted Invulnerable Area for the ES Wall. [Eq. (143), Eq. (144), Eq. (145)]                                                                                                      |
| $a_{IV}$                              | Stored Value | Parameter used to calculate initial velocity of secondary fragments ( $IV_c$ ). [Table A-28, Eq. (115)]                                                                            |
| $aspect\ ratio$                       | Set Value    | Length to width ratio of the ES. [Eq. (59)]                                                                                                                                        |
| $Average\ Fragment\ Mass\ (concrete)$ | Stored Value | Average mass of concrete fragments. [Table 13, Eq. (112), Eq. (116), Eq. (120), Eq. (136)]                                                                                         |
| $Average\ Fragment\ Mass\ (steel)$    | Stored Value | Average mass of steel fragments. [Table 13, Eq. (102), Eq. (112), Eq. (116), Eq. (136)]                                                                                            |
| $b$                                   | Stored Value | Parameter used in calculating PES component damage ( $PES_{damage(i)}$ ). [Table A-6, Table A-9, Eq. (30)]                                                                         |
| $B$                                   | Stored Value | The second-order parameter used in calculating the effective yield ( $Y$ ). [Table A-2, Eq. (19)]                                                                                  |
|                                       | Stored Value | The second-order parameter used in calculating the unmodified pressure ( $P$ ). [Table A-3, Eq. (22)]                                                                              |
|                                       | Stored Value | The second-order parameter used in calculating the unmodified impulse ( $I$ ). [Table A-4, Eq. (23)]                                                                               |
|                                       | Stored Value | The second-order parameter used in calculating the adjusted weight ( $W_a$ ). [Table A-5, Eq. (25)]                                                                                |
|                                       | Stored Value | Parameter used in calculating the <i>Yield adjustment</i> for glass. [Table A-13, Eq. (62)]                                                                                        |
|                                       | Stored Value | Parameter used in calculating Probability of fatality due to glass ( $P_{f(g)2}$ ) (at the boundary between the “transition region” and the “normal region”). [Table 11, Eq. (82)] |
|                                       | Stored Value | Impulse asymptote. Parameter used to calculate the hyperbola defining a curve on a pressure and impulse diagram. [Table A-10, Table A-17, Table A-19, Eq. (85)]                    |
|                                       | Stored Value | Parameter used to calculate region boundary ( $R_2$ ). [Table A-16, Eq. (87)]                                                                                                      |
|                                       | Stored Value | Parameter used in calculating the mass of crater ejecta thrown ( <i>Crater ejecta mass</i> ). [Table 20, Eq. (119)]                                                                |
|                                       | Stored Value | Parameter used in calculating final velocity ( $FV$ ). [Table 25, Eq. (135)]                                                                                                       |

| Term                      | Type         | Variable Name/Explanation                                                                                                                                    |
|---------------------------|--------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------|
| $B3$                      | Variable     | Angle between the evaluated height ( $h$ ) at the PES and base of the ES that is calculated in the ES barricade blocking algorithm. [Eq. (132)]              |
| <i>blocked angle</i>      | Variable     | Angle between the evaluated height ( $h$ ) at the PES and the ES barricade. [Eq. (132)]                                                                      |
| $c$                       | Stored Value | Parameter used in calculating adjusted weight ( $W_a$ ). [Table A-5, Eq. (24)]                                                                               |
| $C$                       | Stored Value | The third-order parameter used in calculating the effective yield ( $Y$ ). [Table A-2, Eq. (19)]                                                             |
|                           | Stored Value | The third-order parameter used in calculating the unmodified pressure ( $P$ ). [Table A-3, Eq. (22)]                                                         |
|                           | Stored Value | The third-order parameter used in calculating the unmodified impulse ( $I$ ). [Table A-4, Eq. (23)]                                                          |
|                           | Stored Value | The third-order parameter used in calculating the adjusted weight ( $W_a$ ). [Table A-5, Eq. (25)]                                                           |
|                           | Stored Value | Parameter used in calculating the <i>Yield adjustment</i> for glass. [Table A-13, Eq. (62)]                                                                  |
|                           | Stored Value | Curvature term. Parameter used to calculate the hyperbola defining a curve on a pressure and impulse diagram. [Table A-10, Table A-17, Table A-19, Eq. (85)] |
|                           | Stored Value | Parameter used to calculate region boundary ( $R_2$ ). [Table A-16, Eq. (87)]                                                                                |
| $C_1$                     | Stored Value | Parameter used in calculating the effective yield ( $Y$ ). [Table A-2, Eq. (18)]                                                                             |
| $C_2$                     | Stored Value | Parameter used in calculating the effective yield ( $Y$ ). [Table A-2, Eq. (18)]                                                                             |
| $CA$                      | Stored Value | Concern Area. Parameter used in determining probability of hit ( $P_{hit}$ ) by debris. [Table 31, Table 32, Table 33, Eq. (157), Eq. (158)]                 |
| $CC_a$                    | Variable     | “Actual Continuity Correction” in glass logic. [Eq. (71), Eq. (72), Eq. (76), Eq. (77)]                                                                      |
| $CC_{max}$                | Variable     | “Maximum Continuity Correction” in glass logic. [Eq. (69), Eq. (71), Eq. (74), Eq. (76)]                                                                     |
| $COV(.)$                  | Variable     | Covariance                                                                                                                                                   |
| $CP$                      | Stored Value | Concrete Parameter. Used to calculate maximum throw values for secondary fragments. [Table 19, Eq. (116)]                                                    |
| <i>Crater ejecta mass</i> | Variable     | Mass of the crater ejecta thrown. [Eq. (119), Eq. (120)]                                                                                                     |
| <i>Crater radius</i>      | Variable     | Radius of the crater produced. [Eq. (121), Eq. (122)]                                                                                                        |
| $d$                       | User Input   | Distance between PES and ES. [Eq. (16), Eq. (20), Eq. (26), Eq. (71), Eq. (76), Eq. (128), Eq. (129), Eq. (132), Eq. (135), Eq. (162), Eq. (163)]            |

| Term                      | Type         | Variable Name/Explanation                                                                                                                                                             |
|---------------------------|--------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| $D$                       | Stored Value | The fourth-order parameter used in calculating the effective yield ( $Y$ ). [Table A-2, Eq. (19)]                                                                                     |
|                           | Stored Value | The fourth-order parameter used in calculating the unmodified pressure ( $P$ ). [Table A-3, Eq. (22)]                                                                                 |
|                           | Stored Value | The fourth-order parameter used in calculating the unmodified impulse ( $I$ ). [Table A-4, Eq. (23)]                                                                                  |
|                           | Stored Value | The fourth-order parameter used in calculating the adjusted weight ( $W_a$ ). [Table A-5, Eq. (25)]                                                                                   |
| $d1$                      | User Input   | Distance between ES and ES barricade. [Eq. (132)]                                                                                                                                     |
| $d2$                      | Variable     | Distance between the PES and the ES barricade. [Eq. (132)]                                                                                                                            |
| $DR$                      | Variable     | Damage Region. Parameter used for determining ES protection provided by roof and walls against debris. [Eq. (138), Eq. (139), Eq. (142), Eq. (146), Eq. (147)]                        |
| $E$                       | Stored Value | The fifth-order parameter used in calculating the effective yield ( $Y$ ). [Table A-2, Eq. (19)]                                                                                      |
|                           | Stored Value | The fifth-order parameter used in calculating the unmodified pressure ( $P$ ). [Table A-3, Eq. (22)]                                                                                  |
|                           | Stored Value | The fifth-order parameter used in calculating the unmodified impulse ( $I$ ). [Table A-4, Eq. (23)]                                                                                   |
|                           | Stored Value | The fifth-order parameter used in calculating the adjusted weight ( $W_a$ ). [Table A-5, Eq. (25)]                                                                                    |
|                           | Variable     | The exposure of personnel to an explosive event based on the number of people present in a facility during the year and the number of hours the exposed site is occupied. [Eq. (173)] |
| $E1$                      | Stored Value | Exponent that the initial velocity ( $IV$ ) is raised to in calculating the maximum throw values for secondary fragments. [Table 19, Eq. (116)]                                       |
| $E2$                      | Stored Value | Exponent that the mass is raised to in calculating the maximum throw values for secondary fragments. [Table 19, Eq. (116)]                                                            |
| $E_f$                     | Variable     | “Expected fatalities”. [Eq. (4)]                                                                                                                                                      |
| $E_{f(ES)Group}$          | Variable     | Expected value of the group expected fatality distribution for an ES. [Eq. (192), Eq. (197), Eq. (213)]                                                                               |
| $E_{f(install)Group}$     | Variable     | Expected value of the group expected fatality distribution for the entire situation (all PES-ES pairs in the situation). [Eq. (213)]                                                  |
| $E_{f(pair)Group}$        | Variable     | Expected value of the group expected fatality distribution for a PES-ES pair. [Eq. (192), Eq. (205)]                                                                                  |
| $E_{f(PES\ Siting)Group}$ | Variable     | Expected value of the group expected fatality distribution resulting from all ESs within the Risk-based evaluation distance of any PES. [Eq. (197)]                                   |
| $E_{f(PES)Group}$         | Variable     | Expected value of the group expected fatality distribution resulting from a unique PES. [Eq. (205)]                                                                                   |

| <b>Term</b>                   | <b>Type</b> | <b>Variable Name/Explanation</b>                                                                                                                    |
|-------------------------------|-------------|-----------------------------------------------------------------------------------------------------------------------------------------------------|
| <i>Effects</i>                | Variable    | Used in the uncertainty methodology to represent the four fatality mechanisms computed by the SAFER science algorithms. [Eq. (173)]                 |
| $E_i$                         | Variable    | Denotes the individual Probability of fatality (pair) the distinct PES sites pose to the ES of interest. [Eq. (194), Eq. (196)]                     |
| $E_j$                         | Variable    | Denotes the individual Probability of fatality (pair) the distinct PES sites pose to the ES of interest. [Eq. (194), Eq. (196)]                     |
| $E_k$                         | Variable    | Denotes the individual Probability of fatality (pair) the distinct PES sites pose to the ES of interest. [Eq. (194)]                                |
| $E_{maji} (ES) Group$         | Variable    | Point estimate for major injuries for a unique ES caused by all PESs. [Eq. (201), Eq. (216)]                                                        |
| $E_{maji} (install) Group$    | Variable    | Point estimate for major injuries over the entire situation (all PES-ES pairs in situation). [Eq. (216)]                                            |
| $E_{maji} (pair) Group$       | Variable    | Point estimate for major injuries at a single ES caused by a single PES. [Eq. (188), Eq. (201), Eq. (209)]                                          |
| $E_{maji} (PES Siting) Group$ | Variable    | Point estimate for major injuries at all ESs within the Risk-based evaluation distance of any PES (resulting from all PESs).                        |
| $E_{maji} (PES) Group$        | Variable    | Point estimate for major injuries resulting from a unique PES to all ESs (within the Risk-based evaluation distance of the unique PES). [Eq. (209)] |
| $E_{mini} (ES) Group$         | Variable    | Point estimate for minor injuries for a unique ES caused by all PESs. [Eq. (203), Eq. (218)]                                                        |
| $E_{mini} (install) Group$    | Variable    | Point estimate for minor injuries over the entire situation (all PES-ES pairs in situation). [Eq. (218)]                                            |
| $E_{mini} (pair) Group$       | Variable    | Point estimate for minor injuries at a single ES caused by a single PES. [Eq. (190), Eq. (203), Eq. (211)]                                          |
| $E_{mini} (PES Siting) Group$ | Variable    | Point estimate for minor injuries at all ESs within the Risk-based evaluation distance of any PES (resulting from all PESs).                        |
| $E_{mini} (PES) Group$        | Variable    | Point estimate for minor injuries resulting from a unique PES to all ESs (within the Risk-based evaluation distance of the unique PES). [Eq. (211)] |
| $E_o$                         | Variable    | The distribution used to estimate the daily number of exposures. [Eq. (187)]                                                                        |
| $E_{oo}$                      | Variable    | Median of the lognormal distribution, $E_o$ , representing the median number of daily exposures. [Eq. (13), Eq. (187)]                              |
| $E_{oo} Group$                | Variable    | Parameter used in computing group risk at an ES from a specific PES. [Eq. (11), Eq. (188), Eq. (190)]                                               |
| $E_{oo} Individual$           | Variable    | Parameter used in computing individual risk at an ES. [Eq. (12), Eq. (189), Eq. (191)]                                                              |
| $E_p$                         | Variable    | Annual exposure of one person to a particular PES. [Eq. (3), Eq. (4)]                                                                               |

| <b>Term</b>                | <b>Type</b>  | <b>Variable Name/Explanation</b>                                                                                                               |
|----------------------------|--------------|------------------------------------------------------------------------------------------------------------------------------------------------|
| $ES_{height}$              | Stored Value | Height of the ES. [Table A-11, Eq. (32)]                                                                                                       |
| $exp_{iv}$                 | Stored Value | Parameter used to calculate initial velocity of secondary fragments ( $IV_c$ ). [Table A-28, Eq. (115)]                                        |
| $Exposure$                 | Variable     | Amount of time that a number of people are susceptible to the possible explosive event. [Eq. (185), Eq. (187)]                                 |
| $Exposure_{people\ group}$ | Variable     | Average daily number of exposures, calculated for each people group at an ES. [Eq. (10), Eq. (11)]                                             |
| $F$                        | Stored Value | The sixth-order parameter used in calculating the effective yield ( $Y$ ). [Table A-2, Eq. (19)]                                               |
|                            | Stored Value | The sixth-order parameter used in calculating the adjusted weight ( $W_a$ ). [Table A-5, Eq. (25)]                                             |
|                            | Variable     | Expected number of fatalities per year used in the uncertainty methodology. [Eq. (173)]                                                        |
| $f$                        | Stored Value | “Reduced debris throw factor”. Parameter used in calculating the sigma ( $\sigma$ ) value for departing debris. [Table 24, Eq. (127)]          |
| $FA_{ES}$                  | User Input   | Floor Area of the ES ( $ft^2$ ). [Eq. (32), Eq. (59), Eq. (60), Eq. (82)]                                                                      |
| $FB$                       | Stored Value | Fragment Blocking coefficient. Parameter used in calculating the fraction of debris contained by the PES ( $PES_{DC}$ ). [Table 17, Eq. (108)] |
| $F_R$                      | Variable     | Fireball Radius. Parameter used in determining the “close-in” region in the thermal branch. [Eq. (167)]                                        |
| $fraction\ each\ bin$      | Stored Value | Fraction of soil thrown per bin. [Table 21, Eq. (120)]                                                                                         |
| $FV$                       | Variable     | Final Velocity. Parameter used in calculating kinetic energy ( $KE$ ) of fragments. An array value indexed by mass bin. [Eq. (135), Eq. (136)] |
| $G$                        | Variable     | “Glass Adjustment”. Parameter used in calculating the Probability of fatality due to glass breakage ( $P_{f(g)}$ ). [Eq. (79), Eq. (80)]       |
|                            | Variable     | Parameter used in calculating the <i>Yield adjustment</i> for glass. [Eq. (62), Eq. (66)]                                                      |
|                            | Stored Value | The seventh-order parameter used in calculating the adjusted weight ( $W_a$ ). [Table A-5, Eq. (25)]                                           |
| $g$                        | Stored Value | “Crater radius coefficient”. Parameter used in calculating the <i>Crater radius</i> . [Table 20, Eq. (121)]                                    |
| $G_p$                      | User Input   | Percentage of glass on the ES. [Eq. (32), Eq. (35), Eq. (60), Eq. (82), Eq. (165)]                                                             |
| $h$                        | Variable     | Height increment under evaluation in equation in the barricade algorithm. [Eq. (132)]                                                          |
| $H$                        | Stored Value | The eighth-order parameter used in calculating the adjusted weight ( $W_a$ ). [Table A-5, Eq. (25)]                                            |

| Term         | Type         | Variable Name/Explanation                                                                                                                                                                                         |
|--------------|--------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| $h_1$        | Stored Value | Height of PES provided in [Table 9, Eq. (132)]                                                                                                                                                                    |
| $h_2$        | User Input   | Height of ES barricade. [Eq. (132)]                                                                                                                                                                               |
| $h_3$        | Stored Value | Height of ES. [Table A-11, Eq. (132)]                                                                                                                                                                             |
| $HRD$        | Stored Value | High Range Damage. Parameter used in determining the damage region ( $DR$ ) for the roofs and walls of the ES. [Table 27, Table 28, Eq. (138)]                                                                    |
| $I$          | Variable     | “Unmodified Impulse” (psi-ms). [Eq. (23)]                                                                                                                                                                         |
|              | Variable     | Impulse derived from the hyperbola equation. Used in producing a curve on the ES building damage diagrams. [Eq. (85)]                                                                                             |
| $I'$         | Variable     | “Adjusted Impulse” (psi-ms) outside the PES. [Eq. (29), Eq. (37), Eq. (68), Eq. (73)]                                                                                                                             |
| $I''$        | Variable     | “Final Impulse” (psi-ms) inside the ES. [Eq. (37), Eq. (43), Eq. (48)]                                                                                                                                            |
| $IA$         | Variable     | Impulse-Adjusted probability of serious injury from glass breakage. [Eq. (68), Eq. (72), Eq. (73), Eq. (77)]                                                                                                      |
| $IA_{roof}$  | Stored Value | “Nominal Invulnerable Area of the ES roof”. [Table 29, Eq. (140)]                                                                                                                                                 |
| $IA_{wall}$  | Stored Value | “Nominal Invulnerable Area of the ES wall”. [Table 30, Eq. (143)]                                                                                                                                                 |
| $IFR$        | Stored Value | Injury to Fatality Ratio. Parameter used in calculating the adjusted Probability of major and minor injury due to building collapse ( $Adj. P_{maji(bc)}$ , $Adj. P_{maji(bc)}$ ). [Table 12, Eq. (89), Eq. (91)] |
| $IRR$        | Stored Value | Initial Reduction Ratio. [Table 18]                                                                                                                                                                               |
| $I_{scaled}$ | Variable     | “Impulse Scaled”. Parameter used in determining the probability of fatality due to lung rupture ( $P_{f(lr)}$ ). [Eq. (43)]                                                                                       |
| $IV$         | Stored Value | Initial Velocity. [Table 15, Eq. (102), Eq. (115), Eq. (116)]                                                                                                                                                     |
| $IV_c$       | Variable     | “Calculated Initial Velocity”. An array value indexed by PES component. [Eq. (115)]                                                                                                                               |
| $IV_{max}$   | Stored Value | “Maximum Initial Velocity”. [Table A-28, Eq. (115)]                                                                                                                                                               |
| $k$          | Variable     | Bin number of first non-zero bin. [Eq. (124)]                                                                                                                                                                     |
|              | Variable     | Represents the four fatality mechanisms used in SAFER. Section 4.6.2.2.13.                                                                                                                                        |
| $KE$         | Variable     | Kinetic Energy. An array value indexed by mass bin. [Eq. (136), Eq. (137)]                                                                                                                                        |
| $KE_a$       | Variable     | “Kinetic Energy adjustment”. Adjustment based on percentage of ES roof and walls intact ( $\% ES_{roof\ intact} / \% ES_{wall\ intact}$ ). [Eq. (139)]                                                            |

| <b>Term</b>                | <b>Type</b>  | <b>Variable Name/Explanation</b>                                                                                                                                                |
|----------------------------|--------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| $KE_R$                     | Variable     | “Resulting Kinetic Energy”. Kinetic energy calculated following impact with the ES roof and walls. An array value indexed by KE and mass bin. [Eq. (148), Eq. (150), Eq. (151)] |
| $L$                        | Variable     | Attachment 13.                                                                                                                                                                  |
| $Local\ reduction$         | Variable     | Fraction of fly-through fragments blocked at the evaluated height ( $h$ ) at the PES. [Eq. (132), Eq. (133)]                                                                    |
| $Lower$                    | Variable     | Lower projection angle of fragments from the PES to the ES. [Eq. (132)]                                                                                                         |
| $LRD$                      | Stored Value | Low Range Damage. Parameter used in determining the damage region ( $DR$ ) for the roofs and walls of the ES. [Table 27, Table 28, Eq. (138)]                                   |
| $m$                        | Stored Value | Upper bound multiplication factor. [Table 38, Eq. (184)]                                                                                                                        |
| $M$                        | Stored Value | Parameter used in calculating the base probability of major injury from glass. [Table A-12, Eq. (61)]                                                                           |
|                            | Variable     | Median, Nominal, or Center Value. Used to characterize nominal factor values in linear space. [Eq. (182), Eq. (183)]                                                            |
| $maj_{(i)}DO$              | Stored Value | “Major injury damage offset”. [Table 12, Eq. (88)]                                                                                                                              |
| $maj_{(i)}max$             | Stored Value | “Major injury maximum”. [Table 12, Eq. (88)]                                                                                                                                    |
| $Mass\ of\ PES\ component$ | Stored Value | Mass distribution for each PES component. [Table A-20, Table A-23, Eq. (111)]                                                                                                   |
| $Mass\ of\ PES\ thrown$    | Stored Value | Parameter used to calculate number of secondary fragments. [Table A-20, Table A-23, Eq. (111), Eq. (113)]                                                                       |
| $MAXInjury$                | Constant     | “Maximum injury value”. Set to 100%. [Eq. (88)]                                                                                                                                 |
| $min_{(i)}DO$              | Stored Value | “Minor injury damage offset”. [Table 12, Eq. (90)]                                                                                                                              |
| $min_{(i)}PD$              | Stored Value | “Minor injury plateau damage”. [Table 12, Eq. (90)]                                                                                                                             |
| $MINInjury$                | Constant     | “Minimum injury value”. Set to 0. [Eq. (88)]                                                                                                                                    |
| $MT_c$                     | Variable     | “Calculated Maximum Throw range”. An array value indexed by mass bin. [Eq. (102), Eq. (104)]                                                                                    |
|                            | Variable     | “Maximum Throw range for concrete fragments”. An array value indexed by mass bin, maximum throw table, and PES component. [Eq. (116), Eq. (117)]                                |
| $MT_m$                     | Stored Value | “Maximum Throw range for multiple weapons”. [Table 15, Eq. (103)]                                                                                                               |
| $MT_{max}$                 | Variable     | “Highest Maximum Throw range”. An array value indexed by mass bin, maximum throw table, and PES component. [Table A-29, Eq. (103), Eq. (104), Eq. (117)]                        |



| <b>Term</b>           | <b>Type</b>  | <b>Variable Name/Explanation</b>                                                                                                                  |
|-----------------------|--------------|---------------------------------------------------------------------------------------------------------------------------------------------------|
| $MT_i$                | Stored Value | “Maximum Throw for an individual weapon”. [Table 15, Eq. (103)]                                                                                   |
| $MT_s$                | Variable     | “Maximum Throw for steel fragments”. An array value indexed by mass bin, maximum throw table, and PES component. [Eq. (116), Eq. (118)]           |
| $M_{un-scaled}$       | Stored Value | The center value for the un-scaled probability of event predicted from the accident data.                                                         |
| $N$                   | Stored Value | Paramter used in calculating the base probability of major injury from glass. [Table A-12, Eq. (61)]                                              |
| $N^*$                 | Variable     | “Total quantity of fragments”. [Eq. (158)]                                                                                                        |
| $N^*_{HA}$            | Variable     | “Total quantity of High-Angle fragments”. An array value indexed by KE bin. [Eq. (154), Eq. (155), Eq. (156), Eq. (157)]                          |
| $N^*_{LA}$            | Variable     | “Total quantity of Low-Angle fragments”. An array value indexed by KE bin. [Eq. (155)]                                                            |
| $N_{af}$              | Variable     | “Number of expected arriving fragments per square foot”. An array value indexed by mass bin. [Eq. (130), Eq. (131), Eq. (134)]                    |
| $N_{ce}$              | Variable     | “Number of crater ejecta fragments”. An array value indexed by mass bin. [Eq. (121)]                                                              |
| $ND_{FT}$             | Variable     | The “Directional Number of Fly-Through fragments”. [Eq. (106)]                                                                                    |
| $ND_{HA}$             | Variable     | The “Directional Number of High-Angle fragments”. [Eq. (107)]                                                                                     |
| $ND_{SI}$             | Variable     | The “Directional number of Side-Impact fragments”. [Eq. (106)]                                                                                    |
| $NEW$                 | User Input   | The Net Explosive Weight of hazardous material contributing to the event used in the uncertainty methodology. [Eq. (173)]                         |
| $NEWQD$ of one weapon | Stored Value | Net Explosive Weight of one weapon. [Table 14, Eq. (19), Eq. (98), Eq. (103)]                                                                     |
| $N_{FT}$              | Variable     | “Number of Fly-Through fragments”. An array value indexed by mass bin. [Eq. (105), Eq. (106), Eq. (125), Eq. (126), Eq. (145), Eq. (147)]         |
| $N'_{FT}$             | Variable     | “Number of primary Fly-Through fragments blocked by the PES front wall, side walls, and rear wall”. An array value indexed by KE bin. [Eq. (109)] |
| $N_{FT}$              | Variable     | “Number of Fly-Through fragments blocked by the ES wall”. [Eq. (147), Eq. (153)]                                                                  |
| $N_{HA}$              | Variable     | “Number of High-Angle fragments”. An array value indexed by mass and KE bin. [Eq. (105), Eq. (107), Eq. (141), Eq. (142), Eq. (154)]              |
| $N'_{HA}$             | Variable     | “Number of primary High-Angle fragments blocked by the PES roof”. An array value indexed by KE bin. [Eq. (110)]                                   |
| $N_{HA}$              | Variable     | “Number of fragments that will be blocked by the ES roof”. [Eq. (142)]                                                                            |
| $N_{LA}$              | Variable     | “Number of Low-Angle fragments”. An array value indexed by mass bin. [Eq. (125), Eq. (126), Eq. (153), Eq. (155)]                                 |

| <b>Term</b>                        | <b>Type</b> | <b>Variable Name/Explanation</b>                                                                                                                                   |
|------------------------------------|-------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| $Nom. P_{maji(bc)}$                | Variable    | “Nominal Probability of major injury due to building collapse”. [Eq. (88)]                                                                                         |
| $Nom. P_{mini(bc)}$                | Variable    | “Nominal Probability of minor injury due to building collapse”. [Eq. (90)]                                                                                         |
| $N_{pf}$                           | Variable    | “Number of departing primary fragments”. An array value indexed by mass bin. [Eq. (101), Eq. (105)]                                                                |
| $N_{pos}$                          | Variable    | “Percentage of weapons on the outer surface of the stack”. [Eq. (99), Eq. (100)]                                                                                   |
| <i>No. of departing fragments</i>  | Variable    | Number of fragments in the respective bins of each departing fragment mass table. [Eq. (129), Eq. (130)]                                                           |
| $N_{sf}$                           | Variable    | “Number of secondary fragments”. An array value indexed by PES component and material. [Eq. (113)]                                                                 |
| $N_{SI}$                           | Variable    | “Number of Side-Impact fragments”. An array value indexed by mass bin. [Eq. (105), Eq. (106), Eq. (126), Eq. (144), Eq. (146)]                                     |
| $N'_{SI}$                          | Variable    | “Number of primary Side-Impact fragments blocked by the PES front wall, side walls, or rear wall”. An array value indexed by PES component. [Eq. (106), Eq. (109)] |
| $NSI$                              | Variable    | “Number of Side-Impact fragments blocked by the ES wall”. [Eq. (146), Eq. (153)]                                                                                   |
| <i>Number of People</i>            | User Input  | The quantity of people entered by the user. [Eq. (10)]                                                                                                             |
| <i>number of height increments</i> | Variable    | Number of height increments used in the barricade fragment blocking algorithm. [Eq. (133)]                                                                         |
| $N_w$                              | Variable    | “Number of weapons”. [Eq. (98), Eq. (99), Eq. (100)]                                                                                                               |
| $N_{wos}$                          | Variable    | “Number of weapons on the outer surface”. [Eq. (100), Eq. (101)]                                                                                                   |
| $P$                                | Variable    | “Unmodified or open-air pressure” (psi). [Eq. (22)]                                                                                                                |
|                                    | Variable    | Pressure derived from the hyperbola equation. Used in producing a curve on the ES building damage diagrams. [Eq. (85)]                                             |
| $P'$                               | Variable    | “Adjusted Pressure” (psi) outside the PES. [Eq. (28), Eq. (33), Eq. (34), Eq. (36)]                                                                                |
| $P''$                              | Variable    | “Final Pressure” (psi) inside the ES. [Eq. (36), Eq. (38), Eq. (39), Eq. (40), Eq. (41), Eq. (46), Eq. (47)]                                                       |
| $P_{(sf)}$                         | Variable    | “Probability of skull fracture”. [Eq. (54)]                                                                                                                        |
| $P_{ambient}$                      | Constant    | “Ambient Pressure”. [Eq. (38), Eq. (39), Eq. (41), Eq. (42)]                                                                                                       |
| $P_{base}$                         | Variable    | “Probability of a major injury from glass breakage”. [Eq. (61), Eq. (67)]                                                                                          |
| $PD_b$                             | Variable    | “Predicted Building Damage”. [Eq. (88), Eq. (90), Eq. (92)]                                                                                                        |
| $P_{dynamic}$                      | Variable    | “Dynamic Pressure”. [Eq. (39), Eq. (40), Eq. (42)]                                                                                                                 |

| <b>Term</b>                       | <b>Type</b>  | <b>Variable Name/Explanation</b>                                                                                                                                 |
|-----------------------------------|--------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| $P_e$                             | Variable     | Probability that an explosive event will occur per Potential Explosion Site per year. [Eq. (3), Eq. (4)]                                                         |
| <i>Percent Mass</i>               | Stored Value | Percentage of component mass in a given mass bin. In an array indexed by PES component and mass bin. [Table A-20, Table A-21, Table A-22, Table A-23, Eq. (113)] |
| <i>Percent Material</i>           | Stored Value | Percentage of component mass that is a given material. In an array indexed by PES component. [Table A-20, Table A-21, Table A-22, Table A-23, Eq. (113)]         |
| <i>PES Annual Operating Hours</i> | User Input   | The typical hours per year that the PES is expected to house explosives based on the activity selected by the user. [Eq. (6)]                                    |
| $PES_{damage(fw)}$                | Variable     | “Fraction of PES front wall damage”. An array value indexed by PES component. [Eq. (30), Eq. (31), Eq. (111)]                                                    |
| $PES_{damage(roof)}$              | Variable     | “Fraction of PES roof damaged”. An array value indexed by PES component. [Eq. (30), Eq. (31), Eq. (111)]                                                         |
| $PES_{damage(rw)}$                | Variable     | “Fraction of PES rear wall damaged”. An array value indexed by PES component. [Eq. (30), Eq. (31), Eq. (111)]                                                    |
| $PES_{damage(sw)}$                | Variable     | “Fraction of PES side walls damaged”. An array value indexed by PES component. [Eq. (30), Eq. (31), Eq. (111)]                                                   |
| $PES_{DC}$                        | Variable     | “The fraction of debris (primary fragments) contained by the PES”. [Eq. (108), Eq. (109), Eq. (110)]                                                             |
| $PES_{fraction}$                  | Stored Value | “Fraction of total PES area by component”. [Table 16, Eq. (106), Eq. (107)]                                                                                      |
| $PES_{intact}$                    | Variable     | “The fraction of PES intact” following the explosive event. [Eq. (31), Eq. (108)]                                                                                |
| $PES_{intact(fw)}$                | Variable     | “Fraction of PES front wall intact”. An array value indexed by PES component. [Eq. (31), Eq. (108)]                                                              |
| $PES_{intact(roof)}$              | Variable     | “Fraction of PES roof intact”. An array value indexed by PES component. [Eq. (31), Eq. (108)]                                                                    |
| $PES_{intact(rw)}$                | Variable     | “Fraction of PES rear wall intact”. An array value indexed by PES component. [Eq. (31), Eq. (108)]                                                               |
| $PES_{intact(sw)}$                | Variable     | “Fraction of PES side walls intact”. An array value indexed by PES component. [Eq. (31), Eq. (108)]                                                              |
| $P_{event}$                       | Variable     | “Probability of event” for purposes of computing injury estimates (with uncertainty). [Eq. (185), Eq. (186)]                                                     |
| $P_f$                             | Variable     | “Annual Probability of fatality”. [Eq. (3)]                                                                                                                      |
| $P_{f(b)}$                        | Variable     | “Probability of fatality due to overall building damage”. [Eq. (95), Eq. (170)]                                                                                  |
| $P_{f(bc)}$                       | Variable     | “Probability of fatality due to building collapse”. [Eq. (86), Eq. (89), Eq. (91), Eq. (95)]                                                                     |

| <b>Term</b>                   | <b>Type</b>  | <b>Variable Name/Explanation</b>                                                                                                                                                                        |
|-------------------------------|--------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| $P_{f(bc)1}$                  | Stored Value | Maximum or “plateau” value assigned to Probability of fatality due to building collapse in the “close in” region. [Table A-15, Eq. (86)]                                                                |
| $P_{f(bc)2}$                  | Variable     | Highest value calculated by standard SAFER logic for Probability of fatality due to building collapse (at the boundary between the “transition region” and the “normal region”). [Table A-15, Eq. (86)] |
| $P_{f(bd)}$                   | Variable     | “Probability of fatality due to whole body displacement”. [Eq. (50), Eq. (56)]                                                                                                                          |
| $P_{f(d)}$                    | Variable     | “Probability of fatality due to debris”. An array value indexed by PES component. [Eq. (158), Eq. (161), Eq. (170)]                                                                                     |
| $P_{f(d)high-angle}$          | Variable     | “Probability of fatality due to debris from the combined high-angle perforating debris table”. [Eq. (161)]                                                                                              |
| $P_{f(d)low-angle}$           | Variable     | “Probability of fatality due to debris from the combined low-angle perforating debris table”. [Eq. (159), Eq. (161)]                                                                                    |
| $P_{f(ES)Individual}$         | Variable     | Expected value of the Probability of fatality distribution for a unique ES caused by all PESs. [Eq. (194), Eq. (199), Eq. (215)]                                                                        |
| $P_{f(g)}$                    | Variable     | Probability of fatality due to glass breakage. [Eq. (80), Eq. (81), Eq. (83), Eq. (84), Eq. (95)]                                                                                                       |
| $P_{f(g)1}$                   | Stored Value | Maximum or “plateau” value assigned to Probability of fatality due to glass in the “close in” region. [Table 11, Eq. (81)]                                                                              |
| $P_{f(g)2}$                   | Variable     | Highest value calculated by standard SAFER logic for Probability of fatality due to glass (at the boundary between the “transition region” and the “normal region”). [Eq. (81), Eq. (82)]               |
| $P_{f(gi)}$                   | Variable     | “Initial Probability of fatality due to glass breakage”. [Eq. (78), Eq. (80)]                                                                                                                           |
| $P_{f(install)Individual}$    | Variable     | Expected value of the Probability of fatality distribution resulting from the entire situation (all PES-ES pairs in the situation). [Eq. (214)]                                                         |
| $P_{f(lr)}$                   | Variable     | “Probability of fatality due to lung rupture”. Section 4.2.4.2. [Eq. (56)]                                                                                                                              |
| $P_{f(o)}$                    | Variable     | “Probability of fatality due to the effects of pressure and impulse”. [Eq. (56), Eq. (170)]                                                                                                             |
| $P_{f(pair)Individual}$       | Variable     | Expected value of the Probability of fatality distribution for a PES-ES pair (Individual). [Eq. (206)]                                                                                                  |
| $P_{f(PES Siting)Individual}$ | Variable     | Expected value of the probability of fatality distribution for all ESs within the Risk-based evaluation distance of any PES (resulting from all PESs). [Eq. (198)]                                      |
| $P_{f(PES)Individual}$        | Variable     | Expected value of the Probability of fatality distribution for all ESs in the Risk-based evaluation distance of a unique PES. [Eq. (206)]                                                               |
| $P_{f(sf)}$                   | Variable     | “Probability of fatality due to skull fracture”. [Eq. (54), Eq. (56)]                                                                                                                                   |

| <b>Term</b>                               | <b>Type</b> | <b>Variable Name/Explanation</b>                                                                                                                                                                                                                                                                          |
|-------------------------------------------|-------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| $P_{f(t)}$                                | Variable    | “Probability of fatality due to thermal effects”. [Eq. (166), Eq. (168), Eq. (169), Eq. (170)]                                                                                                                                                                                                            |
| $P_{f(to)}$                               | Variable    | “Nominal Probability of fatality due to thermal effects”. Figure 10. [Eq. (165)]                                                                                                                                                                                                                          |
| $P_{f(x)}$                                | Variable    | “Probability of fatality at range x”. [Eq. (5)]                                                                                                                                                                                                                                                           |
| $P_{f(x)1}$                               | Set Value   | Value at which the Probability of fatality in the “close-in” region is set to 100% for most fatality mechanisms, with glass being the exception. [Eq. (5)]                                                                                                                                                |
| $P_{f(x)2}$                               | Variable    | Value of the Probability of fatality in the “normal SAFER” region determined at run time, used for calculating the “close-in” fatality mechanism. [Eq. (5)]                                                                                                                                               |
| $P_{f e}$                                 | Variable    | “The Probability of fatality given an explosive event and exposure” – this factor aggregates the effects of the fatality mechanisms: overpressure, debris, building collapse, and glass hazards, or thermal effects. [Eq. (3), Eq. (4), Eq. (170), Eq. (171), Eq. (172), Eq. (173), Eq. (178), Eq. (181)] |
| $P_{harm/event}$                          | Variable    | “The Probability of harm given an explosive event”. Parameter used in the generic risk equation. [Eq. (185)]                                                                                                                                                                                              |
| $P_{f ko}$                                | Variable    | Lognormal distribution of the epistemic uncertainty associated with evaluating the median value of the Probability of fatality due to explosive effect. Section 4.6.2.2.7.                                                                                                                                |
| $P_{f koo}$                               | Variable    | The median value of the lognormal distribution, $P_{f ko}$ , the epistemic uncertainty associated with evaluating the median value of the Probability of fatality due to explosive effect, $k$ , Section 4.6.2.2.7.                                                                                       |
| $P_{gha}$                                 | Variable    | “Probability of a person being in the glass hazard area”. [Eq. (60), Eq. (78)]                                                                                                                                                                                                                            |
| $P_{hit}$                                 | Variable    | “Probability of hit”. An array value indexed by consequence and mass bin. [Eq. (156), Eq. (157)]                                                                                                                                                                                                          |
| $P_{hit(f)}$                              | Variable    | “Probability of hit for fatality”. [Eq. (157), Eq. (158)]                                                                                                                                                                                                                                                 |
| $P_{hit(maji)}$                           | Variable    | “Probability of hit for major injury”. [Eq. (157), Eq. (158)]                                                                                                                                                                                                                                             |
| $P_{hit(mini)}$                           | Variable    | “Probability of hit for minor injury”. [Eq. (157), Eq. (158)]                                                                                                                                                                                                                                             |
| $P_i$                                     | Variable    | Debris probability density at the ES (pieces/sq. ft). An array value indexed by mass bin. [Eq. (128), Eq. (129), Eq. (130), Eq. (131)]                                                                                                                                                                    |
| $P_{maji (ES)}$<br><i>Individual</i>      | Variable    | Point estimate of an “Individual’s Probability of a Major injury at a unique ES resulting from all PESs”. [Eq. (202), Eq. (217)]                                                                                                                                                                          |
| $P_{maji (install)}$<br><i>Individual</i> | Variable    | Point estimate of the “maximum Individual Probability of a Major injury at the installation” (all PES-ES pairs in the situation). [Eq. (217)]                                                                                                                                                             |
| $P_{maji (pair)}$<br><i>Individual</i>    | Variable    | Point estimate of an “Individual’s Probability of a major injury for a PES-ES pair”. [Eq. (189), Eq. (202), Eq. (210)]                                                                                                                                                                                    |

| <b>Term</b>                           | <b>Type</b> | <b>Variable Name/Explanation</b>                                                                                                                                                  |
|---------------------------------------|-------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| $P_{maji}$ (PES Siting)<br>Individual | Variable    | Point estimate of the maximum individual probability of a major injury at any ES within the Risk-based evaluation distance of a unique PES caused by any PES.                     |
| $P_{maji}$ (PES)<br>Individual        | Variable    | Point estimate of the “maximum Individual Probability of a Major injury caused by a unique PES across all ESs within the Risk-based evaluation distance of that PES”. [Eq. (210)] |
| $P_{maji e}$                          | Variable    | Probability of a major injury given an explosives event and the presence of a person. [Eq. (171), Eq. (172), Eq. (188), Eq. (189)]                                                |
| $P_{maji(b)}$                         | Variable    | “Probability of a major injury due to overall building damage”. [Eq. (96), Eq. (171)]                                                                                             |
| $P_{maji(bc)}$                        | Variable    | “Probability of a major injury due to building collapse”. [Eq. (96)]                                                                                                              |
| $P_{maji(bd)}$                        | Variable    | “Probability of a major injury from whole body displacement”. [Eq. (50), (51), (57)]                                                                                              |
| $P_{maji(d)}$                         | Variable    | “Probability of a major injury due to debris”. An array value indexed by mass bin. [Eq. (158), Eq. (171)]                                                                         |
| $P_{maji(g)}$                         | Variable    | “Probability of a major injury due to glass breakage”. [Eq. (83), Eq. (96)]                                                                                                       |
| $P_{maji(lr)}$                        | Variable    | Probability of a major injury from lung rupture. [Eq. (46), Eq. (57)]                                                                                                             |
| $P_{maji(o)}$                         | Variable    | “Probability of a major injury due to the effects of pressure and impulse”. [Eq. (57), Eq. (171)]                                                                                 |
| $P_{maji(sf)}$                        | Variable    | “Probability of a major injury due to skull fracture”. [Eq. (54), Eq. (55), Eq. (57)]                                                                                             |
| $P_{maji(t)}$                         | Variable    | “Probability of a major injury due to thermal effects”. [Eq. (67), Eq. (168)]                                                                                                     |
| $P_{mini}$ (ES)<br>Individual         | Variable    | Point estimate of an “Individual’s Probability of a Minor injury at a unique ES caused by all PESs”. [Eq. (204), Eq. (219)]                                                       |
| $P_{mini}$ (install)<br>Individual    | Variable    | Point estimate of the “maximum Individual Probability of a Minor injury at the installation” (all PES-ES pairs in the situation). [Eq. (219)]                                     |
| $P_{mini}$ (pair)<br>Individual       | Variable    | Point estimate of an “Individual’s Probability of Minor injury for a PES-ES pair”. [Eq. (191), Eq. (204), Eq. (212)]                                                              |
| $P_{mini}$ (PES Siting)<br>Individual | Variable    | Point estimate of the “maximum Individual Probability of a Minor injury at any ES within the Risk-based evaluation distance of a unique PES caused by any PES”.                   |
| $P_{mini}$ (PES)<br>Individual        | Variable    | Point estimate of the maximum individual probability of a minor injury caused by a unique PES across all ESs within the Risk-based evaluation distance of that PES. [Eq. (212)]   |
| $P_{mini e}$                          | Variable    | Probability of minor injury given an explosives event and the presence of a person. [Eq. (172), Eq. (190), Eq. (191)]                                                             |
| $P_{mini(b)}$                         | Variable    | “Probability of a minor injury due to overall building damage”. [Eq. (97), Eq. (172)]                                                                                             |

| <b>Term</b>     | <b>Type</b>  | <b>Variable Name/Explanation</b>                                                                                                       |
|-----------------|--------------|----------------------------------------------------------------------------------------------------------------------------------------|
| $P_{mini(bc)}$  | Variable     | “Probability of a minor injury due to building collapse”. [Eq. (97)]                                                                   |
| $P_{mini(bd)}$  | Variable     | “Probability of a minor injury from whole body displacement”. [Eq. (51), Eq. (58)]                                                     |
| $P_{mini(d)}$   | Variable     | “Probability of a minor injury due to debris”. An array value indexed by mass bin. [Eq. (158), Eq. (172)]                              |
| $P_{mini(g)}$   | Variable     | “Probability of a minor injury due to glass breakage”. [Eq. (84), Eq. (97)]                                                            |
| $P_{mini(lr)}$  | Variable     | “Probability of a minor injury from lung rupture”. [Eq. (47), (58)]                                                                    |
| $P_{mini(o)}$   | Variable     | “Probability of a minor injury due to the effects of pressure and impulse”. [Eq. (58), Eq. (172)]                                      |
| $P_{mini(sf)}$  | Variable     | “Probability of a minor injury due to skull fracture”. [Eq. (55), Eq. (58)]                                                            |
| $P_{mini(t)}$   | Variable     | “Probability of a minor injury due to thermal effects”. [Eq. (169), Eq. (172)]                                                         |
| $P_{nominal}$   | Variable     | “Nominal Pressure”. [Eq. (40), Eq. (41), Eq. (48), Eq. (52)]                                                                           |
| $P_{pha}$       | Variable     | “Probability of a major injury given that the person is in the glass hazard area”. [Eq. (67), Eq. (72), Eq. (77), Eq. (78)]            |
| $P_{reflected}$ | Variable     | “Reflected Pressure”. [Eq. (38), Eq. (41)]                                                                                             |
| $P_{scaled}$    | Variable     | “Scaled Pressure”. Parameter used in determining the probability of fatality due to lung rupture ( $P_{f(lr)}$ ). [Eq. (42), Eq. (44)] |
| $PWHFA$         | Variable     | Potential Window Hazard Floor Area. [Eq. (59), Eq. (60)]                                                                               |
| $r$             | Stored Value | “Crater ejecta range coefficient”. [Table 20, Eq. (123)]                                                                               |
| $R$             | Variable     | Range. [Eq. (5)]                                                                                                                       |
|                 | Variable     | Parameter used in calculating the <i>Yield adjustment</i> for glass. [Eq. (62), Eq. (63)]                                              |
| $R_1$           | Variable     | Boundary between the “plateau” region and the “transition” region. [Eq. (5)]                                                           |
|                 | Stored Value | Boundary between the “plateau” region and the “transition” region for glass. [Table 11, Eq. (81)]                                      |
|                 | Stored Value | Boundary between the “plateau” region and the “transition” region for building collapse. [Table A-16, Eq. (86)]                        |
| $R_2$           | Variable     | Boundary between the “transition” region and the “normal” region. [Eq. (5)]                                                            |
|                 | Stored Value | Boundary between the “transition” region and the “normal” region for glass. [Table 11, Eq. (81)]                                       |
|                 | Variable     | Boundary between the “transition” region and the “normal” region for building collapse. [Eq. (86), Eq. (87)]                           |
| $R_{2min}$      | Stored Value | Minimum value for boundary between the “transition” region and the “normal” region for building collapse. [Table A-16, Eq. (87)]       |

| Term       | Type         | Variable Name/Explanation                                                                                                                                                                                                                                  |
|------------|--------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| $RL$       | Variable     | Reduction Level. Parameter used in calculating the final pressure ( $P''$ ) and impulse ( $I''$ ). [Table 10, Table A-11, Eq. (35), Eq. (36), Eq. (37)]                                                                                                    |
| $R_M$      | Variable     | “Final Maximum throw Range”. [Eq. (104), Eq. (127)]                                                                                                                                                                                                        |
| $R_{Mcr}$  | Variable     | Nominal maximum throw range for crater ejecta. An array value indexed by mass bin. [Eq. (122), Eq. (123), Eq. (124)]                                                                                                                                       |
| $R_{Mc}$   | Variable     | “Final Maximum throw Range for concrete”. An array value indexed by PES component and maximum throw table. [Eq. (117)]                                                                                                                                     |
| $R_{Ms}$   | Variable     | “Final Maximum throw Range for steel”. An array value indexed by PES component and maximum throw table. [Eq. (117)]                                                                                                                                        |
| $RV_{ave}$ | Variable     | “Average Reduction Value”. Parameter used to complete the definition of the 3 points of the pressure reduction function. [Eq. (33), Eq. (34)]                                                                                                              |
| $S$        | Stored Value | Environmental factor that increases the Probability of an event based on extenuating circumstances at the site – such as operations in a remote area or under combat conditions. [Eq. (173), Eq. (186)]                                                    |
|            | Variable     | Parameter used in calculating the <i>Yield adjustment</i> for glass. [Eq. (62), Eq. (64)]                                                                                                                                                                  |
| $SD$       |              | Standard deviation, characterizes the spread or dispersion of factor values in linear space.                                                                                                                                                               |
| $S_{bd}$   | Variable     | Parameter used to calculate the Probability of fatality due to body displacement ( $P_{f(bd)}$ ). [Eq. (48), Eq. (49)]                                                                                                                                     |
| $S_{lr}$   | Variable     | Parameter used to calculate the Probability of fatality due to lung rupture ( $P_{f(lr)}$ ). [Eq. (44), Eq. (45)]                                                                                                                                          |
| $S_o$      | Stored Value | Median of the lognormal distribution representing the Probability of event environmental factor ( $S$ ) that addresses the increase in risk due to extenuating circumstances. [Table 37, Eq. (174), Eq. (186), Eq. (188), Eq. (189), Eq. (190), Eq. (191)] |
| $SP$       | Stored Value | Steel Parameter. Used to calculate maximum throw values for secondary fragments. [Table 19, Eq. (116)]                                                                                                                                                     |
| $S_{sf}$   | Variable     | Parameter used to calculate the Probability of fatality due to skull fracture ( $P_{f(sf)}$ ). [Eq. (52), Eq. (53)]                                                                                                                                        |
| $T2$       | Variable     | Angle from the evaluated height ( $h$ ) at the PES to the top of the ES barricade. [Eq. (132)]                                                                                                                                                             |
| $T3$       | Variable     | Angle from the evaluated height ( $h$ ) at the PES to the top of the ES. [Eq. (132)]                                                                                                                                                                       |
| $TBF$      | Variable     | “Adjusted Thermal Blocking Factor”. Calculated to include effects of the percentage of glass on the ES ( $G_p$ ). [Eq. (165), Eq. (166)]                                                                                                                   |



| <b>Term</b>                           | <b>Type</b>  | <b>Variable Name/Explanation</b>                                                                                                                                |
|---------------------------------------|--------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------|
| $TBF_o$                               | Stored Value | “Thermal Blocking Factor” based on the ES building type. Table 35. [Eq. (165)]                                                                                  |
| <i>throw value</i>                    | Stored Value | “Crater ejecta throw value”. [Table 22, Eq. (124)]                                                                                                              |
| <i>Total angle</i>                    | Variable     | Span of angles at which fragments are ejected from PES. [Eq. (132)]                                                                                             |
| <i>Total No. of primary fragments</i> | Stored Value | Number of primary fragments produced. [Table 14, Eq. (101)]                                                                                                     |
| <i>Total reduction</i>                | Variable     | Total percentage of fragments blocked by the barricade. [Eq. (133), Eq. (134)]                                                                                  |
| $TP$                                  | Variable     | Transition Point. [Eq. (70), Eq. (71), Eq. (75), Eq. (76)]                                                                                                      |
| $UB$                                  | Variable     | Upper Bounds or extreme value. [Eq. (182)]                                                                                                                      |
| $UB_{environmental\ factor}$          | Stored Value | Upper Bound of the environmental factor distribution. [Table 37, Eq. (174)]                                                                                     |
| $UB_{un-scaled\ Pe}$                  | Stored Value | The Upper Bound used to calculate the standard deviation of the lognormal factor that describes the epistemic uncertainty ( $\delta_o$ ). [Table 38, Eq. (175)] |
| $UB_{\Delta t}$                       | Variable     | Upper Bound of the percentage of time that personnel in an ES are exposed to a PES when explosives are present ( $\Delta t$ ). [Eq. (9)]                        |
| $UL$                                  | Variable     | Upper Limit.                                                                                                                                                    |
| $UL_{\Delta t}$                       | Variable     | Upper Limit on the number of personnel present at an ES at any time. [Eq. (13)]                                                                                 |
| <i>Upper</i>                          | Variable     | Upper projection of fragments from the PES to the ES. [Eq. (132)]                                                                                               |
| $V$                                   | Stored Value | Volume of PES. [Table A-24, Table A-25, Table A-26, Table A-27, Eq. (114), Eq. (115)]                                                                           |
| $VAVR$                                | Variable     | Vent Area to Building Volume Ratio. [Eq. (32)]                                                                                                                  |
| $V_{f(ES)Group}$                      | Variable     | Variance of the group expected fatality distribution for a specific ES. [Eq. (193), Eq. (198), Eq. (214)]                                                       |
| $V_{f(ES)Individual}$                 | Variable     | Variance of the individual Probability of fatality distribution for a specific ES. [Eq. (195), Eq. (200)]                                                       |
| $V_{f(install)Group}$                 | Variable     | Variance of the group expected fatality distribution for the entire situation (all PES-ES pairs). [Eq. (214)]                                                   |
| $V_{f(install)Individual}$            | Variable     | Variance of the individual Probability of fatality distribution for the entire situation (all PES-ES pairs). Section 4.6.4.                                     |
| $V_{f(pair)Group}$                    | Variable     | Variance of the group expected fatality distribution for a PES-ES pair. [Eq. (193), Eq. (206)]                                                                  |
| $V_{f(pair)Individual}$               | Variable     | Variance of the individual Probability of fatality distribution for a PES-ES pair. [Eq. (208)]                                                                  |

| <b>Term</b>                    | <b>Type</b>  | <b>Variable Name/Explanation</b>                                                                                                                                                  |
|--------------------------------|--------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| $V_{f(PES\ Siting)Group}$      | Variable     | Variance of the expected fatality distribution for all ESs within the Risk-based evaluation distance of any PES caused by all PESs. [Eq. (198)]                                   |
| $V_{f(PES\ Siting)Individual}$ | Variable     | Variance of the maximum individual Probability of fatality distribution for any ES within the Risk-based evaluation distance of any PES. [Eq. (200)]                              |
| $V_{f(PES)Group}$              | Variable     | Variance of the group expected fatality distribution for a single PES. [Eq. (206)]                                                                                                |
| $V_{f(PES)Individual}$         | Variable     | Variance of the individual Probability of fatality distribution for a single PES. [Eq. (208)]                                                                                     |
| $V_i$                          | Variable     | Denotes the variances in the individual Probability of fatality (pair) that distinct PES sites pose to the ES of interest. [Eq. (195), Eq. (196)]                                 |
| $V_{ij}$                       | Variable     | Denotes the variances in the individual Probability of fatality (pair) that distinct PES sites pose to the ES of interest. [Eq. (195), Eq. (196)]                                 |
| $V_j$                          | Variable     | Denotes the variances in the individual Probability of fatality (pair) that distinct PES sites pose to the ES of interest. [Eq. (196)]                                            |
| $W/V$                          | Variable     | “Weight to Volume ratio”. An array value indexed by PES component. [Eq. (114)]                                                                                                    |
| $W_1$                          | Variable     | “Yield of the event” (lbs). [Eq. (15), Eq. (16), Eq. (18), Eq. (19), Eq. (24), Eq. (25), Eq. (98), Eq. (103), Eq. (162)]                                                          |
| $W_2$                          | Variable     | “Equivalent NEW” (lbs). [Eq. (15), Eq. (111), Eq. (112), Eq. (114), Eq. (115), Eq. (119), Eq. (121), Eq. (167)]                                                                   |
| $W_a$                          | Variable     | “Adjusted Weight” (lbs). [Eq. (24), Eq. (25), Eq. (26), Eq. (33), Eq. (34), Eq. (65), Eq. (82), Eq. (87), Eq. (163)]                                                              |
| $X$                            | Variable     | Natural log of the hazard factor. [Eq. (17), Eq. (19), Eq. (25)]                                                                                                                  |
| $X_1$                          | Variable     | In SCIFM Technical Memo, the distance at which the plateau region ends and the transition region begins.                                                                          |
| $X_2$                          | Variable     | In SCIFM Technical Memo, the distance at which the transition region ends and the regular SAFER algorithms apply.                                                                 |
| $X_a$                          | Variable     | Natural log of the adjusted hazard factor. [Eq. (27)]                                                                                                                             |
| $X_o$                          | Variable     | Natural log of the effective hazard factor. [Eq. (21), Eq. (23), Eq. (27), Eq. (28), Eq. (29)]                                                                                    |
| $Y$                            | Variable     | “Effective Yield”. [Eq. (18), Eq. (19), Eq. (20), Eq. (23)]                                                                                                                       |
| $Y_0$                          | Stored Value | “Initial Breakout Value”. Value at which a PES will begin to damage. [Table A-6, Table A-7, Table A-8, Table A-9, Table A-24, Table A-25, Table A-26, Table A-27, Eq. (111)]      |
| $Y_{100}$                      | Stored Value | “Total Destruction Value”. Value at which PES is 100% damaged. [Table A-6, Table A-7, Table A-8, Table A-9, Table A-24, Table A-25, Table A-26, Table A-27, Eq. (111), Eq. (112)] |

| Term                       | Type         | Variable Name/Explanation                                                                                                                                                                                                                                                                       |
|----------------------------|--------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| $Y_a$                      | Variable     | “Actual Yield”. [Eq. (63), Eq. (64), Eq. (65), Eq. (68), Eq. (69), Eq. (70), Eq. (73), Eq. (74), Eq. (75)]                                                                                                                                                                                      |
| $Yield$                    | Variable     | The percentage of the material contributing energy to the event. [Eq. (173)]                                                                                                                                                                                                                    |
| $Yield Adjustment$         | Variable     | Factor used to calculate the Probability of a major injury given that the person is in the glass hazard area ( $P_{base}$ ). [Eq. (62), Eq. (67)]                                                                                                                                               |
| $Y_n$                      | Constant     | “Nominal Yield”. [Eq. (63), Eq. (64), Eq. (65)]                                                                                                                                                                                                                                                 |
| $Y_R$                      | Variable     | Ratio of the equivalent NEW ( $W_2$ ) to the total destruction value ( $Y_{100}$ ). [Eq. (112)]                                                                                                                                                                                                 |
| $Z$                        | Variable     | “Hazard Factor”. [Eq. (16), Eq. (17)]                                                                                                                                                                                                                                                           |
| $Z_a$                      | Variable     | “Adjusted Hazard Factor”. [Eq. (26), Eq. (27)]                                                                                                                                                                                                                                                  |
|                            | Variable     | “Adjusted Scaled Distance” (ft). [Eq. (79), Eq. (81), Eq. (86)]                                                                                                                                                                                                                                 |
| $Z_{bd}$                   | Variable     | Parameter used to calculate the Probability of fatality due to body displacement ( $P_{fbd}$ ). [Eq. (49)]                                                                                                                                                                                      |
| $Z_{lr}$                   | Variable     | Parameter used to calculate the Probability of fatality due to lung rupture ( $P_{flr}$ ). [Eq. (45)]                                                                                                                                                                                           |
| $Z_o$                      | Variable     | “Effective Hazard Factor”. [Eq. (20), Eq. (21), Eq. (27)]                                                                                                                                                                                                                                       |
| $Z_{sf}$                   | Variable     | Parameter used to calculate the Probability of fatality due to skull fracture ( $P_{f(sf)}$ ). [Eq. (53)]                                                                                                                                                                                       |
| $Z_t$                      | Variable     | “Nominal Thermal Hazard Factor”. [Eq. (162), Eq. (164)]                                                                                                                                                                                                                                         |
| $Z_{ta}$                   | Variable     | “Adjusted Thermal Hazard Factor”. [Eq. (161), Eq. (164)]                                                                                                                                                                                                                                        |
| $\Delta KE_n$              | Stored Value | Parameter used to calculate kinetic energy adjustment ( $KE_a$ ). [Table 29, Table 30, Eq. (139), Eq. (148), Eq. (150), Eq. (151)]                                                                                                                                                              |
| $\Delta t$                 | User Input   | Percentage of time that personnel in an ES are exposed to a PES when explosives are present. [Eq. (5), Eq. (8), Eq. (9), Eq. (10), Eq. (12), Eq. (173), Eq. (187)]                                                                                                                              |
| $\Delta t_{people\ group}$ | Variable     | Parameter used to calculate group risk at an ES. [Eq. (6), Eq. (7), Eq. (8), Eq. (10), Eq. (11)]                                                                                                                                                                                                |
| $\Delta t_o$               | Variable     | Median of the lognormal distribution representing the percentage of time when explosives are present at the PES that exposures are present at the ES. [Eq. (9), Eq. (187)]                                                                                                                      |
| $\Delta t_o\ Group$        | Variable     | Parameter used for computing group risk at an ES. [Eq. (7), Eq. (188), Eq. (190)]                                                                                                                                                                                                               |
| $\Delta t_o\ Individual$   | Variable     | Used for computing individual risk at an ES, the maximum $\{\Delta t_{people\ group}$ : across all people groups at the ES}. [Eq. (8), Eq. (189), Eq. (190)]                                                                                                                                    |
| $\delta_{e1}$              | Variable     | Lognormal multiplicative factor describing the random variation (aleatory uncertainty) in the Probability of an explosive event during a given year based on the type of explosives present and the activity performed at the explosives site ( $\lambda$ ) due to exposure. Section 4.6.2.2.5. |

| Term            | Type         | Variable Name/Explanation                                                                                                                                                                                                                                                                           |
|-----------------|--------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| $\delta_k$      | Variable     | The random variation (aleatory uncertainty) in Probability given and event ( $P_{fle}$ ) due to effect $k$ . Section 4.6.2.2.13.                                                                                                                                                                    |
| $\delta_{ko}$   | Variable     | The epistemic uncertainty associated with evaluating the median value of the Probability of fatality given the event ( $P_{fle}$ ) due to effect $k$ . Section 4.6.2.2.13.                                                                                                                          |
| $\delta_o$      | Variable     | Multiplicative factor describing the epistemic uncertainty in the median number of explosive events per “typical” operating year at a given activity/facility. Section 4.6.2.2.3.                                                                                                                   |
| $\delta_{NEW1}$ | Variable     | Multiplicative factor describing the random variation (aleatory uncertainty) in the Probability of an explosive event during a given year based on the type of explosives present and the activity performed at the explosives site ( $\lambda$ ) due to NEW. Section 4.6.2.2.11.                   |
| $\delta_{NEW2}$ | Variable     | Multiplicative factor describing the random variation (aleatory uncertainty) in Probability of fatality given the event ( $P_{fle}$ ) due to NEW. Section 4.6.2.2.12.                                                                                                                               |
| $\delta_y$      | Variable     | Multiplicative factor describing the random variation (aleatory uncertainty) in the <i>Yield</i> . [Eq. (184)]                                                                                                                                                                                      |
| $\delta_{yo}$   | Variable     | Multiplicative factor describing the epistemic uncertainty in the <i>Yield</i> . Section 4.6.2.2.9.                                                                                                                                                                                                 |
| $\lambda$       | Variable     | The Probability of an explosive event during a given year based on the type of explosives present and the activity performed at the explosives site, also referred to as the Probability that an explosive event will occur per Potential Explosion Site per year ( $P_e$ ). [Eq. (173), Eq. (186)] |
| $\lambda_o$     | Variable     | Un-scaled value of the probability that an explosive event will occur per Potential Explosion Site per year. [Eq. (188), Eq. (189), Eq. (190), Eq. (191)]                                                                                                                                           |
| $\lambda_{oo}$  | Variable     | The median of the lognormal multiplicative factor that describes the epistemic uncertainty in the median number of explosive events per typical operating year at a given activity/facility ( $\delta_o$ ). [Table 38, Eq. (175), Eq. (186)]                                                        |
| $\mu$           | Variable     | The mean of the linear normal distribution associated with a log-normal risk distribution. Section 5.0.                                                                                                                                                                                             |
| $\rho_{Ae}$     | Variable     | The coefficient of correlation between PES activity and Exposure. [Eq. (176)]                                                                                                                                                                                                                       |
| $\rho_{Ne}$     | Stored Value | The coefficient of correlation between <i>NEW</i> and <i>Exposure</i> . [Table 41.]                                                                                                                                                                                                                 |
| $\sigma$        | Variable     | Standard deviation that characterizes the spread or dispersion of factor values in log space.<br>An array value indexed by mass bin. [Eq. (127), Eq. (128), Eq. (182), Eq. (183)]                                                                                                                   |

| Term                                   | Type     | Variable Name/Explanation                                                                                                                                                                                                                                                                                              |
|----------------------------------------|----------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| $\sigma_{\Delta t}$                    | Variable | Standard deviation of the lognormal distribution representing the percentage of time when explosives are present at the site that exposures are also present ( $\Delta t$ ). [Eq. (9), Eq. (187)]                                                                                                                      |
| $\sigma_{\Delta t \text{ Group}}$      | Variable | Standard deviation of the lognormal distribution representing the percentage of time when explosives are present at the site that exposures are also present for a group. [Eq. (188), Eq. (190)]                                                                                                                       |
| $\sigma_{\Delta t \text{ individual}}$ | Variable | Standard deviation of the lognormal distribution representing the percentage of time when explosives are present at the site that exposures are also present for an individual. [Eq. (189), Eq. (191)]                                                                                                                 |
| $\sigma_{\lambda}$                     | Variable | The standard deviation of the Probability of an explosive event during a given year based on the type of explosives present and the activity performed at the explosives site. [Eq. (186), Eq. (188), Eq. (189), Eq. (190), Eq. (191)]                                                                                 |
| $\sigma_{\lambda o}$                   | Variable | The standard deviation of the lognormal factor that describes the epistemic uncertainty in the median number of explosive events per typical operating year at a given activity/facility ( $\delta_o$ ). [Eq. (175)]                                                                                                   |
| $\sigma_e$                             | Variable | Standard deviation of the lognormal distribution representing the median number of daily exposures ( $E_o$ ). [Eq. (176), Eq. (187)]                                                                                                                                                                                   |
| $\sigma_{FT}$                          | Variable | Parameter used to calculate debris probability densities at the ES. [Eq. (129)]                                                                                                                                                                                                                                        |
| $\sigma_e \text{ Group}$               | Variable | Standard deviation of the lognormal distribution representing the median number of daily exposures ( $E_o$ ) for the group. [Eq. (13), Eq. (188), Eq. (190)]                                                                                                                                                           |
| $\sigma_e \text{ Individual}$          | Variable | Standard deviation of the lognormal distribution representing the median number of daily exposures ( $E_o$ ) for the individual. [Eq. (14), Eq. (189), Eq. (191)]                                                                                                                                                      |
| $\sigma_{e1}$                          | Variable | Standard deviation of the lognormal multiplicative factor describing the random variation (aleatory uncertainty) in the Probability of an explosive event during a given year based on the type of explosives present and the activity performed at the explosives site ( $\delta_{e1}$ ) due to exposure. [Eq. (176)] |
| $\sigma_{Eo}$                          | Variable | Standard deviation of the lognormal distribution of the epistemic uncertainty associated with the median number of daily exposures ( $E_o$ ). [Eq. (177)]                                                                                                                                                              |
| $\sigma_k$                             | Variable | The standard deviation of the lognormal distribution of the random variation (aleatory uncertainty) in the Probability of fatality given the event ( $P_{fle}$ ) due to effect $k$ ( $\delta_k$ ). Section 4.6.2.2.13.                                                                                                 |
| $\sigma_{ko}$                          | Variable | The standard deviation of the lognormal distribution of the epistemic uncertainty associated with evaluating the median value of the Probability of fatality given the event ( $P_{fle}$ ) due to effect $k$ ( $\delta_{ko}$ ). Section 4.6.2.2.13                                                                     |

| <b>Term</b>                         | <b>Type</b> | <b>Variable Name/Explanation</b>                                                                                                                                                                                                                                                                                                           |
|-------------------------------------|-------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| $\sigma_{NEW1}$                     | Variable    | The standard deviation of the multiplicative factor describing the random variation (aleatory uncertainty) in the Probability of an explosive event during a given year based on the type of explosives present and the activity performed at the explosives site ( $\lambda$ ) due to <i>NEW</i> ( $\delta_{NEW1}$ ). Section 4.6.2.2.11. |
| $\sigma_{NEW2}$                     | Variable    | The standard deviation of the multiplicative factor describing the random variation (aleatory uncertainty) in the Probability of fatality given an event ( $P_{fle}$ ) due to <i>NEW</i> ( $\delta_{NEW2}$ ). [Eq. (181)]                                                                                                                  |
| $\sigma_S$                          | Variable    | The standard deviation of the lognormal distribution representing the Probability of event environmental factor(S) that addresses the increase in risk due to extenuating circumstances. [Eq. (174), Eq. (186), Eq. (188), Eq. (189), Eq. (190), Eq. (191)]                                                                                |
| $\sigma_{value\ of\ extreme\ data}$ | Set Value   | Parameter used to calculate the standard deviation of departing debris. [Eq. (127)]                                                                                                                                                                                                                                                        |
| $\sigma_y$                          | Variable    | The standard deviation of the lognormal distribution of the multiplicative factor describing the random variation (aleatory uncertainty) in the <i>Yield</i> ( $\delta_y$ ). [Eq. (178), Eq. (179), Eq. (180), Eq. (184)]                                                                                                                  |
| $\sigma_{y0}$                       | Variable    | The standard deviation of the lognormal distribution of the multiplicative factor describing the epistemic uncertainty in yield( $\delta_{y0}$ ). [Eq. (179), (180)]                                                                                                                                                                       |

## ***Definitions***

One of the largest difficulties in risk analyses is clear communications. Often words have many meanings leading to misunderstandings. In this document the definitions below are used.

**Accident** – That occurrence in a sequence of events that usually produces unintended injury, death or property damage.

**Expected Fatalities** – The expected number of individuals who will be fatalities from an unexpected event in a year. This risk is expressed with the following notation:  $1\text{E-}7 = 10^{-7} = 1$  fatality in ten million person years.

**Exposure** – The time per year an individual is exposed to the potential explosives event.

**Group** – The total number of people

- (1) A group of people in an ES with the same exposure information
- (2) All of the people in an ES
- (3) All of the people in all ESs exposed to significant individual risk from a PES
- (4) All of the people in all ESs exposed to significant individual risk from any PES
- (5) Related Group – All individuals in ESs exposed to significant individual risk from a PES to which they are related
- (6) Unrelated Group – All individuals in ESs exposed to significant individual risk from a PES to which they are unrelated

**Group Risk** – Sum of all significant individual risks within a group

- (1) Related Group Risk – Sum of all related individual risks in the group
- (2) Unrelated Group Risk – Sum of all unrelated individual risks in the group
- (3) Worker Group Risk – Sum of all work individual risks in the group

**Hazard** – Any real or potential condition that can cause injury, illness, or death of personnel, or damage to or loss of equipment or property.

**Individual Risk** – The risk to an individual

- (1) The risk to any particular individual, either a worker, related person, or a member of the public. A member of the public can be defined as anyone not related to the explosives mission at the installation.
- (2) The sum of the individual risks to an individual in an exposed site from all PESs presents significant risk to the individual ( $\geq 1 \times 10^{-8}$ ).
- (3) (3) Related Individual Risk – Sum of all significant risks to an individual in an ES from all PESs to which they are related
- (4) Unrelated Individual Risk – Sum of all significant risks to an individual in an ES from all PESs to which they are unrelated

**Inhabited Building Distance (IBD)** – Distance to be maintained between a PES and an inhabited building as defined by QD.

**K factor** - Hazard factor or scaled range.

**Probability of fatality** – The likelihood that an individual person will die from an unexpected event.

**Risk** – A measure that takes into consideration both the probability of occurrence and the consequence of a hazard. Risk is measured in the same units as the consequence such as number of injuries, fatalities, or dollar loss.

**Risk analysis** – A detailed examination including risk assessment, risk evaluation, and risk management alternatives, performed to understand the nature of unwanted, negative consequences to human life, health, property, or the environment; an analytical process to provide information regarding undesirable events; the process of quantification of the probabilities and expected consequences for identified risks.

**Risk assessment** – The process of establishing information regarding acceptable levels of a risk and/or levels of risk for an individual, group, society, or the environment.

**Risk-Based Evaluation Distance** – Distance from a PES within which all exposed sites must be evaluated. Determined by selecting the greater of Inhabited Building Distance or the SAFER Calculated Distance.

**Risk evaluation** – A component of risk assessment in which judgments are made about the significance and acceptability of risk.

**SAFER Calculated Distance (SCD)** – Distance from a PES at which the individual risk for a person in the open is  $1 \times 10^{-8}$  (the explosives at the PES are assumed to be the baseline Hazard Division (HD)).

**Safety** – Relative protection from adverse consequences. In this context,  $\text{Safety} = 1 - \text{Risk}$ .

**Scenario** – In the SAFER context, a scenario is a set of conditions that are under evaluation. In a scenario, conditions are not static.

**Significant Individual Risk** – Risk inside the Risk-based evaluation distance

**Situation** – In the SAFER context, a situation is the set of static conditions that are under evaluation similar to a scenario. Static refers to the period of time under evaluation (i.e. 1 year for SAFER).



## **1.0 INTRODUCTION**

### **1.1 Purpose**

The purpose of this technical paper is to present the underlying logic and algorithms used in risk-based explosives safety analyses as implemented in the Safety Assessment for Explosives Risk (SAFER) Version 3.1 tool.

### **1.2 Scope**

The methodology as described herein applies to risk-based explosives safety analysis, as implemented in the SAFER Version 3.1 tool.

### **1.3 Applicability**

The SAFER Version 3.1 tool may be used for risk-based explosives safety siting as allowed by the Department of Defense Explosives Safety Board (DDESB). The tool may also be used for risk management purposes.

### **1.4 Background**

Quantity-Distance (QD) criteria have been used as the primary means for the safe siting of facilities for more than 70 years. QD criteria consider only explosives quantity, Hazard Division (HD), and facility type to determine a safe separation distance. During the past 30 years, safety professionals have recognized that QD could be improved by considering other factors in the safety analyses to include type of activity, number of people, building construction, and environment to assess the overall risk of an operation.

The DDESB recognized the need to develop a risk-based approach for explosives safety analysis. In 1997, the DDESB chartered the Risk-Based Explosives Safety Criteria Team (RBESCT) to develop such an approach. The result of this effort was the SAFER tool. In 1999, the DDESB approved SAFER for use in DoD safety analyses on a trial basis through 2002.

The RBESCT delivered SAFER Version 1.0 in May 2000. This software allowed the safety professionals to perform their own risk-based explosives analyses. Based on improvements identified during the development of SAFER Version 1.0, the RBESCT sought to produce a follow-on version. SAFER Version 2.0 was approved for distribution in May 2002 on an extended trial basis through December 2004; the trial period was later extended until such time as risk-based explosives siting criteria is incorporated into DoD 6055.09-STD. The trial period ended when SAFER Version 3.0 was approved on May 22, 2007. SAFER Version 3.1 was issued in July 2009. The methods described in this paper were developed by the RBESCT for the SAFER Version 3.1 tool.

| Software Version  | Publication Date of Technical Paper #14 |
|-------------------|-----------------------------------------|
| SAFER Version 1.0 | February 2000                           |
| SAFER Version 2.0 | May 2002                                |
| SAFER Version 2.1 | September 2003                          |
| SAFER Version 3.0 | February 2007                           |
| SAFER Version 3.1 | July 2009                               |

**Table 1. SAFER Publication Dates**

## 1.5 Related Reading

This document contains the description of SAFER Version 3.1 algorithms. As such, it makes no attempt to describe the background or rationale why certain approaches were selected. That related material is contained in other documentation that includes:

- Minutes of the RBESCT. Over 60 team meetings were held as part of the SAFER development process. Meeting minutes are available from team members in hard copy only. (They are currently being documented on CD). These minutes are used as references for a variety of purposes.
- Technical Memoranda and Reports prepared by the RBESCT and A-P-T Research, Inc. document the rationale for key decisions made as part of the development process. The memoranda have been included as attachments to this Technical Paper. These Memoranda and Reports provide referenceable sources explaining why certain decisions were made.
- Published papers relating to specific aspects of the software or criteria development. Numerous aspects of the development have been documented in published papers listed in the bibliography.
- The NATO manual on Risk Analysis (AASTP-4), which contains significant material on the methods used by participating nations for conducting explosives safety risk analysis (Ref 1). The risk-based methodology used in SAFER is summarized in AASTP-4.

## 1.6 Major Modifications in SAFER Version 3.1

The major modifications between SAFER Version 3.1 and previous versions include:

### *Graphical User Interface (GUI)/Integration Changes:*

- Corrected an error that occurs when there is a very small exposure,
- Revised the confidence values associated with “somewhat confident” and “uncertain” exposures,
- Increased the NEWQD allowed for ships from 5M lbs to 15M lbs,
- Revised the roof and walls names and defaults associated with each ES type, and
- Numerous modifications to the validation flags.

### *Science Algorithm Changes:*

- Modified the method of splitting the primary fragments into high-angle, fly-through, and side-impact fragments,
- Incorporated new kinetic energy values for some roof types, and
- Updated TNT conversion factors for some weapon types.

## 2.0 ANALYSIS METHODOLOGY

### 2.1 Origin and Overview

The general method adopted for use in the SAFER model is one that has origins in the 1600s and has been used since in a variety of forms worldwide. In 1662, the French mathematician Blaise Pascal wrote (Ref 2):

*“Our fear of harm ought be proportional not only to the magnitude of the harm, but also the probability of the event.”*

This provides the most basic formulation for risk:

$$Risk = Likelihood * Consequences \quad (1)$$

This basic equation serves as the mathematical origin of many specific risk equations that can be derived directly from the same source. Two such equations are used by SAFER. They both originate from this equation:

$$Risk = Likelihood * Consequences * Exposure \quad (2)$$

Equation (2) is a direct derivative of Pascal's equation where the likelihood of an explosives event is expressed in terms of a probability, and undesired consequences are expressed in terms of the probability of fatality given the presence of people. The basis of selecting fatality as the measure is described in Ref 3.

SAFER uses this basic formulation to calculate the product of three components to estimate the annual probability of fatality,  $P_f$ , as shown in the following equation:

$$Risk = P_f = P_e * P_{f|e} * E_p \quad (3)$$

The  $P_e$  is defined as the probability that an explosives event will occur at the Potential Explosion Site (PES) per year. The  $P_{f|e}$  is defined as the probability of fatality given an explosives event and the presence of a person.  $E_p$  is defined as the exposure of one person to a particular PES on an annual basis.

A second measure is associated with group risk: expected fatalities,  $E_f$ . This is defined as the summation of individual risks and provides an expectancy or expected value (i.e. the average number of fatalities expected per year) as shown:

$$E_f = \sum_n (P_e * P_{f|e} * E_p) \quad (4)$$

In Sections 2.2 to 2.4 each of the three terms of the risk equations (3) and (4) above are described.

The above steps describe the generic risk equation. The risk equation used by SAFER including uncertainty is described in Eq. (173).

### 2.2 Event Analysis

The first term of the risk equation is the probability of event,  $P_e$ . This term is used to assess the likelihood that an explosives event occurs. To incorporate the  $P_e$  into SAFER, a  $P_e$  matrix was

developed using a compilation of historical explosives accident data from the U.S. Army, Navy, Air Force, and Marine Corps. The rationale used to develop the  $P_e$  matrix is documented in Ref 4.

The value of  $P_e$  in the matrix is a function of three parameters:

- Activity at the PES (activity type)
- Storage Compatibility Group (CG)

In addition, environmental factors are used to scale the  $P_e$  when warranted by conditions assessed to increase the probability of an event.

Each of these parameters is described in Section 4.1.2.

## 2.3 Effects Analysis

The second term of the risk equation is the probability of fatality given the event occurs and a person is present,  $P_{fle}$ .  $P_{fle}$  is determined by combining the potentially fatal effects of impulse and overpressure, building collapse, window breakage, debris (fragments from the explosives casing, building debris, and crater ejecta), and thermal effects. These potential fatality mechanisms are analyzed in parallel within the SAFER tool and are grouped into four branches of sequential steps.

Branch 1 – Pressure and Impulse. The explosion produces a blast wave described by pressure and impulse. Pressure-impulse is defined using Kingery-Bulmash equations and the algorithms from the Blast Effects Computer (Refs 5, 6). The effects are followed in sequence from the event through breakup of the PES to impingement on the exposed site (ES) and finally to the exposed person(s) as detailed in Section 4.2.

Branch 2 – Structural Response. The pressure and impulse impinging on the ES from Branch 1 provides the input for Branch 2. Two consequences are assessed here: building collapse and broken windows (flying glass). Each effect is treated as an independent source of injury or fatality as detailed in Section 4.3.

Branch 3 – Debris. The debris branch combines flying debris from three sources into a single table of debris density as a function of Kinetic Energy (KE). Lethality from this debris is then evaluated using the protocol previously developed by the Range Commanders Council (Ref 7). To accomplish this, primary debris (from the explosive item), secondary debris (from the PES), and ejecta (from the crater) are each evaluated. The details of this approach are in Section 4.4. The debris from the ES are evaluated in Branch 2.

Branch 4 – Thermal. The thermal branch is only used for Hazard Division (HD) 1.3 explosives (mass fire). Thermal effects are evaluated using a methodology presented in Attachment 1. The detailed algorithms are described in Section 4.5.

## 2.4 Exposure Analysis

Exposure is the last major factor in the risk equation. The units for exposure are person years per year or simply *people*. Individual exposure is measured as the probability of a person being present when the event occurs (i.e., a number between 0 and 1).

The SAFER Risk model includes two random variables related to exposure:  $\Delta t$ , the percentage of time that personnel are exposed to the PES that the PES is actually operating (housing explosives) and  $E_o$ , the distribution used to estimate the daily number of Exposures. These two variables are represented by lognormal distributions defined by their medians and standard deviations. Section 4.1.3.2 describes how these parameters are calculated from the user input.

## 2.5 Conservatism in the Model

In the context of this paragraph conservatism means biasing an analysis toward safe sided (higher risk) answers.

Pascal argued that risk should be considered as a mathematical formulation without adding bias (Ref 2). This means that equal concern should be given to an event which happens once in a thousand years killing a thousand people and an event happening once a year killing one. It also means that conservatism should not be added out of fear of certain consequences or for any other reason. This Pascalian-based principal is in direct competition with the widely recognized and accepted principle to *err on the safe side*. Pascal's thinking recognized that if the risks originating from fundamentally different sources are to be compared, the comparison can best be done without any biases.

In recognition of these fundamentally different requirements, SAFER has adopted the Pascalian principle with the model design goal of *best estimate* with the pragmatic addendum that where no analytical basis exists conservative estimates will be used. This philosophy is foundational to many of the analytical approaches described in later sections.

Although the model design goal has been to develop best estimate methodologies, for risk-based site plans, a conservative approach is taken. When considering approval of a site plan, established criteria are compared to the best estimate of risk given two conservative assumptions: sited amount of explosives present and maximum yield.

## 3.0 SAFER TOOL OVERVIEW

This section provides an overview of the architecture of the SAFER tool. This architecture describes the organization of the methods executed by the tool to determine the risk from an explosives event.

The SAFER tool conducts a sequence of 26 steps to estimate the annual probability of fatality. These procedures are arranged in the architecture as presented in Figure 1. The architecture presented in Figure 1 is complicated. To facilitate discussion of the tool, the 26 steps are divided into six functional groups presented in Table 2, *Six Functional Groups*.

|         |             |                                                                                                                                                                             |
|---------|-------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Group 1 | Steps 1-4   | Situation Definition, Event and Exposure Analyses<br>Includes user inputs that describe the situation (PES and ES) and calculates $P_e$ , exposure, and yield               |
| Group 2 | Steps 5-8   | Pressure and Impulse Branch<br>Calculates the magnitude of the fatality mechanisms of pressure and impulse                                                                  |
| Group 3 | Steps 9-10  | Structural Response Branch<br>Calculates the magnitude of the fatality mechanisms of building collapse and broken windows (overall building damage)                         |
| Group 4 | Steps 11-18 | Debris Branch<br>Calculates the magnitude of the fatality mechanisms for multiple types of flying debris                                                                    |
| Group 5 | Steps 19-22 | Thermal Branch<br>Calculates the magnitude of the fatality mechanism heat for HD 1.3 scenarios only                                                                         |
| Group 6 | Steps 23-26 | Aggregation and Summation<br>Aggregates the total magnitude and risks of all fatality mechanisms, calculates the desired measures of risk, and assesses overall uncertainty |

**Table 2. Six Functional Groups**

Section 4.0 describes the detailed algorithms used in each of the 26 steps to calculate the risk. Section 5.0 describes the algorithms used in estimating the uncertainty in the risk.

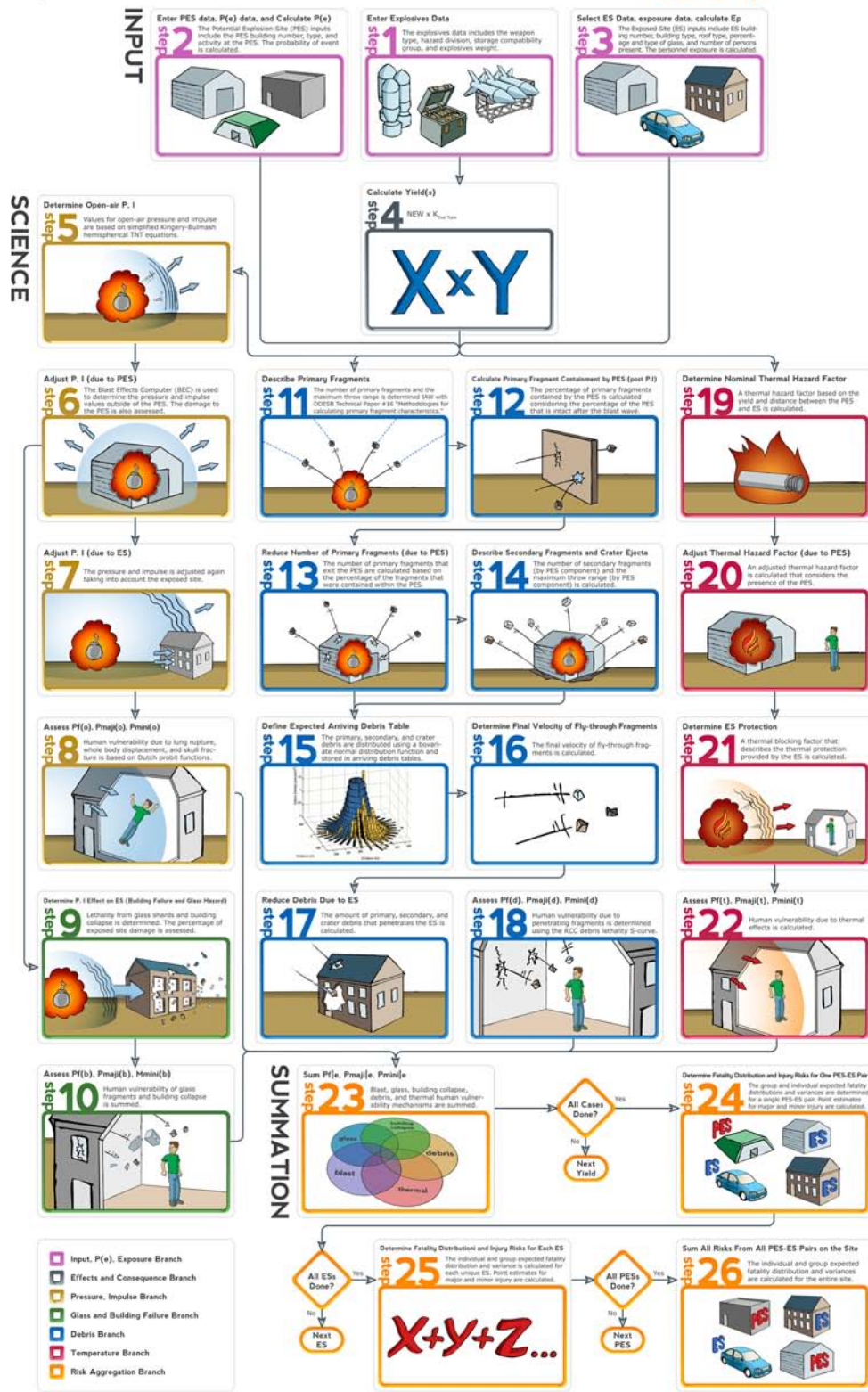


Figure 1. SAFER Version 3.1 Architecture

### 3.1 Close-In Fatality Mechanisms

In SAFER Version 1.0 the software was limited to distances at or beyond Public Traffic Route (PTR) distance. With each SAFER version, algorithms have been developed so the software would be applicable to distances closer to the PES. With SAFER Version 3.1, the software will calculate risk to the persons in the PES and exposed sites within close proximity of the PES.

The specific methodology for determining the probability of close-in fatality values will be discussed within the Step that each fatality mechanism is calculated in and Attachment 2 provides additional details. This section provides a top-level description of how the close-in fatality mechanisms are calculated.

SAFER Version 3.1 assumes that for distances in close proximity to the PES the probability of fatality will be equal to a fixed maximum value. This is defined as the “simplified close-in plateau” region. That distance has been defined for each of the fatality mechanisms and is described later in this paper in the step where the calculation occurs. Another distance has been defined for each of the fatality mechanisms where the RBESCT is confident in the results of the scientific algorithms. This is defined as the “normal” region. The region in between the “simplified close-in plateau” and the “normal” region is defined as the “transition” region. If the distance under evaluation is in the “transition” region, SAFER will interpolate between the “simplified close-in plateau” and the “normal” region to determine the resulting probability of fatality value. The three regions are shown in Figure 2.

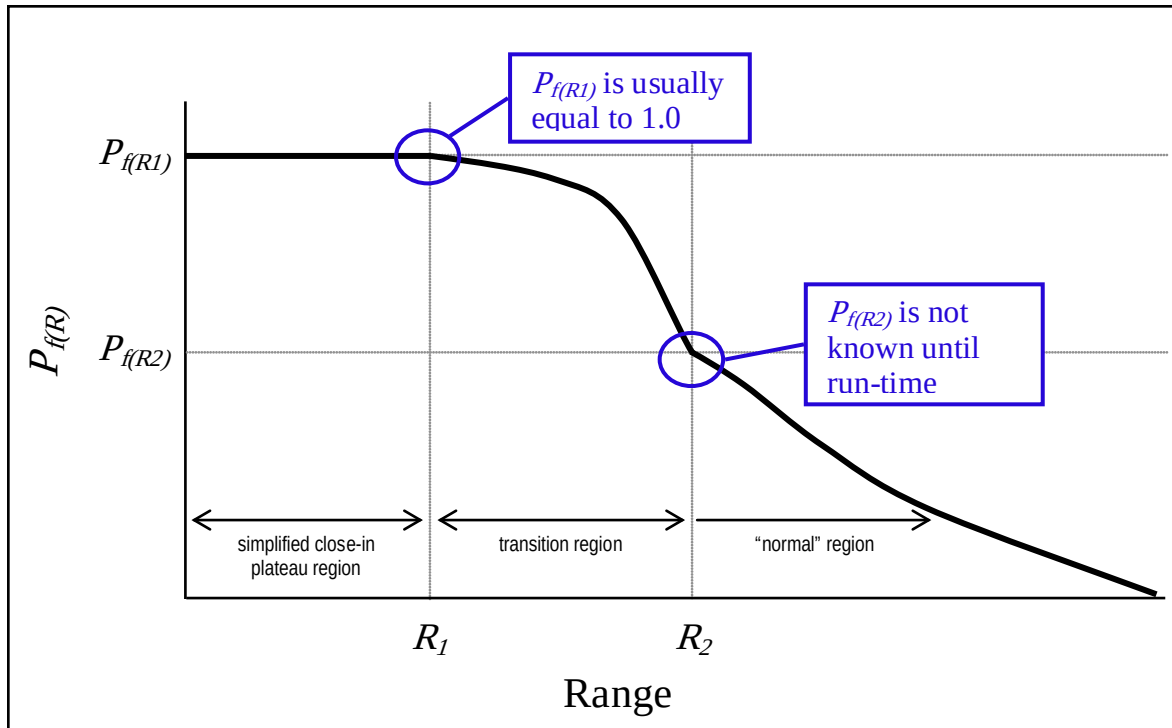


**Figure 2. Determination of  $P_{f(R)}$  Region**

The determination of the probability of fatality at range  $R$ ,  $P_{f(R)}$ , is based on the range (in terms of either scaled distance or simply distance, depending on the fatality mechanism) between the PES



and ES. In SAFER Version 3.1, the determination of  $P_{f(R)}$  is made by selecting which of the following three regions the range falls in:

1. the simplified “close-in” plateau region
2. the transition region (with new algorithms)
3. the “normal” region.

The appropriate region for determining  $P_{f(R)}$  is based on the range (either the hazard factor,  $Z$  [ft/lb<sup>1/3</sup>], or distance,  $d$  [ft]). The  $P_{f(R1)}$  is set to 100% for most fatality mechanisms, with glass fatality being the exception.  $P_{f(R2)}$  is the nominal SAFER Version 3.1  $P_{f(e)}$  at range =  $R_2$ .  $R_2$  is determined at run-time for each fatality mechanism.  $Z$  is calculated at run-time in Step 5 or 6, depending on the PES building type, or is calculated in Step 19 or 20 if the Hazard Division is 1.3.

The general algorithm for determining  $P_{f(R)}$  is described below.

If  $R$  (range) is less than the maximum plateau range,  $R_1$ ,  
     Then  $P_{f(R)} = P_{f(R1)}$   
     Where  $P_{f(R1)} = 1.0$ , except for the glass fatality mechanism, which is 0.1  
 Else If  $R$  (range) is greater than or equal to the minimum normal range,  $R_2$ ,  
     Then  $P_{f(R)} = P_{f(e)}$   
     Where  $P_{f(e)}$  = the nominal value calculated by SAFER Version 3.1  
 Else  $Z$  is within the transition region, so  $P_{f(R)}$  is calculated by:  

$$P_{f(R)} = P_{f(R1)} - [(R - R_1) / (R_2 - R_1)]^2 * (P_{f(R1)} - P_{f(R2)}) \quad (5)$$

The specific implementation of this general algorithm is described for each fatality mechanism in Section 4.0. Attachment 2 contains additional details.

## 4.0 DETAILS OF SAFER ARCHITECTURE

This section presents the logic and algorithms used in the SAFER Version 3.1 tool to determine risk due to an explosives event.

### 4.1 Group 1 Steps: Situation Definition, Event and Exposure Analyses

Group 1 includes Steps 1-4 of the SAFER architecture. These steps cause the user to input data describing the situation of interest – details about the PES and ES. Additionally, these steps perform event and exposure analyses to calculate  $P_e$  and exposure, the first and third terms of the risk equation. Finally, Step 4 calculates explosive yields that will be used in subsequent steps.

To enhance readability, selected reference tables of constants used in the Group 1 steps are located in Appendix A.

#### 4.1.1 STEP 1: Enter explosives data

Step 1 queries the user for information needed to begin the definition of the situation to be analyzed.

SAFER prompts the user to make the following inputs:

- Sited Net Explosives Weight QD (NEWQD) (lbs)
- Expected NEWQD (lbs)
- Hazard Division (HD) of explosives
- Weapon type or description

Table 3, *Weapon Descriptions*, presents the weapon types considered by SAFER. The table presents the weapons by Hazard Division and provides a short description of the weapons. Rationale for the selection and inclusion of the weapon types considered by SAFER is detailed in Attachment 3.

**Table 3. Weapon Descriptions**

| HD    | Weapon Type                                                     | Weapon Description                          |
|-------|-----------------------------------------------------------------|---------------------------------------------|
| 1.1   | MK82                                                            | Robust or thick-skinned bomb                |
|       | M107                                                            | Robust or thick-skinned 155-mm projectile   |
|       | Bulk/light case                                                 | Thin skinned                                |
|       | MK83                                                            | Robust or thick-skinned bomb                |
|       | MK84                                                            | Robust or thick-skinned bomb                |
|       | AIM-7                                                           | Fragmenting or thin-skinned missile warhead |
|       | Unknown (MK82)                                                  | Unknown (Robust or thick-skinned bomb)      |
| 1.2.1 | M1 105 mm projectile                                            | Robust or thick-skinned 105-mm projectile   |
| 1.2.2 | 40 mm projectile                                                | Robust or thick-skinned 40-mm projectile    |
| 1.2.3 | MK82 bomb – only 1 round detonates                              | Robust or thick-skinned bomb                |
| 1.3   | Bulk propellant                                                 | Bulk propellant                             |
| 1.4   | NA                                                              | NA                                          |
| 1.5   | Bulk/light case                                                 | Thin skinned                                |
| 1.6   | MK82 bomb – only 1 round detonates, consider only blast effects | Robust or thick-skinned bomb                |

SAFER does not perform an equivalent yield calculation for HD 1.4 items because the output for HD 1.4 cases is determined instead by definition; therefore, the calculation is not required.

HD 1.4 items are not evaluated in SAFER Version 3.1. The hazards associated with a PES containing solely HD 1.4 items are not considered life threatening. Injury algorithms have yet to be developed for HD 1.4 items.

Outputs of Step 1:

- Sited NEWQD (lbs)
- Expected NEWQD (lbs)
- Hazard Division
- Weapon type

#### **4.1.2 STEP 2: Enter PES data, $P_e$ data, and compute $P_e$ .**

Step 2 performs two functions in SAFER. In Step 2a, SAFER queries the user for information on the PES needed to define the situation. In Step 2b, SAFER calculates the probability of event,  $P_e$ .

#### 4.1.2.1 Step 2a: User Inputs for PES

A description of each of the user inputs is provided in the following paragraphs.

Input data includes:

- PES building identifier
- PES building category
- PES building type
- Number of people at the PES
- Soil type
- Compatibility Group (CG) of explosives
- Activity type
- Applicable environmental factors
- Inhabited Building Distance (IBD)
- PES Operating Hours, *PES Annual Operating Hrs*

##### 4.1.2.1.1 PES Building Identifier

The PES building identifier is the building name or number entered by the user. It is used for informational purposes only to identify the PES if multiple PESs are present in the situation.

##### 4.1.2.1.2 PES Building Categories

PES building categories are used as inputs for subsequent steps. The building categories considered by SAFER were selected by the RBESCT to represent the majority of the facilities containing explosives within DoD. The building categories considered by SAFER Version 3.1 include:

- Open
- Earth-Covered Magazine (ECM)
- Above-Ground Brick structure (AGBS)
- Pre-Engineered Metal Building (PEMB)
- Hollow clay tile
- Operating building (concrete)
- Hardened Aircraft Shelter (HAS)
- Ship
- ISO Container

Rationale for the selection and inclusion of the building categories considered by SAFER is detailed in Attachment 3.

##### 4.1.2.1.3 PES Building Types

PES building types are used to distinguish between size and construction type for certain building categories. The building types considered by SAFER Version 3.1 are shown in Table 4, *PES Building Categories and Types*.

**Table 4. PES Building Categories and Types**

| PES Building Category              | PES Building Types                                                                                                                                                                                                                           |
|------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Earth-covered magazine (ECM)       | <ul style="list-style-type: none"><li>• Small Concrete Arch ECM</li><li>• Medium Concrete Arch ECM</li><li>• Large Concrete Arch ECM</li><li>• Small Steel Arch ECM</li><li>• Medium Steel Arch ECM</li><li>• Large Steel Arch ECM</li></ul> |
| Aboveground Brick Structure (AGBS) | <ul style="list-style-type: none"><li>• Small AGBS (square)</li><li>• Medium AGBS</li><li>• Large AGBS</li></ul>                                                                                                                             |
| Operating Building (concrete)      | <ul style="list-style-type: none"><li>• Small Concrete Building</li><li>• Medium Concrete Building</li></ul>                                                                                                                                 |
| Ship                               | <ul style="list-style-type: none"><li>• Small Ship</li><li>• Medium Ship</li><li>• Large Ship</li></ul>                                                                                                                                      |

#### 4.1.2.1.4 Number of people at the PES

The user enters the number of people at the PES, the numbers of hours the people are present at the PES, and the percentage of time that people are present at the PES when explosives are present at the PES. These values are used to calculate the personnel exposure. Section 2.4 discusses inputs and calculations for exposure. The personnel at the PES are considered to be “workers” rather than “related” or “unrelated” personnel.

#### 4.1.2.1.5 Soil Type

The user enters the soil type around the PES. The soil types considered by SAFER include rock or hard clay, loose, and concrete soils.

#### 4.1.2.1.6 Activity Types

The activity type describes the primary operation that is performed at the PES. This input is used in determining the  $P_e$ . Historical data show that this factor can vary the  $P_e$  by up to four orders of magnitude.

The activity types considered by SAFER were selected by the RBESCT to represent the majority of the explosives activities within the DoD. The activity types considered by SAFER Version 3.1 include:

- Assembly
- Burning Ground
- Demilitarization
- Demolition
- Disassembly
- Disposal
- Inspection
- Lab
- Load-Assemble-Packout (LAP)
- Loading
- Unloading
- Maintenance
- Manufacturing
- Painting
- Packing
- Renovation
- Storage - Deep
- Storage - Temporary
- Storage - In Transit
- Test
- Training

Rationale for the selection and inclusion of the activity types considered by SAFER is detailed in Attachment 3.

#### 4.1.2.1.7 *Compatibility Groups*

The explosives storage Compatibility Groups (CG) are used to describe the types of explosives in the PES (see Chapter 3 in DoD 6055.09-STD for a description of the principle of hazard classification and Compatibility Groups) (Ref 8). This input is used in determining the  $P_e$ . This factor results in variations of  $P_e$  up to  $1\frac{1}{2}$  orders of magnitude. The Compatibility Groups are divided into three sets designated by Roman numerals in the matrix in Figure 3. Set one (I) contains Compatibility Groups *L*, *A*, *B*, *G*, *H*, *J*, and *F*; set two (II) contains *C*; and set three (III) contains *D*, *E*, and *N*.

If the CG is unknown, SAFER assigns a default CG of *D* to all Hazard Divisions except for HD 1.3 items. A CG of *C* is the default for HD 1.3 items.

Compatibility Groups *K* and *S* are not considered by SAFER. CG *K* is not considered because the predominant hazard from lethal chemical agents is toxicity and this is not addressed by SAFER. Compatibility Group *S* is not considered because it is assigned only to HD 1.4 items and there is no life-threatening hazard external to the shipping container.

#### 4.1.2.1.8 *Environmental Factors*

Environmental factors are used to increase the  $P_e$ . The environmental factors consist of a variety of environmental circumstances. The RBESCT selected environmental factors to represent conditions that increase the probability of an event occurring. Each activity type has a set of applicable environmental factors for that particular activity. If more than one environmental factor applies, only one adjustment is made using the factor with the highest adjustment. The applicable environmental factors for each activity are shown in the second column of the matrix in Figure 3.

The environmental factors were divided into two groups: Group A represents a large increase in the probability of event (a factor of 10) and Group B represents a smaller increase in the probability of event (a factor of 3).

#### 4.1.2.1.9 Inhabited Building Distance (IBD)

The user enters the Inhabited Building Distance. This is used to determine the Risk-Based Evaluation Distance.

#### 4.1.2.1.10 PES Operating Hours

The user enters the PES operating hours. This is the typical number of hours per year that the PES is expected to house explosives based on the activity selected by the user. This input is used to calculate personnel exposure. Typical operating hours are provided in Table 5, *Typical PES Annual Operating Hours*.

**Table 5. Typical PES Annual Operating Hours**

| Activity at PES             | Explosives Present at PES (hours) |
|-----------------------------|-----------------------------------|
| Assembly                    | 2080                              |
| Burning Ground              | 1560                              |
| Demilitarization            | 1560                              |
| Demolition                  | 1560                              |
| Disassembly                 | 2080                              |
| Disposal                    | 1560                              |
| Inspection                  | 2080                              |
| Lab                         | 2080                              |
| Load-Assemble-Packout (LAP) | 2080                              |
| Loading                     | 1560                              |
| Unloading                   | 1560                              |
| Maintenance                 | 1560                              |
| Manufacturing               | 6240                              |
| Painting                    | 1560                              |
| Packing                     | 1560                              |
| Renovation                  | 1560                              |
| Storage - Deep              | 8736                              |
| Storage - Temporary         | 8736                              |
| Storage - In Transit        | 8736                              |
| Test                        | 1560                              |
| Training                    | 2080                              |

#### 4.1.2.2 Step 2b: $P_e$ Determination

Based on the activity type, compatibility group, and environmental factors, SAFER determines the  $P_e$  using the  $P_e$  matrix shown in Figure 3. The  $P_e$  is determined for each PES in the situation.

To use the  $P_e$  matrix shown in Figure 3, the activity type and storage CG are used to determine the un-scaled  $P_e$ . The un-scaled  $P_e$  is then adjusted by applicable environmental factors, which results in the final  $P_e$ . Note that potential variations in both the unscaled  $P_e$  and the environmental factor are addressed in the uncertainty model.

| PES used primarily for:                             | Allowable Environmental Factors                | Probability of Event (PES-year) |         |         |
|-----------------------------------------------------|------------------------------------------------|---------------------------------|---------|---------|
|                                                     |                                                | I                               | II      | III     |
| Burning Ground/Demilitarization/Demolition/Disposal | A1, A2, A5, A6, B2, B4                         | 2.4E-02                         | 2.4E-03 | 8.1E-04 |
| Assembly/Disassembly/LAP/Maintenance/Renovation     | A1, A4, A5, A6, A8, B1, B2                     | 4.7E-03                         | 4.7E-04 | 1.6E-04 |
| Lab/Test/Training                                   | A1, A2, A3, A4, A5, A6, A7, A8, B1, B2, B3, B4 | 4.3E-03                         | 4.3E-04 | 1.4E-04 |
| Manufacturing                                       | A4, A5                                         | 1.7E-03                         | 1.7E-03 | 1.7E-03 |
| Inspection/Painting/Packing                         | A1, A2, A4, A6, A7, B1, B2, B4                 | 8.2E-04                         | 8.2E-05 | 2.7E-05 |
| Loading/Unloading                                   | A1, A2, A6, A7, B1, B2, B3, B4                 | 5.7E-04                         | 5.7E-05 | 1.9E-05 |
| In-Transit Storage (hrs – few days)                 | A1, A2, A6, A7, B1, B2, B4                     | 3.0E-04                         | 1.0E-04 | 3.3E-05 |
| Temporary Storage (1 day - 1 mth)                   | A1, A2, A6, A7, B1, B2, B4                     | 1.0E-04                         | 3.3E-05 | 1.1E-05 |
| Deep Storage (1 month - year)                       | A1, A2, B1                                     | 2.5E-05                         | 2.5E-05 | 2.5E-06 |

| Environmental Factors                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |                                                                                                                                                                                                                                                                                                                           |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <p>A. Increase <math>P_e</math> by a factor of 10 for:</p> <ol style="list-style-type: none"> <li>1. Outside Continental United States (OCONUS) operations in support of wartime actions</li> <li>2. Operations involving dangerously unserviceable items awaiting destruction</li> <li>3. Initial tests of new systems</li> <li>4. Operations occurring in hazardous environments with gases, fibers, etc.</li> <li>5. Required remote operations</li> <li>6. Temporary Duty (TDY) activities during exercises/contingencies/alerts</li> <li>7. Concurrent servicing operations, forward arming and refueling, hot arming and refueling or Integrated Combat Turn (ICT) operations</li> <li>8. Operations involving exposed explosives</li> </ol> | <p>B. Increase <math>P_e</math> by a factor of 3 for:</p> <ol style="list-style-type: none"> <li>1. Outdoor storage/operations normally done indoors</li> <li>2. Home station activities during exercises/contingencies/alert</li> <li>3. Flightline holding areas</li> <li>4. TDY operations during peacetime</li> </ol> |

| Elements | Compatibility Group |
|----------|---------------------|
| I        | L, A, B, G, H, J, F |
| II       | C                   |
| III      | D, E, N             |

Notes: The elements in the matrix are comprised of Compatibility Groups. Definitions of the Compatibility Groups can be found in DoD 6055.09-STD. <sup>Ref 5</sup>

**Figure 3.  $P_e$  Matrix.**

*This matrix is used to estimate the probability of an explosives event per PES-year.*

#### 4.1.2.2.1 Examples of Calculating $P_e$ Using the $P_e$ Matrix.

##### Example 1:

An assembly activity is performed at a PES on exposed explosives with a CG of D. The unscaled  $P_e$  is 1.6E-4. Since the operation involves exposed explosives environmental factor A8 applies. This would increase the un-scaled  $P_e$  by a factor of 10 and the final  $P_e$  would be 1.6E-3.

### Example 2:

An earth-covered magazine is used to store explosives during the year. The CG is A. The unscaled  $P_e$  is 2.5E-5. None of the environmental factors are applicable, so the final  $P_e$  is also 2.5E-5.

### Outputs of Step 2:

- PES building identifier
- PES building category
- PES building type
- Number of people at the PES
- Soil type
- Activity type
- Inhabited Building Distance (IBD)
- PES Operating Hours, *PES Annual Operating Hours*
- Compatibility Group (CG) of explosives
- Applicable environmental factors
- Probability of event,  $P_e$

### **4.1.3 STEP 3: Enter ES data, exposure data, and calculate exposure.**

Step 3 performs two functions in SAFER. In Step 3a, SAFER continues to query the user for information needed to further define the situation. In Step 3b, SAFER calculates the personnel exposure.

#### *4.1.3.1 Step 3a: User Inputs for ES*

A description of each of the user inputs is provided in the following paragraphs.

Input data includes:

- ES building identifier
- ES building category
- ES building type
- ES roof type
- Type of glass on the ES
- Percentage of glass on ES
- Floor area of ES
- Distance between the PES and ES
- Orientation of PES to ES
- Barricade information
- Number of people at the ES
- Relationship of personnel in ES to PES (Related or Unrelated/Public)
- Number of hours people are present at ES
- Percentage of time people are present in the ES when explosives are present in the PES



- Upper limit (largest number of people exposed at any time during year)

#### *ES Building, Roof, and Wall Types*

Table A-1, *Default ES Roof and Wall Types*, presents the ES building types considered by SAFER. The table presents building data by building category, building type, and associated default wall and roof types.

##### *4.1.3.1.1 ES Roof Types*

Table A-1, *Default ES Roof and Wall Types*, presents a default roof type that has been defined for each ES building type.

##### *4.1.3.1.2 Type of Glass on the ES*

SAFER queries the user to describe the type of glass present at the ES. Types of glass considered by SAFER Version 3.1 include:

- Annealed
- Dual-paned
- Tempered

##### *4.1.3.1.3 Percentage of Glass on the ES*

SAFER queries the user to identify the percentage of glass on all of the exterior walls of the ES (total glass area/total wall area),  $G_P$ . The range of acceptable values is 0% - 99%. If the ES is a vehicle, SAFER assumes there is no flying glass hazard, and sets the percentage of glass to 0%.

##### *4.1.3.1.4 Floor Area of the ES*

SAFER queries the user to enter the floor area of the ES in square feet,  $FA_{ES}$ .

##### *4.1.3.1.5 Orientation of the PES to the ES*

If the PES building category is either an earth-covered magazine (ECM) or a hardened aircraft shelter (HAS), SAFER queries the user to describe the orientation of the PES relative to the ES. Valid orientation choices considered by SAFER Version 3.1 include:

- Front
- Side
- Rear

##### *4.1.3.1.6 Distance between the PES and the ES*

SAFER queries the user to enter the distance,  $d$ , between the center of the PES and the center of the ES in feet.

##### *4.1.3.1.7 Exposure data at the ES*

SAFER queries the user to enter the number of people at the ES, the relationship of the people in the ES to the PES (related or public), the number of hours the people are present at the ES, and

the percentage of time that people are present at the ES when explosives are present at the PES. The user is also prompted to enter the largest number of persons exposed at any time during the year. The values are used to calculate the personnel exposure. Section 2.4 discusses inputs and calculations for exposure.

#### 4.1.3.1.8 ES Barricade Information

If an ES barricade is present, SAFER queries the user to enter the height of the barricade,  $h2$ , and the distance between the barricade and the exposed site,  $d1$ . Since the barricade is an ES barricade, the distance between the ES and the barricade must be less than the distance between the PES and the barricade (i.e., less than half the distance between the PES and the ES).

#### 4.1.3.2 Step 3b: Calculation of Personnel Exposure at the ES

Exposure data are entered for the Exposed Site (ES) in groups of one or more people having similar levels of exposure. The data needed for each group are the number of people present at the ES, the number of hours they are present during the year, and the percentage of that time that the PES is operating (housing explosives). The number of hours the PES operates in a typical year is also needed, but is implemented in SAFER as a lookup table (Table 5, *Typical PES Annual Operating Hours*) based on the activity type at the PES. An example exposure computation is shown in Section 4.1.3.2.3.

##### 4.1.3.2.1 $\Delta t$ , Fraction of PES Operating Year with Exposures

The lognormal statistical distribution  $\Delta t \sim \ln(\Delta t_o, \sigma_{\Delta t})$  is defined by its median,  $\Delta t_o$ , and its standard deviation,  $\sigma_{\Delta t}$ . This section provides the equations used to calculate these two parameters when computing both Group and Individual Risk.<sup>1</sup>

The  $\Delta t_o$  is first calculated for each group as:

$$\Delta t_{\text{people group}} = \text{AHrs at ES}_{\text{group}} * \% \text{ ES Hrs}_{\text{explosives}} / \text{PES Annual Operating Hrs} \quad (6)$$

where  $\text{AHrs at ES}_{\text{group}}$  is the number of hours per year that the group is at the ES,  $\% \text{ ES Hrs}_{\text{explosives}}$  is the percentage of the hours that the group spends at the ES that explosives are also present at the PES, and  $\text{PES Annual Operating Hrs}$  is the typical number of hours per year that the PES is expected to house explosives based on user input (from Step 2). The  $\Delta t_o$  used for computing Group Risk at the ES is then calculated as:

$$\Delta t_o \text{ Group} = \Sigma \Delta t_{\text{people group}} \quad (7)$$

and the  $\Delta t_o$  used for computing Individual Risk at the ES is:

$$\Delta t_o \text{ Individual} = \text{Maximum} \{ \Delta t_{\text{people group}} : \text{across all people groups at the ES} \} \quad (8)$$

The computation of  $\sigma_{\Delta t}$  assumes the possibility that exposure at the ES could exist at all times when explosives are housed at the PES. This assumption results in an Upper Limit of 1.0 for  $\Delta t$  that applies to both Group and Individual Risk computations. The equation used to compute  $\sigma_{\Delta t}$  is then:

---

<sup>1</sup> In this section, the Individual Risk is defined as the risks to an individual in an ES from a specific PES. The Group Risk is defined as the sum of all the individual risks in an ES from a specific PES.

$$\sigma_{\Delta t} = \ln(UB_{\Delta t} / \Delta t_o) / 6 = \ln(1.0 / \Delta t_o) / 6 \quad (9)$$

It should be noted that the value of  $\Delta t_o$  Group is not allowed to exceed 1.0. This value indicates that exposures are present at all times during the year when explosives are housed at the PES. People groups should be defined so that group exposure times do not overlap. If the user were to erroneously input people groups whose exposure times overlapped, scenarios could exist where the standard calculation of  $\Delta t_o$  Group results in values greater than 1.0. In these cases, SAFER resets the value to 1.0.

The parameters  $\Delta t_o$  and  $\sigma_{\Delta t}$  that define the lognormal distribution  $\Delta t \sim \ln(\Delta t_o, \sigma_{\Delta t})$ , have been defined. This distribution is used in the SAFER model of the world to compile the Risk Distribution.

#### 4.1.3.2.2 $E_o$ , Daily Exposures

The lognormal statistical distribution  $E_o \sim \ln(E_{oo}, \sigma_e)$  is defined by its median,  $E_{oo}$ , and its standard deviation,  $\sigma_e$ . This section provides the equations used to calculate these two parameters when computing both Group and Individual Risk.

The average daily number of exposures is first calculated for each people group as:

$$Exposure_{people\ group} = Number\ of\ People * \Delta t_{people\ group} \quad (10)$$

where,

$Number\ of\ People$  = the quantity of people input by the user for that group

$\Delta t_{people\ group}$  = the  $\Delta t_{people\ group}$  computed for that group as described in Section 4.1.3.2.1.

The  $E_{oo}$  used for computing group risk at the ES is then calculated as:

$$E_{oo\ Group} = \Sigma (Exposure_{people\ group}) / \Sigma (\Delta t_{people\ group}) \quad (11)$$

and the  $E_{oo}$  used for computing individual risk at the ES is:

$$E_{oo\ Individual} = 1.0 \text{ (by definition)} \quad (12)$$

The value of  $\sigma_e$  used to compute Group Risk is computed using the Upper Limit (UL) on the Number of People Exposed input by the user and the  $E_{oo}$  calculated. The equation used is:

$$\sigma_{e\ Group} = \ln(UL_{\Delta t} / E_{oo}) / 3 \quad (13)$$

The  $\sigma_e$  used to compute Individual Risk uses an Upper Limit of 1.0 resulting in:

$$\sigma_{e\ Individual} = \ln(1.0 / 1.0) / 3 = 0.0 \text{ (also by definition)} \quad (14)$$

#### 4.1.3.2.3 Exposure Example

In this example there are six groups of *public* personnel operating at the same ES shown in Table 6, *Exposure Example*. The groups have 10, 5, 6, 8, 9, and 5 people who are present 2080, 500, 350, 156, 750.5, and 654 hours per year respectively.

**Table 6. Exposure Example**

| People Group                | Number of People | Annual Hours at ES | % of ES Hours that PES has explosives | Annual Hours Exposed | PES Operating Hours | ES Exposure as % of Operating Year ( $\Delta t$ ) | Group Exposure per Operating Year |
|-----------------------------|------------------|--------------------|---------------------------------------|----------------------|---------------------|---------------------------------------------------|-----------------------------------|
| 1                           | 10               | 2080               | 50%                                   | 1040                 | 1560                | 0.667                                             | 6.667                             |
| 2                           | 5                | 500                | 10%                                   | 50                   | 1560                | 0.032                                             | 0.160                             |
| 3                           | 6                | 350                | 20%                                   | 70                   | 1560                | 0.045                                             | 0.269                             |
| 4                           | 8                | 156                | 10%                                   | 15.6                 | 1560                | 0.010                                             | 0.080                             |
| 5                           | 9                | 750.5              | 25%                                   | 187.625              | 1560                | 0.120                                             | 1.082                             |
| 6                           | 5                | 654                | 75%                                   | 490.5                | 1560                | 0.314                                             | 1.572                             |
| Total                       |                  |                    |                                       | 1853.7               | 1560                | 1.188                                             | 9.831                             |
| Maximum Individual Exposure |                  |                    |                                       |                      |                     | 0.667                                             |                                   |

The exposure for each people group is first determined by computing the  $\Delta t_{\text{people group}}$  and  $Exposure_{\text{people group}}$  for each group as described in sections 4.1.3.2.1 and 4.1.3.2.2 above. The four parameters that define the Exposure related distributions are then computed as:

For Group Risk:

$$\Delta t_{o \text{ Group}} = \sum \Delta t_{\text{people group}} = 1.188 \text{ which is reset to the maximum value of 1.000}$$

$$\sigma_{\Delta t} = \ln(UB_{\Delta t} / \Delta t_o) / 6 = \ln(1.0 / 1.0) / 6 = 0.000$$

$$E_{oo \text{ Group}} = \sum (Exposure_{\text{people group}}) / \sum (\Delta t_{\text{people group}}) = 9.831 / 1.000 = 9.831$$

and, assuming the user entered a value of 10 for the Upper Limit on the number of personnel present at the ES at any time, then

$$\sigma_{e \text{ Group}} = \ln(UL_{\Delta t} / E_{oo}) / 3 = \ln(10 / 9.83) / 3 = 5.7\text{E-}03$$

For Individual Risk:

$$\Delta t_{o \text{ Individual}} = \text{Maximum} \{ \Delta t_{\text{people group}} \} = 0.667$$

$$\sigma_{\Delta t \text{ Individual}} = \ln(UB_{\Delta t} / \Delta t_o) / 6 = \ln(1.0 / 0.667) / 6 = 6.76\text{E-}02$$

$$E_{oo \text{ Individual}} = 1.0 \text{ (by definition)}$$

$$\sigma_{e \text{ Individual}} = \ln(1.0 / 1.0) / 3 = 0.0 \text{ (also by definition)}$$

The parameters  $E_{oo}$  and  $\sigma_e$  that define the lognormal distribution  $E_o \sim \ln(E_{oo}, \sigma_e)$  have been determined. This distribution is used in the SAFER model of the world to compile the Risk Distribution.

Rationale for the selection of the SAFER input menus is detailed in Attachment 3.

Outputs of Step 3:

- ES building type
- ES roof type
- Type of glass on the ES
- Percentage of glass on the ES (%),  $G_P$

- Floor area of the ES (ft<sup>2</sup>),  $FA_{ES}$
- Orientation of the PES to the ES
- Barricade height,  $h_2$
- Distance between the barricade and the ES,  $d_1$
- Distance between the PES and ES (ft),  $d$
- Median,  $E_{oo}$ , and standard deviation,  $\sigma_e$ , of Exposure distribution

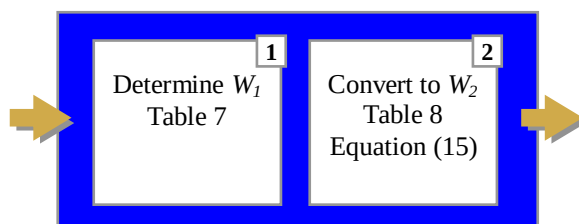
#### 4.1.4 STEP 4: Calculate yields.

Step 4 calculates explosives yield values that will be used in subsequent steps.

This process is performed twice, first for the sited NEWQD and second for the expected NEWQD using parameters in Table 7, *Determination of  $W_1$* , below.

Inputs to Step 4:

- NEWQD (lbs) [from Step 1], sited and expected NEWQD
- Hazard Division, HD [from Step 1]
- Weapon type [from Step 1]



Given the NEWQD, HD, and weapon type, calculate the yield<sup>2</sup> of the event,  $W_1$ , based on the instructions presented in Table 7, *Determination of  $W_1$* . Rationale for the instructions presented in Table 7, *Determination of  $W_1$* , is detailed in Attachment 3.

**Table 7. Determination of  $W_1$**

| Type  | Sited or Maximum Yield (NEWQD)                                       | Expected Yield (NEWQD)                                                     |
|-------|----------------------------------------------------------------------|----------------------------------------------------------------------------|
| 1.1   | 100% of NEWQD                                                        | 80% of NEWQD                                                               |
| 1.2.1 | Greater of:<br>50% of total NEWQD<br>OR<br>one M1-105 mm projectile  | Greater of:<br>3% of total NEWQD<br>OR<br>1s1% of one M1-105 mm projectile |
| 1.2.2 | Greater of:<br>50% of total NEWQD<br>OR<br>one MK 2 40 mm projectile | Greater of:<br>3% of total NEWQD<br>OR<br>11% of one MK 2 40 mm projectile |
| 1.2.3 | One item (MK82)                                                      | 11% of one item (MK82)                                                     |
| 1.3   | 100%                                                                 | 100%                                                                       |
| 1.5   | 100%                                                                 | 80%                                                                        |
| 1.6   | One item (MK82)                                                      | 11% of one item (MK82)                                                     |

Calculate the equivalent NEW,  $W_2$ , by:

$$W_2 = W_1 * TNT \text{ conversion factor} \quad (15)$$

<sup>2</sup> The terms “yield” and “weight” are mathematically equivalent throughout Section 4.0. The parameters are referred to by the term most appropriate for the context based upon common usage.

where the *TNT conversion factor* is taken from Table 8, *TNT Conversion Factors*, Rationale for explosive types and TNT conversion factors presented in Table 8, *TNT Conversion Factors*, is detailed in Attachment 3.

**Table 8. TNT Conversion Factors**

| Weapon Type          | Explosive Type | TNT Conversion Factor* |
|----------------------|----------------|------------------------|
| MK82                 | Tritonal       | 1.07                   |
| M107                 | Composition B  | 1.16                   |
| Bulk/light case      | TNT            | 1.0                    |
| MK83                 | Tritonal       | 1.07                   |
| MK84                 | Tritonal       | 1.07                   |
| AIM-7 Missile        | H-6            | 1.38                   |
| M1 105 mm projectile | Composition B  | 1.16                   |
| 40 mm projectile     | TNT            | 1.0                    |

Notes: \*assumes "TNT equivalence" does not vary with distance

\*\* A TNT conversion factor of 1.0 is applied to HD 1.3 (bulk propellant).

Outputs of Step 4:

- Yield of the event (lbs),  $W_1$
- Equivalent NEW (lbs),  $W_2$

#### 4.2 Group 2 Steps: Pressure and Impulse Branch

Group 2 includes Steps 5-8 of the SAFER architecture. These steps determine the effect of the fatality mechanisms of pressure and impulse. This branch applies to HD 1.1, 1.2.1, 1.2.2, 1.2.3, 1.5, and 1.6 scenarios.

Steps 5-7 calculate the pressures and impulses for the situation. Unmodified pressure and impulse values are calculated in Step 5. These values take into account only the effect of the weapon type – not the presence of a PES or an ES. Step 6 then adjusts the unmodified values to account for the PES, if a structure is present. A further adjustment is made due to the presence of an ES in Step 7.

Finally, Step 8 determines the probability of fatality due to the effects of pressure and impulse,  $P_{f(o)}$ . If no PES or ES is present in the situation, fatalities are based on pressure and impulse values determined in Step 5. If the situation includes a PES but no ES, fatalities are based on pressure and impulse values determined in Step 6. If the situation includes an ES, fatalities are based on pressure and impulse values determined in Step 7.

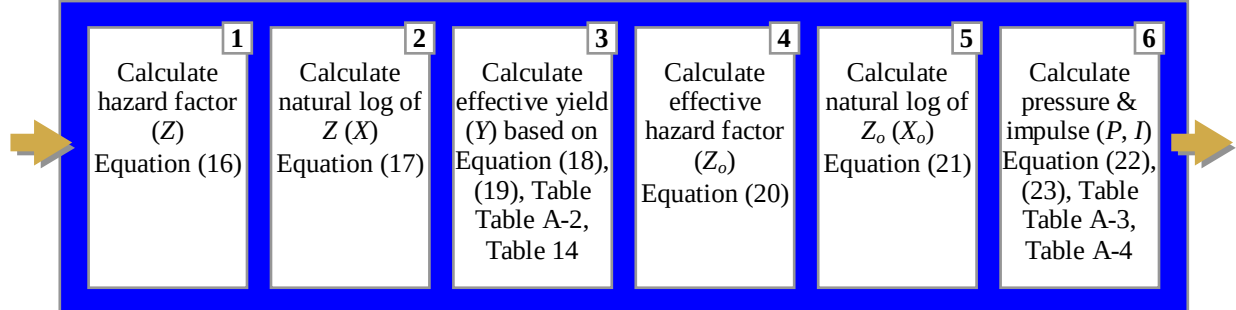
To enhance readability, selected reference tables of constants used in the Group 2 steps are located in Appendix A.

##### 4.2.1 STEP 5: Determine open-air Pressure, Impulse ( $P$ , $I$ ).

Step 5 calculates the unmodified, or open-air pressure,  $P$ , and impulse  $I$ . Values for pressure and impulse are based on simplified Kingery-Bulmash hemispherical TNT equations (Ref 5).

Inputs to Step 5:

- Yield of the event (lbs),  $W_1$  [from Step 4]
- Distance between the PES and ES (ft),  $d$  [from Step 3]
- Weapon type [from Step 1]



Pressure and impulse values for weapon types that are not classified as *bulk/light case* are based on the effective yield,  $Y$ . The pressure and impulse is calculated based on the effective yield; however, the effective yield is equal to the yield of the event for *bulk/light case* weapon types. The following procedures are used to calculate effective yield and then open-air pressure and impulse.

#### Substep 1

Calculate the hazard factor,<sup>3</sup>  $Z$ , by:

$$Z = \frac{d}{(W_1)^{\frac{1}{3}}} \quad (16)$$

#### Substep 2

Given the value of  $Z$  from Eq. (16), calculate  $X$  as the natural log of the hazard factor:

$$X = \ln(Z) \quad (17)$$

#### Substep 3

Calculate the effective yield,  $Y$ . This is done by consulting Table A-2, *Effective Yield*, and selecting an appropriate method based on weapon type and scaled range (hazard factor). For some combinations of weapon type and scaled range, Table A-2, *Effective Yield*, provides the equation for  $Y$  in the form:

$$Y = C_1 * (W_1 / C_2) \quad (18)$$

where  $C_1$  and  $C_2$  are constants given in the table. For the remaining combinations of weapon type and scaled range, Table A-2, *Effective Yield*, provides the coefficients  $A$ ,  $B$ ,  $C$ ,  $D$ ,  $E$ , and  $F$  to be used in the following equation for  $Y$ :

<sup>3</sup> The hazard factor is also known as the scaled range or *K factor* in usage and literature.

$$Y = \left( \frac{W_1}{\text{NEWQD of one weapon}} \right) * e^{(A+B*X+C*X^2+D*X^3+E*X^4+F*X^5)} \quad (19)$$

where the NEWQD of one weapon is provided in Table 14, *Primary Fragment Distribution by Mass Bins*.

#### Substep 4

Calculate the effective hazard factor,  $Z_o$ , by:

$$Z_o = \frac{d}{(Y)^{\frac{1}{3}}} \quad (20)$$

#### Substep 5

Calculate  $X_o$  as the natural log of the effective hazard factor by:

$$X_o = \ln(Z_o) \quad (21)$$

#### Substep 6

With the values of  $Z_o$  and  $X_o$  known, the unmodified values of pressure (psi) and impulse (psi-ms) can be determined.

Calculate unmodified pressure,  $P$ , by:

$$P = e^{(A+B*X_o+C*X_o^2+D*X_o^3+E*X_o^4)} \quad (22)$$

where the coefficients  $A$ ,  $B$ ,  $C$ ,  $D$ , and  $E$  are provided in Table A-3, *Pressure Calculation Coefficients*, based on the range of  $Z_o$ .

Calculate unmodified impulse,  $I$ , by:

$$I = e^{(A+B*X_o+C*X_o^2+D*X_o^3+E*X_o^4)} * Y^{\frac{1}{3}} \quad (23)$$

where the coefficients  $A$ ,  $B$ ,  $C$ ,  $D$ , and  $E$  are provided in Table A-4, *Impulse Calculation Coefficients*, based on the range of  $Z_o$ .

Rationale for this methodology to determine unmodified pressure and impulse is detailed in Attachment 4.

Outputs of Step 5:

- Unmodified pressure (psi),  $P$
- Unmodified impulse (psi-ms),  $I$

#### 4.2.2 STEP 6: Adjust $P$ , $I$ due to PES.

Step 6 performs two functions in SAFER. In Step 6a, SAFER calculates the pressure,  $P'$ , and impulse,  $I'$ , outside of the PES. Section 4.2.2.1 describes this process. In Step 6b, SAFER



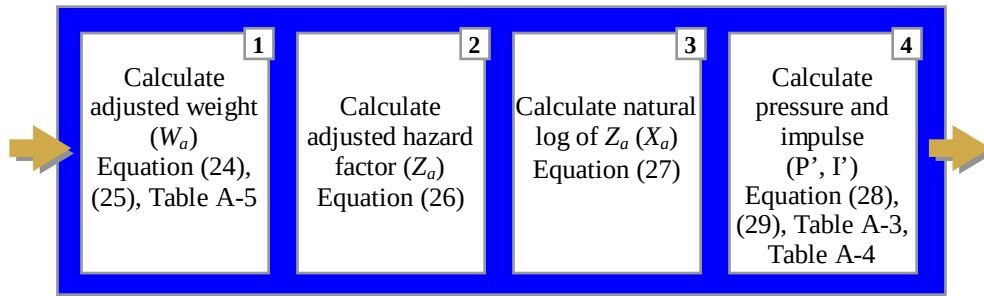
determines the damage to the PES by calculating percentages of the PES roof and walls that remain intact following an explosive event as described in Section 4.2.2.2.

Inputs to Step 6:

- Yield of the event (lbs),  $W_1$  [from Step 4]
- Equivalent NEW (lbs),  $W_2$  [from Step 4]
- Distance between the PES and ES (ft),  $d$  [from Step 3]
- Orientation of PES to ES [from Step 3]
- Hazard factor,  $Z$  [from Step 5]
- Natural log of the hazard factor,  $X$  [from Step 5]
- PES building type [from Step 2]

#### 4.2.2.1 Step 6a: Adjust $P, I$

This step calculates the pressure and impulse values outside of the PES. To perform the required calculations, SAFER uses the same logic as the Blast Effects Computer to determine an effective yield (Ref 6). Adjustments are not required if there is not a PES structure (i.e. open) or if the PES selected is a pre-engineered metal building or hollow clay tile building.



##### Substep 1

Calculate the adjusted weight,  $W_a$ . This is done by consulting Table A-5, *Adjusted Weight Coefficients*, and selecting an applicable method based on PES building type, the hazard factor ( $Z$ ), and the orientation of the PES to the ES (when appropriate). For some combinations of weapon type and scaled range, Table A-5, *Adjusted Weight Coefficients*, provides the equation for  $W_a$  in the form:

$$W_a = c * W_1 \quad (24)$$

where  $c$  is a constant given in the table. For the remaining combinations of PES building type, the hazard factor ( $Z$ ), and orientation, Table A-5, *Adjusted Weight Coefficients*, provides the coefficients  $A, B, C, D, E, F, G$ , and  $H$  to be used in the following equation for  $W_a$ :

$$W_a = W_1 * e^{(A+B*X+C*X^2+D*X^3+E*X^4+F*X^5+G*X^6+H*X^7)} \quad (25)$$

##### Substep 2

Calculate the adjusted hazard factor,  $Z_a$ , by:

$$Z_a = \frac{d}{(W_a)^{\frac{1}{3}}} \quad (26)$$

### Substep 3

Calculate  $X_a$  as the natural log of the adjusted hazard factor by:

$$X_a = \ln(Z_a) \quad (27)$$

### Substep 4

With the values of  $Z_a$  and  $X_a$  known, the adjusted values of pressure and impulse can be determined. The equations SAFER uses to calculate these values are in the same form as those used in Step 5.

Calculate adjusted pressure,  $P'$ , by:

$$P' = e^{(A+B*X_a+C*X_a^2+D*X_a^3+E*X_a^4)} \quad (28)$$

where the coefficients  $A$ ,  $B$ ,  $C$ ,  $D$ , and  $E$  are provided in Table A-3, *Pressure Calculation Coefficients*, based on the range of  $Z_a$ . For “open” PES cases,  $P'$  is set to the  $P$  value from Step 5.

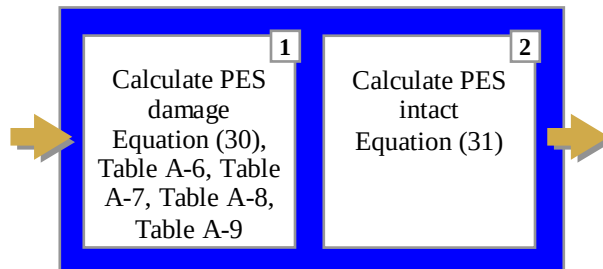
Calculate adjusted impulse,  $I'$  (psi-ms), by:

$$I' = e^{(A+B*X_a+C*X_a^2+D*X_a^3+E*X_a^4)} * W_a^{\frac{1}{3}} \quad (29)$$

where the coefficients  $A$ ,  $B$ ,  $C$ ,  $D$ , and  $E$  are provided in Table A-4, *Impulse Calculation Coefficients*, based on the range of  $Z_a$ . For “open” PES cases,  $I'$  is set to the value calculated for  $I$  in Step 5.

#### 4.2.2.2 Step 6b: Calculate PES Intact

The fraction of the PES intact is a function of the equivalent NEW ( $W_2$ ) and the PES building type.



### Substep 1

The fractional damage (a value between 0 and 1) of each PES component (roof, front wall, side walls, and rear wall) is determined. Calculate the fractional damage,  $PES_{damage}$ , by:

For  $i = 1$  to 4  
PES Component  $i$ :

```

    If  $W_2 < Y_0$ ,
    Then  $PES_{damage(i)} = 0$ 
    Else If  $Y_0 \leq W_2 \leq Y_{100}$ ,
    Then
         $PES_{damage(i)} = a * (W_2 - Y_0)^b$ 
    Else  $PES_{damage(i)} = 1$ 
    End If
Next  $i$ ,

```

(30)

where  $a = 1/(Y_{100} - Y_0)^b$ , and the constants  $Y_0$ ,  $Y_{100}$ , and  $b$  are provided in the appropriate table for the PES component: Table A-6, *Damage Coefficients for the PES Roof*, Table A-7, *Damage Coefficients for the PES Front Wall*, Table A-8, *Damage Coefficients for the PES Side Walls*, Table A-9, *Damage Coefficients for the PES Rear Wall*; coefficients in the tables are based on the PES building type.

Outputs of *Substep 1*:

- Fraction of PES roof damaged,  $PES_{damage(roof)}$
- Fraction of PES front wall damaged,  $PES_{damage(fw)}$
- Fraction of PES side walls damaged,  $PES_{damage(sw)}$
- Fraction of PES rear wall damaged,  $PES_{damage(rw)}$

*Substep 2*

For each PES component, calculate the fraction PES intact following the explosives event,  $PES_{intact}$ , by:

```

    For  $i = 1$  to 4
    PES Component  $i$ :
         $PES_{intact(i)} = 1 - PES_{damage(i)}$ 
    Next  $i$ ,

```

(31)

Outputs of *Substep 2*:

- Fraction of PES roof intact,  $PES_{intact(roof)}$
- Fraction of PES front wall intact,  $PES_{intact(fw)}$
- Fraction of PES side walls intact,  $PES_{intact(sw)}$
- Fraction of PES rear wall intact,  $PES_{intact(rw)}$

The following assumptions are made with respect to PES damage calculations:

- No blow-out paneling or other venting/containment measures are considered except where an earth-covered magazine (ECM) or hardened aircraft shelter (HAS) orientation is considered.
- Dimensions used in modeling the PES types in SAFER are presented in Table 9, *PES Assumptions*.

**Table 9. PES Assumptions**

| PES Type                      | Length (ft) | Width (ft) | Height (ft) | Volume (ft <sup>3</sup> ) |
|-------------------------------|-------------|------------|-------------|---------------------------|
| Pre-engineered metal building | 72          | 36         | 12          | 31,104                    |
| Hollow Clay Tile              | 72          | 36         | 12          | 31,104                    |
| HAS                           | 120         | 66         | 29          | 229,680                   |
| Large Concrete Arch ECM       | 80          | 25         | 12.5        | 25,000                    |
| Medium Concrete Arch ECM      | 60          | 25         | 12.5        | 18,750                    |
| Small Concrete Arch ECM       | 40          | 25         | 12.5        | 12,500                    |
| Large Steel Arch ECM          | 80          | 25         | 12.5        | 25,000                    |
| Medium Steel Arch ECM         | 60          | 25         | 12.5        | 18,750                    |
| Small Steel Arch ECM          | 40          | 25         | 12.5        | 12,500                    |
| Large AGBS                    | 86.33       | 62.67      | 25          | 135,258                   |
| Medium AGBS                   | 66.33       | 66.33      | 24.42       | 107,440                   |
| Small AGBS (Square)           | 48          | 48         | 16          | 36,864                    |
| Medium Concrete Building      | 66.33       | 66.33      | 24.42       | 107,440                   |
| Small Concrete Building       | 48          | 48         | 16          | 36,864                    |
| Ship (large)                  | 200         | 45         | 67          | 603,000                   |
| Ship (medium)                 | 150         | 45         | 67          | 452,250                   |
| Ship (small)                  | 100         | 30         | 50          | 150,000                   |
| ISO Container                 | 20          | 8          | 8.5         | 1,360                     |

Rationale for the methodology used in this substep is detailed in Attachment 4.

#### Outputs of Step 6:

- Adjusted pressure (psi),  $P'$
- Adjusted impulse (psi-ms),  $I'$
- Adjusted weight (lbs),  $W_a$
- Adjusted scaled distance (ft),  $Z_a$
- Fraction of PES roof intact,  $PES_{intact(roof)}$
- Fraction of PES front wall intact,  $PES_{intact(fw)}$
- Fraction of PES side walls intact,  $PES_{intact(sw)}$
- Fraction of PES rear wall intact,  $PES_{intact(rw)}$
- Fraction of PES roof damaged,  $PES_{damage(roof)}$
- Fraction of PES front wall damaged,  $PES_{damage(fw)}$
- Fraction of PES side walls damaged,  $PES_{damage(sw)}$
- Fraction of PES rear wall damaged,  $PES_{damage(rw)}$

#### 4.2.3 STEP 7. Adjust $P$ , $I$ (due to ES).

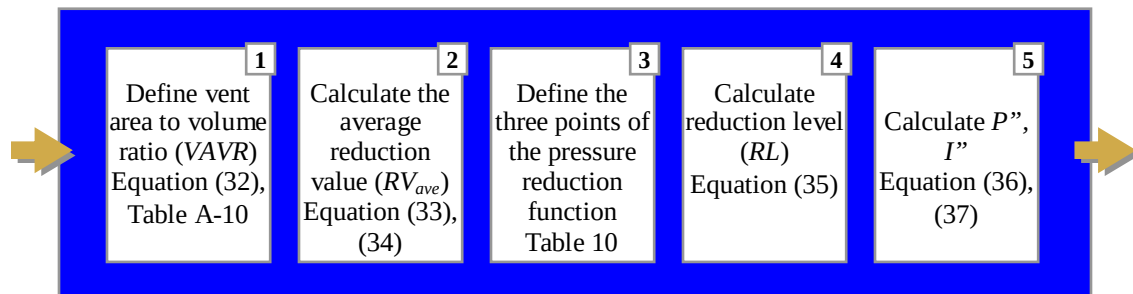
In Step 7, SAFER calculates the final pressure,  $P''$ , and final impulse,  $I''$ , values inside the ES. Given the adjusted pressure,  $P'$ , and impulse,  $I'$ , outside of the PES as determined in Step 6, another adjustment is made to determine the pressure and impulse inside the ES. If the situation

has exposed personnel in the open, this adjustment is not made because there is no structure to reduce the pressure and impulse.

Inputs to Step 7:

- ES building type [from Step 3]
- Percentage of glass on the ES (%),  $G_P$  [from Step 3]
- Floor area of the ES ( $\text{ft}^2$ ),  $FA_{ES}$  [from Step 3]
- Adjusted pressure (psi),  $P'$  [from Step 6]
- Adjusted impulse (psi-ms),  $I'$  [from Step 6]
- Adjusted weight (lbs),  $W_a$  [from Step 6]

The following 5 substeps describe this process.



Pressure and impulse reductions are determined from a pressure reduction function containing two line segments as illustrated in Figure 4.

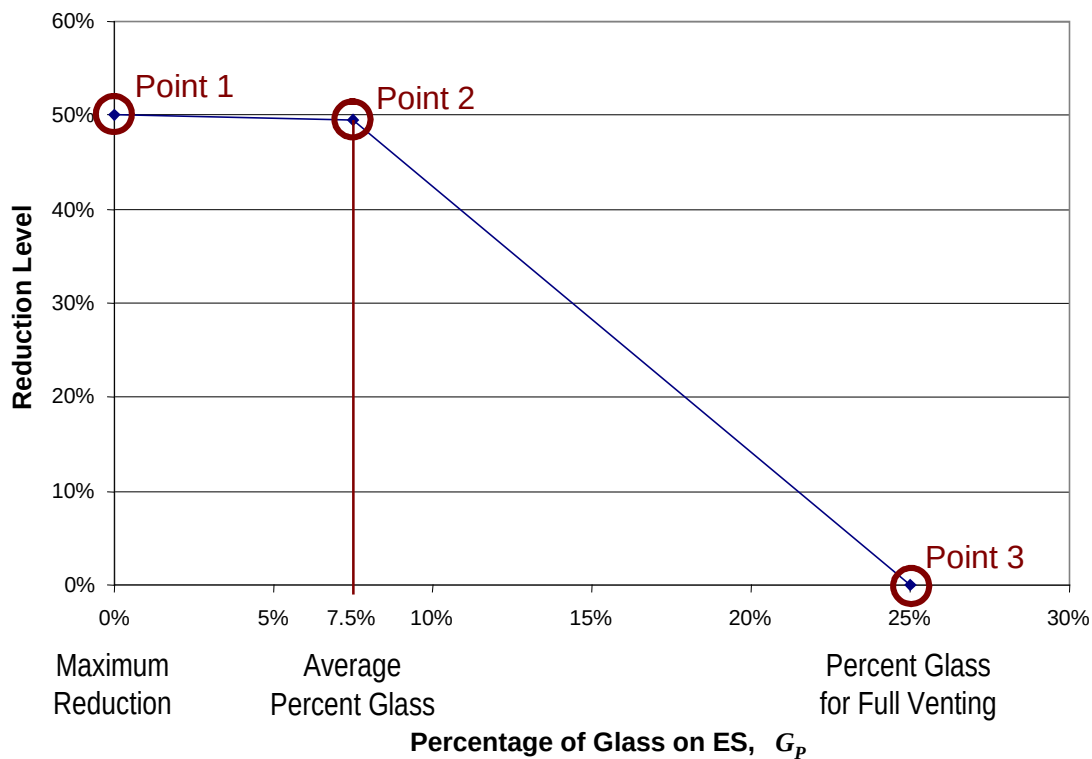


**Figure 4. Reduction Function**

The two line segments are defined by the three points characterized in Table 10, *Pressure Reduction Function Parameters*.

**Table 10. Pressure Reduction Function Parameters**

|         | Glass Fraction                                             | Reduction Level                                          |
|---------|------------------------------------------------------------|----------------------------------------------------------|
| Point 1 | 0                                                          | Max Reduction<br>(from Table A-10)                       |
| Point 2 | Glass Fraction for Average Protection<br>(from Table A-10) | RV <sub>ave</sub><br>(calculated using Eq. (33) or (34)) |
| Point 3 | Glass Fraction for Full Venting<br>(from Table A-10)       | 0                                                        |

#### Substep 1

Calculate the vent area to building volume ratio, VAVR, by:

$$VAVR = \frac{(2.5\% + G_p)}{100} \div (FA_{ES} * ES \text{ height}) \quad (32)$$

where *ES height* is taken from Table A-10, *Pressure and Impulse Reduction Values Due to Glass Percentage*.

#### Substep 2

Calculate the average reduction value,  $RV_{ave}$ . If the VAVR is greater than 0.005, calculate the average reduction value by:

$$RV_{ave} = 0.3 * W_a^{0.095} * P'^{-0.32} \quad (33)$$

If the VAVR is less than 0.005, calculate the average reduction value by:

$$RV_{ave} = (0.3 * W_a^{0.095} * P'^{-0.32}) * (0.392 + 0.0568 * \log_{10}(W_a)) \quad (34)$$

#### Substep 3

The  $RV_{ave}$  calculated in Substep 2 is used to complete the definition of the 3 points of the pressure reduction function in Table 10, *Pressure Reduction Function Parameters*.

#### Substep 4

The reduction level, *RL*, is dependent on the percentage of glass that is entered by the user. The entered percentage of glass is compared to the average protection (shown in Table A-10, *Pressure and Impulse Reduction Values Due to Glass Percentage*) to determine which line segment of the pressure reduction function (shown in Figure 4) is applicable. Then, using the line segment defined in Table 10, *Pressure Reduction Function Parameters*, and the calculated average reduction level, the equation of the line is determined in the form:

$$RL = \left( slope * \frac{G_p}{100} \right) + y - intercept \quad (35)$$

#### Substep 5

This reduction level is used to calculate  $P''$  and  $I''$ .

Calculate final pressure,  $P''$ , by:

$$P'' = (1 - RL) * P' \quad (36)$$

For “open” ES cases,  $P''$  is set to the  $P'$  value from Step 6.

Calculate final impulse,  $I''$ , by:

$$I'' = (1 - RL) * I' \quad (37)$$

For “open” ES cases,  $I''$  is set to the  $I'$  value from Step 6.

Rationale for the methodology used in this step is detailed in Attachment 4.

Outputs of Step 7:

- Final pressure (psi),  $P''$
- Final impulse (psi-ms),  $I''$

#### **4.2.4 STEP 8: Assess $P_{f(o)}$ , $P_{maji(o)}$ , $P_{mini(o)}$**

Step 8 completes the Pressure and Impulse Branch by determining the probability of fatality,  $P_{f(o)}$ , probability of major injury,  $P_{maji(o)}$ , and probability of minor injury due to the effects of pressure and impulse,  $P_{mini(o)}$ . In determining the probability of fatality, major injury, and minor injury, SAFER calculates three consequences:

- Lung rupture
- Whole body displacement
- Skull fracture

Calculations in Step 8 are grouped in five parts. Step 8a performs additional pressure and impulse calculations; Step 8b determines the probability of fatality and injury from lung rupture; Step 8c determines the probability of fatality and injury from whole body displacement; Step 8d determines the probability of fatality and injury from skull fracture; and Step 8e aggregates all probabilities of fatality and injury to determine the overall probability of fatality and injury due to the effects of pressure and impulse,  $P_{f(o)}$ ,  $P_{maji(o)}$ , and  $P_{mini(o)}$

There are three potential input conditions:

Condition 1: Situation with no PES or ES

- Unmodified pressure (psi),  $P$  [from Step 5]
- Unmodified impulse (psi-ms),  $I$  [from Step 5]

Condition 2: Situation includes a PES but no ES

- Adjusted pressure (psi),  $P'$  [from Step 6]
- Adjusted impulse (psi-ms),  $I'$  [from Step 6]

Condition 3: Situation includes an ES

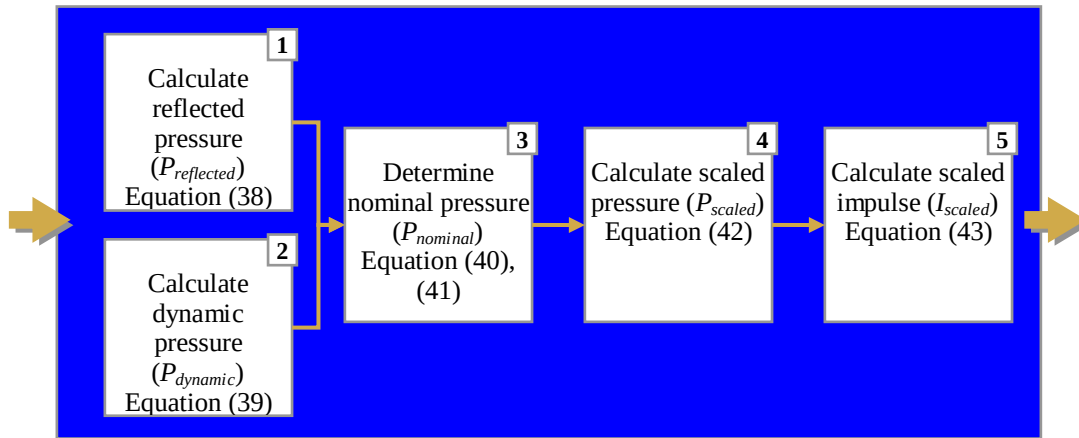
- Final pressure (psi),  $P''$  [from Step 7]
- Final impulse (psi-ms),  $I''$  [from Step 7]

With the values of pressure and impulse known (from Step 5, 6, or 7), the human vulnerability due to direct pressure and impulse effects is calculated.

SAFER considers the human vulnerability due to the effects of pressure and impulse to be a function of lung rupture, whole body displacement, or skull fracture (or the combination of the three). The probability of fatality due to lung rupture, body displacement, or skull fracture is based on the probit functions originally published by The Netherlands Organization for Applied Scientific Research TNO (Ref 9). Those functions determine the probability of fatality as a function of incident pressure and impulse, the ambient atmospheric pressure, and an assumed mass of the human body.

#### 4.2.4.1 Step 8a: Pressure and Impulse Calculations

Prior to using the probit functions to determine the human vulnerability, SAFER must first calculate reflected pressure, dynamic pressure, nominal pressure, scaled pressure, and scaled impulse.



##### Substep 1

Calculate reflected pressure,  $P_{reflected}$ , by:

$$P_{reflected} = 2 * P'' * \left( \frac{(4 * P'') + (7 * P_{ambient})}{P'' + (7 * P_{ambient})} \right) \quad (38)$$

where the ambient pressure,  $P_{ambient}$  is assumed to be 14.5 psi.

##### Substep 2

Calculate dynamic pressure,  $P_{dynamic}$ , by:

$$P_{dynamic} = \frac{2.5 * P''^2}{(7 * P_{ambient} + P'')} \quad (39)$$

where the ambient pressure,  $P_{ambient}$  is assumed to be 14.5 psi.

##### Substep 3

If the ES in the situation is open, calculate the nominal pressure,  $P_{nominal}$ , by:



$$P_{nominal} = P'' + P_{dynamic} \quad (40)$$

otherwise, calculate the nominal pressure,  $P_{nominal}$ , by:

$$P_{nominal} = P_{reflected} = \frac{(2 * P'' * ((4 * P'') + (7 * P_{ambient})))}{(P'' + (7 * P_{ambient}))} \quad (41)$$

#### Substep 4

Calculate the scaled pressure,  $P_{scaled}$ , by:

$$P_{scaled} = \frac{(P_{dynamic} * 6.895)}{(P_{ambient} * 0.001)} \quad (42)$$

#### Substep 5

Calculate the scaled impulse,  $I_{scaled}$ , by:

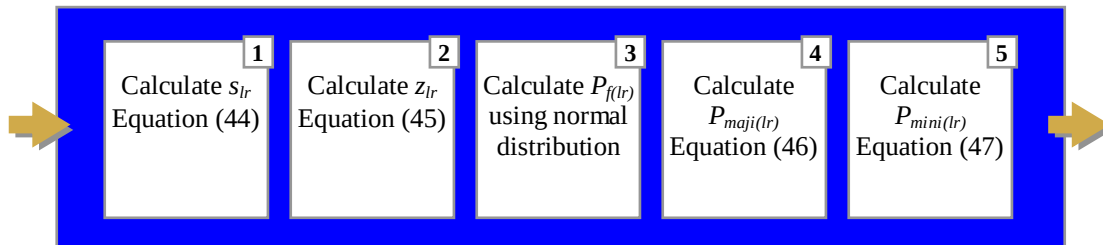
$$I_{scaled} = I'' * 0.005291 \quad (43)$$

where  $I''$  is from Step 7 and the constant is based on the conversion of pressure, time, and mass to the appropriate English units.

The parameters calculated in Step 8a are used as inputs to the remainder of Step 8 equations for calculating the probability of fatality or injury due to lung rupture, whole body displacement, and skull fracture.

#### 4.2.4.2 Step 8b: Lung Rupture

Step 8b determines the probability of fatality and major and minor injuries resulting from lung rupture. This is accomplished by calculating the  $s$  and  $z$  parameters associated with a standard normal curve used in the TNO probit functions. The TNO probit functions are based on the standard normal distribution translated by subtracting 5 from the  $z$  value. However, SAFER uses the standard normal distribution without translation.



#### Substep 1

To determine the probability of fatality due to lung rupture,  $P_{f(lr)}$ , SAFER calculates  $s_{lr}$  by:

$$s_{lr} = \frac{4.2}{P_{scaled}} + \frac{1.3}{I_{scaled}} \quad (44)$$

#### Substep 2

Using the calculated  $s_{lr}$ , SAFER calculates  $z_{lr}$  by:

$$z_{lr} = -5.74 * \ln(s_{lr}) \quad (45)$$

#### Substep 3

Given the value calculated for  $z_{lr}$ , SAFER determines  $P_{f(lr)}$  by using a normal distribution where  $P_{f(lr)}$  is equal to the area under the standard normal distribution to the left of the  $z_{lr}$  value.

#### Substep 4

Using the pressure calculated from Step 7 ( $P''$ ), calculate the probability of a *major* injury from lung rupture ( $P_{maji(lr)}$ ). The relationship between the pressure and the probability of major injury is estimated by curve-fitting actual data with the following linear function.

$$P_{maji(lr)} = 0.01 * P'' - 0.18 \quad (46)$$

#### Substep 5

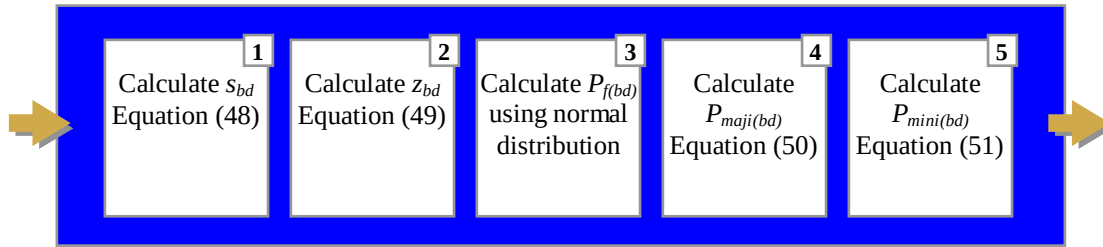
Using the pressure calculated from Step 7 ( $P''$ ), calculate the probability of a *minor* injury from lung rupture ( $P_{mini(lr)}$ ). The relationship between the pressure and the probability of minor injury is estimated by curve-fitting actual data with the following linear function.

$$P_{mini(lr)} = 0.032 * P'' - 0.046 \quad (47)$$

The probability of major injury and minor injury is based on available models and literature, as detailed Attachment 5.

#### 4.2.4.3 Step 8c: Whole Body Displacement

Step 8c determines the probability of fatality, major injury, and minor injury resulting from whole body displacement. As in Step 8b, this is accomplished by calculating the  $s$  and  $z$  parameters associated with a standard normal distribution and the TNO probit functions.



#### Substep 1

To determine the probability of fatality due to body displacement,  $P_{f(bd)}$ , SAFER calculates  $s_{bd}$  by:

$$s_{bd} = \frac{7280}{(P_{nominal} * 6895)} + \frac{1.3 * 10^9}{((P_{nominal} * 6895) * (I'' * 6.895))} \quad (48)$$

where  $I''$  is from Step 7.

#### Substep 2

Using the calculated  $s_{bd}$ , SAFER calculates  $z_{bd}$  by:

$$z_{bd} = -2.44 * \ln(s_{bd}) \quad (49)$$

### Substep 3

Given the value calculated for  $z_{bd}$ , SAFER determines  $P_{f(bd)}$  by using a normal distribution where  $P_{f(bd)}$  is equal to the area under the standard normal distribution to the left of the  $z_{bd}$  value.

### Substep 4

Given the value for probability of fatality due to whole body displacement ( $P_{f(bd)}$ ), SAFER determines the probability of a major injury from whole body displacement ( $P_{maji(bd)}$ ).

$$P_{maji(bd)} = 1 - \exp(-7 * P_{f(bd)}) \quad (50)$$

### Substep 5

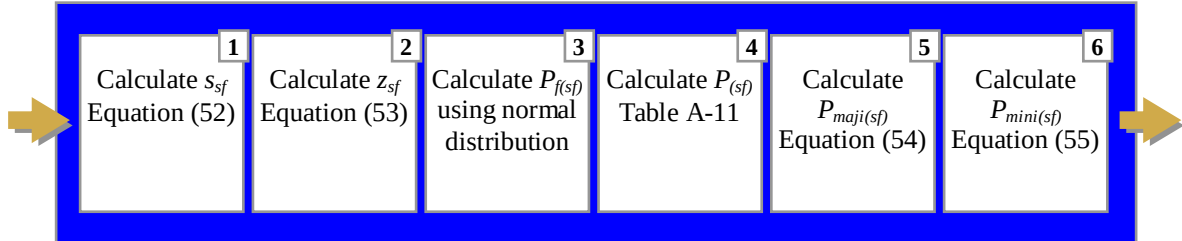
Given the value for probability of major injury from whole body displacement ( $P_{maji(bd)}$ ), SAFER determines the probability of a minor injury from whole body displacement ( $P_{mini(bd)}$ ).

$$P_{mini(bd)} = 1 - \exp(-7 * P_{maji(bd)}) \quad (51)$$

The probability of major injury and minor injury is based on available models and literature, as detailed Attachment 5.

#### 4.2.4.4 Step 8d: Skull Fracture

Step 8d determines the probability of fatality, major injury, and minor injury resulting from skull fracture. As in Steps 8b and 8c, this is accomplished by calculating the  $s$  and  $z$  parameters associated with a standard normal distribution and the TNO probit functions.



### Substep 1

To determine the probability of fatality due to skull fracture,  $P_{f(sf)}$ , SAFER calculates  $s_{sf}$  by:

$$s_{sf} = \frac{2430}{(P_{nominal} * 6895)} + \frac{4 * 10^8}{((P_{nominal} * 6895) * (I'' * 6.895))} \quad (52)$$

### Substep 2

Using the calculated  $s_{sf}$ , SAFER calculates  $z_{sf}$  by:

$$z_{sf} = -8.49 * \ln(s_{sf}) \quad (53)$$

### Substep 3

Given the value calculated for  $z_{sf}$ , SAFER determines  $P_{f(sf)}$  by using a normal distribution where  $P_{f(sf)}$  is equal to the area under the standard normal distribution to the left of the  $z_{sf}$  value.

#### Substep 4

To determine the probability of major injury due to skull fracture, SAFER calculates the probability of skull fracture,  $P_{(sf)}$  using  $P''$  and  $I''$  from Step 7. The probability of skull fracture uses the same hyperbolae interpolation methodology from Section 4.3.1.2, Substep 1. The skull fracture hyperbolae parameters are contained in Table A-11, *Pressure-impulse Coefficients for  $P_{(sf)}$* .

#### Substep 5

Given the value of probability of skull fracture,  $P_{(sf)}$ , the probability of *major* injury due to skull fracture,  $P_{maji(sf)}$ , is determined.

$$\begin{aligned} &\text{If } P_{(sf)} < 0.01 \\ &\quad \text{Then } P_{maji(sf)} = 0.25 \times P_{(sf)} \\ &\text{Else} \\ &\quad P_{maji(sf)} = -1.34 \times P_{(sf)}^2 + 2.09 \times P_{(sf)} + 0.25 \\ &\text{End If} \end{aligned} \tag{54}$$

#### Substep 6

Given the probability of major injury due to skull fracture,  $P_{maji(sf)}$ , calculate the probability of a *minor* injury from skull fracture ( $P_{mini(sf)}$ ).

$$\begin{aligned} &\text{If } P_{maji(sf)} < 0.01 \\ &\quad \text{Then } P_{mini(sf)} = 10 \times P_{maji(sf)} \\ &\text{Else} \\ &\quad P_{mini(sf)} = -1.34 \times P_{maji(sf)}^2 + 2.09 \times P_{maji(sf)} + 0.25 \\ &\text{End If} \end{aligned} \tag{55}$$

The probability of major injury and minor injury is based on available models and literature, as detailed Attachment 5.

#### 4.2.4.5 Step 8e: Aggregation of Consequences

Given the probability of fatality for lung rupture, whole body displacement, and skull fracture, calculate the probability of fatality due to the effects of pressure and impulse,  $P_{f(o)}$ , by:

$$P_{f(o)} = P_{f(lr)} + \left( (1 - P_{f(lr)}) * P_{f(bd)} \right) + \left( (1 - P_{f(lr)}) * (1 - P_{f(bd)}) * P_{f(sf)} \right) \tag{56}$$

Calculate the probability of major injury due to the effects of pressure and impulse,  $P_{maji(o)}$ , by:

$$P_{maji(o)} = P_{maji(lr)} + \left( (1 - P_{maji(lr)}) * P_{maji(bd)} \right) + \left( (1 - P_{maji(lr)}) * (1 - P_{maji(bd)}) * P_{maji(sf)} \right) \tag{57}$$

Calculate the probability of fatality due to the effects of pressure and impulse,  $P_{mini(o)}$ , by:

$$P_{mini(o)} = P_{mini(lr)} + \left( (1 - P_{mini(lr)}) * P_{mini(bd)} \right) + \left( (1 - P_{mini(lr)}) * (1 - P_{mini(bd)}) * P_{mini(sf)} \right) \tag{58}$$

Outputs of Step 8:

- Probability of fatality due to overpressure effects,  $P_{f(o)}$

- Probability of major injury due to overpressure effects,  $P_{maji(o)}$
- Probability of minor injury due to overpressure effects,  $P_{mini(o)}$

### 4.3 Group 3 Steps: Structural Response Branch

Group 3 includes Steps 9-10 of the SAFER architecture. These steps analyze human vulnerability from building collapse and glass hazards.

Step 9 considers the effect of six human vulnerability mechanisms by calculating the probability of fatality, probability of major injury, and probability of minor injury due to window breakage, and the probability of fatality, probability of major injury, and probability of minor injury due to building collapse. Given these outputs, Step 10 calculates the probability of fatality due to overall building damage,  $P_{f(b)}$ , the probability of major injury due to overall building damage,  $P_{maji(b)}$ , and the probability of minor injury due to overall building damage,  $P_{mini(b)}$ .

To enhance readability, selected reference tables of constants used in the Group 3 steps are located in Appendix A.

#### 4.3.1 STEP 9: Determine adjusted $P$ , $I$ effect on ES (building collapse and glass hazard).

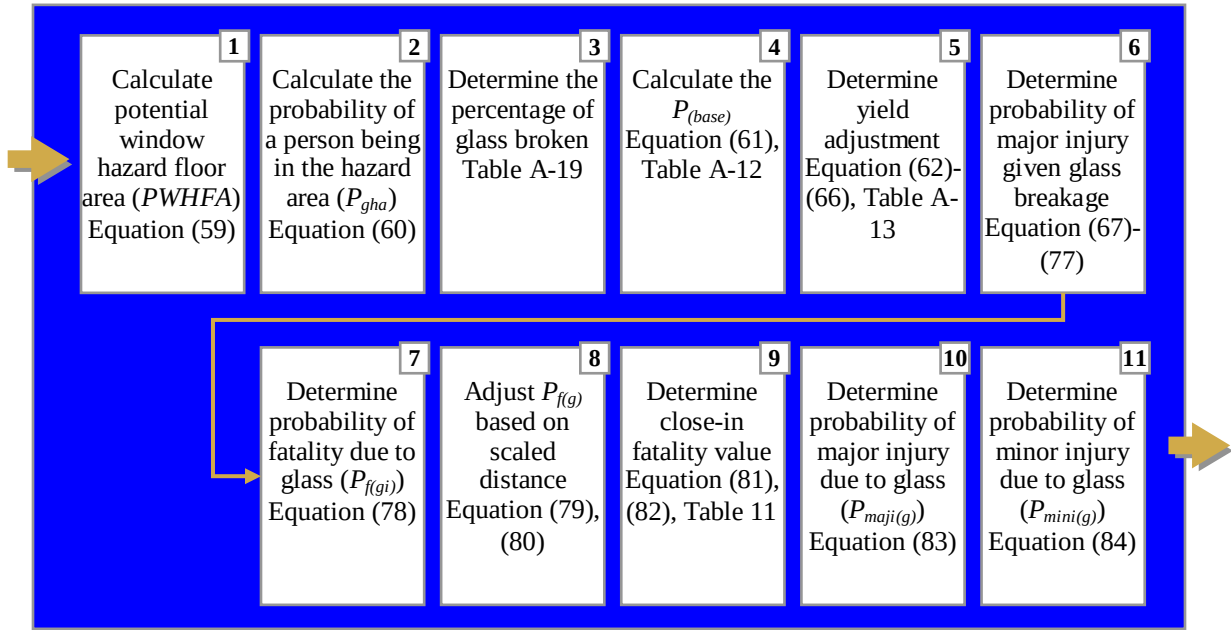
Step 9 performs three functions in SAFER. In Step 9a, SAFER calculates the probability of fatality due to window breakage,  $P_{f(g)}$ . Section 4.3.1.1 describes the procedures for this step. In Step 9b, SAFER calculates the probability of fatality due to building collapse,  $P_{f(bc)}$ . Section 4.3.1.2 describes the procedures for this step. In Step 9c, SAFER determines the damage to the ES by calculating percentages of the ES roof and walls that remain intact following an explosives event. Section 4.3.1.3 describes the procedures for this step.

Inputs to Step 9:

- ES building type [from Step 3]
- ES roof type [from Step 3]
- Type of glass on the ES [from Step 3]
- Distance between the PES and ES (ft),  $d$  [from Step 3]
- Percentage of glass on the ES (%),  $G_P$  [from Step 3]
- Floor area of the ES (ft<sup>2</sup>),  $FA_{ES}$  [from Step 3]
- Adjusted pressure (psi),  $P'$  [from Step 6]
- Adjusted impulse (psi-ms),  $I'$  [from Step 6]
- Adjusted weight (lbs),  $W_a$  [from Step 6]
- Adjusted scaled distance (ft),  $Z_a$  [from Step 6]

##### 4.3.1.1 Step 9a: Human vulnerability due to window breakage

This step determines the probability of fatality due to window breakage,  $P_{f(g)}$ , the probability of major injury due to window breakage,  $P_{maji(g)}$ , and the probability of minor injury due to glass breakage,  $P_{mini(g)}$ . To determine  $P_{f(g)}$ , SAFER calculates the probability of a person being in the glass hazard area followed by the probability of a major injury given that the person is in a glass hazard area. Finally, SAFER determines the probability of fatality based on the probability of major injury.



#### Substep 1

To determine the probability of a person being in the glass hazard area, SAFER calculates Potential Window Hazard Floor Area,  $PWHFA$ , by:

$$PWHFA = 22.5 * \left( (FA_{ES} * aspect\ ratio)^{1/2} + (FA_{ES} \div aspect\ ratio)^{1/2} \right) \quad (59)$$

where the *aspect ratio* = 2 for all ES building types except *modular/trailers*. The *aspect ratio* = 3 for an ES building type of *modular/trailers*.

#### Substep 2

Calculate the probability of a person being in the glass hazard area,  $P_{gha}$ , by:

$$P_{gha} = \frac{G_P}{100} * \left( \frac{PWHFA}{FA_{ES}} \right) \quad (60)$$

This equation simply represents the percentage of glass present multiplied by the ratio of the glass hazard area to the total area.

#### Substep 3

The pressure and impulse at the ES ( $P'$  and  $I'$ ) are used with stored Pressure-impulse diagrams to determine the percentage of glass broken, % *glass breakage* (Attachment 6). This method uses  $P$  and  $I$  coefficients from Table A-19, *Pressure-impulse Coefficients – Glass Breakage*, as described in Section 4.3.1.2, Substep 1.

#### Substep 4

To determine the probability of a major injury given that the person is in a glass hazard area, SAFER calculates the base probability of major injury,  $P_{base}$ , by:

$$P_{base} = M * (\% \text{ glass breakage})^N \quad (61)$$

where the coefficients  $M$  and  $N$  are provided in Table A-12, *Power Curve Parameters for Major Injury as a Function of Glass Breakage*, and are based on the type of glass on the ES.

#### Substep 5

The base probability of major injury,  $P_{base}$ , is associated with a fixed yield; therefore, it must be adjusted to the relative NEWQD experienced at the ES. A yield adjustment factor is calculated by:

$$Yield\ adjustment = (A * R) + B * G^{(C * R * S)} \quad (62)$$

where

$$R = \ln(Y_a / Y_n) \quad (63)$$

$$S = (Y_n / Y_a)^{\frac{1}{3}} \quad (64)$$

$$Y_a = W_a \text{ (lbs) from Step 6} \quad (65)$$

$$Y_n = \text{nominal yield} = 50,000 \text{ (lbs)}$$

$$G = 100 / \% \text{ glass breakage} \quad (66)$$

Coefficients  $A$ ,  $B$ , and  $C$  are provided in Table A-13, *Yield Adjustment Curve Parameters*, and are based on the type of glass on the ES.

Rationale for the yield adjustment curves and the associated parameters in this substep is detailed in Attachment 6.

#### Substep 6

SAFER Version 3.1 takes higher-velocity glass fragments into account for annealed or dual pane glass when the 100% glass breakage level is met or exceeded. For annealed and dual pane glass with less than 100% glass breakage and for tempered glass regardless of percent glass breakage, calculate the probability of a major injury given that the person is in the glass hazard area,  $P_{pha}$ , by:

$$P_{pha} = P_{base} * Yield\ adjustment \quad (67)$$

For annealed glass with 100% glass breakage, calculate the  $P_{pha}$  as follows:

Calculate the impulse-adjusted probability of major injury,  $IA$ , by:

$$IA = (8.1216 * Y_a^{0.015541}) * LN(I') - (18.103 * Y_a^{0.066969}) \quad (68)$$

To ensure a smooth transition region at the 100% glass breakage level, a continuity correction is introduced. Calculate the maximum continuity correction,  $CC_{max}$ , by:

$$CC_{max} = -0.337 + 0.26 * LN(Y_a) - 0.0103 * (LN(Y_a))^2 \quad (69)$$

Calculate the transition point,  $TP$ , by:

$$TP = \exp(1.1924 + 0.66148 * LN(Y_a) - 0.010167 * (LN(Y_a))^2) \quad (70)$$

Calculate the actual continuity correction,  $CC_a$ , by:

$$CC_a = [(CC_{max} - 1) / TP] * d + 1 \quad (71)$$

Calculate the probability of major injury,  $P_{pha}$ , by:

$$P_{pha} = IA * CC_a \quad (72)$$

For dual pane glass with 100% glass breakage, calculate the  $P_{pha}$  as follows:

Calculate the impulse-adjusted probability of major injury,  $IA$ , by:

$$IA = (7.0757 * Y_a^{0.035394}) * LN(I') - (15.233 * Y_a^{0.086094}) \quad (73)$$

Calculate the maximum continuity correction,  $CC_{max}$ , by:

$$CC_{max} = -1.413 + 0.43 * LN(Y_a) - 0.0171 * (LN(Y_a))^2 \quad (74)$$

Calculate the transition point,  $TP$ , by:

$$TP = exp(0.89573 + 0.73204 * LN(Y_a) - 0.013288 * (LN(Y_a))^2) \quad (75)$$

Calculate the actual continuity correction,  $CC_a$ , by:

$$CC_a = [(CC_{max} - 1) / TP] * d + 1 \quad (76)$$

Calculate the probability of major injury,  $P_{pha}$ , by:

$$P_{pha} = IA * CC_a \quad (77)$$

Rationale for the yield adjustment curves and the associated parameters in this substep is detailed in Attachment 6.

#### Substep 7

SAFER uses the assumption that one glass fatality occurs per 30 major injuries. Therefore, SAFER calculates the initial probability of fatality due to window breakage,  $P_{f(gi)}$ , by:

$$P_{f(gi)} = P_{gha} * P_{pha} * \frac{1}{30} \quad (78)$$

Rationale for the methodology used in this substep is detailed in Attachment 6.

#### Substep 8

SAFER adjusts the  $P_{f(gi)}$  based on the scaled distance. The glass adjustment,  $G$ , is calculated by:

$$G = 10.958 - 0.417 * Z_a \quad (79)$$

If  $G$  is greater than or equal to 24, the value is reset to 1; if  $G$  is less than 12, the value is reset to 6. Then, the probability of fatality due to window breakage is calculated by:

$$P_{f(g)} = G * P_{f(gi)} \quad (80)$$

Rationale for the methodology used in this substep is detailed in Attachment 6.

#### Substep 9

If necessary, SAFER determines the probability of fatality due to glass in the “close-in” or transition region.



$$\begin{aligned}
&\text{If } Z_a < R_1 \\
&\quad P_{f(g)} = P_{f(g)1} \\
&\text{Else If } Z_a \geq R_2 \\
&\quad P_{f(g)} = P_{f(g)} \text{ (from Substep 8)} \\
&\text{Else If } R_1 \leq Z_a < R_2 \\
&\quad P_{f(g)} = P_{f(g)1} - [(Z_a - R_1) / (R_2 - R_1)]^2 * (P_{f(g)1} - P_{f(g)2}) \\
&\text{End If}
\end{aligned} \tag{81}$$

where  $R_1$ ,  $R_2$ ,  $P_{f(g)1}$  are provided in Table 11, *Close-in Adjustment Parameters for Glass Fatality*, and are based on the type of glass on the ES. Then  $P_{f(g)2}$  is calculated by:

$$P_{f(g)2} = (A + B \times \log_{10}(W_a)) \times (G_P/10\%) \times (5000/FA_{ES})^{1/2} \tag{82}$$

where  $A$  and  $B$  are provided in Table 11, *Close-in Adjustment Parameters for Glass Fatality*,  $W_a$  is from Step 5 or 6,  $G_P$  is from Step 3, and  $FA_{ES}$  is from Step 3.

**Table 11. Close-in Adjustment Parameters for Glass Fatality**

| Window Type | $R_1$<br>(ft/lb <sup>1/3</sup> ) | $R_2$<br>(ft/lb <sup>1/3</sup> ) | $P_{f(g)2}$ |            | $P_{f(g)1}$ |
|-------------|----------------------------------|----------------------------------|-------------|------------|-------------|
|             |                                  |                                  | $A$         | $B$        |             |
| Annealed    | 6                                | 12                               | -0.00019264 | 0.00051619 | 10%         |
| Dual Pane   | 6                                | 12                               | -0.00010599 | 0.00078248 | 10%         |
| Tempered    | 6                                | 12                               | -0.0014939  | 0.0008458  | 10%         |

#### Substep 10

SAFER calculates the probability of major injury due to window breakage,  $P_{maji(g)}$ , by:

$$P_{maji(g)} = P_{f(g)} * 30 \tag{83}$$

Rationale for the methodology used in this substep is detailed in Attachment 5.

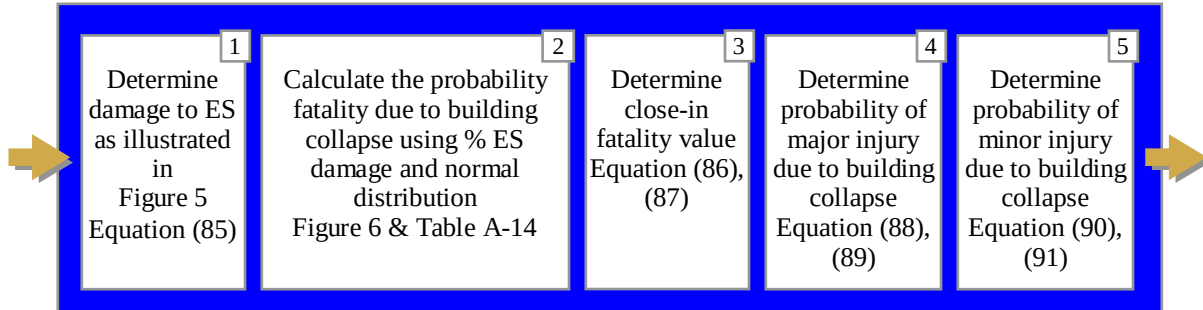
#### Substep 11

SAFER calculates the probability of minor injury due to window breakage,  $P_{mini(g)}$ , by:

$$P_{mini(g)} = P_{f(g)} * 500 \tag{84}$$

#### 4.3.1.2 Step 9b: Human vulnerability due to building collapse

This step determines the probability of fatality due to building collapse,  $P_{f(bc)}$ , probability of major injury due to building collapse,  $P_{maji(bc)}$ , and probability of minor injury due to building collapse,  $P_{mini(bc)}$ .



### Substep 1

ES damage is determined using standard pressure and impulse diagrams of the form shown in Figure 5 using the adjusted pressure,  $P'$ , and adjusted impulse,  $I'$ , from Step 6. Damage curves are hyperbolae, which are defined by the standard equation for a hyperbola:

$$C = (P - A) * (I - B) \quad (85)$$

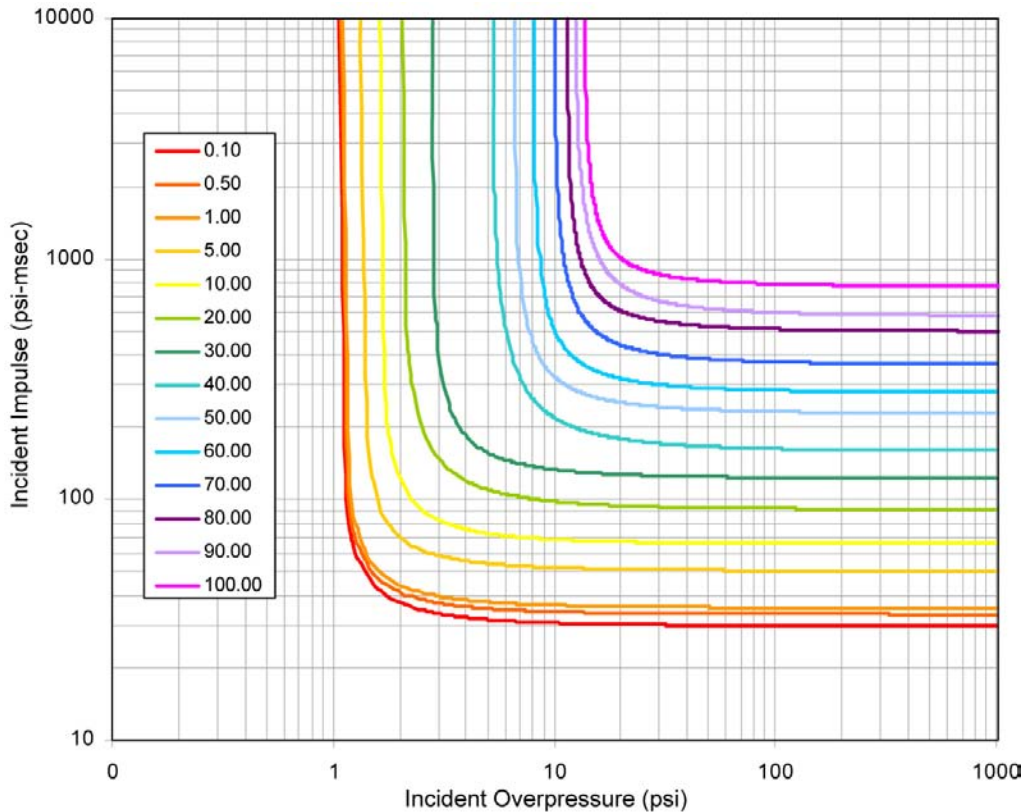


**Figure 5. P-I Diagram Example**

There are 16 families of these curves, one for each ES (Ref 10). Table A-17, *Pressure / Impulse Coefficients – ES Building Percent Damage*, provides the constants used to generate each family of hyperbolae. The damage to the ES is determined in SAFER using an interpolation routine. This interpolation results in the predicted ES building damage,  $PD_b$ .

### Substep 2

Then, using the  $PD_b$  and the truncated normal distribution curves shown in Figure 6, the probability of fatality as a function of structural damage,  $P_{f(bc)}$ , is found. The parameters defining the truncated normal curves are shown in Table A-14, *Structure Damage / Fatality Normal Distribution Parameters*.

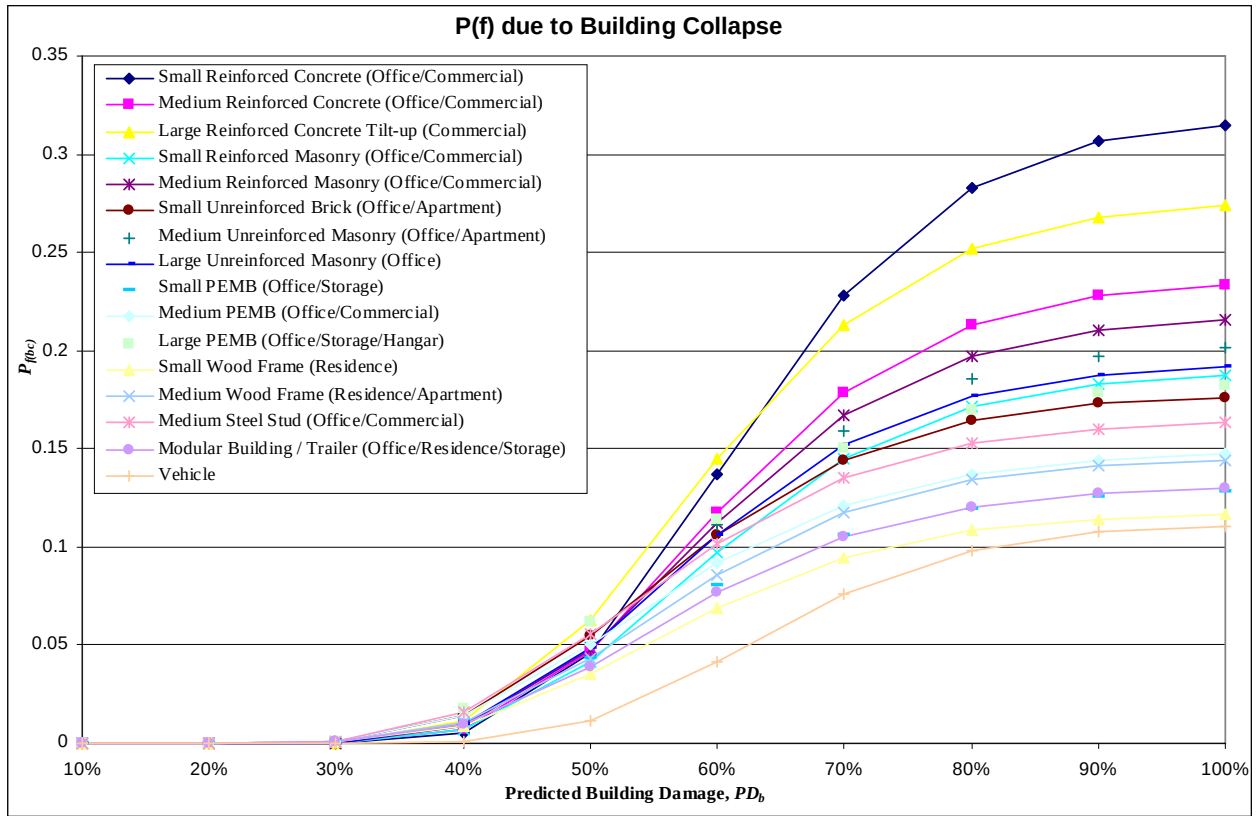


**Figure 6. Building Collapse S-curves**

Rationale for the methodology used in this substep is detailed in Attachment 7.

### Substep 3

If appropriate, SAFER determines the probability of fatality due to building collapse in the “close-in” or transition region.

$$\begin{aligned}
 &\text{If } Z_a < R_1 \\
 &\quad P_{f(bc)} = P_{f(bc)1} \\
 &\text{Else If } Z_a \geq R_2 \\
 &\quad P_{f(bc)} = P_{f(bc)} \text{ (from Substep 2)} \\
 &\text{Else If } R_1 \leq Z_a < R_2 \\
 &\quad P_{f(bc)} = P_{f(bc)1} - [(Z_a - R_1) / (R_2 - R_1)]^2 * (P_{f(bc)1} - P_{f(bc)2}) \\
 &\text{End If}
 \end{aligned} \tag{86}$$

where  $P_{f(bc)1}$  and  $P_{f(bc)2}$  are provided in Table A-15, *Close-in Adjustment Parameters for  $P_{f(bc)}$* , is provided in Table A-16, *Close-in Adjustment Parameters for Building Collapse Region Boundaries*, and  $R_2$  is calculated by:

$$\begin{aligned}
 &R_2 = A + ((B \times W_a) / (C + W_a)) \\
 &\text{If } R_2 > R_{2min} \\
 &\quad \text{Then } R_2 = R_2 \\
 &\text{Else} \\
 &\quad R_2 = R_{2min}
 \end{aligned} \tag{87}$$

EndIf

where  $A$ ,  $B$ ,  $C$  and  $R_{2min}$  are provided in Table A-16, *Close-in Adjustment Parameters for Building Collapse Region Boundaries*, and  $W_a$  is from Step 5 or 6.

#### Substep 4

SAFER calculates the probability of major injury due to building collapse,  $P_{maji(bc)}$ . First a nominal  $P_{maji(bc)}$  is calculated by:

$$Nom. P_{maji(bc)} = [(maj_{(i)}max - MINinjury) / (MAXinjury - maj_{(i)}DO) \times PD_b] - [(maj_{(i)}max \times maj_{(i)}DO) / (MAXinjury - maj_{(i)}DO)] \quad (88)$$

where the  $PD_b$  is from Substep 1, major injury damage offset,  $maj_{(i)}DO$ , and major injury maximum,  $maj_{(i)}max$ , is from Table 12, *Major and Minor Injury Parameters for Building Collapse*. MAXInjury is a constant set to 100% and MINInjury is a constant set to 0.

An adjusted probability of major injury due to building collapse is determined by:

$$Adj. P_{maji(bc)} = IFR \times P_{f(bc)} \quad (89)$$

where  $IFR$  is the injury to fatality ratio from Table 12, *Major and Minor Injury Parameters for Building Collapse*. A comparison is made between the  $Nom. P_{maji(bc)}$  and  $Adj. P_{maji(bc)}$ . The variable with the highest value is assigned as the final  $P_{maji(bc)}$ .

**Table 12. Major and Minor Injury Parameters for Building Collapse**

| ES Type                     | Major Injury                    |                            | Minor Injury                    |                                  | Injury Fatality Ratio (IFR) |
|-----------------------------|---------------------------------|----------------------------|---------------------------------|----------------------------------|-----------------------------|
|                             | Damage offset ( $maj_{(i)}DO$ ) | Maximum ( $maj_{(i)}max$ ) | Damage offset ( $min_{(i)}DO$ ) | Plateau damage ( $min_{(i)}PD$ ) |                             |
| Small R/C (office building) | 25                              | 95                         | 5                               | 65                               | 2.25                        |
| Large tilt-up R/C           | 22                              | 90                         | 4.4                             | 66                               | 2.5                         |
| Large unreinforced masonry  | 20                              | 75                         | 4                               | 73                               | 3                           |
| Medium reinforced masonry   | 22.5                            | 85                         | 4.5                             | 68                               | 3                           |
| Small reinforced masonry    | 22.5                            | 80                         | 4.5                             | 72                               | 3.25                        |
| Small unreinforced brick    | 15                              | 70                         | 3                               | 75                               | 3.1                         |
| Medium metal structure      | 15                              | 70                         | 3                               | 75                               | 3.75                        |
| Small metal structure       | 15                              | 65                         | 3                               | 72                               | 4                           |
| Medium wood structure       | 17.5                            | 65                         | 3.5                             | 81                               | 3.5                         |
| Small wood structure        | 17.5                            | 60                         | 3.5                             | 86                               | 4                           |
| Modular/trailers            | 17.5                            | 62.5                       | 3.5                             | 83                               | 3.75                        |
| Medium R/C                  | 23.5                            | 85                         | 4.7                             | 68                               | 2.75                        |
| Medium unreinforced masonry | 20                              | 80                         | 4                               | 70                               | 3.05                        |
| Medium Metal Stud           | 15                              | 72.5                       | 3                               | 73                               | 3.5                         |
| High Bay Metal              | 15                              | 75                         | 3                               | 80                               | 3.25                        |
| Passenger Vehicle           | 27.5                            | 60                         | 5.5                             | 88                               | 4                           |

### Substep 5

Similar to the calculation of probability of major injury due to building collapse, the probability of a minor injury from building collapse ( $P_{mini(bc)}$ ) is determined. First a nominal  $P_{mini(bc)}$  is calculated by:

$$Nom. P_{mini(bc)} = [(PD_b - min_{(i)}DO) / (min_{(i)}PD - min_{(i)}DO)] \times 100 \quad (90)$$

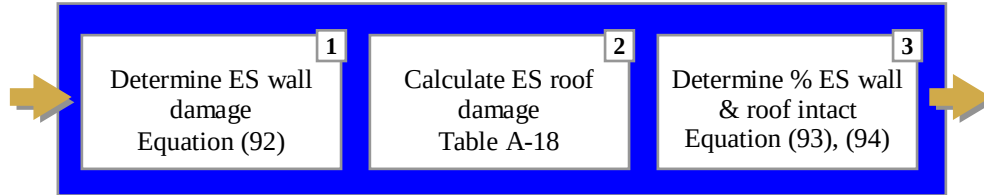
where the  $PD_b$  is from Substep 1, minor injury damage offset,  $min_{(i)}DO$ , and minor injury plateau damage,  $min_{(i)}PD$ , is from Table 12, *Major and Minor Injury Parameters for Building Collapse*.

An adjusted probability of major injury due to building collapse is determined by:

$$Adj. P_{mini(bc)} = IFR^2 \times P_{f(bc)} \quad (91)$$

where IFR is the injury to fatality ratio from Table 12, *Major and Minor Injury Parameters for Building Collapse*. A comparison is made between the  $Nom. P_{mini(bc)}$  and  $Adj. P_{mini(bc)}$ . The variable with the highest value is assigned as the final  $P_{mini(bc)}$ .

#### 4.3.1.3 Step 9c: ES Roof and Wall Damage



The percentage of the ES remaining intact (roof and walls) is determined for use in Step 17.

### Substep 1

The wall damage is set equal to the predicted building damage,  $PD_b$  (from Section 4.3.1.2, Substep 1).

$$\%ES_{wall\ damaged} = PD_b \quad (92)$$

### Substep 2

The roof damage,  $\%ES_{roof\ damaged}$ , uses the same hyperbolic interpolation methodology from Section 4.3.1.2, Substep 1. The roof hyperbolae parameters are contained in Table A-18, *Pressure-impulse Coefficients – ES Roof Damage*.

### Substep 3

The percentage of the walls and roof intact is the percentage not damaged, as shown by:

$$\%ES_{wall\ intact} = 100 - \%ES_{wall\ damaged} \quad (93)$$

$$\%ES_{roof\ intact} = 100 - \%ES_{roof\ damaged} \quad (94)$$

The development of the methodology for determining the percentage ES intact is detailed in Attachment 7.

Outputs of Step 9:

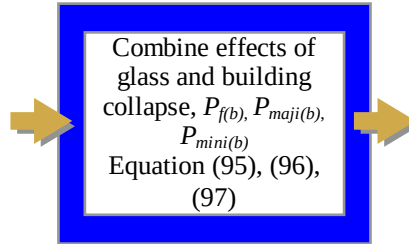
- Probability of fatality due to window breakage,  $P_{f(g)}$
- Probability of major injury due to window breakage,  $P_{maji(g)}$
- Probability of minor due to window breakage,  $P_{mini(g)}$
- Probability of fatality due to building collapse,  $P_{f(bc)}$
- Probability of major injury due to building collapse,  $P_{maji(bc)}$
- Probability of minor injury due to building collapse,  $P_{mini(bc)}$
- Percentage of ES roof intact,  $\%ES_{wall\ intact}$
- Percentage of ES walls intact,  $\%ES_{roof\ intact}$

#### 4.3.2 STEP 10: Assess $P_{f(b)}$ , $P_{maji(b)}$ , $P_{mini(b)}$ .

Step 10 completes the Structural Response Branch by determining the probability of fatality due to overall building damage,  $P_{f(b)}$ , probability of major injury due to overall building damage,  $P_{maji(b)}$ , probability of minor due to overall building damage,  $P_{mini(b)}$ .

Inputs to Step 10:

- Probability of fatality due to window breakage,  $P_{f(g)}$  [from Step 9]
- Probability of fatality due to building collapse,  $P_{f(bc)}$  [from Step 9]
- Probability of major injury due to window breakage,  $P_{maji(g)}$  [from Step 9]
- Probability of major injury due to building collapse,  $P_{maji(bc)}$  [from Step 9]
- Probability of minor injury due to window breakage,  $P_{mini(g)}$  [from Step 9]
- Probability of minor injury due to building collapse,  $P_{mini(bc)}$  [from Step 9]



Calculate the probability of fatalities due to overall building damage,  $P_{f(b)}$ , by:

$$P_{f(b)} = P_{f(g)} + [(1 - P_{f(g)}) * P_{f(bc)}] \quad (95)$$

Calculate the probability of major injury due to overall building damage,  $P_{maji(b)}$ , by:

$$P_{maji(b)} = P_{maji(g)} + [(1 - P_{maji(g)}) * P_{maji(bc)}] \quad (96)$$

Calculate the probability of minor injury due to overall building damage,  $P_{mini(b)}$ , by:

$$P_{mini(b)} = P_{mini(g)} + [(1 - P_{mini(g)}) * P_{mini(bc)}] \quad (97)$$

Outputs of Step 10:

- Probability of fatality due to overall building damage,  $P_{f(b)}$
- Probability of major injury due to overall building damage,  $P_{maji(b)}$
- Probability of minor injury due to overall building damage,  $P_{mini(b)}$

#### 4.4 Group 4 Steps: Debris Branch

Group 4 includes Steps 11-18 of the SAFER architecture. These steps determine the consequences of flying debris.

SAFER considers three types of debris: primary debris, secondary debris, and ejecta. Primary debris originates from the explosives item. Secondary debris originates from the PES. The PES roof, front wall, side walls, and rear wall are sources of secondary debris. Ejecta are debris originating from the ground or foundation of the PES. The debris generated by the ES is addressed in the building collapse portion of the tool in Group 3, Steps 9-10, Structural Response Branch.

All of the debris is characterized as a function of mass and Kinetic Energy (KE) in Steps 11-14. Steps 11-13 describe the primary fragments and determine maximum throw ranges and mass of the primary fragments that escape the PES. Step 14 describes the secondary fragments and ejecta and determines maximum throw ranges and mass of these fragments.

Steps 15-18 characterize the debris arriving at the ES and then determine the ultimate effect. Step 15 defines a debris density as a function of distance from the PES using a bivariate-normal distribution. Step 16 produces a combined KE table for all arriving fragments at the ES. Step 17 determines the arriving fragments that perforate the ES and describes the KE of the fragments after perforating the ES roof and walls. Finally, Step 18 calculates the probability of fatality due to debris,  $P_{f(d)}$ .

To enhance readability, selected reference tables of constants used in the Group 4 steps are located in Appendix A.

##### 4.4.1 KE/Mass Bin Methodology

The goal of Steps 11-17 is to determine the KE for each bin of fragments at the location of the exposed personnel. This permits the calculation of the probability of fatality due to debris as a function of KE in Step 18.

To facilitate the characterization of debris KE, SAFER first defines ten bins in terms of KE, which will be useful in Step 18. Each bin is  $\frac{1}{2}$  order of magnitude in width. SAFER then defines the average mass that, at terminal velocity, produces the KE midpoint for each bin, which allows for the creation of ten corresponding mass bins.

Table 13, *SAFER KE/Mass Bin Format*, presents these ten bins. Table 13 also shows the maximum and minimum KE values for each bin and the average mass of each departing fragment associated with the KE bins.

**Table 13. SAFER KE/Mass Bin Format**

| Bin #                                  | Bin 1  | Bin 2 | Bin 3 | Bin 4 | Bin 5 | Bin 6 | Bin 7 | Bin 8  | Bin 9  | Bin 10 |
|----------------------------------------|--------|-------|-------|-------|-------|-------|-------|--------|--------|--------|
| KE Min (ft-lbs)                        | 100k   | 30k   | 10k   | 3k    | 1k    | 300   | 100   | 30     | 10     | 3      |
| KE Average (ft-lbs)                    | 173k   | 54k   | 17k   | 5k    | 1.7k  | 547   | 173   | 54     | 17     | 5      |
| KE Max (ft-lbs)                        | ≥ 300k | 100k  | 30k   | 10k   | 3k    | 1k    | 300   | 100    | 30     | 10     |
| Average Fragment Mass (steel) (lbs)    | 35.7   | 14.9  | 6.34  | 2.66  | 1.13  | 0.473 | 0.199 | 0.0852 | 0.0379 | 0.0142 |
| Average Fragment Mass (concrete) (lbs) | 75.4   | 31.5  | 13.4  | 5.61  | 2.38  | 1     | 0.42  | 0.18   | 0.08   | 0.03   |

#### 4.4.2 STEP 11: Describe primary fragments.

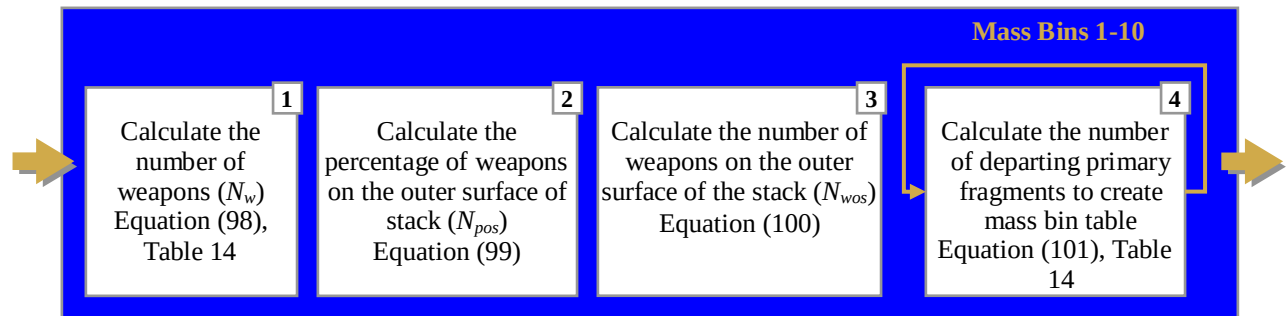
Step 11 begins the characterization of the primary fragments by performing two functions in SAFER. In Step 11a, SAFER determines the number of primary fragments distributed over ten mass bins. Section 4.4.2.1 describes the procedures for this step. In Step 11b, SAFER determines the maximum throw range of the primary fragments. Section 4.4.2.2 describes the procedures for this step.

Inputs to Step 11:

- $W_1$  (lbs), [from Step 4]
- Weapon type [from Step 1]

##### 4.4.2.1 Step 11a: Primary Fragment Determination

Primary fragments result from the breakup of the explosives casing or packaging. The departing primary fragments for the explosive event are determined in five substeps.



##### Substep 1

The number of weapons,  $N_w$ , is calculated by:

$$N_w = \frac{W_1}{\text{NEWQD of one weapon}} \quad (98)$$

where the NEWQD of one weapon is provided in Table 14, *Primary Fragment Distribution by Mass Bins*.



**Table 14. Primary Fragment Distribution by Mass Bins**

| Weapon Type            | NEWQD of one weapon (lbs) | Fragments Resulting from One Single Item |   |   |   |   |    |     |      |      |      |
|------------------------|---------------------------|------------------------------------------|---|---|---|---|----|-----|------|------|------|
|                        |                           | Mass Bin #s                              |   |   |   |   |    |     |      |      |      |
|                        |                           | 1                                        | 2 | 3 | 4 | 5 | 6  | 7   | 8    | 9    | 10   |
| MK82                   | 192                       | 0                                        | 0 | 0 | 0 | 7 | 49 | 226 | 746  | 1227 | 1738 |
| MK83                   | 445                       | 0                                        | 0 | 0 | 0 | 0 | 75 | 344 | 1134 | 1866 | 2643 |
| MK84                   | 945                       | 0                                        | 0 | 0 | 0 | 1 | 72 | 338 | 1116 | 1835 | 2599 |
| M107                   | 15.1                      | 0                                        | 0 | 0 | 0 | 0 | 4  | 34  | 165  | 372  | 667  |
| Bulk/light case        | 30                        | 0                                        | 0 | 0 | 0 | 0 | 0  | 0   | 1    | 5    | 10   |
| AIM-7 missile          | 35                        | 0                                        | 0 | 0 | 0 | 0 | 0  | 3   | 155  | 30   | 12   |
| M1 (105 mm) projectile | 5                         | 0                                        | 0 | 0 | 0 | 0 | 2  | 20  | 99   | 224  | 401  |
| MK2 (40 mm)            | 0.2                       | 0                                        | 0 | 0 | 0 | 0 | 0  | 4   | 19   | 44   | 79   |

#### Substep 2

The proportion of weapons on the outer surface of the stack,  $N_{pos}$ , is calculated by:

$$N_{pos} = 3.8474 * N_w^{-1/3} \quad (99)$$

Rationale for Eq. (99) is detailed in Attachment 8.

#### Substep 3

The number of weapons on the outer surface,  $N_{wos}$ , is calculated by:

$$N_{wos} = N_w * N_{pos} \quad (100)$$

Note, if  $N_{wos}$  is greater than  $N_w$ , then  $N_{wos}$  is set equal to  $N_w$ .

#### Substep 4

SAFER next creates the departing primary fragment mass bin table. This table describes the number of departing primary fragments from the stack. The number of fragments is based on the weapon type, number of primary fragments, and number of weapons on the outer surface. SAFER determines the number of departing primary fragments,  $N_{pf}$ , for the mass bins of this table by using the following algorithm:

For  $n = 1$  to 10

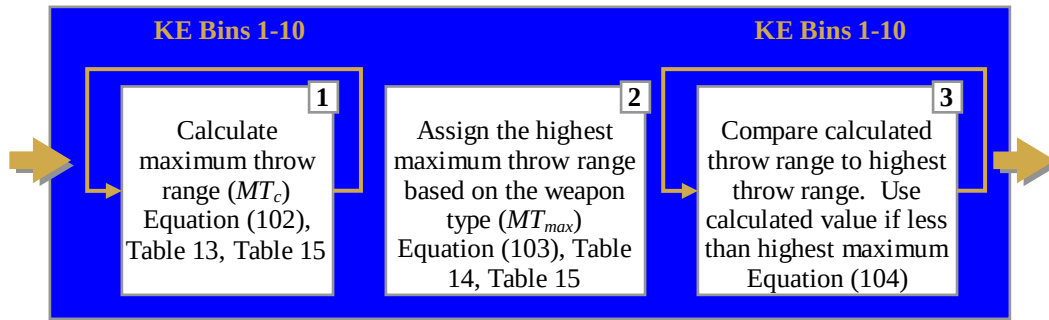
$$\text{Bin } n: N_{pf} = \text{Total No. of primary fragments} * N_{wos} * 0.75 \quad (101)$$

Next  $n$ ,

where the *Total No. of primary fragments* is provided in Table 14, *Primary Fragment Distribution by Mass Bins*. Rationale for Eq. (101) is detailed in Attachment 8.

#### 4.4.2.2 Step 11b: Primary Fragment Maximum Throw Determination

In Step 11b, SAFER creates the primary maximum throw range table.



#### Substep 1

Calculate the maximum throw range,  $MT_c$ , by:

For  $n = 1$  to 10

$$\text{Bin } n: MT_c = 300 * IV^{0.36} * (\text{Average Fragment Mass (steel)})^{0.21} \quad (102)$$

Next  $n$ ,

where the initial velocity,  $IV$ , is provided in Table 15, *Primary Fragment Initial Velocity and Maximum Throw Values*, and the *Average Fragment Mass (steel)* is found in Table 13, *SAFER KE/Mass Bin Format*.

**Table 15. Primary Fragment Initial Velocity and Maximum Throw Values**

| Weapon Type            | IV (ft/s) | $MT_i$ (ft) | $MT_m$ (ft) |
|------------------------|-----------|-------------|-------------|
| MK82                   | 5200      | 3177        | 3812        |
| MK83                   | 6100      | 3288        | 3946        |
| MK84                   | 4710      | 3882        | 4658        |
| M107                   | 3430      | 2577        | 3092        |
| Bulk/light case        | 4000      | 1870        | 1870        |
| AIM-7 missile          | 6500      | 2200        | 2640        |
| M1 (105 mm) projectile | 4100      | 1939        | 2327        |
| MK2 (40 mm)            | 3600      | 1095        | 1314        |

#### Substep 2

Assign the highest maximum throw range,  $MT_{max}$ , based on the weapon type.

If  $W_1 > NEWQD$  of one weapon,

Then  $MT_{max} = MT_m$

Else  $MT_{max} = MT_i$  (103)

where *NEWQD of one weapon* is provided Table 14, *Primary Fragment Distribution by Mass Bins*, and the maximum throw for multiple weapons,  $MT_m$ , and the maximum throw for a single weapon,  $MT_i$ , are provided in Table 15, *Primary Fragment Initial Velocity and Maximum Throw Values*.

### Substep 3

SAFER compares the calculated maximum throw,  $MT_c$ , to  $MT_{max}$  to determine the final maximum throw values,  $R_M$ .

```

For  $n = 1$  to 10
  Bin  $n$ : If  $MT_c > MT_{max}$ ,
    Then  $R_M = MT_{max}$ 
    Else  $R_M = MT_c$ 
Next  $n$ ,

```

(104)

Outputs of Step 11:

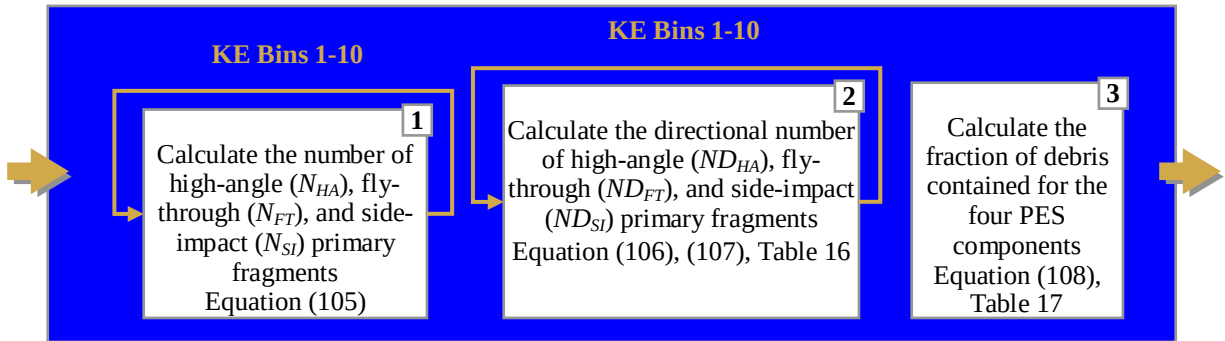
- Departing primary fragment mass bin table
- Primary maximum throw range table
- Primary fragment initial velocity,  $IV$

### 4.4.3 STEP 12: Calculate primary fragment containment by PES (post P, I).

If the situation includes a PES structure, the components of the structure remaining after the explosives event may block departing primary fragments. Step 12 calculates the fraction of primary fragments blocked by the components of the PES structure (roof, front wall, side walls, and rear wall).

Inputs to Step 12:

- PES building type [from Step 2]
- Fraction of PES roof intact,  $PES_{intact(roof)}$  [from Step 6]
- Fraction of PES front wall intact,  $PES_{intact(fw)}$  [from Step 6]
- Fraction of PES side walls intact,  $PES_{intact(sw)}$  [from Step 6]
- Fraction of PES rear wall intact,  $PES_{intact(rw)}$  [from Step 6]
- Departing primary fragment mass bin table [from Step 11]
- Orientation of PES to ES [from Step 3]



### Substep 1

For all primary fragments, calculate the number of high-angle fragments,  $N_{HA}$ , side-impact fragments,  $N_{SI}$ , and fly-through fragments,  $N_{FT}$ , for each bin by using the following algorithm:

For  $n = 1$  to 10

$$\text{Bin } n: N_{HA} = N_{pf} * 0.25$$

$$\text{Bin } n: N_{FT} = N_{pf} * 0.675 \quad (105)$$

$$\text{Bin } n: N_{SI} = N_{pf} * 0.075$$

Next  $n$ ,

### Substep 2

The primary fragments are further split into fragments that could be blocked by each PES component. Side-impact fragments,  $N_{SI}$ , and fly-through fragments,  $N_{FT}$ , are blocked by the front wall, side walls, and rear wall components. The high-angle fragments,  $N_{HA}$ , are all assumed to be blocked by the roof component.

For each wall component, the directional number of side-impact fragments,  $ND_{SI}$ , and the directional number of fly-through fragments,  $ND_{FT}$ , are calculated.

For  $j = 1$  to 3

component table (front wall, side walls, rear wall)  $j$ :

For  $n = 1$  to 10

$$\text{Bin } n: ND_{FT} = N_{FT} * PES_{fraction}$$

$$\text{Bin } n: ND_{SI} = N_{SI} * PES_{fraction} \quad (106)$$

Next  $n$ ,

Next  $j$ ,

For the roof the directional number of high-angle fragments,  $ND_{HA}$ , is calculated.

component table (roof)  $j$ :

For  $n = 1$  to 10

$$\text{Bin } n: ND_{HA} = N_{HA} * PES_{fraction} \quad (107)$$

Next  $n$ ,

where  $N_{FT}$ ,  $N_{SI}$ , and  $N_{HA}$  are from Substep 1 and  $PES_{fraction}$  is the fraction of PES area by component provided in Table 16, *Ratio of Area of each PES Component to Total PES Surface Area*, based on the PES building type.

**Table 16. Ratio of Area of each PES Component to Total PES Surface Area**

| PES                           | Orientation of PES to ES | Fraction Area Roof | Fraction Area Front Wall | Fraction Area Side Walls | Fraction Area Rear Wall |
|-------------------------------|--------------------------|--------------------|--------------------------|--------------------------|-------------------------|
| Pre-engineered metal building | NA                       | 1                  | 0.17                     | 0.67                     | 0.17                    |
| Large concrete arch ECM       | Front                    | 1                  | 1                        | 0                        | 0                       |
|                               | Side                     | 1                  | 0                        | 1                        | 0                       |
|                               | Rear                     | 1                  | 0                        | 0                        | 1                       |
| Medium concrete arch ECM      | Front                    | 1                  | 1                        | 0                        | 0                       |
|                               | Side                     | 1                  | 0                        | 1                        | 0                       |
|                               | Rear                     | 1                  | 0                        | 0                        | 1                       |
| Small concrete arch ECM       | Front                    | 1                  | 1                        | 0                        | 0                       |
|                               | Side                     | 1                  | 0                        | 1                        | 0                       |
|                               | Rear                     | 1                  | 0                        | 0                        | 1                       |
| Large steel arch ECM          | Front                    | 1                  | 1                        | 0                        | 0                       |
|                               | Side                     | 1                  | 0                        | 1                        | 0                       |
|                               | Rear                     | 1                  | 0                        | 0                        | 1                       |
| Medium steel arch ECM         | Front                    | 1                  | 1                        | 0                        | 0                       |
|                               | Side                     | 1                  | 0                        | 1                        | 0                       |
|                               | Rear                     | 1                  | 0                        | 0                        | 1                       |
| Small steel arch ECM          | Front                    | 1                  | 1                        | 0                        | 0                       |
|                               | Side                     | 1                  | 0                        | 1                        | 0                       |
|                               | Rear                     | 1                  | 0                        | 0                        | 1                       |
| Hardened aircraft shelter     | Front                    | 1                  | 1                        | 0                        | 0                       |
|                               | Side                     | 1                  | 0                        | 1                        | 0                       |
|                               | Rear                     | 1                  | 0                        | 0                        | 1                       |
| Large AGBS                    | NA                       | 1                  | 0.29                     | 0.42                     | 0.29                    |
| Medium AGBS                   | NA                       | 1                  | 0.25                     | 0.50                     | 0.25                    |
| Small AGBS (square)           | NA                       | 1                  | 0.25                     | 0.50                     | 0.25                    |
| Medium concrete building      | NA                       | 1                  | 0.25                     | 0.50                     | 0.25                    |
| Small concrete building       | NA                       | 1                  | 0.25                     | 0.50                     | 0.25                    |
| Hollow clay tile              | NA                       | 1                  | 0.17                     | 0.67                     | 0.17                    |
| Ship (large)                  | NA                       | 1                  | 0.09                     | 0.82                     | 0.09                    |
| Ship (medium)                 | NA                       | 1                  | 0.12                     | 0.77                     | 0.12                    |
| Ship (small)                  | NA                       | 1                  | 0.16                     | 0.69                     | 0.16                    |
| ISO Container                 | NA                       | 1                  | 0.14                     | 0.72                     | 0.14                    |

Note: for the PESs that have an orientation associated with them (earth covered magazines and hardened aircraft shelter), the  $PES_{intact}$  is assigned based on the orientation. For example, if the orientation is “front” then the front wall component is assigned a “1” and the other 2 components are assigned a “zero.”

### Substep 3

For the four PES components (roof, front wall, side walls, and rear wall), calculate the fraction of debris (primary fragments) contained by the PES,  $PES_{DC}$ , by:

$$PES_{DC} = PES_{intact} * FB \quad (108)$$

where  $PES_{intact}$  is determined in Step 6 for each component,  $FB$  is the fragment blocking coefficient provided in Table 17, *Fragment Blocking Coefficients by PES Component*, based on the PES building type.

**Table 17. Fragment Blocking Coefficients by PES Component**

| PES                                        | Roof | Front Wall | Side Walls | Rear Wall |
|--------------------------------------------|------|------------|------------|-----------|
| Pre-engineered metal building              | 0.15 | 0.10       | 0.10       | 0.10      |
| Large concrete arch ECM                    | 0.80 | 0.60       | 0.90       | 0.90      |
| Medium concrete arch ECM                   | 0.80 | 0.60       | 0.90       | 0.90      |
| Small concrete arch ECM                    | 0.80 | 0.60       | 0.90       | 0.90      |
| Large steel arch ECM                       | 0.80 | 0.60       | 0.90       | 0.90      |
| Medium steel arch ECM                      | 0.80 | 0.60       | 0.90       | 0.90      |
| Small steel arch ECM                       | 0.80 | 0.60       | 0.90       | 0.90      |
| Hardened aircraft shelter                  | 0.80 | 0.60       | 0.80       | 0.90      |
| Large aboveground brick structure          | 0.25 | 0.60       | 0.60       | 0.60      |
| Medium aboveground brick structure         | 0.25 | 0.60       | 0.60       | 0.60      |
| Small aboveground brick structure (square) | 0.25 | 0.60       | 0.60       | 0.60      |
| Medium concrete building                   | 0.25 | 0.60       | 0.60       | 0.60      |
| Small concrete building                    | 0.25 | 0.60       | 0.60       | 0.60      |
| Hollow clay tile                           | 0.25 | 0.25       | 0.25       | 0.25      |
| Ship (small)                               | 0.20 | 0.20       | 0.20       | 0.20      |
| Ship (medium)                              | 0.20 | 0.20       | 0.20       | 0.20      |
| Ship (large)                               | 0.20 | 0.20       | 0.20       | 0.20      |
| ISO Container                              | 0.15 | 0.10       | 0.10       | 0.10      |

Outputs of Step 12:

- Directional number of departing primary fly-through fragment tables,  $ND_{FT}$  (one for the front wall, side wall, and rear wall)
- Directional number of departing primary side-impact fragment tables,  $ND_{SI}$  (one for the front wall, side wall, and rear wall)
- Directional number of departing primary high-angle fragment tables,  $ND_{HA}$  (one for roof)
- Fraction of debris (primary fragments) contained by each PES component,  $PES_{DC}$

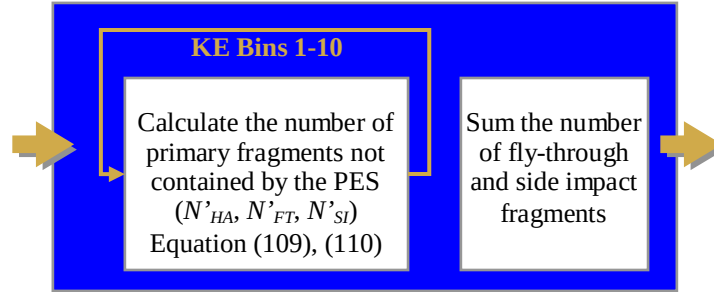
#### **4.4.4 STEP 13: Reduce number of primary fragments (due to PES).**

Step 13 adjusts the departing primary fragment KE bin table to account for those fragments that are contained by the PES.

Inputs to Step 13:

- Directional number of departing primary fly-through fragment tables,  $ND_{FT}$  (one for the front wall, side wall, and rear wall) [from Step 12]
- Directional number of departing primary side-impact fragment tables,  $ND_{SI}$  (one for the front wall, side wall, and rear wall) [from Step 12]

- Directional number of departing primary high-angle fragment tables,  $ND_{HA}$  (one for roof) [from Step 12]
- Fraction of debris (primary fragments) contained by each PES component,  $PES_{DC}$  [from Step 12]



### Substep 1

SAFER determines the number of primary fragments not contained by the PES,  $N'_{HA}$ ,  $N'_{FT}$ ,  $N'_{SI}$ , for each bin of the departing primary fragment KE bin tables by using the following algorithm:

For  $j = 1$  to 3  
     component table (front wall, side walls, rear wall)  $j$ :  
     For  $n = 1$  to 10  
         Bin  $n$ :  $N'_{FT} = N'_{FT} * (1 - PES_{DC})$   
         Bin  $n$ :  $N'_{SI} = N'_{SI} * (1 - PES_{DC})$   
     Next  $n$ ,  
 Next  $j$ ,

(109)

component table (roof)  $j$ :  
 For  $n = 1$  to 10  
     Bin  $n$ :  $N'_{HA} = N'_{HA} * (1 - PES_{DC})$   
 Next  $n$ ,

(110)

where  $PES_{DC}$  is calculated in Substep 3 of Step 12 and the number of fragments ( $N'_{FT}$ ,  $N'_{SI}$ , and  $N'_{HA}$ ) are determined in Substep 2 of Step 12.

### Substep 2

To prepare the departing primary fragment tables for Step 15, the three wall fly-through tables are summed to form one fly-through table and the three wall side-impact tables are summed to form one side-impact table.

Outputs of Step 13:

- Adjusted departing primary high-angle fragment mass bin table
- Adjusted departing primary fly-through fragment mass bin table
- Adjusted departing primary side-impact fragment mass bin table

#### 4.4.5 STEP 14: Describe secondary fragments and crater ejecta.

Step 14 characterizes secondary fragments and ejecta by performing four functions in SAFER. In Step 14a, SAFER determines the number of secondary fragments distributed over ten KE bins. Section 4.4.5.1 describes the procedures for this step. In Step 14b, SAFER determines the maximum throw range of the secondary fragments. Section 4.4.5.2 describes the procedures for this step. In Step 14c, SAFER determines the number of ejecta fragments distributed over ten KE bins. Section 4.4.5.3 describes the procedures for this step. In Step 14d, SAFER determines the maximum throw range of the ejecta fragments. Section 4.4.5.4 describes the procedures for this step.

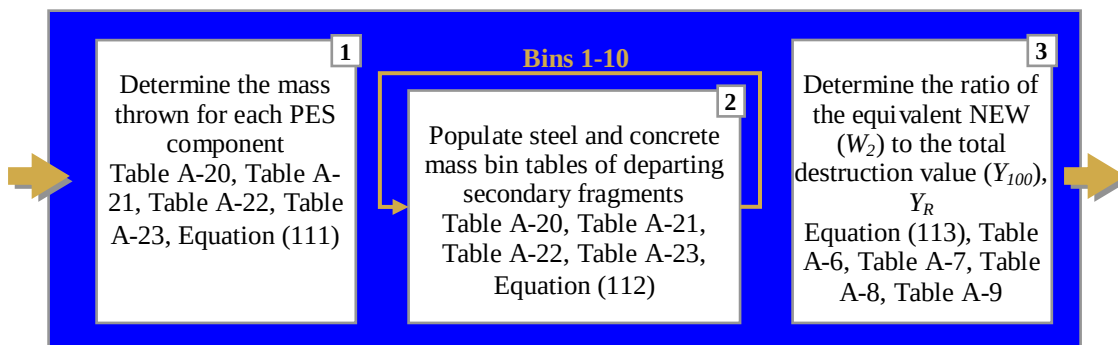
Inputs to Step 14:

- PES building type [from Step 2]
- Soil type [from Step 2]
- Equivalent NEW (lbs),  $W_2$  [from Step 4]
- Fraction of PES roof damaged,  $PES_{damage(roof)}$  [from Step 6]
- Fraction of PES front wall damaged,  $PES_{damage(fw)}$  [from Step 6]
- Fraction of PES side walls damaged,  $PES_{damage(sw)}$  [from Step 6]
- Fraction of PES rear wall damaged,  $PES_{damage(rw)}$  [from Step 6]

##### 4.4.5.1 Step 14a: Secondary Fragment Determination

Secondary debris is defined as the debris resulting from the breakup of the PES. The departing secondary debris is stored in mass bin tables that are converted into KE bin tables. A separate table is created for each of the four PES components (roof, front wall, side walls, and rear wall).

The departing secondary debris is determined using four substeps.



##### Substep 1

For each PES component, the mass of the PES thrown is determined by comparing the equivalent NEW to an initial breakout value ( $Y_0$ ) and a total destruction value ( $Y_{100}$ ), as described in Section 4.2.2.2.

For each of the four PES components, SAFER adjusts the PES mass thrown by using Eq. (5).

For  $i = 1$  to 4  
PES Component  $i$ :



$$\text{Mass of PES thrown} = \text{mass of PES component} * \text{PES}_{\text{damage}(i)} \quad (111)$$

Next  $i$ ,

where  $\text{PES}_{\text{damage}}$  is calculated for each component in Step 6 and the mass of each PES component by PES building type is provided in Table A-20, *Mass Distribution for PES Roof*, Table A-21, *Mass Distribution for PES Front Wall*, Table A-22, *Mass Distribution for PES Side Walls*, and Table A-23, *Mass Distribution for PES Rear Wall*.

### Substep 2

SAFER creates departing secondary fragments mass bin tables. A unique table is created for each type of material (concrete and steel) in each PES component. Therefore, a total of eight departing secondary fragments mass bin tables are created from this procedure. The mass bin tables are created by using the following algorithm to determine the number of secondary fragments,  $N_{sf}$ , in each bin:

$$\begin{aligned} &\text{For } i = 1 \text{ to } 4 \\ &\quad \text{For } j = 1 \text{ to } 2 \\ &\quad \quad \text{PES Component } i \text{ and Material } j: \\ &\quad \quad \text{For } n = 1 \text{ to } 10 \\ &\quad \quad \quad \text{Bin } n: \\ &\quad \quad \quad N_{sf} = \frac{\text{Mass of PES thrown} * (\text{Percent Mass})}{\text{Average Fragment Mass (by material)}} * (\text{Percent Material}) \\ &\quad \quad \quad \text{Next } n, \\ &\quad \quad \text{Next } j, \\ &\quad \text{Next } i, \end{aligned} \quad (112)$$

where *Mass of PES thrown* is calculated in Substep 1, *Average Fragment Mass* is found in Table 13, *SAFER KE/Mass Bin Format*, and the percentage of mass per bin, *Percent mass*, and the percentages of material in each material in each PES component, *Percent Material*, are provided in the following tables: Table A-20, *Mass Distribution for PES Roof*, Table A-21, *Mass Distribution for PES Front Wall*, Table A-22, *Mass Distribution for PES Side Walls*, and Table A-23, *Mass Distribution for PES Rear Wall*.

Rationale for the methodology used in this Step 14a is detailed in Attachment 8.

### Substep 3

Finally, the percentage of mass thrown per bin is determined by taking the nominal mass distribution (from Substep 2) and adjusting it based on the yield. As the yield increases beyond the total destruction value,  $Y_{100}$ , the mass distribution percentages by bin are re-calculated. This method allows the modeling of the phenomena that produces more, smaller pieces in larger explosive events.

The methodology for this recalculation is as follows:

The ratio ( $Y_R$ ) of the equivalent NEW ( $W_2$ ) to the total destruction value ( $Y_{100}$ ) is determined using Eq. (113):

$$Y_R = \frac{W_2}{Y_{100}} \quad (113)$$

where  $W_2$  = Equivalent NEW (lbs), [from Step 4], and the  $Y_{100}$  values are provided in Table A-6, *Damage Coefficients for the PES Roof*, Table A-7, *Damage Coefficients for the PES Front Wall*, Table A-8, *Damage Coefficients for the PES Side Walls*, and Table A-9, *Damage Coefficients for the PES Rear Wall*.  $Y_R$  is compared to a stored parameter (for each bin) that represents the Initial Reduction Ratio, *IRR*, shown in Table 18, *Initial Reduction Ratios for Each Bin*.

**Table 18. Initial Reduction Ratios for Each Bin**

|            | Bin 1 | Bin 2 | Bin 3 | Bin 4 | Bin 5 | Bin 6 | Bin 7  | Bin 8  | Bin 9  | Bin 10  |
|------------|-------|-------|-------|-------|-------|-------|--------|--------|--------|---------|
| <i>IRR</i> | 1     | 64    | 729   | 4096  | 15625 | 46656 | 117649 | 262144 | 531441 | 1000000 |

If  $Y_R > IRR$  for that bin, a reduction for that bin is calculated as shown in Figure 7. If  $Y_R < IRR$ , no adjustment is made (to this or any subsequent bins).

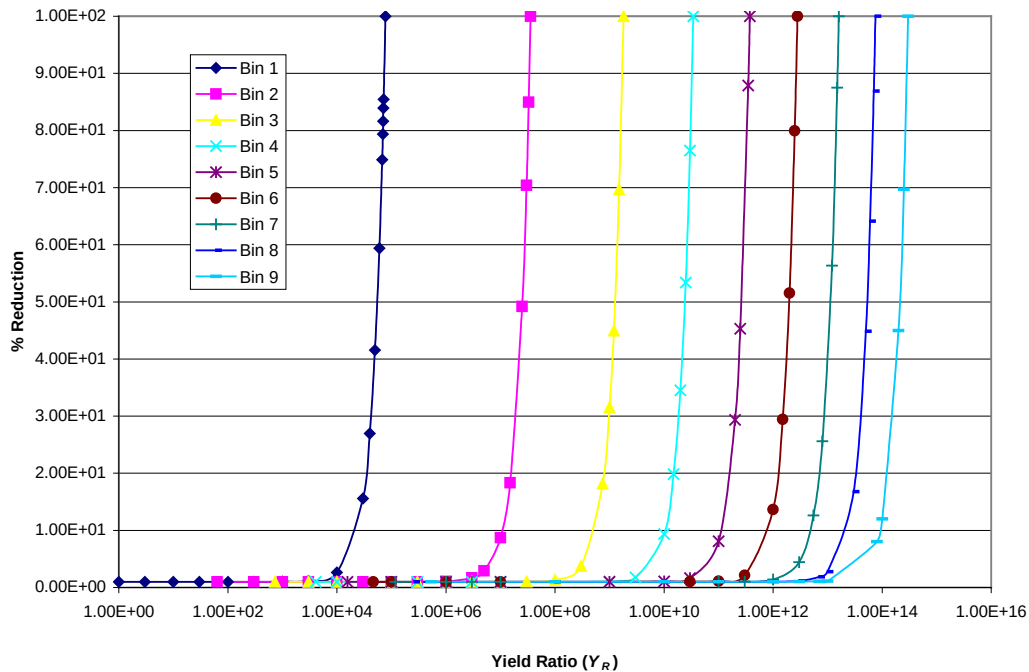
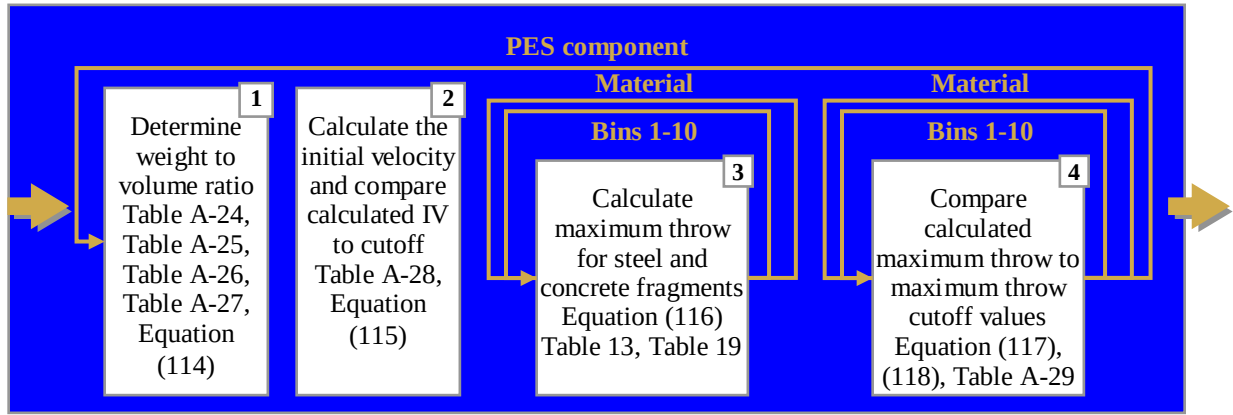


**Figure 7. % Reduction by Bin**

The reduced mass is redistributed evenly among the lower bins and then the process continues by comparing  $Y_R$  to the *IRR* value for the next bin.

#### 4.4.5.2 Step 14b: Secondary Fragment Maximum Throw Determination

In Step 14b, SAFER creates a unique maximum throw range table for each type of material (concrete and steel) in each PES component. Therefore, a total of eight tables are created in Substep 14b. The maximum throw range for secondary fragments is accomplished in four substeps.



#### Substep 1

For each of the four PES components, calculate the weight-to-volume ratio,  $W/V$ , by using the following algorithm:

For  $i = 1$  to 4  
 PES Component  $i$ :  $W/V = W_2 / V$  (114)  
 Next  $i$ ,

where  $W_2$  = Equivalent NEW (lbs), [from Step 4], and the volumes of each PES component,  $V$ , by PES building type are provided in the following tables: Table A-24, *Roof Component Characteristics*; Table A-25, *Front Wall Component Characteristics*; Table A-26, *Side Wall Component Characteristics*; and Table A-27, *Rear Wall Component Characteristics*.

#### Substep 2

For each of the four PES components, an initial velocity is calculated,  $IV_c$ . The calculated velocity is compared to a maximum initial velocity value. If the calculated value is greater than the maximum value, the maximum value is used. Alternatively, if the calculated value is less than the maximum value, the calculated value is used. Calculate the initial velocity,  $IV_c$ , for each PES component as follows:

For  $i = 1$  to 4  
 PES Component  $i$ :  
 $IV_c = a_{IV} * (W / V)^{exp_{iv}}$  (115)  
 If  $IV_c > IV_{max}$   
 Then  $IV = IV_{max}$   
 Else If  $IV_c < IV_{max}$   
 Then  $IV = IV_c$   
 Next  $i$ ,

where the constants  $a_{iv}$  and  $exp_{iv}$  and the initial velocity maximum value,  $IV_{max}$ , are provided for each PES component in Table A-28, *Secondary Fragment Initial Velocity*.

#### Substep 3

Create a throw range table for concrete and steel fragments for each PES component. Calculate the maximum throw range for the concrete fragments,  $MT_c$ , and steel fragments,  $MT_s$ , by:

For  $i = 1$  to 4

PES Component  $i$ :  
For  $n = 1$  to 10  
Bin  $n$ :  $MT_c = CP * IV^{E1} * (Average\ Fragment\ Mass\ (concrete))^{E2}$   
 $MT_s = SP * IV^{E1} * (Average\ Fragment\ Mass\ (steel))^{E2}$   
Next  $n$ ,  
Next  $i$ ,

(116)

where the *Average fragment mass* is found in Table 13, *SAFER KE/Mass Bin Format*, and  $CP$ ,  $SP$ ,  $E1$ , and  $E2$  are found in Table 19, *Secondary Maximum Throw Parameters*.

**Table 19. Secondary Maximum Throw Parameters**

| PES                      | SP    | CP    | E1    | E2    |
|--------------------------|-------|-------|-------|-------|
| PEMB                     | 236.2 | 127.4 | 0.304 | 0.264 |
| Hollow Clay Tile         | 300   | 160   | 0.36  | 0.21  |
| HAS                      | 236.2 | 127.4 | 0.304 | 0.264 |
| Large Concrete Arch ECM  | 300   | 160   | 0.36  | 0.21  |
| Medium Concrete Arch ECM | 300   | 160   | 0.36  | 0.21  |
| Small Concrete Arch ECM  | 300   | 160   | 0.36  | 0.21  |
| Large Steel Arch ECM     | 300   | 160   | 0.36  | 0.21  |
| Medium Steel Arch ECM    | 300   | 160   | 0.36  | 0.21  |
| Small Steel Arch ECM     | 300   | 160   | 0.36  | 0.21  |
| Large AGBS               | 300   | 160   | 0.36  | 0.21  |
| Medium AGBS              | 300   | 160   | 0.36  | 0.21  |
| Small AGBS (Square)      | 300   | 160   | 0.36  | 0.21  |
| Medium Concrete Building | 300   | 160   | 0.36  | 0.21  |
| Small Concrete Building  | 300   | 160   | 0.36  | 0.21  |
| Ship (small)             | 236.2 | 127.4 | 0.304 | 0.264 |
| Ship (medium)            | 236.2 | 127.4 | 0.304 | 0.264 |
| Ship (large)             | 236.2 | 127.4 | 0.304 | 0.264 |
| ISO Container            | 236.2 | 127.4 | 0.304 | 0.264 |

#### Substep 4

SAFER compares the calculated maximum throws for concrete and steel,  $MT_c$  and  $MT_s$ , to  $MT_{max}$  to determine the final maximum throw values for concrete and steel,  $R_{MC}$  and  $R_{MS}$ .

For  $i = 1$  to 4  
PES Component  $i$ :  
For  $n = 1$  to 10 (concrete maximum throw table)  
Bin  $n$ : If  $MT_c > MT_{max}$ ,  
Then  $R_{MC} = MT_{max}$   
Else  $R_{MC} = MT_c$   
Next  $n$ ,

(117)

For  $n = 1$  to 10 (steel maximum throw table)  
Bin  $n$ : If  $MT_s > MT_{max}$ ,  
Then  $R_{MS} = MT_{max}$   
Else  $R_{MS} = MT_s$   
Next  $n$ ,

(118)

Next  $i$ ,

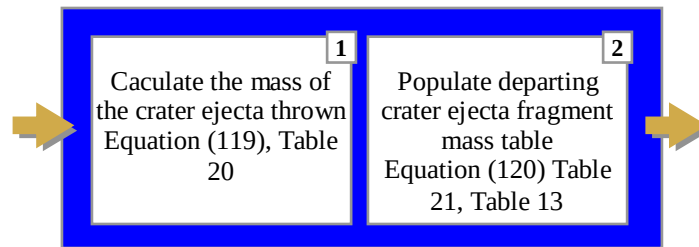
where  $MT_{max}$  is provided for each PES by component in Table A-29, *Secondary Fragment Maximum Throw Cutoff Values*.

#### 4.4.5.3 Step 14c: Crater Ejecta Determination

Ejecta is debris originating from the ground or foundation of the PES. The departing ejecta fragments are stored in a mass bin table that is converted into a KE bin table.

Characterization of the ejecta is based on the type of soil around the PES. Soil types considered by SAFER are dependent on the PES building type. SAFER considers soil types of either *rock or hard clay* or *looser soils* for PES building types of *open*, *pre-engineered metal building*, or *hollow clay tile*. The looser soils option is for soil less densely packed than rock or hard clay and would be expected to break up into smaller pieces. For all other PES types (excluding ships) the default soil type is *concrete*. SAFER prompts the user to select an appropriate soil type as part of the situation definition.

Based on these user inputs, crater ejecta is determined using two substeps.



##### Substep 1

Calculate the mass of the crater ejecta thrown, *Crater ejecta mass*, by:

$$\text{Crater ejecta mass} = A * (W_2)^B \quad (119)$$

where the crater mass coefficient,  $A$ , and the crater mass exponent,  $B$ , are provided in Table 20, *Soil Type Parameters*, based on the soil type.

**Table 20. Soil Type Parameters**

|                   | $A$   | $B$  | $g$ | $r$ |
|-------------------|-------|------|-----|-----|
| Rock or Hard Clay | 104.0 | 1.04 | 1.0 | 75  |
| Looser Soils      | 72.2  | 1.04 | 1.1 | 40  |
| Concrete          | 2.7   | 1.16 | 0.5 | 50  |

##### Substep 2

SAFER completes Step 14c by creating the departing crater ejecta fragment mass table. SAFER determines the number of crater ejecta fragments,  $N_{ce}$ , for the mass bins of this table by using the following algorithm:

For  $n = 1$  to 10

$$\text{Bin } n: N_{ce} = \frac{(\text{Crater ejecta mass} * \text{fraction each bin})}{\text{Average Fragment Mass (concrete)}} \quad (120)$$

Next  $n$ ,

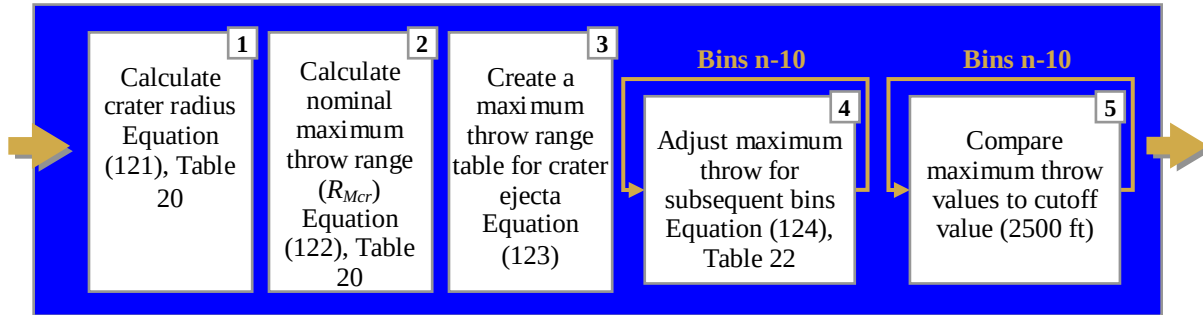
where the *fraction each bin* is provided in Table 21, *Fraction of Soil Thrown*, by soil type and the *Average fragment mass* for concrete fragments is found in Table 13, *SAFER KE/Mass Bin Format*.

**Table 21. Fraction of Soil Thrown**

| Soil Type         | Bin 1  | Bin 2   | Bin 3   | Bin 4   | Bin 5   | Bin 6  | Bin 7  | Bin 8  | Bin 9  | Bin 10 |
|-------------------|--------|---------|---------|---------|---------|--------|--------|--------|--------|--------|
| Rock or Hard Clay | 0.1666 | 0.0417  | 0.0417  | 0.0417  | 0.0417  | 0.0833 | 0.0833 | 0.0833 | 0.1667 | 0.25   |
| Looser soils      | 0.005  | 0.00125 | 0.00125 | 0.00125 | 0.00125 | 0.0025 | 0.0025 | 0.0025 | 0.56   | 0.4225 |
| Concrete          | 0.05   | 0.05    | 0.05    | 0.05    | 0.075   | 0.075  | 0.075  | 0.075  | 0.1    | 0.4    |

#### 4.4.5.4 Step 14d: Crater Ejecta Maximum Throw Range

In Step 14d, SAFER calculates the maximum throw range for crater ejecta.



##### Substep 1

Calculate the crater radius, *Crater radius*, by:

$$\text{Crater radius} = g * (W_2)^{\frac{1}{3}} \quad (121)$$

where the crater radius coefficient,  $g$  (ft/lb<sup>1/3</sup>), is provided in Table 20, *Soil Type Parameters*, by soil type and  $W_2$  = Equivalent NEW (lbs), [from Step 4].

##### Substep 2

Calculate the nominal maximum throw range,  $R_{Mcr}$ , by:

$$R_{Mcr} = r * \text{Crater radius} \quad (122)$$

where the crater ejecta range coefficient,  $r$ , is provided in Table 20, *Soil Type Parameters*, by soil type.

##### Substep 3

Create a maximum throw range table for crater ejecta by assigning the nominal maximum throw range,  $R_{Mcr}$ , to the lowest numbered bin that has fragments (first non-zero bin).

$k$  = bin number of first non-zero bin

$$R_{Mcr} ( \text{for bin } k ) = R_{Mcr} \quad (123)$$

#### Substep 4

SAFER determines the maximum throw ranges,  $R_{Mcr}$ , for the remaining bins of this table by using the following algorithm:

$k$  = bin number of first non-zero bin

For  $n = k + 1$  to 10

$$R_{Mcr} ( \text{for bin } n ) = (R_M \text{ for bin } n - 1) * \text{throw value for bin } n \quad (124)$$

Next  $n$ ,

where the ejecta throw values are provided in Table 22, *Nominal Maximum Throw Values for Ejecta*.

**Table 22. Nominal Maximum Throw Values for Ejecta**

| Material | Bin 1 | Bin 2 | Bin 3 | Bin 4 | Bin 5 | Bin 6 | Bin 7 | Bin 8 | Bin 9 | Bin 10 |
|----------|-------|-------|-------|-------|-------|-------|-------|-------|-------|--------|
| Ejecta   | 1.00  | 0.84  | 0.83  | 0.82  | 0.82  | 0.81  | 0.81  | 0.81  | 0.81  | 0.77   |

#### Substep 5

SAFER compares the calculated maximum throw ranges for each bin to 2,500 feet. If the calculated maximum range is greater than 2,500 feet, the value is reset to 2,500 feet.

Rationale for the methodology used in Step 14d is detailed in Attachment 8.

Outputs of Step 14:

- 4 Departing secondary steel debris mass tables (one table for each PES component)
- 4 Departing secondary concrete debris mass tables (one table for each PES component)
- 4 Steel maximum throw tables (one table for each PES component)
- 4 Concrete maximum throw tables (one table for each PES component)
- Departing crater ejecta fragment mass table
- Maximum throw range table for crater ejecta
- Initial velocity for each PES component,  $IV$

#### 4.4.6 STEP 15: Define expected arriving debris tables.

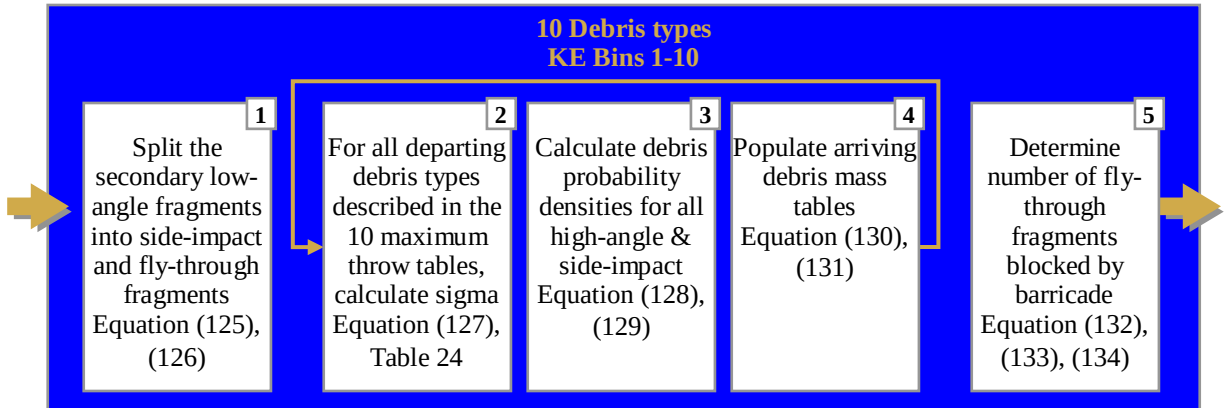
Steps 11 – 14 characterized debris fragments departing the PES. These fragments must now be translated from the donor to the target. Step 15 performs this task by creating arriving debris mass tables.

Inputs to Step 15:

- PES building type [from Step 2]
- Orientation of the PES to the ES [from Step 3]
- Distance between the PES and ES (ft),  $d$  [from Step 3]
- Barricade height (ft),  $h_2$  [from Step 3]
- Distance between the barricade and the ES (ft),  $d_1$  [from Step 3]
- ES building type [from Step 3]

- 12 departing fragment mass bin tables
  - Adjusted departing primary high-angle fragment mass bin table [from Step 13]
  - Adjusted departing primary fly-through fragment mass bin table [from Step 13]
  - Adjusted departing primary side-impact fragment mass bin table [from Step 13]
  - 4 Departing secondary steel debris mass tables [from Step 14]
  - 4 Departing secondary concrete debris mass tables [from Step 14]
  - Departing crater ejecta fragment mass table [from Step 14]
- 10 maximum throw tables
  - Primary maximum throw range table [from Step 11]
  - 4 Steel maximum throw tables [from Step 14]
  - 4 Concrete maximum throw tables [from Step 14]
  - Maximum throw range table for crater ejecta [from Step 14]

Translation of debris from departing to arriving fragments requires the calculation of debris probability densities at the ES,  $P_i$ , for primary, secondary, and crater debris.



Before SAFER calculates the probability densities, SAFER partitions the number of fragments departing the PES into high-angle and low-angle fragments. The low-angle fragments will impact the ES walls and the high-angle fragments will impact the ES roof in Step 17. The primary fragments were partitioned between high-angle and low-angle (side-impact and fly-through) fragments in Step 12. SAFER assumes that all PES roof material (steel and concrete) and crater ejecta are high-angle fragments. The steel and concrete from all other PES components (front wall, side walls, and rear wall) are assumed to be low-angle fragments. All secondary low-angle fragments are further partitioned into side-impact and fly-through debris (Substep 1). After the fragments are partitioned into high-angle and low-angle, and further partitioned into side-impact and fly-through fragments, there will be 18 departing debris tables, as shown in Table 23, *Debris Type Summary*.



**Table 23. Debris Type Summary**

| Fragment Source           | High-Angle | Side-Impact | Fly-through |
|---------------------------|------------|-------------|-------------|
| Primary                   | X          | X           | X           |
| PES Roof (Steel)          | X          |             |             |
| PES Roof (Concrete)       | X          |             |             |
| PES Front Wall (Steel)    |            | X           | X           |
| PES Front Wall (Concrete) |            | X           | X           |
| PES Side Walls (Steel)    |            | X           | X           |
| PES Side Walls (Concrete) |            | X           | X           |
| PES Rear Wall (Steel)     |            | X           | X           |
| PES Rear Wall (Concrete)  |            | X           | X           |
| Crater Ejecta             | X          |             |             |

The sigma value,  $\sigma$ , is a measure of the spread or dispersion of the fragments under consideration and determined by using the maximum throw as an extreme value. For primary and secondary debris, the extreme maximum throw is equal to  $3\sigma$ . For crater ejecta, the extreme maximum throw is  $4\sigma$ . These values are based on empirical data. Rationale for selecting these maximum throw values is detailed in Attachment 8.

Values for  $P_i$  are based on the maximum throw distances and the spatial distribution of these fragments. SAFER assumes that arriving high-angle and side-impact fragments follow a bivariate-normal distribution or pseudo-trajectory normal distribution. Rationale for selecting these distributions is detailed in Attachment 8.

#### *Substep 1*

SAFER splits the secondary low-angle fragments into side-impact and fly-through fragments. The side-impact fragments represent fragments that have reached terminal velocity and are falling when they hit a wall of the exposed site. The fly-through fragments are not falling at terminal velocity and have a predominately horizontal trajectory and are on their way up when they hit a wall of the exposed site. Note: The PES roof (steel and concrete) and crater ejecta fragments are not partitioned into fly-through and side-impact fragments. Therefore, the low-angle partition applies to only 6 out of the 12 fragment tables.

To create the fly-through and side-impact fragment tables, SAFER calculates the number of fly-through fragments,  $N_{FT}$ , for each bin using the following algorithm:

```
For  $j = 1$  to 6
  Fly-through fragment table  $j$ :
  For  $n = 1$  to 10
    Bin  $n$ :  $N_{FT} = N_{LA} * 0.5$ 
  Next  $n$ ,
Next  $j$ ,
```

(125)

where  $N_{LA}$  is the number of low-angle fragments for each bin.

To determine the number of secondary side-impact fragments per bin,  $N_{SI}$ , SAFER uses the following algorithm:

```
For  $j = 1$  to 6
```

Side-impact fragment table  $j$ :

For  $n = 1$  to 10

$$\text{Bin } n: N_{SI} = N_{LA} - N_{FT} \quad (126)$$

Next  $n$ ,

Next  $j$ ,

where  $N_{LA}$  is the number of low-angle fragments and  $N_{FT}$  is the number of fly-through fragments.

### Substep 2

For all departing debris types described in the 10 maximum throw tables, calculate a sigma value,  $\sigma$ , for each bin by:

For  $j = 1$  to 10

Maximum throw table  $j$ :

For  $n = 1$  to 10

$$\text{Bin } n: \sigma = \frac{f * R_M}{\sigma \text{ value of extreme data}} \quad (127)$$

Next  $n$ ,

Next  $j$ ,

where  $R_M$  is the maximum throw range in each bin and the reduced debris throw factor,  $f$ , is provided in Table 24, *Reduced Debris Throw Factors (f)*, by PES building type and debris type (for all other PES types  $f$  is equal to 1.0), and the  $\sigma$  value of extreme data is assumed to be 3.0 for primary and secondary fragments and 4.0 for crater ejecta fragments.

**Table 24. Reduced Debris Throw Factors (f)**

|               | Earth Covered Magazine |           | Hardened Aircraft Shelter |           |
|---------------|------------------------|-----------|---------------------------|-----------|
| Orientation   | Front                  | Side/Rear | Front                     | Side/Rear |
| Primary       | 1                      | 1         | 1                         | 1         |
| Roof          | 1                      | 1         | 1                         | 1         |
| Front wall    | 1                      | 0.01      | 1                         | 0.01      |
| Side walls    | 0.1                    | 1         | 0.1                       | 1         |
| Rear          | 0.001                  | 1         | 0.0001                    | 1         |
| Crater ejecta | 1                      | 1         | 1                         | 1         |

### Substep 3

For all high-angle and side-impact departing debris types described in the 11 associated departing fragment mass bin tables, calculate debris probability densities at the ES,  $P_i$ , for each bin by using the following algorithm:

For  $j = 1$  to 11

Maximum throw table  $j$ :

For  $n = 1$  to 10

$$\text{Bin } n: P_i = \frac{1}{(2\pi\sigma^2)} * e^{\left(\frac{-d^2}{2\sigma^2}\right)} \quad (128)$$

Next  $n$ ,

Next  $j$ ,

where  $\sigma$  is calculated in Substep 2 and  $d$  is the distance between the PES and ES.

For all fly-through departing debris types described in the 7 associated departing fragment mass bin tables, calculate debris probability densities at the ES,  $P_i$ , for each bin using the following algorithm:

$$\begin{aligned}
 &\text{For } j = 1 \text{ to } 7 \\
 &\quad \text{Maximum throw table } j: \\
 &\quad \text{For } n = 1 \text{ to } 10 \\
 &\quad \quad \text{Bin } n: P_i = \frac{1}{(2\pi\sigma_{FT}^2)} * e^{-0.5 * \left(\frac{d}{\sigma_{FT}}\right)^2} * \left(\frac{2\pi\sigma_{FT}^2}{2\pi d + \pi}\right)^{(1 - (d / 3\sigma_{FT})^{0.5})} \\
 &\quad \quad \text{Next } n, \\
 &\quad \text{Next } j,
 \end{aligned} \tag{129}$$

where  $\sigma_{FT}$  is equal to  $\sigma/2$  and  $d$  is the distance between the PES and ES.

#### Substep 4

SAFER creates arriving debris mass bin tables. For the high-angle and side-impact fragments described in the 11 departing fragment mass bin tables, the number of expected arriving fragments per square foot,  $N_{af}$ , per mass bin is calculated using the following algorithm:

$$\begin{aligned}
 &\text{For } j = 1 \text{ to } 11 \\
 &\quad \text{Arriving debris mass table } j: \\
 &\quad \text{For } n = 1 \text{ to } 10 \\
 &\quad \quad \text{Bin } n: N_{af} = P_i * \text{No. of departing fragments} \\
 &\quad \quad \text{Next } n, \\
 &\quad \text{Next } j,
 \end{aligned} \tag{130}$$

where *No. of departing fragments* is the number of fragments in the respective bins of each departing fragment mass bin table.

For the fly-through fragments described in the 7 departing fragment mass tables, the number of expected arriving fragments per square foot,  $N_{af}$ , per mass bin is calculated using the following algorithm:

$$\begin{aligned}
 &\text{For } j = 1 \text{ to } 7 \\
 &\quad \text{Arriving debris mass table } j: \\
 &\quad \text{For } n = 1 \text{ to } 10 \\
 &\quad \quad \text{Bin } n: N_{af} = P_i * \text{No. of departing fragments} \\
 &\quad \quad \text{Next } n,
 \end{aligned} \tag{131}$$

#### Substep 5: Barricade Reduction of Low Angle Fragments

In this substep, SAFER determines the percentage of arriving low angle fragments that would be blocked by the presence of a fixed barricade of a given height and distance from the PES. The computations in this substep are based on a number of assumptions:

- the trajectories of arriving low angle fragments can be modeled as straight lines
- all fragments leaving the PES at low angle are constrained to impinge on the ES if not blocked by a barricade

- fragments that are dispersed from the wall of a PES depart within a fixed half angle from the normal to the PES wall
- fragments are dispersed uniformly both with respect to height on the PES wall and with respect to their angle of departure

The blocking routine considers fragments ejected from the wall in even increments of height up to the height of the PES. Fragments are assumed to be ejected from the PES at angles between the *normal + (plus) the specified half angle* and the *normal – (minus) the specified half angle*. SAFER uses 5° for the half angle. At each height increment, the routine tests to determine whether the +/- half angles from normal impinge on the ES. If the full angular range (+/- the half angle) impinges on the ES, no adjustment is necessary. If not, the routine rotates the range of departure angles to ensure that all fly-through fragments leaving the PES arrive at the ES.

At each height increment, a number of angles are computed as shown in Figure 8, *Parameters Used in the ES Barricade Fragment Blocking Algorithm*, (all are measured from zenith). These angles are used for two purposes: first, to determine the shift required to focus all fly-through fragments onto the ES, and then to compute the fraction of the possible ejection angles that would be blocked by the barricade. After the blocked fraction is computed for each height increment, the fraction blocked is averaged over the entire height of the PES to determine the barricade effectiveness at blocking low angle PES fragments. The section below provides the equations used.

SAFER calculates the fraction of fragments blocked by the barricade at varying heights until the PES height,  $h1$ , is reached by:

For  $h = 0$  to  $h1$

$$T3 = \text{ACOS}[(h3-h) / \sqrt{d^2 + (h3-h)^2}]$$

$$B3 = \text{ACOS}[-(h) / \sqrt{d^2 + h^2}]$$

$$T2 = \text{ACOS}[(h2 - h) / \sqrt{d2^2 + (h2 - h)^2}]$$

If  $B3 < (90 + \frac{1}{2} \text{ angle})$

Then  $upper = \text{Maximum} [(B3 - 2 * \frac{1}{2} \text{ angle}), T3]$

Else  $upper = \text{Maximum} [(90 - \frac{1}{2} \text{ angle}), T3]$

If  $T3 > (90 - \frac{1}{2} \text{ angle})$

Then  $lower = \text{Minimum} [(T3 + 2 * \frac{1}{2} \text{ angle}), B3]$

Else  $lower = \text{Minimum} [(90 + \frac{1}{2} \text{ angle}), B3]$

$total \text{ angle} = lower - upper$

$blocked \text{ angle} = \text{Maximum} [0, (lower - \text{Maximum} [T2, upper])]$

$local \text{ reduction} = \text{Maximum} [0, (blocked \text{ angle} / total \text{ angle})]$

Next  $h$ ,

where  $h1$  is the height of the PES provided in Table 9, *PES Assumptions*,  $h2$  is the height of the barricade [from Step 3],  $h3$  is the height of the ES provided in Table A-10, *Pressure and Impulse Reduction Values Due to Glass Percentage*,  $h$  is the height increment under evaluation,  $d$  is the distance between the PES and ES,  $d1$  is the distance between the barricade and the ES [from Step

3],  $d2$  is the distance between the barricade and the PES,  $T3$  is the angle from  $h$  to the top of the ES,  $B3$  is the angle from  $h$  to the base of the ES,  $T2$  is the angle from  $h$  to the top of the barricade, *upper* is the upper projection of fragments from the PES to the ES, *lower* is the lower projection angle of fragments from the PES to the ES, *total angle* is the span of angles at which fragments are ejected, and *local reduction* is the fraction of fly-through fragments blocked at height  $h$ . The *local reduction* value is stored for each value of  $h$ . These values are depicted in Figure 8.

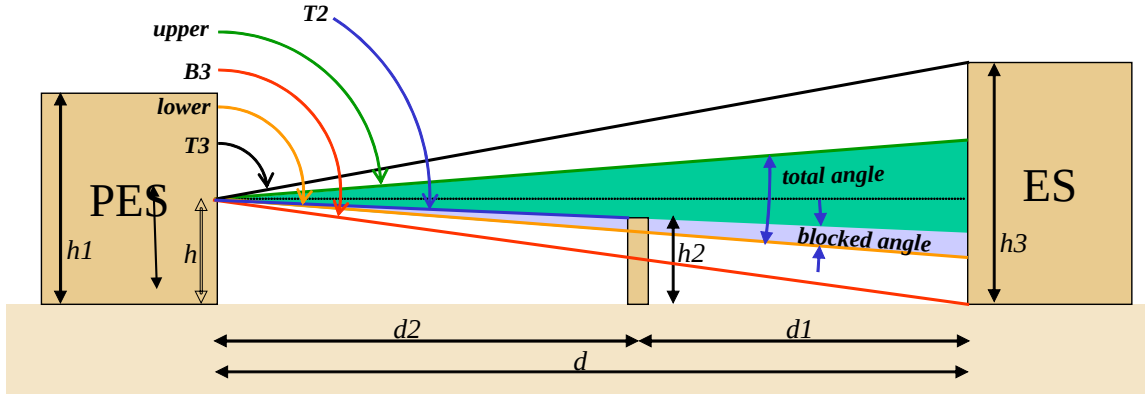


**Figure 8. Parameters Used in the ES Barricade Fragment Blocking Algorithm**

SAFER calculates the total fraction of fragments blocked by the barricade, *total reduction*, by:

$$totalreduction = \frac{\sum localreduction}{number\ of\ height\ increments} \quad (133)$$

SAFER then reduces the number of fly-through fragments per mass bin to account for those fragments that have been blocked by the barricade by:

$$\begin{aligned} &\text{For } j = 1 \text{ to } 7 \\ &\quad \text{Arriving debris mass table } j: \\ &\quad \text{For } n = 1 \text{ to } 10 \\ &\quad \quad \text{Bin } n: N_{af} = N_{af} * (1 - totalreduction) \\ &\quad \text{Next } n, \end{aligned} \quad (134)$$

where  $N_{af}$  is the number of fly-through fragments from Substep 7.

Rationale for the methodology used in this step and a comparison of SAFER predictions for arriving debris to empirical test data are detailed in Attachment 8.

Outputs of Step 15:

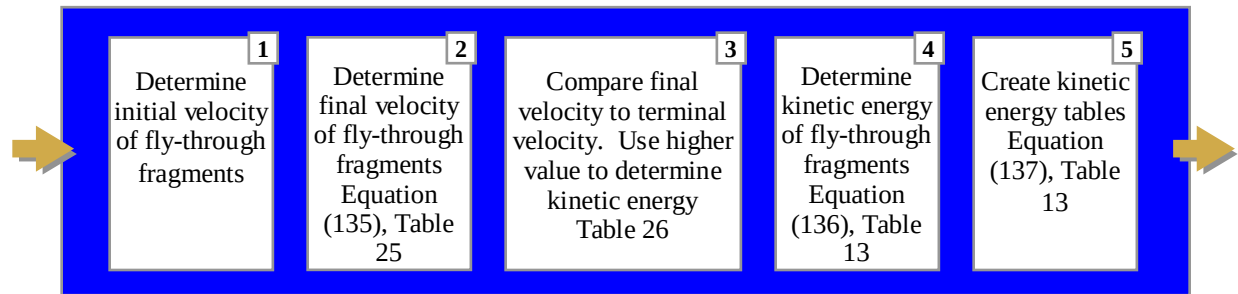
- Arriving primary fragment high-angle mass bin table
- Arriving primary fragment side-impact mass bin table
- Arriving primary fragment fly-through mass bin table
- 2 Arriving secondary high-angle debris mass tables (roof)
- 6 Arriving secondary side-impact debris mass tables (front wall, side wall, rear wall)
- 6 Arriving secondary fly-through debris mass tables (front wall, side wall, rear wall)
- Arriving crater ejecta high-angle debris mass table

#### 4.4.7 STEP 16: Determine final velocity of fly-through fragments.

Since the fly-through fragments are not falling at terminal velocity, a final velocity is determined so the kinetic energy can be calculated and fragments placed in the appropriate kinetic energy bins. Side-impact and high-angle fragments use terminal velocity as the final velocity; therefore, those fragments are in the appropriate kinetic energy bin. *Substeps 1-5* describe how SAFER determines the final velocity of the fly-through fragments.

Inputs to Step 16:

- Distance between the PES and ES (ft),  $d$  [from Step 3]
- Primary fragment initial velocity,  $IV$  [from Step 11]
- Initial velocity for each PES component,  $IV$  [from Step 14]
- Arriving primary fragment fly-through mass bin table [from Step 15]
- 6 Arriving secondary fly-through debris mass tables (front wall, side wall, rear wall) [from Step 15]



##### Substep 1: Determine the initial velocity of the fly-through fragments

SAFER assigns the primary fragment  $IV$  determined in Step 11 from Table 15, *Primary Fragment Initial Velocity and Maximum Throw Values*, to the fly-through primary fragments and assigns the secondary fragment initial velocities calculated in Eq. (115) in Step 14 to the fly-through secondary fragments.

##### Substep 2: Determine the final velocity of fly-through fragments

The final velocity,  $FV$ , of the fly-through fragments per mass bin is calculated by:

$$\begin{aligned}
 &\text{For } j = 1 \text{ to } 7 \\
 &\quad \text{Fly-through fragment table } j: \\
 &\quad \text{For } n = 1 \text{ to } 10 \\
 &\quad \quad \text{Bin } n: \quad FV = IV * (A * \exp^{-(d*B)}) \\
 &\quad \quad \text{Next } n, \\
 &\quad \text{Next } j,
 \end{aligned} \tag{135}$$

where  $A$  and  $B$  are provided in Table 25, *Final Velocity Parameters*, and  $d$  is the distance between the PES and ES.

**Table 25. Final Velocity Parameters**

| Mass Bin | Steel Parameters |          | Concrete Parameters |          |
|----------|------------------|----------|---------------------|----------|
|          | A                | B        | A                   | B        |
| 1        | 0.99146          | 0.000312 | 0.97972             | 0.000653 |
| 2        | 0.97901          | 0.00039  | 0.96693             | 0.000837 |
| 3        | 0.96521          | 0.00049  | 0.96271             | 0.001105 |
| 4        | 0.95929          | 0.000663 | 0.95264             | 0.001448 |
| 5        | 0.94637          | 0.000979 | 0.92723             | 0.001838 |
| 6        | 0.89636          | 0.001218 | 0.90141             | 0.00238  |
| 7        | 0.899            | 0.001657 | 0.86595             | 0.003074 |
| 8        | 0.8168           | 0.002002 | 0.88862             | 0.004202 |
| 9        | 0.8171           | 0.002696 | 0.86728             | 0.005365 |
| 10       | 0.79687          | 0.003726 | 0.83715             | 0.007271 |

*Substep 3: Compare final velocity to terminal velocity.*

The final velocity calculated in Substep 2 is compared to the terminal velocity for the corresponding bins by material type; the terminal velocity by bin is found in Table 26, *Terminal Velocity (ft/s)*. The greater of the two values is used to calculate the kinetic energy in Substep 4.

**Table 26. Terminal Velocity (ft/s)**

|          | Bin 1  | Bin 2  | Bin 3  | Bin 4  | Bin 5  | Bin 6  | Bin 7  | Bin 8  | Bin 9  | Bin 10 |
|----------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| Steel    | 604.34 | 522.37 | 452.89 | 391.6  | 339.35 | 293.6  | 254.01 | 220.49 | 192.57 | 163.47 |
| Concrete | 366.93 | 317.17 | 274.98 | 237.76 | 206.04 | 178.27 | 154.22 | 133.88 | 116.92 | 99.25  |

The steel values are used when determining the terminal velocity of primary fragments.

*Substep 4: Determine kinetic energy of fly-through fragments.*

The fragment mass bin tables are translated to kinetic energy tables using the calculated kinetic energy. The calculated kinetic energy determines which bin the fragments are assigned to.

SAFER calculates the kinetic energy, *KE*, of each fly-through kinetic energy table using the following algorithm:

```

For j = 1 to 7
  For n = 1 to 10
    Bin n:  $KE = 0.5 * (Average\ Fragment\ Mass\ (per\ material) / 32.2) * FV^2$       (136)
  Next n,
Next j,

```

where the *Average Fragment Mass* by bin is found in Table 13, *SAFER KE/Mass Bin Format*, for both concrete and steel. The calculation of *KE* allows the creation of a kinetic energy table for each of the seven fly-through fragment tables.

*Substep 5: Create kinetic energy tables.*

Using the kinetic energy calculated in *Substep 4*, the fragments are translated from mass bins to kinetic energy bins using the following algorithm.

```

For j = 1 to 7 (KE table)
  For n = 1 to 10 (bin in KE table)

```

```

If minimum KE of bin  $n < KE <$  maximum KE of bin  $n$ 
Then add corresponding fragments to bin  $n$  of fragment table
Else
Check next  $n$ 
End If

```

(137)

```

Next  $n$ ,
Next  $j$ ,

```

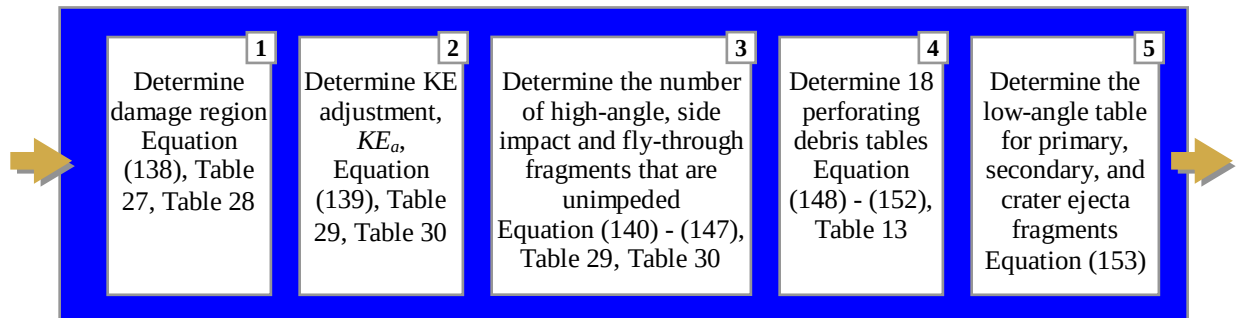
where the minimum and maximum KE for each bin is provided in Table 13, *SAFER KE/Mass Bin Format*.

Outputs of Step 16:

- Arriving primary fragment fly-through KE bin table
- 6 Arriving secondary fly-through debris KE tables (front wall, side wall, rear wall)

#### 4.4.8 STEP 17: Reduce debris due to ES

Step 17 determines the amount of debris that perforates the ES. The debris was divided into high-angle and low-angle debris in Step 15; in Step 17 the amount of debris that perforates the roof and walls is determined.



SAFER first determines the amount of damage sustained by the walls and roof. This damage enhances the capability of the fragments to perforate the walls and roof. Damage is classified by damage region. The damage region determines whether an adjustment is made to the amount of kinetic energy that the walls and roof can withstand. There are three damage regions. In damage region 1, the nominal KE values shown in Table 29, *Roof Protection Parameters*, and Table 30, *Wall Protection Parameters* are used as the amount of KE required to perforate the roof and walls. In damage region 2, the walls and roof have sustained greater damage so the nominal KE required to perforate the structure is less and an adjustment is made to the nominal KE. In damage region 3, the building has sustained even greater damage so the nominal KE required to perforate is adjusted lower and a percentage of the ES is assumed to have “voids” which allow debris to hazard the personnel at the ES without obstruction.

This is accomplished in 5 substeps.

Inputs to Step 17:

- ES building type [from Step 3]
- ES roof type [from Step 3]



- Distance between the PES and ES (ft),  $d$  [from Step 3]
- Percentage of glass on the ES (%),  $G_P$  [from Step 3]
- Percentage of ES roof intact,  $\%ES_{roof\ intact}$  [from Step 9]
- Percentage of ES walls intact,  $\%ES_{wall\ intact}$  [from Step 9]
- Percentage of ES roof damaged,  $\%ES_{roof\ damaged}$  [from Step 9]
- Percentage of ES walls damaged,  $\%ES_{wall\ damaged}$  [from Step 9]
- 11 arriving fragment mass bin tables [all tables from Step 15]
  - Arriving primary fragment high-angle mass bin table
  - Arriving primary fragment side-impact mass bin table
  - 2 Arriving secondary high-angle debris mass tables (roof)
  - 6 Arriving secondary side-impact debris mass tables (front wall, side wall, rear wall)
  - Arriving crater ejecta high-angle debris mass table
- Arriving primary fragment fly-through KE bin table [from Step 16]
- 6 Arriving secondary fly-through debris KE tables (front wall, side wall, rear wall) [from Step 16]

#### Substep 1

SAFER determines the damage region,  $DR$  for the roof and walls. Table 27, *Roof Damage Ranges*, and Table 28, *Wall Damage Ranges*, show the damage region boundaries for the roof and walls. The percentage of the ES roof and wall damaged is compared to the values in Table 27, *Roof Damage Ranges*, and Table 28, *Wall Damage Ranges*, to determine which of the three damage regions is applicable.

$$\begin{aligned}
 &\text{If } \%ES_{roof\ damaged} < LRD \\
 &\quad \text{Then } DR = 1 \\
 &\text{Else If } LRD \leq \%ES_{roof\ damaged} \leq HRD \\
 &\quad \text{Then } DR = 2 \\
 &\text{Else } DR = 3 \\
 &\text{End If}
 \end{aligned} \tag{138}$$

where the values for  $LRD$  (Low Range Damage) and  $HRD$  (High Range Damage) are provided in Table 27, *Roof Damage Ranges*.

Similarly, the damage region is determined for the ES walls using Table 28, *Wall Damage Ranges*.

**Table 27. Roof Damage Ranges**

| ES Roof Types                                 | Low Range<br>Damage<br>LRD (%) | High Range<br>Damage<br>HRD (%) |
|-----------------------------------------------|--------------------------------|---------------------------------|
| 4" Reinforced Concrete                        | 40                             | 65                              |
| 14" Reinforced Concrete                       | 40                             | 65                              |
| Plywood / Wood Joist (2x10 @16")              | 20                             | 50                              |
| Gypsum / Fiberboard / Steel Joist             | 20                             | 50                              |
| Plywood Panelized (2x6 @ 24")                 | 20                             | 50                              |
| 2" Lightweight Concrete / Steel Deck & Joists | 30                             | 50                              |
| Medium Steel Panel (18 gauge)                 | 15                             | 30                              |
| Light Steel Panel (22 gauge)                  | 15                             | 30                              |
| Steel (automobile)                            | 15                             | 30                              |

**Table 28. Wall Damage Ranges**

| ES Wall Types                  | Low Range<br>Damage<br>LRD (%) | High Range<br>Damage<br>HRD (%) |
|--------------------------------|--------------------------------|---------------------------------|
| Steel siding (22 gauge)        | 15                             | 25                              |
| 8" Unreinforced CMU            | 15                             | 25                              |
| 8" Reinforced CMU              | 25                             | 50                              |
| 8" Reinforced Concrete         | 25                             | 50                              |
| 14" Reinforced concrete        | 25                             | 50                              |
| 6" Reinforced Concrete Tilt-up | 25                             | 50                              |
| ½" Plywood Siding              | 15                             | 25                              |
| 8" Unreinforced Brick          | 25                             | 50                              |
| Steel (automobile doors)       | 25                             | 35                              |

**Substep 2**

SAFER determines the KE adjustment,  $KE_a$ , for the roof and walls based on the damage region by:

$$\begin{aligned}
 &\text{If } DR = 1 \\
 &\quad \text{Then } KE_a = \Delta KE_n \\
 &\text{Else If } DR = 2 \\
 &\quad \text{Then } KE_a = \Delta KE_n * \%ES_{\text{roof intact}} \\
 &\text{Else If } DR = 3 \\
 &\quad \text{Then } KE_a = \Delta KE_n * \%ES_{\text{roof intact}} \\
 &\text{End If}
 \end{aligned} \tag{139}$$

where  $\Delta KE_n$  values are provided in Table 29, *Roof Protection Parameters*, and Table 30, *Wall Protection Parameters*. Note that if the damage region is three, then a void is created and a

percentage of fragments will pass through the ES without obstruction (the kinetic energy value that the walls and roof will withstand is zero).

**Table 29. Roof Protection Parameters**

| ES Roof Types                                 | % Invulnerable area (Nominal)<br>$IA_{roof}$ | KE absorbed by roof (ft-lbs)<br>$\Delta KE_n$ |
|-----------------------------------------------|----------------------------------------------|-----------------------------------------------|
| 4" Reinforced Concrete                        | 10                                           | 10,000                                        |
| 14" Reinforced Concrete                       | 15                                           | 200,000                                       |
| Plywood / Wood Joist (2x10 @16")              | 5                                            | 50                                            |
| Gypsum / Fiberboard / Steel Joist             | 5                                            | 25                                            |
| Plywood Panelized (2x6 @ 24")                 | 5                                            | 50                                            |
| 2" Lightweight Concrete / Steel Deck & Joists | 7.5                                          | 2,000                                         |
| Medium Steel Panel (18 gauge)                 | 7.5                                          | 1,500                                         |
| Light Steel Panel (22 gauge)                  | 7.5                                          | 1,000                                         |
| Steel (automobile)                            | 2.5                                          | 200                                           |

**Table 30. Wall Protection Parameters**

| ES Wall Types                  | % Invulnerable area (Nominal)<br>$IA_{wall}$ | KE absorbed by wall (ft-lbs)<br>$\Delta KE_n$ |
|--------------------------------|----------------------------------------------|-----------------------------------------------|
| Steel siding (22 gauge)        | 2                                            | 1,000                                         |
| 8" Unreinforced CMU            | 2                                            | 500                                           |
| 8" Reinforced CMU              | 2                                            | 500                                           |
| 8" Reinforced Concrete         | 2                                            | 50,000                                        |
| 14" Reinforced concrete        | 2                                            | 200,000                                       |
| 6" Reinforced Concrete Tilt-up | 2                                            | 37,500                                        |
| ½" Plywood Siding              | 2                                            | 100                                           |
| 8" Unreinforced Brick          | 2                                            | 10,000                                        |
| Steel (automobile doors)       | 4                                            | 1000                                          |

### Substep 3

Each of the roof and wall types includes a *percentage invulnerable area*. The invulnerable area is assumed to totally block arriving fragments from any and all KE bins. The invulnerable area varies proportionally to the percentage of the ES that is intact; the nominal values ( $IA_{roof}$ ,  $IA_{wall}$ ) are shown in Table 29, *Roof Protection Parameters*, and Table 30, *Wall Protection Parameters*.

The adjusted invulnerable area for the ES roof,  $AIAR$ , is calculated by:

$$AIAR = IA_{roof} * \% ES_{roof\ intact} \quad (140)$$

The 4 high-angle arriving fragment tables are then adjusted by  $AIAR$ .

For  $j = 1$  to 4

High-angle fragment table  $j$ :

```

For  $n = 1$  to 10
  Bin  $n$ :  $N_{HA} = N_{HA} * (1 - AIAR)$ 
Next  $n$ ,
Next  $j$ ,

```

Next, the number of high-angle fragments that are unimpeded by the roof,  $NHA$ , is calculated and removed from each bin of each high-angle table by:

```

If  $DR = 1$  or  $DR = 2$ 
  Then  $NHA = 0$ 
Else If  $DR = 3$ 
  Then  $NHA = N_{HA} * \%ES_{roofdamaged}$ 
End If
For  $j = 1$  to 4
  For  $n = 1$  to 10
    If  $DR = 1$  or  $DR = 2$ 
      Then  $NHA = 0$ 
    Else If  $DR = 3$ 
      Then  $NHA = N_{HA} * \%ES_{roofdamaged}$ 
    End If
     $N_{HA} = N_{HA} - NHA$ 
  Next  $n$ ,
Next  $j$ ,

```

If the damage region is three, it is assumed that a number of fragments are unimpeded by the structure, so an adjustment is made to remove these unimpeded fragments from the number of fragments that will be impeded by the roof. The unimpeded fragments are added back to the number of fragments that perforate the roof in Substep 4.

Similarly, the adjusted invulnerable area for the ES wall,  $AIAW$ , is calculated by:

$$AIAW = IA_{wall} * \%ES_{wall\ intact} \quad (143)$$

The 14 low-angle arriving fragment tables are then adjusted by  $AIAW$ .

```

For  $j = 1$  to 7
  Side-impact fragment table  $j$ :
  For  $n = 1$  to 10
    Bin  $n$ :  $N_{SI} = N_{SI} * (1 - AIAW)$ 
  Next  $n$ ,
Next  $j$ ,

For  $j = 1$  to 7
  Fly-through fragment table  $j$ :
  For  $n = 1$  to 10
    Bin  $n$ :  $N_{FT} = N_{FT} * (1 - AIAW)$ 
  Next  $n$ ,
Next  $j$ ,

```

Next the number of side-impact fragments that are unimpeded by the wall,  $NSI$ , is calculated and removed from each bin of each side impact table by:

$$\begin{aligned}
& \text{If } DR = 1 \text{ or } DR = 2 \\
& \quad \text{Then } NSI = N_{SI} * G_p \\
& \text{Else If } DR = 3 \\
& \quad NSI = N_{SI} * (G_p + \%ES_{wall \text{ damaged}}) \\
& \text{End If} \\
& \text{For } j = 1 \text{ to } 7 \\
& \quad \text{For } n = 1 \text{ to } 10 \\
& \quad \quad \text{If } DR = 1 \text{ or } DR = 2 \\
& \quad \quad \quad \text{Then } NSI = N_{SI} * G_p \\
& \quad \quad \text{Else If } DR = 3 \\
& \quad \quad \quad NSI = N_{SI} * (G_p + \%ES_{wall \text{ damaged}}) \\
& \quad \quad \text{End If} \\
& \quad \quad N_{SI} = N_{SI} - NSI \\
& \quad \text{Next } n, \\
& \text{Next } j,
\end{aligned} \tag{146}$$

Next the number of fly-through fragments that are unimpeded by the wall,  $N_{FT}$ , is calculated and removed from each bin of each fly-through table by:

$$\begin{aligned}
& \text{If } DR = 1 \text{ or } DR = 2 \\
& \quad \text{Then } N_{FT} = N_{FT} * G_p \\
& \text{Else If } DR = 3 \\
& \quad N_{FT} = N_{FT} * (G_p + \%ES_{wall \text{ damaged}}) \\
& \text{End If} \\
& \text{For } j = 1 \text{ to } 7 \\
& \quad \text{For } n = 1 \text{ to } 10 \\
& \quad \quad \text{If } DR = 1 \text{ or } DR = 2 \\
& \quad \quad \quad \text{Then } N_{FT} = N_{FT} * G_p \\
& \quad \quad \text{Else If } DR = 3 \\
& \quad \quad \quad N_{FT} = N_{FT} * (G_p + \%ES_{wall \text{ damaged}}) \\
& \quad \quad \text{End If} \\
& \quad \quad N_{FT} = N_{FT} - N_{FT} \\
& \quad \text{Next } n, \\
& \text{Next } j,
\end{aligned} \tag{147}$$

It is assumed that the windows will not provide protection from debris, so the number of side-impact and fly-through fragments that can pass through the windows are taken out of the blocked fragment count. The number of side-impact and fly-through fragments taken out is based on the percentage of windows on the ES. These fragments are added back to the number of fragments that perforate the walls in Substep 4. If the damage region is three, it is assumed that a number of fragments are unimpeded by the structure, so an adjustment is made to remove these unimpeded fragments from the number of fragments that will be impeded by the walls. The unimpeded fragments are added back to the number of fragments that perforate the wall in Substep 4.

#### Substep 4

SAFER creates 18 perforating debris tables that describe the outcome of fragment impacts on the ES. This procedure determines if fragments are able to perforate the ES and for those that do perforate, it determines if the resultant KE (151) causes the fragment to shift to a lower KE bin or remain in the current KE bin.

For all debris types described in the 4 high-angle fragment tables, SAFER calculates the resulting kinetic energy,  $KE_R$ , following impact with the roof. SAFER then determines perforating fragments and their resulting KE by using the following algorithm:

```

For  $j = 1$  to 4
  For  $n = 1$  to 10
    Bin  $n$ :  $KE_R = \text{Average KE of bin } n - \text{KE absorbed by ES roof}$  (148)
    If  $KE_R \leq 0$ ,
      Then the ES roof stopped fragment perforation for bin  $n$ 
    Else If  $KE_R \geq \text{lower KE limit of bin } n$ ,
      Then the fragment perforates the roof and remains in current KE bin
    Else If  $KE_R < \text{lower KE limit of bin } n$ 
      Then the fragment perforates the roof but shifts to a lower KE bin
  Next  $n$ ,
Next  $j$ ,

```

where the average (logarithmic) and lower KE limit of bin  $n$  is provided in Table 13, *SAFER KE/Mass Bin Format*, and the KE absorbed by the ES roof is  $KE_a$ , as determined by Eq. (139).

As mentioned previously, the unimpeded high-angle fragments are added back to the adjusted perforating high-angle fragment tables per bin by:

```

For  $n = 1$  to 10
   $N_{HA} = N_{HA} + N_{HA}$  (149)
Next  $n$ ,

```

Note, if the damage region is three then the unimpeded fragments are added back to the high-angle fragment tables in the appropriate KE bin, otherwise the table will be unchanged by Eq. (149).

For all debris types described in the 14 low-angle fragment tables, SAFER calculates the resulting kinetic energy,  $KE_R$ , following impact with an ES wall. SAFER then determines perforating fragments and their resulting KE by using the following algorithm:

```

For  $j = 1$  to 7
  Side-impact fragment table  $j$ :
  For  $n = 1$  to 10
    Bin  $n$ :  $KE_R = \text{Average KE of bin } n - \text{KE absorbed by ES wall}$  (150)
    If  $KE_R \leq 0$ ,
      Then an ES wall stopped fragment perforation for bin  $n$ 
    Else If  $KE_R \geq \text{lower KE limit of bin } n$ ,
      Then the fragment perforates an ES wall and remains in current KE bin
    Else If  $KE_R < \text{lower KE limit of bin } n$ 
      Then the fragment perforates an ES wall but shifts to a lower KE bin
  Next  $n$ ,
Next  $j$ ,
For  $j = 1$  to 7
  Fly-through fragment table  $j$ :

```

For  $n = 1$  to 10  
 Bin  $n$ :  $KE_R = \text{Average KE of bin } n - \text{KE absorbed by ES wall}$  (151)  
 If  $KE_R \leq 0$ ,  
 Then an ES wall stopped fragment perforation for bin  $n$   
 Else If  $KE_R \geq \text{lower KE limit of bin } n$ ,  
 Then the fragment perforates an ES wall and remains in current KE bin  
 Else If  $KE_R < \text{lower KE limit of bin } n$   
 Then the fragment perforates an ES wall but shifts to a lower KE bin  
 Next  $n$ ,  
 Next  $j$ ,

where the average (logarithmic) and lower KE limit of bin  $n$  is provided in Table 13, *SAFER KE/Mass Bin Format*, and the KE absorbed by the ES wall is  $KE_a$ , as determined by Eq. (139).

The percentage of fragments that passed through the windows is added back to the low-angle fragment tables in the appropriate KE bin. If the damage region is three, then the unimpeded fragments are also added back to the appropriate KE bin. This accounting is shown in Eq. (154)

For  $n = 1$  to 10  
 $N_{SI} = N_{SI} + NSI$   
 $N_{FT} = N_{FT} + N_{FT}$  (152)  
 Next  $n$ ,

Rationale for the methodology used in this Substep is detailed in Attachment 8.

#### Substep 5

SAFER sums the number of side-impact and fly-through fragments into one low-angle table for primary, secondary, and crater ejecta fragments.

For  $j = 1$  to 7  
 Low-angle fragment table  $j$ :  
 For  $n = 1$  to 10  
 Bin  $n$ :  $N_{LA} = N_{SI} + N_{FT}$  (153)  
 Next  $n$ ,  
 Next  $j$ ,

Outputs of Step 17:

- 11 perforating debris tables
  - 2 high-angle fragment debris tables (primary, crater ejecta)
  - 1 high-angle fragment steel debris table (roof)
  - 1 high-angle fragment concrete debris table (roof)
  - 1 low-angle fragment debris table (primary)
  - 3 low-angle fragment steel debris tables (primary, front wall, side wall, rear wall)
  - 3 low-angle fragment concrete debris tables (primary, front wall, side wall, rear wall)

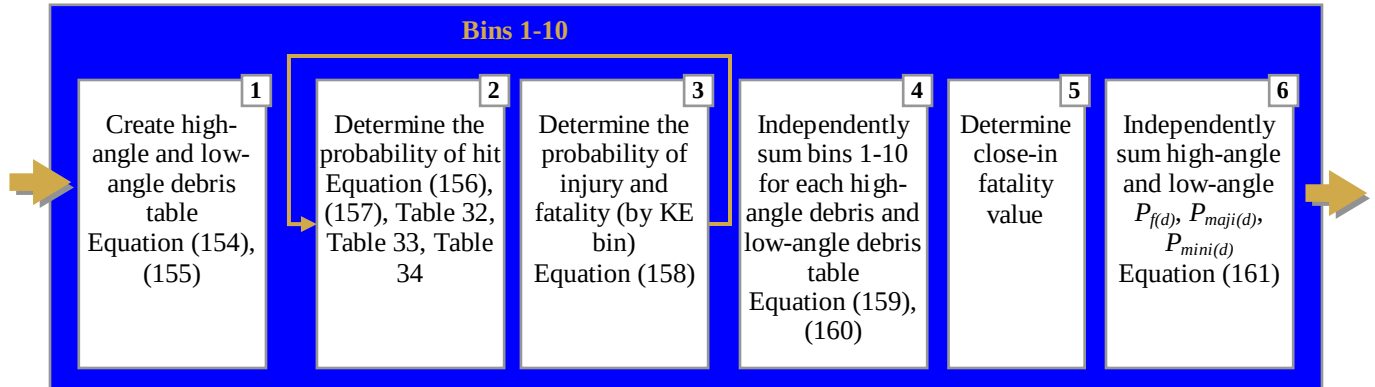
#### 4.4.9 STEP 18: Assess $P_{f(d)}$ , $P_{maji(d)}$ , $P_{mini(d)}$

Step 18 completes the Debris Branch by determining the human vulnerability from debris. All debris is defined in terms of the kinetic energy (KE) of perforating fragments. SAFER estimates fatality, major injury, and minor injury as a function of KE. SAFER considers the perforating fragment description, the vulnerable area of an exposed human, the probability of lethality, major injury, or minor injury given a fragment hit, and the probability of a hit. The vulnerable area of the exposed human is assumed to be 3.0 ft<sup>2</sup> as defined by RCC Standard 321-00 (Ref 7).

Inputs to Step 18:

- Distance between the PES and ES (ft),  $d$  [from Step 3]
- 11 perforating debris tables [from Step 17]
  - 2 high-angle fragment debris tables (primary, crater ejecta)
  - 1 high-angle fragment steel debris table (roof)
  - 1 high-angle fragment concrete debris table (roof)
  - 1 low-angle fragment debris table (primary)
  - 3 low-angle fragment steel debris tables (primary, front wall, side wall, rear wall)
  - 3 low-angle fragment concrete debris tables (primary, front wall, side wall, rear wall)

Step 18 is accomplished in 6 substeps.



##### Substep 1

For the four high-angle perforating debris tables, SAFER creates one combined high-angle perforating debris table by summing the number of high-angle fragments,  $N_{HA}$ , across corresponding bins in each of the four tables. The total quantity of high-angle fragments,  $N_{HA}^*$ , in each bin of the combined table is calculated with the following algorithm:

```

For j = 1 to 4
  High-angle perforating debris table j:
  For n = 1 to 10
     $N_{HA}^* = N_{HA}^* + N_{HA}$  in bin n of high-angle debris tables j
  Next n,
Next j,
  
```

(154)

The result of this procedure is a combined high-angle perforating debris table.



Similarly, SAFER creates one combined low-angle perforating debris table from the seven low-angle debris tables. The total quantity of low-angle fragments,  $N_{LA}^*$ , in each bin of the combined table is calculated with the following algorithm:

```

For j = 1 to 7
  Low-angle perforating debris table j:
  For n = 1 to 10
     $N_{LA}^* = N_{LA}^* + N_{LA}$  in bin n of low-angle debris tables j
  Next n,
Next j,

```

(155)

The result of this procedure is a combined low-angle perforating debris table.

### Substep 2

SAFER calculates a probability of hit for each bin of the combined high-angle and combined low-angle tables. A unique probability of hit is calculated for the three consequences: fatality,  $P_{hit(f)}$ , major injury,  $P_{hit(maji)}$ , and minor injury,  $P_{hit(mini)}$ . These are stored in a  $P_{hit}$  table for each consequence.

Calculate the probability of hit,  $P_{hit}$ , for each bin of the high-angle combined table by using the following algorithm:

```

For c = 1 to 3 (for each consequence – fatality, major injury, minor injury)
  For n = 1 to 10 of combined high-angle perforating debris table:
     $P_{hit} = 1 - e^{-(CA \times N_{HA}^*)}$ 
  Next n,
Next c,

```

(156)

where  $N_{HA}^*$  is from Substep 1 and CA is the concern area provided in Table 31, *Fatality Concern Area (ft<sup>2</sup>)*, Table 32, *Major Injury Concern Area (ft<sup>2</sup>)*, and Table 33, *Minor Injury Concern Area (ft<sup>2</sup>)*. Note that the concern area for major injury and minor injury considers whether the person is in the open or inside a structure.

Similarly, the  $P_{hit}$  for each bin of the low-angle combined table is calculated using the same methodology where  $N_{LA}^*$  is from Substep 1 and CA is provided in Table 31, *Fatality Concern Area (ft<sup>2</sup>)*, Table 32, *Major Injury Concern Area (ft<sup>2</sup>)*, and Table 33, *Minor Injury Concern Area (ft<sup>2</sup>)*.

```

For c = 1 to 3 (for each consequence – fatality, major injury, minor injury)
  For n = 1 to 10 of combined low-angle perforating debris table:
     $P_{hit} = 1 - e^{-(CA \times N_{LA}^*)}$ 
  Next n,
Next c,

```

(157)

where  $N_{LA}^*$  is from Substep 1 and CA is the concern area provided in Table 31, *Fatality Concern Area (ft<sup>2</sup>)*, Table 32, *Major Injury Concern Area (ft<sup>2</sup>)*, and Table 33, *Minor Injury Concern Area (ft<sup>2</sup>)*. Note that the concern area for major injury and minor injury considers whether the person is in an ES that is open or a structure.

**Table 31. Fatality Concern Area (ft<sup>2</sup>)**

| ES Type                | Bin Number |   |   |   |   |   |   |   |   |    |
|------------------------|------------|---|---|---|---|---|---|---|---|----|
|                        | 1          | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| All (ft <sup>2</sup> ) | 3          | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3  |

**Table 32. Major Injury Concern Area (ft<sup>2</sup>)**

| ES Type                      | Bin Number |      |      |      |      |      |      |      |      |    |
|------------------------------|------------|------|------|------|------|------|------|------|------|----|
|                              | 1          | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10 |
| Open (ft <sup>2</sup> )      | 5          | 4.78 | 4.56 | 4.33 | 4.11 | 3.89 | 3.67 | 3.44 | 3.22 | 3  |
| Structure (ft <sup>2</sup> ) | 7.5        | 7    | 6.5  | 6    | 5.5  | 5    | 4.5  | 4    | 3.5  | 3  |

**Table 33. Minor Injury Concern Area (ft<sup>2</sup>)**

| ES Type                      | Bin Number |       |       |      |      |      |      |      |      |    |
|------------------------------|------------|-------|-------|------|------|------|------|------|------|----|
|                              | 1          | 2     | 3     | 4    | 5    | 6    | 7    | 8    | 9    | 10 |
| Open (ft <sup>2</sup> )      | 10         | 9.22  | 8.44  | 7.67 | 6.89 | 6.11 | 5.33 | 4.56 | 3.78 | 3  |
| Structure (ft <sup>2</sup> ) | 15         | 13.67 | 12.33 | 11   | 9.67 | 8.33 | 7    | 5.67 | 4.33 | 3  |

The result of this procedure is six probability of hit tables. Three probability of hit tables are defined for the 10 KE bins of a combined high-angle perforating debris table. Three probability of hit tables are defined for the 10 KE bins of a combined low-angle perforating debris table.

### Substep 3

Calculate the probability of fatality due to debris,  $P_{f(d)}$ , probability of major injury due to debris,  $P_{maji(d)}$ , and probability of minor injury due to debris,  $P_{mini(d)}$  for each bin in the two combined perforating debris tables by using the following algorithm:

For  $j = 1$  to 2

For  $n = 1$  to 10

Bin  $n$ :  $P_{f(d)} = CA * lethality\ value * N^*$  for bin  $n * P_{hit(f)}$  for bin  $n$

Bin  $n$ :  $P_{maji(d)} = CA * major\ injury\ value * N^*$  for bin  $n * P_{hit(maji)}$  for bin  $n$  (158)

Bin  $n$ :  $P_{mini(d)} = CA * minor\ injury\ value * N^*$  for bin  $n * P_{hit(mini)}$  for bin  $n$

Next  $n$ ,

Next  $j$ ,

where  $CA$  values are the concern areas provided in Table 31, *Fatality Concern Area (ft<sup>2</sup>)*, Table 32, *Major Injury Concern Area (ft<sup>2</sup>)*, and Table 33, *Minor Injury Concern Area (ft<sup>2</sup>)*, and  $N^*$  is the total quantity of fragments ( $N_{HA}^*$  or  $N_{LA}^*$ ) and  $P_{hit}$  is the probability of hit for each bin under consideration and the *lethality value*, *major injury value*, and *minor injury value* are provided in Table 34, *Debris Lethality/Injury Probability Values*. The values in Table 34, *Debris Vulnerability Values*, were obtained by approximating a bin value from the curve shown in Figure 9,  $P_{fle}$  vs.  $KE$ .

**Table 34. Debris Vulnerability Values**

| Vulnerability | Bin Number |   |   |   |   |   |      |      |      |       |
|---------------|------------|---|---|---|---|---|------|------|------|-------|
|               | 1          | 2 | 3 | 4 | 5 | 6 | 7    | 8    | 9    | 10    |
| Fatality      | 1          | 1 | 1 | 1 | 1 | 1 | 0.9  | 0.25 | 0.02 | 1E-10 |
| Major Injury  | 1          | 1 | 1 | 1 | 1 | 1 | 0.98 | 0.5  | 0.1  | 1E-04 |
| Minor Injury  | 1          | 1 | 1 | 1 | 1 | 1 | 1    | 0.97 | 0.75 | 0.22  |

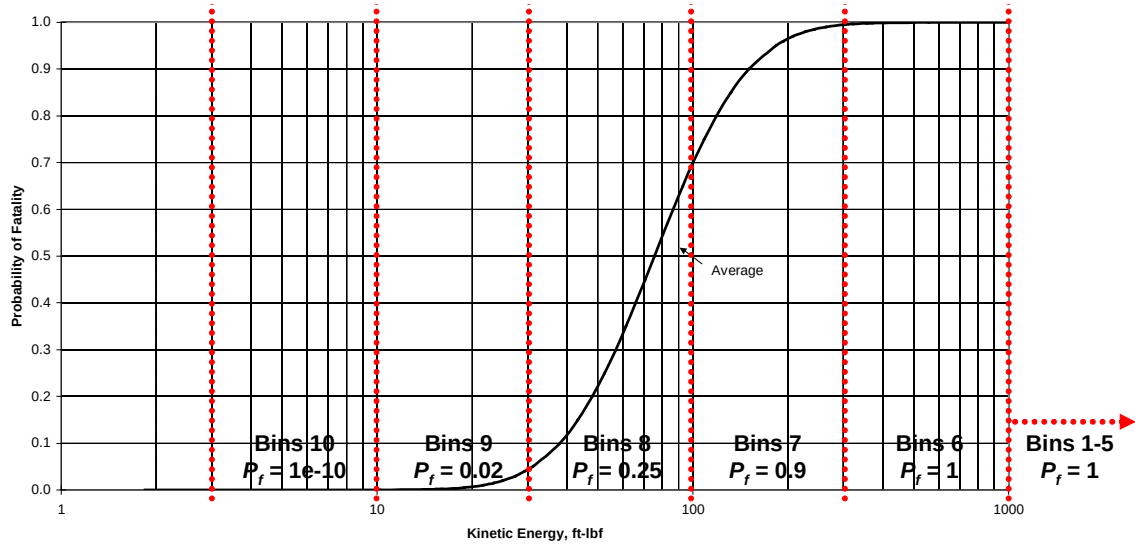


**Figure 9.  $P_{fe}$  vs. KE**

#### Substep 4

Using the additive rule for the union of non-mutually exclusive events, a total probability of fatality due to debris from the combined high-angle perforating debris table,  $P_{f(d)high-angle}$ , is calculated, as shown in Eq. (159).

$$P_{f(d)high-angle} = P_{f(d)bin1} + (P_{f(d)bin2})(1 - P_{f(d)bin1}) + (P_{f(d)bin3})(1 - P_{f(d)bin1})(1 - P_{f(d)bin2})) + \dots \quad (159)$$

A total probability of fatality due to debris from the combined low-angle perforating debris table,  $P_{f(d)low-angle}$ , is also calculated, as shown in Eq. (160).

$$P_{f(d)low-angle} = P_{f(d)bin1} + (P_{f(d)bin2})(1 - P_{f(d)bin1}) + (P_{f(d)bin3})(1 - P_{f(d)bin1})(1 - P_{f(d)bin2})) + \dots \quad (160)$$

#### Substep 5

SAFER then checks if the scenario is in the “close-in” region. For the debris branch, the “close-in” region is determined based on the crater radius. The crater radius is calculated in Step 14. If the distance between the PES and ES,  $d$ , is less than twice the crater radius, then the probability of fatality, probability of major injury, and probability of minor injury due to debris are each set to 1.0; otherwise the vulnerability values are the values calculated in Eq. (159) and Eq. (160).

### Substep 6

Finally, SAFER calculates the overall probability of fatality due to debris,  $P_{f(d)}$ , by summing the high-angle and low-angle probabilities of fatalities using the additive rule for the union of non-mutually exclusive events. Solve for  $P_{f(d)}$  by:

$$P_{f(d)} = P_{f(d)low-angle} + (1 - P_{f(d)low-angle})P_{f(d)high-angle} \quad (161)$$

$P_{f(d)}$  represents the probability a person has of being struck and killed by an incoming fragment. Similarly, SAFER calculates the overall probability of major injury due to debris,  $P_{maji(d)}$ , and the probability of minor injury due to debris,  $P_{mini(d)}$ .

Rationale for the methodology used in this step is detailed in Attachment 8.

Outputs of Step 18:

- Probability of fatality due to debris,  $P_{f(d)}$
- Probability of major injury due to debris,  $P_{maji(d)}$
- Probability of minor injury due to debris,  $P_{mini(d)}$

## 4.5 Group 5 Steps: Thermal Branch

Group 5 includes Steps 19-22 of the SAFER architecture. These steps contribute to effects analysis by determining the effect of the fatality mechanism heat.

SAFER considers the effects and consequences due to heat if the situation includes a HD 1.3 event. In this situation, SAFER does not consider the other consequence mechanisms (pressure and impulse, structural response, and debris) due to the lack of a blast wave being formed by a HD 1.3 event.

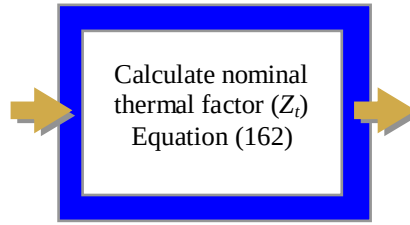
Step 19 determines a thermal hazard factor based on the yield and distance between the PES and the ES. Step 20 determines an adjusted thermal hazard factor due to the presence of the PES. Step 21 determines a thermal blocking factor that describes the thermal protection provided by the ES to personnel. Finally, Step 22 calculates the probability of fatality due to thermal effects,  $P_{f(t)}$ , probability of major injury due to thermal effects,  $P_{maji(t)}$ , and the probability of minor injury due to thermal effects,  $P_{mini(t)}$ .

### 4.5.1 STEP 19: Determine nominal thermal hazard factor.

Step 19 determines a thermal hazard factor based on the yield and distance between the PES and the ES.

Inputs to Step 19:

- Distance between the PES and ES (ft),  $d$  [from Step 3]
- Yield of the event (lbs),  $W_1$  [from Step 4]



The nominal thermal hazard factor,  $Z_t$ , is determined by using the entered amount of HD 1.3 material.

$$Z_t = \frac{d}{W_1^{\frac{1}{3}}} \quad (162)$$

Note that  $Z_t$  is identical to the hazard factor,  $Z$ , found in Step 5. The unmodified value of temperature is not expressly considered.

Output of Step 19:

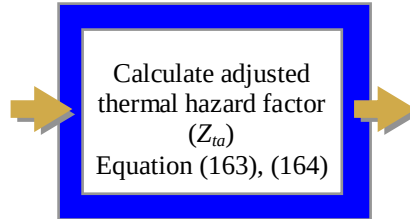
- Thermal hazard factor,  $Z_t$

#### 4.5.2 STEP 20: Adjust thermal hazard factor (due to PES).

Step 20 determines an adjusted thermal hazard factor due to the presence of the PES.

Inputs to Step 20:

- Distance between the PES and ES (ft),  $d$  [from Step 3]
- Adjusted weight (lbs),  $W_a$  [from Step 6]



The adjusted thermal hazard factor,  $Z_{ta}$ , is calculated by:

$$Z_{ta} = \frac{d}{W_a^{\frac{1}{3}}} \quad (163)$$

If there is no PES, or the PES type is pre-engineered metal building or hollow clay tile, there is no adjustment, thus:

$$Z_{ta} = Z_t \quad (164)$$

Note that  $Z_{ta}$  is identical to the adjusted hazard factor,  $Z_a$ , found in Step 6. The adjusted value of temperature is not expressly considered.

Rationale for the methodology used in this step is detailed in Attachment 1.

Output of Step 20:

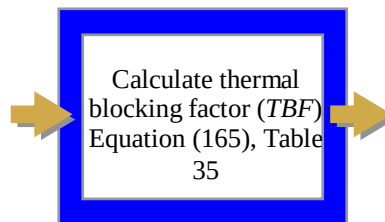
- Adjusted thermal hazard factor,  $Z_{ta}$

#### 4.5.3 STEP 21: Determine ES protection.

Step 21 determines a thermal blocking factor that describes the thermal protection provided by the ES to personnel within. This blocking factor considers the ES building type and the amount of windows (glass) in the structure.

Inputs to Step 21:

- ES building type [from Step 3]
- Percentage of glass on the ES (%),  $G_p$  [from Step 3]



The thermal blocking factor,  $TBF$ , is calculated by:

$$TBF = TBF_0 * \frac{100 - G_p}{100} \quad (165)$$

where  $TBF_0$  is the nominal thermal blocking factor based on the ES building type and is provided in Table 35, *Nominal Thermal Blocking Factors*.

**Table 35. Nominal Thermal Blocking Factors**

| ES Building Type                                   | Nominal Thermal Blocking Factor ( $TBF_o$ ) |
|----------------------------------------------------|---------------------------------------------|
| Small reinforced concrete (< 5,000 sq ft)          | 1.0                                         |
| Medium reinforced concrete (5,000-20,000 sq ft)    | 1.0                                         |
| Large tilt-up reinforced concrete (> 20,000 sq ft) | 1.0                                         |
| Small reinforced masonry (< 5,000 sq ft)           | 1.0                                         |
| Medium reinforced masonry (5,000-20,000 sq ft)     | 1.0                                         |
| Small unreinforced brick (< 5,000 sq ft)           | 1.0                                         |
| Medium unreinforced masonry (5,000-20,000 sq ft)   | 1.0                                         |
| Large unreinforced masonry (> 20,000 sq ft)        | 1.0                                         |
| Small PEMB (< 5,000 sq ft)                         | 0.2                                         |
| Medium PEMB (5,000-20,000 sq ft)                   | 0.2                                         |
| Large PEMB (> 20,000 sq ft)                        | 0.2                                         |
| Small wood frame (< 5,000 sq ft)                   | 0.2                                         |
| Medium wood frame (5,000-20,000 sq ft)             | 0.2                                         |
| Medium steel stud (5,000-20,000 sq ft)             | 0.2                                         |
| Wood frame (~500 sq ft)                            | 0.2                                         |
| Moving vehicle                                     | 0.6                                         |
| Stationary Vehicle                                 | 0.6                                         |

Rationale for the methodology used in this step is detailed in Attachment 1.

Output of Step 21:

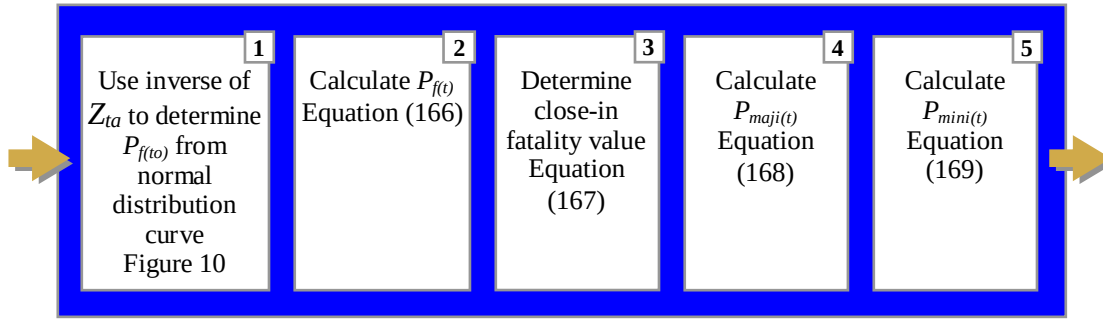
- Thermal blocking factor,  $TBF$

#### **4.5.4 STEP 22: Assess $P_{f(t)}$ , $P_{maji(t)}$ , $P_{mini(t)}$ .**

Step 22 completes the Thermal Branch by determining the probability of fatality due to thermal effects,  $P_{f(t)}$ , probability of major injury due to thermal effects,  $P_{maji(t)}$ , and probability of minor injury due to thermal effects,  $P_{mini(t)}$ .

Inputs to Step 22:

- Distance between the PES and ES (ft),  $d$  [from Step 3]
- Equivalent NEW (lbs),  $W_2$  [from Step 4]
- Adjusted thermal hazard factor,  $Z_{ta}$  [from Step 20]
- Thermal blocking factor,  $TBF$  [from Step 21]



#### Substep 1

Using the inverse of the adjusted thermal hazard factor,  $Z_{ta}$ , the nominal probability of fatality due to thermal effects,  $P_{f(to)}$ , is determined from the “S-curve” as presented in Figure 10, *Nominal Probability of Fatality Due to Thermal Effects*.

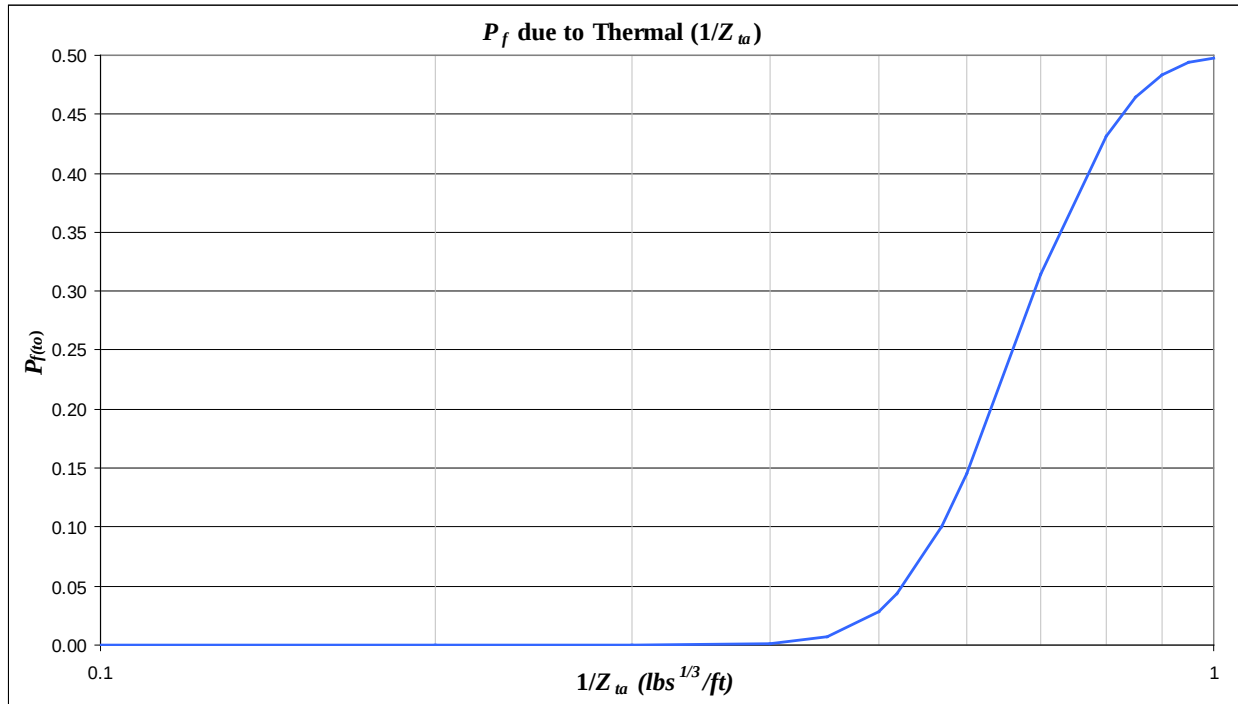


**Figure 10. Nominal Probability of Fatality Due to Thermal Effects**

#### Substep 2

The probability of fatality due to thermal effects,  $P_{f(t)}$ , is calculated using the Thermal Blocking Factor,  $TBF$ :

$$P_{f(t)} = (1 - TBF) * P_{f(to)} \quad (166)$$

To ensure that the probability of fatality does not exceed 1.0, an adjustment is made.

If  $P_{f(t)}$  is greater than 1.0

Then  $P_{f(t)} = 1.0$

Else  $P_{f(t)}$  is the value calculated in Equation (166).



### Substep 3

SAFER determines if the situation is in the “close-in” region. For the thermal branch, the “close-in” region is determined based on the fireball radius. The fireball radius,  $F_r$ , is calculated by:

$$F_R = 2.77 \times \left( \frac{W_2}{0.45} \right)^{0.36} \quad (167)$$

If the distance between the PES and ES,  $d$ , is less than the fireball radius, then the probability of fatality due to thermal effects,  $P_{f(t)}$ , is set to 1.0; otherwise the  $P_{f(t)}$  is the value calculated from Eq. (166).

### Substep 4

The probability of major injury due to thermal effects,  $P_{maji(t)}$ , is calculated by:

$$P_{maji(t)} = P_{f(t)} * 3 \quad (168)$$

### Substep 5

The probability of minor injury due to thermal effects,  $P_{mini(t)}$ , is calculated by:

$$P_{mini(t)} = P_{f(t)} * 20 \quad (169)$$

Rationale for the methodology used in this step is detailed in Attachment 1.

Outputs of Step 22:

- Probability of fatality due to thermal effects,  $P_{f(t)}$
- Probability of major injury due to thermal effects,  $P_{maji(t)}$
- Probability of minor injury due to thermal effects,  $P_{mini(t)}$

## 4.6 Group 6 Steps: Effects Aggregation and Risk Calculation

Group 6 includes Steps 23-26 of the SAFER architecture. Steps 23-26 are performed for both related and public personnel.

Step 23 completes the effects analysis by performing four SAFER runs using different combinations of the expected value and maximum value of two driving parameters: the amount of explosives present and the yield.

Step 24 uses the results of Step 23 to compute the risks (individual and group for related and public) for a given PES/ES pair. These risks are represented by the Expected Value and the Variance of the risk distributions. These risks have been termed Pair Risks and are calculated for each PES/ES pair in the situation. Pair Risks represent the risks between a single PES and a single ES only.

After the Pair Risks (Step 24) have been computed for all ESs within the hazard arc of a particular PES, Step 25 aggregates the risks (individual and group risks for related and public)

that each PES poses to all ESs. These risks have been termed the PES risks and are calculated for each PES in the situation. Step 25 also aggregates the risks (individual and group risks for related and public) to each individual ES from all PESs to which it is exposed. These risks have been termed ES risks and are calculated for each ES in the situation. In addition to these, Step 25 also computes the total risks to all ESs within the hazard arc of each PES. These risks are termed PES Siting risks and are computed for individuals and groups of related and public personnel.

When the total PES risk (Step 25) has been determined for each PES, Step 26 aggregates the risks (individual and group risks for related and public) that all PESs in the situation pose to all the ESs. These risks have been termed Installation Risks. They represent the total risks of the situation analyzed.

#### **4.6.1 STEP 23: $P_{fle}$ for variations of AP and Y**

Step 23 completes the effects analysis by compiling the effects probabilities of fatality due to pressure-impulse, overall building damage, debris, and thermal effects for different combinations of Amount Present and Yield. Holding all other parameters fixed, four SAFER runs are performed as follows:

- Run 1: Maximum (Sited) Amount Present and Maximum Yield
- Run 2: Expected Amount Present and Expected Yield
- Run 3: Maximum (Sited) Amount Present and Expected Yield
- Run 4: Expected Amount Present and Maximum Yield

Run 1 is performed to compute the risk due to a maximum event. This is the risk measure contained in currently established Explosives Risk Criteria approved by the DDESB. The expected value computed in this run is denoted by the “sited value” on the SAFER uncertainty display.

Run 2 computes the  $P_{fle}$  due to each of the effects for an event defined by the expected values of Amount Present and Yield. The results of this run are used in step 24 to determine the median values of  $P_{fle}$  for each effect. The total  $P_{fle}$  for this run is also used as the median value when determining the individual variations caused by increases in either Amount Present or Yield.

Run 3 computes the total  $P_{fle}$  when the Amount Present is set to the maximum (sited) value for the situation being analyzed. This information is used in step 25 to determine the variation due to Amount Present.

Finally, Run 4 computes the total  $P_{fle}$  when the Yield is set to the maximum value based on the type of explosive present. This information is used in step 25 to determine the variation due to Yield.

Inputs to Step 23:

- Situation data [from Steps 1 through 5]
- Expected and Maximum values for Amount Present and Yield [Steps 1, 2, and 4]

Calculate the probability of fatality and injury given an explosives event and the presence of a person for each effects branch using Steps 5 through 22 and compute the total  $P_{fle}$ ,  $P_{majile}$ , and  $P_{minile}$  for this PES/ES pair by:

$$P_{fle} = P_{f(o)} + (P_{f(b)})(1 - P_{f(o)}) + (P_{f(d)})(1 - P_{f(b)})(1 - P_{f(o)}) + (P_{f(t)})(1 - P_{f(d)})(1 - P_{f(b)})(1 - P_{f(o)}) \quad (170)$$

$$P_{majile} = (1 - P_{fle}) * [P_{maji(o)} + (P_{maji(b)})(1 - P_{maji(o)}) + (P_{maji(d)})(1 - P_{maji(b)})(1 - P_{maji(o)}) + (P_{maji(t)})(1 - P_{maji(d)})(1 - P_{maji(b)})(1 - P_{maji(o)})] \quad (171)$$

$$P_{minile} = (1 - P_{fle} - P_{majile}) * [P_{mini(o)} + (P_{mini(b)})(1 - P_{mini(o)}) + (P_{mini(d)})(1 - P_{mini(b)})(1 - P_{mini(o)}) + (P_{mini(t)})(1 - P_{mini(d)})(1 - P_{mini(b)})(1 - P_{mini(o)})] \quad (172)$$

Outputs of Step 23:

- Probability of fatality given an explosives event and the presence of a person,  $P_{fle}$ , for each effect and the total  $P_{fle}$  for each of the four runs described above
- Probability of major injury given an explosives event and the presence of a person,  $P_{majile}$ , for each effect and the total  $P_{majile}$  for each of the four runs described above
- Probability of minor injury given an explosives event and the presence of a person,  $P_{minile}$ , for each effect and the total  $P_{minile}$  for each of the four runs described above

#### 4.6.2 STEP 24: Determine Fatality Distribution & Injury Risks for one PES-ES Pair

The risk due to an explosives event calculated by SAFER is a prediction. There are many sources of uncertainty in a given prediction. The estimate of risk determined by SAFER is a function of user input, assumptions, approximations, estimates, and mathematical algorithms. Each of these has variability that contributes to uncertainty. A major design goal for SAFER Version 2.0 was to *model uncertainty*. Since SAFER was designed to be a decision aide, the interest in uncertainty included all factors that contribute to uncertainty in the expected risk estimate. This includes the uncertainty in the model, uncertainty in the input, uncertainty in the imbedded science, as well as real world variation in explosive effects and vulnerabilities. This broad design goal became a requirement that was first accomplished as part of the SAFER Version 2.0.

The uncertainty model within SAFER Version 2.0 operated as a post processor executed following completion of Step 26 of the architecture. The SAFER Version 3.1 risk model combines the computation of the Expected Risk with the uncertainty model in an integrated statistical model of the world that estimates the distribution of Expected Fatality.

Step 24 calculates the expected fatality distribution for one PES-ES pair. The computations in this step are based on the results of an extended collaboration between the RBESCT and the Defense Threat Reduction Agency (DTRA). A detailed description and development of the statistical model of the world (MOW) are provided in the paper, *An Analytical Approach for Treating Uncertainty in Probabilistic Risk Assessments* by Dr. R. W. Mensing presented to the 31<sup>st</sup> Explosives Safety Seminar, 24-26 August 2004 (Ref. 11).

The sections below summarize the methodology used to estimate the expected fatalities and the associated uncertainty of this prediction in SAFER Version 3.1.

#### 4.6.2.1 Uncertainty Methodology

The SAFER Version 3.1 uncertainty methodology considers both aleatory (random variation inherent in real life events) and epistemic (knowledge uncertainty inherent in the model of the world and associated scientific algorithms) uncertainties. The RBESCT and DTRA collaboration resulted in a Model of the World that incorporates both types of uncertainty into a combined risk model (as described in Section 4.6.2). To successfully apply the resulting model, a parallel effort was conducted to develop the estimates of parameter uncertainties required as inputs to the uncertainty model. Formal expert elicitations and expert panels were used to estimate the uncertainties present in the scientific algorithms used to compute the probability of fatality and in the historical data used to compute the probability of an explosive event.

The Model of the World (MOW) leverages the risk equation in previous versions of SAFER to formulate the risk estimator for the expected number of fatalities per year ( $F$ ):

$$F = \Delta t * S * \lambda(NEW, E) * P_{fle}(NEW, Yield, Effects) * E \quad (173)$$

where the factors are lognormally distributed and,

- $\Delta t$  = the fraction of the personnel exposure time that explosives are present,
- $\lambda$  = the probability of an explosive event during a given year based on the type of explosives present and the activity performed at the explosives site, also referred to as  $P_e$ ,
- $S$  = an environmental factor that increases the probability of an event based on extenuating circumstances at the site – such as operations in a remote area or under combat conditions,
- $P_{fle}$  = the probability of fatality given an explosive event and exposure – this factor aggregates the effects of the fatality mechanisms: overpressure, debris, building collapse, glass hazards, and thermal effects
- $E$  = the exposure of personnel to an explosive event based on the number of people present in a facility during the year and the number of hours the exposed site is occupied
- $NEW$  = the Net Explosive Weight of hazardous material contributing to the event
- $Yield$  = the percentage of the material contributing energy to the event
- $Effects$  = the four fatality mechanisms computed by SAFER science algorithms

This risk estimator includes each of the elements of the SAFER Version 2.0 risk estimator and incorporates correlation effects such as the impact of:

- Net Explosive Weight ( $NEW$ ) and Exposure ( $E$ ) on the Probability of Event,  $\lambda$
- $NEW$  and explosive yield on the Probability of Fatality given an event,  $P_{fle}$

#### 4.6.2.2 Model Input Descriptions and Derivation from SAFER User Inputs

Estimating the risk distribution using this MOW requires the input of twenty-eight (28) parameters that describe a number of lognormal distributions representing the various factors in the risk equation.

Inputs to Step 24:

Table 36, *Risk Model Input Parameters*, provides a listing of the input parameters and a short title describing what each parameter represents. A detailed description of each parameter and the method used to compute it are provided in the following paragraphs.

**Table 36. Risk Model Input Parameters**

| Symbol               | Short Title                                   | Symbol          | Short Title                                   |
|----------------------|-----------------------------------------------|-----------------|-----------------------------------------------|
| $\Delta t_o$         | median value of $\Delta t$                    | $\sigma_y$      | standard deviation yield                      |
| $\sigma_{\Delta t}$  | standard deviation of $\Delta t$              | $\sigma_{y0}$   | epistemic standard deviation yield            |
| $S_o$                | median value of environmental factor          | $\rho_{Ne}$     | correlation between NEW and exposure          |
| $\sigma_S$           | standard deviation of environmental factor    | $\rho_{Ae}$     | correlation between PES activity and exposure |
| $\lambda_{oo}$       | median value of lambda                        | $\sigma_{NEW1}$ | standard deviation NEW                        |
| $\sigma_{\lambda o}$ | standard deviation of lambda                  | $\sigma_{NEW2}$ | standard deviation NEW                        |
| $E_{oo}$             | epistemic median daily exposure               | $\sigma_1$      | standard deviation for variation in o/p       |
| $\sigma_e$           | random variation standard deviation exposure  | $\sigma_2$      | standard deviation for variation in b/c       |
| $\sigma_{e1}$        | random variation in lambda due to exposure    | $\sigma_3$      | standard deviation for variation in debris    |
| $\sigma_{Eo}$        | epistemic standard deviation of exposure      | $\sigma_4$      | standard deviation for variation in glass     |
| $P_{\eta 100}$       | epistemic median $P_{\eta e}$ blast           | $\sigma_{10}$   | epistemic standard deviation for overpressure |
| $P_{\eta 200}$       | epistemic median $P_{\eta e}$ building damage | $\sigma_{20}$   | epistemic standard deviation for bldg damage  |
| $P_{\eta 300}$       | epistemic median $P_{\eta e}$ debris          | $\sigma_{30}$   | epistemic standard deviation for debris       |
| $P_{\eta 400}$       | epistemic median $P_{\eta e}$ glass           | $\sigma_{40}$   | epistemic standard deviation for glass        |

The remainder of this section describes the derivation of a value for each of these input parameters using the data input through the SAFER screens and the data resulting from runs 1 through 4 of Step 23.

#### 4.6.2.2.1 $\Delta t_o$ and $\sigma_{\Delta t}$

$\Delta t_o$  and  $\sigma_{\Delta t}$  are the median and standard deviation of the lognormal distribution representing the percentage of time,  $\Delta t$ , when explosives are present at the site that exposures are also present. The equations used to compute these two parameters are provided in Section 4.1.3.2.1.

#### 4.6.2.2.2 $S_o$ and $\sigma_S$

$S_o$  and  $\sigma_S$  are the median and standard deviation of the lognormal distribution representing the  $P_e$  environmental factor,  $S$ , that addresses the increase in risk due to extenuating circumstances (ex. OCONUS or hostile area processing).

The RBESCT determined the center value (median) and an upper bound value ( $3\sigma$ ) for each environmental factor. This information is shown in Table 37, *P<sub>e</sub> Environmental Factor (S) Center Values and Upper Bounds*.

**Table 37.  $P_e$  Environmental Factor (S) Center Values and Upper Bounds**

| Environmental Factors                                                                                                              | Center Value ( $S_o$ ) | Upper Bound ( $UB_{\text{environmental factor}}$ ) |
|------------------------------------------------------------------------------------------------------------------------------------|------------------------|----------------------------------------------------|
| Outside Continental United States (OCONUS) operations in support of wartime actions                                                | 10                     | 100                                                |
| Operations involving dangerously unserviceable items awaiting destruction                                                          | 10                     | 25                                                 |
| Initial tests of new systems                                                                                                       | 10                     | 15                                                 |
| Operation occurring in hazardous environments with gases, fibers, etc.                                                             | 10                     | 100                                                |
| Required remote operations                                                                                                         | 10                     | 25                                                 |
| Temporary Duty (TDY) activities during exercises/contingencies/alerts                                                              | 10                     | 15                                                 |
| Concurrent servicing operations, forward arming and refueling, hot arming and refueling or Integrated Combat Turn (ICT) operations | 10                     | 15                                                 |
| Operations involving exposed explosives                                                                                            | 10                     | 25                                                 |
| Outdoor storage / operations normally done indoors                                                                                 | 3.1                    | 5                                                  |
| Home station activities during exercises / contingencies / alert                                                                   | 3.1                    | 5                                                  |
| Flight line holding areas                                                                                                          | 3.1                    | 5                                                  |
| TDY operations during peacetime                                                                                                    | 3.1                    | 5                                                  |

SAFER uses  $S_o$  and  $\sigma_S$  to characterize the Environmental Factor distribution. The standard deviation,  $\sigma_S$  is calculated by:

$$\sigma_S = \sigma_{\text{environmental factor}} = \frac{\ln(UB_{\text{environmental factor}}) - \ln(S_o)}{3} \quad (174)$$

where  $UB_{\text{environmental factor}}$  and  $S_o$  are provided in Table 37,  $P_e$  Environmental Factor (S) Center Values and Upper Bounds.

#### 4.6.2.2.3 $\lambda_{oo}$ and $\sigma_{\lambda o}$

$\lambda_{oo}$  and  $\sigma_{\lambda o}$  are the median and standard deviation of the lognormal factor,  $\delta_o$ , that describes the epistemic uncertainty in  $\lambda_o$ , the median number of explosive events per “typical” operating year at a given activity/facility. The factor  $\lambda_o$  was previously known as  $P_e \text{ Unscaled}$ .

The RBESCT originally compiled the  $P_e$  Matrix and estimated upper bound or  $3\sigma$  values for each activity type. In making these estimates the team considered the following contributors to  $P_e$  uncertainty:

- Amount of data supporting the original  $P_e$ ,
- Variations in the definition of activity type,
- Variations within the type of activity, and
- Variations within the explosives type

In the case of  $\lambda_o$  (previously called unscaled  $P_e$ ), the RBESCT used an upper bound multiplication factor to define the upper bound. The upper bound is found by multiplying the center (median) value by the multiplication factor. Table 38, *Un-scaled  $P_e$  ( $\lambda_o$ ) Center Values and Upper Bounds*, shows the center value, multiplication factor, and upper bound for each explosives activity type.

**Table 38. Un-scaled  $Pe$  ( $\lambda_o$ ) Center Values and Upper Bounds**

| Activity Types     | Center Value ( $\lambda_{oo}$ )<br>(Element I from $P_e$ matrix) | Upper Bound<br>Multiplication Factor | Upper<br>Bound ( $UB_{un-scaled Pe}$ ) |
|--------------------|------------------------------------------------------------------|--------------------------------------|----------------------------------------|
| Assembly           | 4.7E-03                                                          | 5                                    | 2.4E-02                                |
| Disassembly        | 4.7E-03                                                          | 5                                    | 2.4E-02                                |
| LAP                | 4.7E-03                                                          | 10                                   | 4.7E-02                                |
| Maintenance        | 4.7E-03                                                          | 5                                    | 2.4E-02                                |
| Renovation         | 4.7E-03                                                          | 5                                    | 2.4E-02                                |
| Burning Ground     | 2.4E-02                                                          | 4                                    | 9.7E-02                                |
| Demilitarization   | 2.4E-02                                                          | 5                                    | 1.2E-01                                |
| Demolition         | 2.4E-02                                                          | 10                                   | 2.4E-01                                |
| Disposal           | 2.4E-02                                                          | 10                                   | 2.4E-01                                |
| Lab                | 4.3E-03                                                          | 6                                    | 2.6E-02                                |
| Training           | 4.3E-03                                                          | 4                                    | 1.7E-02                                |
| Test               | 4.3E-03                                                          | 4                                    | 1.7E-02                                |
| Loading            | 5.7E-04                                                          | 5                                    | 2.9E-03                                |
| Unloading          | 5.7E-04                                                          | 7                                    | 4.0E-03                                |
| Inspection         | 8.2E-04                                                          | 4                                    | 3.3E-03                                |
| Painting           | 8.2E-04                                                          | 4                                    | 3.3E-03                                |
| Packing            | 8.2E-04                                                          | 4                                    | 3.3E-03                                |
| Manufacturing      | 1.7E-03                                                          | 5                                    | 8.3E-03                                |
| Deep Storage       | 2.5E-05                                                          | 3                                    | 7.6E-05                                |
| Temporary Storage  | 1.0E-04                                                          | 5                                    | 5.0E-04                                |
| In-transit Storage | 3.0E-04                                                          | 7                                    | 2.1E-03                                |

SAFER uses  $\lambda_{oo}$  and  $\sigma_{\lambda o}$  to characterize the distribution of the probability of an explosive event. The “center value” in Table 38, *Un-scaled  $Pe$  ( $\lambda_o$ ) Center Values and Upper Bounds*, is used for the median,  $\lambda_{oo}$ , and the standard deviation,  $\sigma_{\lambda o}$  is calculated by:

$$\sigma_{\lambda o} = \sigma_{un-scaled Pe} = \frac{\ln(UB_{un-scaled Pe}) - \ln(\lambda_{oo})}{3} \quad (175)$$

where  $\lambda_{oo}$  (previously un-scaled  $P_e$ ) and  $UB_{un-scaled Pe}$  is the upper bound provided in Table 38, *Un-scaled  $Pe$  ( $\lambda_o$ ) Center Values and Upper Bounds*.

#### 4.6.2.2.4 $E_{oo}$ and $\sigma_e$

$E_{oo}$  and  $\sigma_e$  are the median and standard deviation of the lognormal distribution,  $E_o$ , representing the median number of daily exposures. Exposures are calculated both for the group and for the worst-case individual. The equations used to compute these parameters are provided in Section 4.1.3.2.2.



#### 4.6.2.2.5 $\sigma_{e1}$

$\sigma_{e1}$  is the standard deviation of  $\delta_{e1}$ , a lognormal multiplicative factor describing the random variation (aleatory uncertainty) in  $\lambda$  due to exposure. This parameter is based on the user input correlation between the PES activity type and the number of people present ( $\rho_{Ae}$ ) and is computed by:

$$\sigma_{e1} = \sigma_e * \rho_{Ae} \quad (176)$$

where  $\sigma_e$  is determined in Section 4.1.3.2 and  $\rho_{Ae}$  is provided in Table 39, *Correlation between PES Activity Type and the Number of People Present*.

**Table 39. Correlation between PES Activity Type and the Number of People Present**

| Correlation                                                                               | User Input                  | Correlation Coefficient ( $\rho_{Ae}$ ) |
|-------------------------------------------------------------------------------------------|-----------------------------|-----------------------------------------|
| Does the PES activity vary on a periodic schedule which correlates to personnel exposure? | No Correlation              | 0.0                                     |
|                                                                                           | Positive correlation        | 0.5                                     |
|                                                                                           | Strong positive correlation | 0.9                                     |

#### 4.6.2.2.6 $\sigma_{Eo}$

$\sigma_{Eo}$  is the standard deviation of the lognormal distribution,  $E_o$ , of the epistemic uncertainty associated with evaluating the median number of daily exposures.

This uncertainty is based on the confidence of the user in their estimate of the exposure. The user selects from the following choices: confident (0.0), somewhat confident (1.461), and not confident (2.246).

The  $\sigma_{Eo}$  parameter is then computed by:

$$\sigma_{Eo} = \ln(1 + \text{assigned value}) \quad (177)$$

**Table 40. Assigned Values for User Confidence in Exposure**

| User Confidence    | Assigned value | Standard deviation of the lognormal distribution ( $\sigma_{Eo}$ ) |
|--------------------|----------------|--------------------------------------------------------------------|
| Confident          | 0              | 0.0                                                                |
| Somewhat Confident | 1.461          | 0.901                                                              |
| Uncertain          | 2.246          | 1.77                                                               |

#### 4.6.2.2.7 $P_{f|koo}$

The median value of the lognormal distribution,  $P_{f|ko}$ , is the epistemic uncertainty associated with evaluating the median value of the probability of fatality due to explosive effect, k, where k = 1, 2, 3, 4 represents the four fatality mechanisms: blast overpressure, building collapse, debris, and glass. For Hazard Division 1.3, these four mechanisms are replaced by thermal.

Two values of  $P_{f|koo}$  are generated: one to support computation of the “sited NEWQD” risk and one for the general risk model. The “sited NEWQD” value of  $P_{f|koo}$  is taken from the  $P_{fle}$  computed in Run 1 for that fatality mechanism. The  $P_{fle}$  value computed in Run 2 is used in the general risk model. These are computed as  $P_{f(o)}$  in Step 8,  $P_{f(g)}$  and  $P_{f(b)}$  in Step 10, and  $P_{f(d)}$  in Step 18.

#### 4.6.2.2.8 $\sigma_y$

$\sigma_y$  is the standard deviation of the lognormal distribution,  $\delta_y$ , a multiplicative factor describing the random (aleatory uncertainty) variation in risk due to yield. For the “sited NEWQD” run where Amount Present and Yield are set to their maximum value, no variation due to yield is allowed and  $\sigma_y$  is set to zero (0). In the general risk model, the variation due to yield is derived from the Total  $P_{fle}$  computed for Run 2 (Expected Yield and Amount Present) and Run 4 (Expected Amount Present, Maximum Yield) and is calculated by:

$$\sigma_y = \ln( P_{fleTotal \text{ for Run4}} / P_{fleTotal \text{ for Run2}} ) / 3 \quad (178)$$

#### 4.6.2.2.9 $\sigma_{yo}$

$\sigma_{yo}$  is the standard deviation of the lognormal distribution,  $\delta_{yo}$ , a multiplicative factor describing the epistemic uncertainty in risk due to yield. SAFER calculates  $\sigma_{yo}$  by:

$$\sigma_{yo} = 0.5 * \sigma_y \quad (179)$$

when the weapon description is “unknown” and

$$\sigma_{yo} = 0.25 * \sigma_y \quad (180)$$

when a specific weapon is selected as the explosive source.

#### 4.6.2.2.10 $\rho_{Ne}$

$\rho_{Ne}$  is the coefficient of correlation between NEW and Exposure. This parameter is selected by the user. The user choices and corresponding correlation coefficient are provided in Table 41, *Correlation between Amount of Explosives Present and Exposure*. Negative correlations are not considered in SAFER.

**Table 41. Correlation between Amount of Explosives Present and Exposure**

| Correlation                                                                                                    | User Input                  | Correlation Coefficient ( $\rho_{Ne}$ ) |
|----------------------------------------------------------------------------------------------------------------|-----------------------------|-----------------------------------------|
| Does the amount of explosives present correlate to the number of people on a periodic (daily or weekly) cycle? | No Correlation              | 0.0                                     |
|                                                                                                                | Positive correlation        | 0.5                                     |
|                                                                                                                | Strong positive correlation | 0.9                                     |

#### 4.6.2.2.11 $\sigma_{NEW1}$

$\sigma_{NEW1}$  is the standard deviation of  $\delta_{NEW1}$ , a multiplicative factor describing the random variation (aleatory uncertainty) in  $\lambda$  due to NEW. SAFER currently sets  $\sigma_{NEW1}$  to zero (0). The ability to model this uncertainty has been included in the risk model for possible future use.

#### 4.6.2.2.12 $\sigma_{NEW2}$

$\sigma_{NEW2}$  is the standard deviation of  $\delta_{NEW2}$ , a multiplicative factor describing the random variation (aleatory uncertainty) in  $P_{fle}$  due to NEW.

For the “sited NEWQD” run where Amount Present and Yield are set to their maximum value, no variation due to NEW is allowed and  $\sigma_{NEW2}$  is set to zero (0). In the general risk model, the variation due to NEW is derived from the Total  $P_{fle}$  computed for Run 2 (Expected Yield and Amount Present) and Run 3 (Expected Yield, Maximum NEW) and is calculated by:

$$\sigma_{NEW2} = \ln( P_{fleTotal\ Run3} / P_{fleTotal\ Run2} ) / 3 \quad (181)$$

#### 4.6.2.2.13 $\sigma_k$ and $\sigma_{ko}$

$\sigma_k$  is the standard deviation of the lognormal distribution,  $\delta_k$ , the random variation (aleatory uncertainty) in  $P_{fle}$  due to effect  $k$ , where  $k = 1, 2, 3, 4$  represents the four fatality mechanisms.  $\sigma_{ko}$  is the standard deviation of the lognormal distribution,  $\delta_{ko}$ , the epistemic uncertainty associated with evaluating the median value of the probability of fatality,  $P_{fle}$ , due to effect  $k$ .

For each fatality mechanism, a  $P_{fle}$  distribution is assumed that has a median value ( $M$ ) calculated by SAFER as described in Section Table 40, *Assigned Values for User Confidence in Exposure*. The upper bound ( $UB$ ) value is then found by multiplying the median value by an upper bound multiplication factor and the sigma is determined by the equation:

$$\sigma = \frac{\ln(UB) - \ln(M)}{3} \quad (182)$$

similarly to other sigmas used in the risk model. A key difference, however, is the fact that the Upper Bounds ( $UB$ s) for the  $P_{fle}$  mechanisms are found by multiplying the Median ( $M$ ) by a factor. Utilizing this fact, the above equation can be rewritten as:

$$\sigma = \frac{\ln(m * M) - \ln(M)}{3} = \frac{\ln(m * M / M)}{3} = \frac{\ln(m)}{3} \quad (183)$$

where  $m$  is the Upper Bound Multiplication Factor provided in Table 42, *Fatality Mechanism Upper Bound Multiplication Factors*.

The RBESCT panel had previously examined the science used in SAFER Version 2.0 to determine multiplicative factors based on uncertainties found in the science for each fatality mechanism. For SAFER Version 3.1, the panel has further refined this approach to determine Upper Bound Multiplication Factors for both Aleatory (Real World) and Epistemic (Modeling) uncertainties. It should be noted that the multipliers previously defined for each of the four fatality mechanisms in SAFER Version 2.0 are the root sum squares of the two multipliers (aleatory and epistemic) used in SAFER Version 3.1.

The values of the multiplication factors determined by the panel are shown in Table 42, *Fatality Mechanism Upper Bound Multiplication Factors*.

**Table 42. Fatality Mechanism Upper Bound Multiplication Factors**

| Fatality Mechanism | Upper Bound Multiplication Factor |           |           |
|--------------------|-----------------------------------|-----------|-----------|
|                    | aleatory                          | epistemic | SAFER 2.0 |
| Overpressure       | 3.34251                           | 8.35629   | 9         |
| Glass              | 8.94427                           | 17.88854  | 20        |
| Building Damage    | 7.07106                           | 7.07106   | 10        |
| Debris             | 3.63803                           | 14.55213  | 15        |
| Thermal            | 16.6410                           | 11.0940   | 20        |

The *Thermal* parameters are used only for calculations involving HD 1.3 items (burning). The other four parameters are used for all other events. An individual SAFER run will either use calculations for HD 1.3 items or calculations for all others but not both.

SAFER uses all of the inputs described in Section 4.6.2 and the equations described in Attachment 9 to estimate the Expected Values of the Expected Fatality distributions (Group and Individual) for one PES-ES pair,  $E_{f(pair)Group}$  and  $P_{f(pair)Individual}$  and the variances of the Expected Fatality distributions (Group and Individual) for one PES-ES pair,  $V_{f(pair)Group}$  and  $V_{f(pair)Individual}$ .

#### 4.6.2.3 Monte Carlo Approach Used to Validate Uncertainty Model

A Monte Carlo approach can be used to model distributions composed of randomly distributed input factors. Using this approach, a large number of replications of the model are run with values of the input factors randomly drawn from appropriate probability distributions at the beginning of each replication. The outputs of the model resulting from each replication are evaluated to determine expected values and measures of dispersion.

Since the MOW has several input factors that are random variates, its implementation in the analytical model can be evaluated using a Monte Carlo approach. This requires drawing random variates for all factors in the MOW and subsequent evaluation of the expected fatality estimate by the MOW. Multiple replications can be performed and the resulting expected fatalities (EF) and uncertainty (variation in expected fatalities) determined.

A two-loop Monte Carlo model was developed to evaluate the MOW as depicted in Figure 11. This two-loop experimental design addresses both epistemic and aleatory uncertainties. The outer loop considers those risk factors with known epistemic or modeling uncertainties. The inner loop considers those risk factors with known aleatory uncertainties due to random, real world variation.

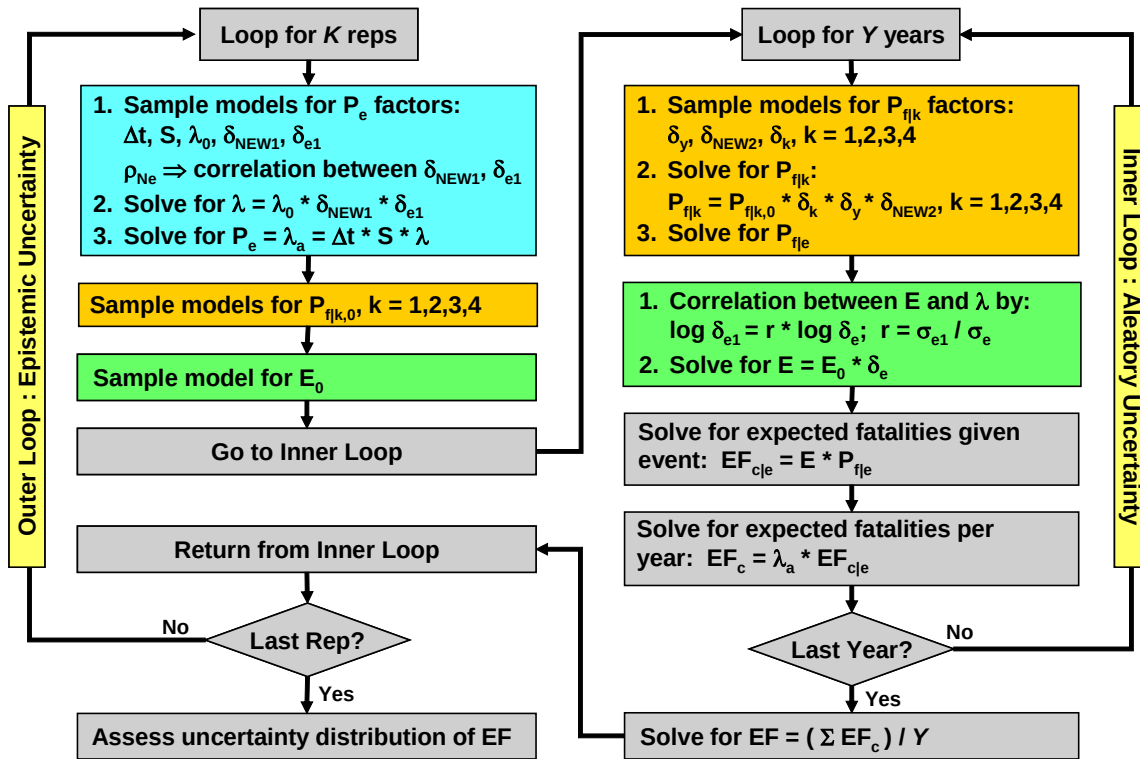


**Figure 11. Two-Loop Monte Carlo Experiment to Evaluate SAFER MOW**

The  $\delta$  terms in the inner and outer loops are multiplicative factors that describe uncertainty or random variation as noted in Section 4.6.2.2. Values of the  $\delta$  terms are random variates drawn from a lognormal distribution. For example,  $\delta_y$  is a multiplicative factor describing the random variation in yield used in the inner loop. The distribution of the random variate  $\delta_y$  is described by  $\sigma_y$ , the standard deviation of the lognormal distribution. A random draw of  $\delta_y$  is determined by:

$$\delta_y = \text{Exp} [\text{Normal} (\text{mean} = 0, \text{standard deviation} = 1) * \sigma_y] \quad (184)$$

Fifty thousand replications of the inner loop for each 50,000 replications of the outer loop were used to evaluate the MOW using the Monte Carlo approach. Several hours of computing time were required to run the needed replications.

#### 4.6.2.4 Analytical Approach to Estimate Risk and Uncertainty

To eliminate the computation time needed to employ a Monte Carlo approach in SAFER, an analytical approach was developed to estimate risk and uncertainty. This analytical model was validated using the Monte Carlo approach described in Section 4.6.2.3 above. A comparison of results produced by the analytical model to those generated by the Monte Carlo analysis is included in the paper, *Uncertainty as Modeled in SAFER 3.0* by R. G. Baker presented to the 31<sup>st</sup> Explosives Safety Seminar, 24-26 August 2004 (Ref 12).

Four test cases that have become “standard” for SAFER testing were used in the evaluation. Three parameters of the risk distributions were compared for each of the four cases using the analytical model and the Monte Carlo approach. These parameters were: the mean, the standard deviation, and the 95<sup>th</sup> percentile value. When the values of these parameters were compared, the maximum difference was less than 2% across the four test cases. This excellent agreement

provides high confidence in the ability of the analytical model to accurately determine the risk distribution based on the input distributions.

#### 4.6.2.5 SAFER Version 3.1 Injury Risk Model

The paragraphs below provide the equations used to compute point estimates of the risk of major and minor injuries. SAFER uses the generic risk equation,

$$Risk = P_{event} * P_{harm | event} * Exposure \quad (185)$$

to compute the risks of major and minor injury. In the risk model described in Section 4.6.2.2,  $P_{event}$  is represented by the distributions  $\lambda$  and  $S$  and Exposure is represented by the distributions  $E_o$  and  $\Delta t$ . For the purposes of computing injury estimates, SAFER computes  $P_{event}$  and Exposure as:

$$P_{event} = E(\lambda) * E(S) = \lambda_{oo} * S_o * \exp[0.5 * (\sigma_\lambda^2 + \sigma_S^2)] \quad (186)$$

and

$$Exposure = E(\Delta t) * E(E_o) = \Delta t_o * E_{oo} * \exp[0.5 * (\sigma_{\Delta t}^2 + \sigma_e^2)] \quad (187)$$

The four point estimates of the potential for injury at a single ES caused by a single PES are then given by:

$$E_{maji (pair) Group} = \lambda_o * S_o * \exp[0.5 * (\sigma_\lambda^2 + \sigma_S^2)] * P_{maji|e} * \Delta t_o Group * E_{oo} Group * \exp[0.5 * (\sigma_{\Delta t Group}^2 + \sigma_e Group^2)] \quad (188)$$

$$P_{maji (pair) Individual} = \lambda_o * S_o * \exp[0.5 * (\sigma_\lambda^2 + \sigma_S^2)] * P_{maji|e} * \Delta t_o Individual * E_{oo} Individual * \exp[0.5 * (\sigma_{\Delta t Ind}^2 + \sigma_e Ind^2)] \quad (189)$$

and

$$E_{mini (pair) Group} = \lambda_o * S_o * \exp[0.5 * (\sigma_\lambda^2 + \sigma_S^2)] * P_{mini|e} * \Delta t_o Group * E_{oo} Group * \exp[0.5 * (\sigma_{\Delta t Group}^2 + \sigma_e Group^2)] \quad (190)$$

$$P_{mini (pair) Individual} = \lambda_o * S_o * \exp[0.5 * (\sigma_\lambda^2 + \sigma_S^2)] * P_{mini|e} * \Delta t_o Individual * E_{oo} Individual * \exp[0.5 * (\sigma_{\Delta t Ind}^2 + \sigma_e Ind^2)] \quad (191)$$

where  $P_{maji|e}$  and  $P_{mini|e}$  are defined in Equations (171) and (172) in Section 4.6.1.

Outputs of Step 24:

- Expected Values of the Expected Fatality distributions (Group and Individual) for one PES-ES pair,  $E_{f(pair)Group}$  and  $P_{f(pair)Individual}$  computed using the inputs described in the entirety of Section 4.6.2.2 and the equations described in Attachment 9
- Variances of the Expected Fatality distributions (Group and Individual) for one PES-ES pair,  $V_{f(pair)Group}$  and  $V_{f(pair)Individual}$  computed using the inputs described in the entirety of Section 4.6.2.2 and the equations described in Attachment 9
- Point Estimates of Major Injury (Group and Individual),  $E_{maji (pair) Group}$  and  $P_{maji (pair) Individual}$
- Point Estimates of Minor Injury (Group and Individual),  $E_{mini (pair) Group}$  and  $P_{mini (pair) Individual}$

SAFER Version 3.1 includes a fully integrated statistical Model of the World that directly estimates the distribution of the Expected Fatality random variable using an analytical method. The risk estimator and uncertainty model were developed in collaboration with DTRA and have been validated by Monte Carlo analysis. Point estimates for Major and Minor Injury are also computed. While no estimates of the variation in these risks are computed, available knowledge of variation in two of the three factors,  $P(event)$  and  $Exposure$ , is incorporated into the point estimate computation.

#### 4.6.3 STEP 25: Aggregate all risks to each ES and all risks caused by each PES

Step 25 has been broken into two parts: Substep 1 which computes the total risk to an ES due to all PESs surrounding it, and Substep 2 which computes the total risks caused by a PES to all ESs surrounding it.

##### Substep 1

This step calculates the expected fatalities and injury point estimates at a unique ES. This is accomplished by aggregating the risk contributions of all PESs posing a hazard to that ES.

Inputs to Substep 1:

- Definition of the Group Risk distribution for all PES-ES pairs that share a common ES [from Step 24]. The distributions are defined by the Expected number of fatalities,  $E_{f(pair)group}$ , and the associated Variance,  $V_{f(pair)group}$
- Definition of the Individual Probability of Fatality distribution for all PES-ES pairs that share a common ES [from Step 24]. The distributions are defined by the Probability of Fatality,  $P_{f(pair)Individual}$ , and associated Variance,  $V_{f(pair)Individual}$
- Point estimates of the Group Risk of Major and Minor Injury for all PES-ES pairs that share a common ES [from Step 24],  $E_{maji (pair) Group}$  and  $E_{mini (pair) Group}$
- Point estimates of the Individual Risk of Major and Minor Injury for all PES-ES pairs that share a common ES [from Step 24],  $E_{maji (pair) Individual}$  and  $E_{mini (pair) Individual}$

##### Fatality Distributions

SAFER calculates the group expected fatalities at a unique ES,  $E_{f(ES)Group}$ , by:

$$E_{f(ES)Group} = \sum_{PES\ sites} E_{f(pair)Group} \quad (192)$$

and the Variance in the ES Group Risk distribution by:

$$V_{f(ES)Group} = \sum_{PES\ sites} V_{f(pair)Group} \quad (193)$$

SAFER calculates the individual expected fatalities at a unique ES,  $P_{f(ES)Individual}$ , by:

$$P_{f(ES)Individual} = \sum_{PESsites} E_i - \sum_{i \neq j} E_i E_j + \sum_{i \neq j \neq k} E_i E_j E_k \quad (194)$$

where the  $E_i$  and  $E_j$  denote the individual probability of fatality,  $P_{f(pair)Individual}$ , that distinct PES sites pose to the ES of interest.

Then SAFER calculates the Variance of the ES Individual Risk distribution by:

$$V_{f(ES)Individual} = \sum_{PESsites} V_i + \sum_{i \neq j} V_{ij} \quad (195)$$

with

$$V_{ij} = E_i^2 V_j + E_j^2 V_i + V_i V_j \quad (196)$$

where the  $E_i$  and  $V_i$  denote the Expected Values,  $P_{f(pair)Individual}$ , and Variances,  $V_{f(pair)Individual}$ , in the individual probability of fatality that distinct PES sites pose to the ES of interest.

In addition, SAFER calculates the Group expected fatalities due to all hazards for ESs within the Risk-based evaluation distance of a given PES (PES Siting Risk),  $E_{f(PES Siting)Group}$ , by:

$$E_{f(PES Siting)Group} = \sum_{ES sites} E_{f(ES)Group} \quad (197)$$

and the Variance in the PES Group Risk distribution by:

$$V_{f(PES Siting)Group} = \sum_{ES sites} V_{f(ES)Group} \quad (198)$$

SAFER calculates the Individual expected fatalities due to all hazards for ESs within the Risk-based evaluation distance of a given PES,  $P_{f(PES Siting)Individual}$ , by:

$$P_{f(PES Siting)Individual} = \text{Maximum}\{ P_{f(ES)Individual} : \text{across all ESs within the Risk-based evaluation distance of the PES} \} \quad (199)$$

and the Variance in the PES Individual Risk distribution by:

$$V_{f(PES Siting)Individual} = \text{the } V_{f(ES)Individual} \text{ associated with the ES having the maximum risk estimate as determined by Equation (199)} \quad (200)$$

### *Injury Point Estimates*

SAFER calculates the point estimates for Major Injuries at a unique ES by:

$$E_{maji(ES)Group} = \sum_{PESs} E_{maji(pair)Group} \quad (201)$$

$$P_{maji(ES)Individual} = 1 - \prod_{PESs} (1 - P_{maji(pair)Individual}) \quad (202)$$

and the point estimates for Minor Injuries at the ES by:

$$E_{mini(ES)Group} = \sum_{PESs} E_{mini(pair)Group} \quad (203)$$

$$P_{mini(ES)Individual} = 1 - \prod_{PESs} (1 - P_{mini(pair)Individual}) \quad (204)$$

Outputs of *Substep 1*:

- Expected fatality (Group Risk) distribution for each unique ES, defined by  $E_{f(ES)Group}$  and  $V_{f(ES)Group}$



- Maximum Individual Probability of Fatality distribution for each unique ES, defined by  $P_{f(ES)Individual}$  and  $V_{f(ES)Individual}$
- Expected fatality (Group Risk) distribution for all ESs within the Risk-based evaluation distance of any PESs (Siting Risk), defined by  $E_{f(PES\ Siting)Group}$  and  $V_{f(PES\ Siting)Group}$
- Maximum Individual Probability of Fatality distribution for all ESs within the Risk-based evaluation distance of any PESs (Siting Risk), defined by  $P_{f(PES\ Siting)Individual}$  and  $V_{f(PES\ Siting)Individual}$
- Point estimates for Major Injuries (Group and Individual) for each ES,  $E_{maji\ (ES)\ Group}$  and  $P_{maji(ES)Individual}$
- Point estimates for Minor Injuries (Group and Individual) for each ES,  $E_{mini\ (ES)\ Group}$  and  $P_{mini(ES)Individual}$

### Substep 2

This step calculates the expected fatalities and point estimates of injuries caused by a unique PES. This is accomplished by aggregating the risks the PES poses to multiple ESs.

Inputs to *Substep 2*:

- Definition of the Group Risk distribution for all PES-ES pairs that share a common PES [from Step 24]. The distributions are defined by the Expected number of fatalities,  $E_{f(pair)group}$ , and its Variance,  $V_{f(pair)group}$
- Definition of the Individual Probability of Fatality distribution for all PES-ES pairs that share a common PES [from Step 24]. The distributions are defined by the Probability of Fatality,  $P_{f(pair)Individual}$ , and its Variance,  $V_{f(pair)Individual}$
- Point estimates of the Group Risk of Major and Minor Injury for all PES-ES pairs that share a common PES [from Step 24],  $E_{maji\ (pair)\ Group}$  and  $E_{mini\ (pair)\ Group}$
- Point estimates of the Individual Risk of Major and Minor Injury for all PES-ES pairs that share a common PES [from Step 24],  $P_{maji\ (pair)\ Individual}$  and  $P_{mini\ (pair)\ Individual}$

### Fatality Distributions

SAFER calculates the Group expected fatalities caused by a unique PES,  $E_{f(PES)Group}$ , by:

$$E_{f(PES)Group} = \sum_{ES\ sites} E_{f(pair)Group} \quad (205)$$

and the Variance in the PES Group Risk distribution by:

$$V_{f(PES)Group} = \sum_{ES\ sites} V_{f(pair)Group} \quad (206)$$

SAFER calculates the Individual expected fatalities caused by a unique PES,  $P_{f(PES)Individual}$ , by:

$$P_{f(PES)Individual} = \text{Maximum}\{ P_{f(pair)Individual} : \text{across all ESs exposed to the PES} \} \quad (207)$$

and the Variance in the PES Individual Risk distribution by:

$$V_{f(PES)Individual} = \text{the } V_{f(pair)Individual} \text{ associated with the ES having the maximum risk} \quad (208)$$

### Injury Point Estimates

SAFER calculates the point estimates for Major Injuries at a unique PES as:

$$E_{maji(PES)Group} = \sum_{ES \text{ sites}} E_{maji(pair)Group} \quad (209)$$

and

$$P_{maji(PES)Individual} = \text{Maximum}\{ P_{maji(pair)Individual} : \text{across all ESs exposed to the PES} \} \quad (210)$$

SAFER calculates the point estimates for Minor Injuries for a unique PES as:

$$E_{mini(PES)Group} = \sum_{ES \text{ sites}} E_{mini(pair)Group} \quad (211)$$

and

$$P_{mini(PES)Individual} = \text{Maximum}\{ P_{mini(pair)Individual} : \text{across all ESs exposed to the PES} \} \quad (212)$$

Outputs of *Substep 2*:

- Expected fatalities (Group Risk) distribution caused by a unique PES, defined by  $E_{f(PES)Group}$  and  $V_{f(PES)Group}$
- Maximum Individual Probability of Fatality distribution for a single PES, defined by  $P_{f(PES)Individual}$  and  $V_{f(PES)Individual}$
- Point estimates for Major Injuries (Group and Individual) for each PES,  $E_{maji(PES)Group}$  and  $P_{maji(PES)Individual}$
- Point estimates for Minor Injuries (Group and Individual) for each PES,  $E_{mini(PES)Group}$  and  $P_{mini(PES)Individual}$

#### 4.6.4 STEP 26: Sum $E_f$ values from all PESs.

Step 26 is the final SAFER step where the total explosive risk for an entire situation (installation) is calculated. In this step, SAFER calculates expected fatalities and point estimates for the situation by summing the expected fatalities/injuries for all ES locations in the situation due to all PES sites that hazard them.

Inputs to Step 26:

- Definition of the Group Risk distribution for each ES location on the installation [from Step 25, *Substep 1*]. The distributions are defined by the Expected number of fatalities,  $E_{f(ES)group}$ , and the associated Variance,  $V_{f(ES)group}$
- Definition of the Individual Probability of Fatality distribution for each ES location on the installation [from Step 25, *Substep 1*]. The distributions are defined by the Probability of Fatality,  $P_{f(ES)Individual}$ , and the associated Variance,  $V_{f(ES)Individual}$

#### Fatality Distributions

SAFER calculates the expected fatalities (Group Risk) for the entire situation,  $E_{f(install)Group}$ , by:

$$E_{f(install)Group} = \sum_{ES \text{ sites}} E_{f(ES)Group} \quad (213)$$

and its associated variance by:

$$V_{f(install)Group} = \sum_{ES \text{ sites}} V_{f(ES)Group} \quad (214)$$

The individual probability of fatality (Individual Risk) for the situation,  $P_{f(install)Individual}$ , is then calculated as:

$$P_{f(install)Individual} = \text{Maximum}\{ P_{f(ES)Individual} : \text{across the installation} \} \quad (215)$$

and its associated variance by:

$$V_{f(install)Individual} = V_{f(ES)Individual} \text{ associated with the ES having the maximum risk} \quad (216)$$

### *Injury Point Estimates*

SAFER calculates the point estimates for Major Injuries over the entire situation (installation) as:

$$E_{maji(install)Group} = \sum_{ES \text{ sites}} E_{maji(ES)Group} \quad (217)$$

and

$$P_{maji(install)Individual} = \text{Maximum}\{ P_{maji(ES)Individual} : \text{across the installation} \} \quad (218)$$

and the point estimates for Minor Injuries over the installation as:

$$E_{mini(install)Group} = \sum_{ES \text{ sites}} E_{mini(ES)Group} \quad (219)$$

and

$$P_{mini(install)Individual} = \text{Maximum}\{ P_{mini(ES)Individual} : \text{across the installation} \} \quad (220)$$

Outputs of Step 26:

- Expected fatality distribution for the entire situation, defined by expected value,  $E_{f(install)Group}$ , and variance,  $V_{f(install)Group}$
- Individual Probability of Fatality distribution for the entire situation, defined by expected value,  $P_{f(install)Individual}$ , and variance,  $V_{f(install)Individual}$
- Point estimates for Major Injuries (Group and Individual) for the entire situation (installation),  $E_{maji(install)Group}$  and  $P_{maji(install)Individual}$
- Point estimates for Minor Injuries (Group and Individual) for each ES,  $E_{mini(install)Group}$  and  $P_{mini(install)Individual}$

After Step 26, all of the steps in the SAFER Architecture have been completed.

## **5.0 UNCERTAINTY DISPLAY**

At this time, uncertainty criteria have not been developed or approved by the DDESB. The information on uncertainty provided in SAFER Version 3.1 is provided for informational purposes only. This section presents an overview of the uncertainty display SAFER Version 3.1 utilizes to communicate the results of the risk analysis and the use of the log-normal distribution for modeling risk.

The uncertainty model integrated within SAFER computes a variety of risk measures in Steps 24 through 26. The SAFER Version 3.1 uncertainty model provides an optional uncertainty display for group and individual risks associated with a single PES-ES pair and the PES Siting Risk. A sample of this display is shown in Figure 12. This display provides a graphical representation of the uncertainty distribution on both a logarithmic and a linear risk scale.

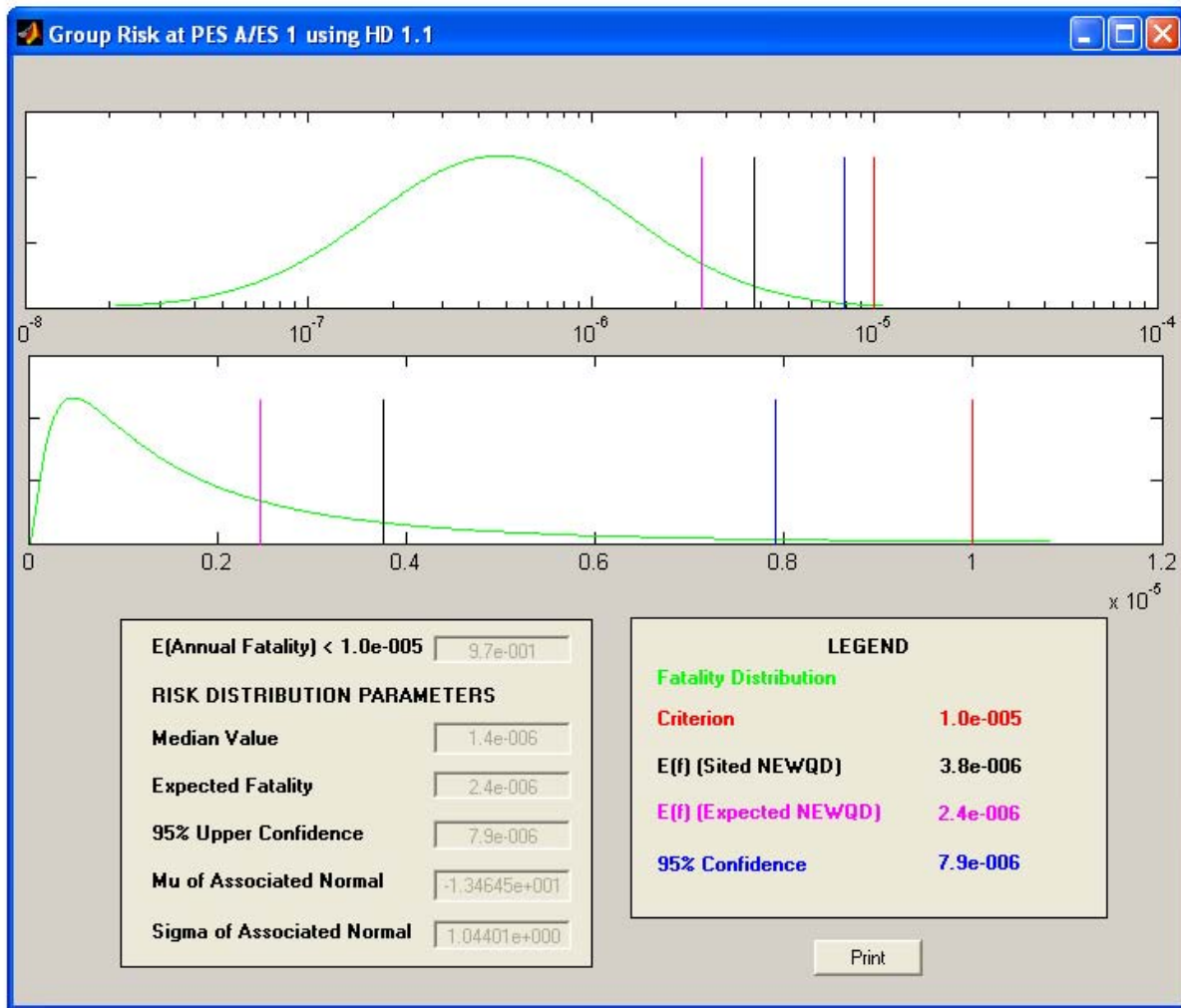


**Figure 12. SAFER Version 3.1 Uncertainty Display**

The screen also displays several risk measures to assist in interpretation of the analysis results:

- Fatality distribution. This curve displays the combined effects of all uncertainty drivers that have been incorporated into the general risk model ( $E_f$  for group risk or  $P_f$  for individual risk).
- Criterion line. This is the level of risk that is acceptable without a waiver, exemption, or other informed decision to accept risk. The criterion is based on the threshold approved by the DDESB.
- $E_f$  or  $P_f$  (Sited value) line (decision point). This line represents the risk value calculated by SAFER that is to be compared to the criterion. The decision point risk estimate is calculated by biasing two critical parameters to the conservative side: the Amount of Explosives Present and

the Explosive Yield. To compute this risk, the results of Run 1 (Maximum Yield, Sited NEWQD) are used to define the median values of the four fatality mechanisms and variances due to yield and NEW are set to zero.

- $E_f$  or  $P_f$  (Expected value) line. This line represents the expected value of the group or individual risk distribution calculated by SAFER, which is the output of the general risk model. To compute this risk, the distribution of amount present (expected NEWQD and sited NEWQD) and the yield is calculated in Step 4 (Section 4.1.4).
- 95% Confidence. This line represents the 95% confidence point on the  $E_f$  or  $P_f$  risk distribution.
- The mean ( $\mu$ ) and standard deviation ( $\sigma$ ) of the associated linear normal distribution. Each risk distribution computed by SAFER is represented by a lognormal distribution having an expected value ( $E_f$  or  $P_f$ ) and variance (V). From these two parameters, the mean ( $\mu$ ) and standard deviation ( $\sigma$ ) of the associated normal distribution can be computed as:

$$\mu = \ln \{ E^2 / \text{Sqrt}(V+E^2) \} \quad \text{and} \quad \sigma = \text{Sqrt} \{ \ln [ (V/E^2) + 1 ] \}$$

These are currently displayed on the uncertainty screen in the Risk Distribution Parameters box. Using  $\mu$  and  $\sigma$ , the lognormal probability density function (distribution curve) of the risk and remaining parameters of the distribution can be computed as follows:

Curve:  $f(x) = \exp[ -0.5 * \{ (\ln(x) - \mu) / \sigma \}^2 ] / [ \text{Sqrt}(2\pi)\sigma x ]$

Mode:  $\exp(\mu - \sigma^2)$

Median:  $\exp(\mu)$

Mean:  $\exp(\mu + 0.5\sigma^2)$

Variance:  $\exp[2(\mu + \sigma^2)] - \exp[2\mu + \sigma^2]$

- Risk distribution parameters. Selected parameters describing the risk distribution are also presented on the display. These include:
  - Probability that the actual  $E_f$  or  $P_f$  is less than the criterion
  - Median and Expected Value of the expected fatality distribution
  - 95% upper confidence bound

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## Appendix A Supplemental Tables

**Table A-1. Default ES Roof and Wall Types**

| Building Category            | Building Type & Default Roof <sup>1,2</sup>                              | ES Building Type                               | Wall Type (default – not user selectable) | Default Roof Type                           |
|------------------------------|--------------------------------------------------------------------------|------------------------------------------------|-------------------------------------------|---------------------------------------------|
| Open                         | Open [NA]                                                                | NA                                             | NA                                        | NA                                          |
| Reinforced concrete building | Small reinforced concrete [4" reinforced concrete]                       | Small reinforced concrete (office/commercial)  | 8" reinforced concrete                    | 4" reinforced concrete                      |
|                              | Medium reinforced concrete [2" lightweight concrete/steel deck & joists] | Medium reinforced concrete (office/commercial) | 8" reinforced concrete                    | 2" lightweight concrete/steel deck & joists |
|                              | Large tilt-up reinforced concrete [Plywood panelized (2x6 @ 24")]        | Large tilt-up reinforced concrete (commercial) | 6" reinforced concrete tilt-up            | Plywood panelized (2x6 @ 24")               |
| Reinforced masonry           | Small reinforced masonry [Plywood/wood joists (2x10 @ 16")]              | Small reinforced masonry (office/commercial)   | 8" reinforced CMU                         | Plywood/wood joists (2x10 @ 16")            |
|                              | Medium reinforced masonry [Light steel panel (22 gauge)]                 | Medium reinforced masonry (office/commercial)  | 8" reinforced CMU                         | Light steel panel (22 gauge)                |
| Unreinforced brick/masonry   | Small unreinforced brick [Plywood/wood joists (2x10 @ 16")]              | Small unreinforced brick (office/residence)    | 8" unreinforced brick                     | Plywood/wood joists (2x10 @ 16")            |
|                              | Medium unreinforced masonry [Plywood panelized (2x6 @ 24")]              | Medium unreinforced masonry (office/apartment) | 8" unreinforced CMU                       | Plywood panelized (2x6 @ 24")               |
|                              | Large unreinforced masonry [Gypsum/fiberboard/steel joist]               | Large unreinforced masonry (office)            | 8" unreinforced CMU                       | Gypsum/fiberboard/steel joist               |
| Steel PEMB                   | Small PEMB [Light steel panel (22 gauge)]                                | Small PEMB (office/storage)                    | Steel siding (22 gauge)                   | Light steel panel (22 gauge)                |
|                              | Medium PEMB [Light steel panel (22 gauge)]                               | Medium PEMB (office/commercial)                | Steel siding (22 gauge)                   | Light steel panel (22 gauge)                |
|                              | Large Hi-Bay PEMB [Light steel panel (22 gauge)]                         | Large Hi-Bay PEMB (office/storage/hangar)      | Steel siding (22 gauge)                   | Light steel panel (22 gauge)                |
| Stud wall building           | Small wood frame [Plywood/wood joists (2x10 @ 16")]                      | Small wood frame (single family residence)     | 1/2" plywood siding                       | Plywood/wood joists (2x10 @ 16")            |
|                              | Medium wood frame [Plywood/wood joists (2x10 @ 16")]                     | Medium wood frame (residence/apartment)        | 1/2" plywood siding                       | Plywood/wood joists (2x10 @ 16")            |
|                              | Medium steel stud [Light steel panel (22 gauge)]                         | Medium steel stud (office/commercial)          | 22 gauge steel siding                     | Light steel panel (22 gauge)                |
| Modular building or trailer  | Wood frame [Plywood panelized (2x6 @ 24")]                               | Wood frame (office/residence)                  | 1/2" plywood siding                       | Plywood panelized (2x6 @ 24")               |
| Passenger vehicle            | Moving vehicle [Steel (automobile)]                                      | Moving vehicle                                 | Steel (automobile doors)                  | Steel (automobile)                          |
|                              | Stationary vehicle [Steel (automobile)]                                  | Stationary vehicle                             | Steel (automobile doors)                  | Steel (automobile)                          |

<sup>1</sup> Small, medium, and large sizes refer to approximate area/floor in ft<sup>2</sup>.

Small < 5000 ft<sup>2</sup>

5,000 ft<sup>2</sup> < Medium < 20,000 ft<sup>2</sup>

Large > 20,000 ft<sup>2</sup>

Modular Bldg or Trailer = approx 500 ft<sup>2</sup>

<sup>2</sup> Default roof (in parenthesis) is automatically shown in *Roof type* window in *Define Exposed Site (ES) Information* Dialog. If the default roof is replaced by the user, then the user-defined roof will be used to calculate the risk from the PES fragment and debris.

The default roof is always used in the calculations for the building response to overpressure.



**Table A-2. Effective Yield**

| Weapon Type     | Z (Hazard Factor)<br>(ft/lbs <sup>1/3</sup> ) | Yield Equation (lbs)<br>$Y = C_1 * (W_1 / C_2)$ | A         | B          | C         | D         | E          | F          |
|-----------------|-----------------------------------------------|-------------------------------------------------|-----------|------------|-----------|-----------|------------|------------|
| MK82            | 86 – 350                                      | $Y = 275 * (W_1 / 192)$                         |           |            |           |           |            |            |
|                 | 2.9 – 86                                      | Equation (19)                                   | 4.44477   | 1.2902     | -0.34374  | 0.025341  | 0          | 0          |
|                 | 1.2 – 2.9                                     | $Y = 235 * (W_1 / 192)$                         |           |            |           |           |            |            |
| MK83            | 86 – 350                                      | $Y = 590 * (W_1 / 445)$                         |           |            |           |           |            |            |
|                 | 2.9 – 86                                      | Equation (19)                                   | 5.5293    | 1.11439    | -0.30437  | 0.021737  | 0          | 0          |
|                 | 1.2 – 2.9                                     | $Y = 560 * (W_1 / 445)$                         |           |            |           |           |            |            |
| MK84            | 86 – 350                                      | $Y = 1220 * (W_1 / 945)$                        |           |            |           |           |            |            |
|                 | 2.9 – 86                                      | Equation (19)                                   | 6.3317    | 11.0624    | -0.28844  | 0.019965  | 0          | 0          |
|                 | 1.2 – 2.9                                     | $Y = 1200 * (W_1 / 945)$                        |           |            |           |           |            |            |
| M107            | 86-350                                        | $Y = 12.8 * (W_1 / 15.1)$                       |           |            |           |           |            |            |
|                 | 2.9 – 86                                      | Equation (19)                                   | 3.7993    | 0.35294    | -0.51476  | 0.11606   | -0.0073289 | 0          |
|                 | 1.2 – 2.9                                     | $Y = 42 * (W_1 / 15.1)$                         |           |            |           |           |            |            |
| AIM-7           | 1.2 – 350                                     | Equation (19)                                   | 4.43036   | -0.838135  | 0.544216  | -0.184942 | 0.019430   | -0.000231  |
| Bulk/light case |                                               | $Y = W_1 * 1$                                   |           |            |           |           |            |            |
| M1 (105 mm)     | 1.2 – 2.9                                     | $Y = 6.5 * (W_1 / 5)$                           |           |            |           |           |            |            |
|                 | 2.9 – 350                                     | Equation (19)                                   | 1.952732  | -0.4599533 | 0.529341  | -0.166752 | 0.020306   | -0.0007978 |
| MK2 (40 mm)     | 1.2 – 260                                     | Equation (19)                                   | -2.980723 | 1.944348   | -0.293102 | -0.173221 | 0.049327   | -0.0035675 |
|                 | 260- 350                                      | $Y = 0.06 * (W_1 / 0.2)$                        |           |            |           |           |            |            |

**Table A-3. Pressure Calculation Coefficients**

| Z Range<br>(ft/lbs <sup>1/3</sup> ) | A      | B       | C       | D       | E       |
|-------------------------------------|--------|---------|---------|---------|---------|
| 0.5-7.25                            | 6.9137 | -1.4398 | -0.2815 | -0.1416 | 0.0685  |
| 7.25-60                             | 8.8035 | -3.7001 | 0.2709  | 0.0733  | -0.0127 |
| 60-500                              | 5.4233 | -1.4066 | 0       | 0       | 0       |

Note:  $Z = Z_o$  for Step 5 and  $Z = Z_a$  for Step 6

**Table A-4. Impulse Calculation Coefficients**

| Z Range<br>(ft/lbs <sup>1/3</sup> ) | A      | B      | C        | D      | E        |
|-------------------------------------|--------|--------|----------|--------|----------|
| .5 – 2.41                           | 2.975  | -0.466 | 0.963    | 0.03   | -0.087   |
| 2.41 – 6                            | 0.911  | 7.26   | -7.459   | 2.960  | -0.432   |
| 6 - 85                              | 3.2484 | 0.1633 | - 0.4416 | 0.0793 | -0.00554 |
| 85 - 400                            | 4.7702 | -1.062 | 0        | 0      | 0        |

Note:  $Z = Z_o$  for Step 5 and  $Z = Z_a$  for Step 6

**Table A-5. Adjusted Weight Coefficients**

|                                            | Z<br>(ft/lbs <sup>1/3</sup> ) | Adjusted Weight<br>(lbs)<br>$W_a = c * W_1$ | A         | B         | C           | D            | E              | F            | G           | H |
|--------------------------------------------|-------------------------------|---------------------------------------------|-----------|-----------|-------------|--------------|----------------|--------------|-------------|---|
| ECM-front (all<br>sizes/types)             | > 60                          | $W_a = 0.35 * W_1$                          |           |           |             |              |                |              |             |   |
|                                            | 1.5 – 60                      | Equation (25)                               | -0.43864  | -8.4165   | 16.7060     | -12.7490     | 4.755400       | -0.866790    | 0.061526    | 0 |
|                                            | < 1.5                         | $W_a = 0.10 * W_1$                          |           |           |             |              |                |              |             |   |
| ECM – side<br>(all<br>sizes/types)         | > 60                          | $W_a = 0.35 * W_1$                          |           |           |             |              |                |              |             |   |
|                                            | 2 – 60                        | Equation (25)                               | -1.2832   | -3.6111   | 5.4064      | -3.1582      | 1.0194         | -0.17738     | 0.012497    | 0 |
|                                            | < 2                           | $W_a = 0.13 * W_1$                          |           |           |             |              |                |              |             |   |
| ECM – rear<br>(all<br>sizes/types)         | > 60                          | $W_a = 0.20 * W_1$                          |           |           |             |              |                |              |             |   |
|                                            | 2.5 – 60                      | Equation (25)                               | 0.72068   | -8.8511   | 10.700      | -6.0891      | 1.8914         | -0.30811     | 0.020299    | 0 |
|                                            | < 2.5                         | $W_a = 0.14 * W_1$                          |           |           |             |              |                |              |             |   |
| HAS – front                                | > 63                          | $W_a = 0.68 * W_1$                          |           |           |             |              |                |              |             |   |
|                                            | 3.5 – 63                      | Equation (25)                               | 5.811198  | -13.94288 | 11.12264    | -4.566028    | 1.050035       | -0.1293674   | 0.006702599 | 0 |
|                                            | < 3.5                         | $W_a = 0.38 * W_1$                          |           |           |             |              |                |              |             |   |
| HAS – side<br>(W> 250 lbs)                 | > 100                         | $W_a = 1.2 * W_1$                           |           |           |             |              |                |              |             |   |
|                                            | 2.5 – 100                     | Equation (25)                               | -5.568345 | 2.664608  | -0.6710276  | 0.4365081    | -0.1465799     | 0.01495905   | 0           | 0 |
|                                            | < 2.5                         | $W_a = 0.03 * W_1$                          |           |           |             |              |                |              |             |   |
| HAS – side<br>(W <= 250<br>lbs)            | > 100                         | $W_a = 0.05 * W_1$                          |           |           |             |              |                |              |             |   |
|                                            | 2.5 – 100                     | Equation (25)                               | -8.572503 | 1.282287  | 0.180446    | -0.2260388   | .03947517      | 0            | 0           | 0 |
|                                            | < 2.5                         | $W_a = 0.01 * W_1$                          |           |           |             |              |                |              |             |   |
| HAS – rear                                 | > 50                          | $W_a = 0.07 * W_1$                          |           |           |             |              |                |              |             |   |
|                                            | 2.67 – 50                     | Equation (25)                               | -7.345585 | 5.90604   | -3.846292   | 1.787642     | -0.4084985     | 0.03173365   | 0           | 0 |
|                                            | < 2.67                        | $W_a = 0.07 * W_1$                          |           |           |             |              |                |              |             |   |
| AGBS (all<br>sizes/types)                  | > 140                         | $W_a = 0.85 * W_1$                          |           |           |             |              |                |              |             |   |
|                                            | 1.15 – 140                    | Equation (25)                               | -4.18694  | 2.28941   | -0.16247187 | -0.071019971 | -0.00044634702 | 0.0018659168 | 0           | 0 |
|                                            | < 1.15                        | $W_a = 0.02 * W_1$                          |           |           |             |              |                |              |             |   |
| Operating<br>Building (all<br>sizes/types) | > 140                         | $W_a = 0.85 * W_1$                          |           |           |             |              |                |              |             |   |
|                                            | 1.15 – 140                    | Equation (25)                               | -4.18694  | 2.28941   | -0.16247187 | -0.071019971 | -0.00044634702 | 0.0018659168 | 0           | 0 |
|                                            | < 1.15                        | $W_a = 0.02 * W_1$                          |           |           |             |              |                |              |             |   |
| Ship (all<br>sizes)                        | > 100                         | $W_a = 1.33 * W_1$                          |           |           |             |              |                |              |             |   |
|                                            | 7.8 – 100                     | Equation (25)                               | -11.81948 | 16.42335  | -8.991386   | 2.277275     | -0.2687593     | 0.01236889   | 0           | 0 |
|                                            | < 7.8                         | $W_a = 0.5 * W_1$                           |           |           |             |              |                |              |             |   |
| ISO<br>Containers                          | > 100                         | $W_a = 0.47 * W_1$                          |           |           |             |              |                |              |             |   |
|                                            | 2 – 100                       | Equation (25)                               |           |           |             |              |                |              |             |   |

**Table A-6. Damage Coefficients for the PES Roof**

| PES (roof)               | Initial Breakout Value<br>$Y_0$ (lbs) | Total Destruction Value<br>$Y_{100}$ (lbs) | $b$  |
|--------------------------|---------------------------------------|--------------------------------------------|------|
| PEMB                     | 3                                     | 40                                         | 0.4  |
| Hollow Clay Tile         | 1                                     | 8                                          | 0.25 |
| HAS                      | 1,000                                 | 2,000                                      | 0.9  |
| Large Concrete Arch ECM  | 15                                    | 250                                        | 1.0  |
| Medium Concrete Arch ECM | 15                                    | 250                                        | 1.0  |
| Small Concrete Arch ECM  | 15                                    | 250                                        | 1.0  |
| Large Steel Arch ECM     | 15                                    | 250                                        | 1.0  |
| Medium Steel Arch ECM    | 15                                    | 250                                        | 1.0  |
| Small Steel Arch ECM     | 15                                    | 250                                        | 1.0  |
| Large AGBS               | 1                                     | 16                                         | 0.5  |
| Medium AGBS              | 1                                     | 16                                         | 0.5  |
| Small AGBS (Square)      | 1                                     | 16                                         | 0.5  |
| Medium Concrete Building | 1                                     | 16                                         | 0.5  |
| Small Concrete Building  | 1                                     | 16                                         | 0.5  |
| Ship (small)             | 100                                   | 5,000                                      | 1.1  |
| Ship (medium)            | 100                                   | 5,000                                      | 1.1  |
| Ship (large)             | 100                                   | 5,000                                      | 1.1  |
| ISO Container            | 3                                     | 40                                         | 0.4  |

**Table A-7. Damage Coefficients for the PES Front Wall**

| PES (front wall)         | Initial Breakout Value<br>$Y_0$ (lbs) | Total Destruction Value<br>$Y_{100}$ (lbs) | $b$  |
|--------------------------|---------------------------------------|--------------------------------------------|------|
| PEMB                     | 3                                     | 40                                         | 0.4  |
| Hollow Clay Tile         | 1                                     | 8                                          | 0.25 |
| HAS                      | 40                                    | 2,000                                      | 0.9  |
| Large Concrete Arch ECM  | 1                                     | 10                                         | 0.6  |
| Medium Concrete Arch ECM | 1                                     | 10                                         | 0.6  |
| Small Concrete Arch ECM  | 1                                     | 10                                         | 0.6  |
| Large Steel Arch ECM     | 1                                     | 10                                         | 0.6  |
| Medium Steel Arch ECM    | 1                                     | 10                                         | 0.6  |
| Small Steel Arch ECM     | 1                                     | 10                                         | 0.6  |
| Large AGBS               | 1                                     | 8                                          | 0.25 |
| Medium AGBS              | 1                                     | 8                                          | 0.25 |
| Small AGBS (Square)      | 1                                     | 8                                          | 0.25 |
| Medium Concrete Building | 3                                     | 100                                        | 0.4  |
| Small Concrete Building  | 3                                     | 100                                        | 0.4  |
| Ship (small)             | 100                                   | 5,000                                      | 1.1  |
| Ship (medium)            | 100                                   | 5,000                                      | 1.1  |
| Ship (large)             | 100                                   | 5,000                                      | 1.1  |
| ISO Container            | 3                                     | 40                                         | 0.4  |

**Table A-8. Damage Coefficients for the PES Side Walls**

| PES (side walls)         | Initial Breakout Value<br>$Y_0$ (lbs) | Total Destruction Value<br>$Y_{100}$ (lbs) | $b$  |
|--------------------------|---------------------------------------|--------------------------------------------|------|
| PEMB                     | 1                                     | 40                                         | 0.4  |
| Hollow Clay Tile         | 1                                     | 8                                          | 0.25 |
| HAS                      | 1,000                                 | 2,000                                      | 0.9  |
| Large Concrete Arch ECM  | 2,000                                 | 10,000                                     | 0.9  |
| Medium Concrete Arch ECM | 2,000                                 | 10,000                                     | 0.9  |
| Small Concrete Arch ECM  | 2,000                                 | 10,000                                     | 0.9  |
| Large Steel Arch ECM     | 2,000                                 | 10,000                                     | 0.9  |
| Medium Steel Arch ECM    | 2,000                                 | 10,000                                     | 0.9  |
| Small Steel Arch ECM     | 2,000                                 | 10,000                                     | 0.9  |
| Large AGBS               | 1                                     | 8                                          | 0.25 |
| Medium AGBS              | 1                                     | 8                                          | 0.25 |
| Small AGBS (Square)      | 1                                     | 8                                          | 0.25 |
| Medium Concrete Building | 3                                     | 100                                        | 0.4  |
| Small Concrete Building  | 3                                     | 100                                        | 0.4  |
| Ship (small)             | 100                                   | 5,000                                      | 1.1  |
| Ship (medium)            | 100                                   | 5,000                                      | 1.1  |
| Ship (large)             | 100                                   | 5,000                                      | 1.1  |
| ISO Container            | 1                                     | 40                                         | 0.4  |

**Table A-9. Damage Coefficients for the PES Rear Wall**

| PES (rear wall)          | Initial Breakout Value<br>$Y_0$ (lbs) | Total Destruction Value<br>$Y_{100}$ (lbs) | $b$  |
|--------------------------|---------------------------------------|--------------------------------------------|------|
| PEMB                     | 1                                     | 40                                         | 0.4  |
| Hollow Clay Tile         | 1                                     | 8                                          | 0.25 |
| HAS                      | 2,000                                 | 10,000                                     | 0.9  |
| Large Concrete Arch ECM  | 2,000                                 | 10,000                                     | 0.9  |
| Medium Concrete Arch ECM | 2,000                                 | 10,000                                     | 0.9  |
| Small Concrete Arch ECM  | 2,000                                 | 10,000                                     | 0.9  |
| Large Steel Arch ECM     | 2,000                                 | 10,000                                     | 0.9  |
| Medium Steel Arch ECM    | 2,000                                 | 10,000                                     | 0.9  |
| Small Steel Arch ECM     | 2,000                                 | 10,000                                     | 0.9  |
| Large AGBS               | 1                                     | 8                                          | 0.25 |
| Medium AGBS              | 1                                     | 8                                          | 0.25 |
| Small AGBS (Square)      | 1                                     | 8                                          | 0.25 |
| Medium Concrete Building | 3                                     | 100                                        | 0.4  |
| Small Concrete Building  | 3                                     | 100                                        | 0.4  |
| Ship (small)             | 100                                   | 7,500                                      | 1.1  |
| Ship (medium)            | 100                                   | 7,500                                      | 1.1  |
| Ship (large)             | 100                                   | 7,500                                      | 1.1  |
| ISO Container            | 1                                     | 40                                         | 0.4  |

**Table A-10. Pressure and Impulse Reduction Values Due to Glass Percentage**

| ES Name                                             | Max Reduction | Fraction Average Protection | Glass Fraction for Full Venting | Height of ES (ft) |
|-----------------------------------------------------|---------------|-----------------------------|---------------------------------|-------------------|
| Small Reinforced Concrete (Office/Commercial)       | 0.5           | 0.075                       | 0.25                            | 12                |
| Medium Reinforced Concrete (Office/Commercial)      | 0.5           | 0.075                       | 0.25                            | 12                |
| Large Reinforced Concrete Tilt-up (Commercial)      | 0.5           | 0.075                       | 0.25                            | 20                |
| Small Reinforced Masonry (Office/Commercial)        | 0.5           | 0.075                       | 0.25                            | 12                |
| Medium Reinforced Masonry (Office/Commercial)       | 0.5           | 0.075                       | 0.25                            | 12                |
| Small Unreinforced Brick (Office/Apartment)         | 0.5           | 0.075                       | 0.25                            | 12                |
| Medium Unreinforced Masonry (Office/Apartment)      | 0.5           | 0.075                       | 0.25                            | 12                |
| Large Unreinforced Masonry (Office)                 | 0.5           | 0.075                       | 0.25                            | 12                |
| Small PEMB (Office/Storage)                         | 0.5           | 0.075                       | 0.25                            | 12                |
| Medium PEMB (Office/Commercial)                     | 0.5           | 0.075                       | 0.25                            | 12                |
| Large PEMB (Office/Storage/Hangar)                  | 0.5           | 0.075                       | 0.25                            | 24                |
| Small Wood Frame (Residence)                        | 0.5           | 0.075                       | 0.25                            | 12                |
| Medium Wood Frame (Residence/Apartment)             | 0.5           | 0.075                       | 0.25                            | 12                |
| Medium Steel Stud (Office/Commercial)               | 0.5           | 0.075                       | 0.25                            | 12                |
| Modular Building/Trailer (Office/Residence/Storage) | 0.5           | 0.075                       | 0.25                            | 10                |
| Vehicle                                             | 0.5           | 0.075                       | 0.25                            | 4                 |

**Table A-11. Pressure-impulse Coefficients for  $P_{(sf)}$**

| % Skull Fracture | A (psi) | B (psi-ms) | C (psi <sup>2</sup> -ms) |
|------------------|---------|------------|--------------------------|
| 0.1              | 0.347   | 10.821     | 4934.9                   |
| 50               | 0.377   | 14.501     | 7097.7                   |
| 99.9             | 0.497   | 19.613     | 8948.1                   |

**Table A-12. Power Curve Parameters for Major Injury as a Function of Glass Breakage**

| Glass Type | M      | N     |
|------------|--------|-------|
| Annealed   | 7E-12  | 6.015 |
| Dual Pane  | 1E-9   | 4.953 |
| Tempered   | 0.0446 | 1.382 |

**Table A-13. Yield Adjustment Curve Parameters**

| Glass Type | A      | B      | C    |
|------------|--------|--------|------|
| Annealed   | 0.0905 | 1.0556 | 0.5  |
| Dual Pane  | 0.1476 | 1.1395 | 0.5  |
| Tempered   | 0.032  | 1.0072 | 0.01 |

**Table A-14. Structure Damage / Fatality Normal Distribution Parameters**

| ES Type                                             | Pf @ 40% | Pf @ 90% | Sigma   | Mean    | Pf (max) |
|-----------------------------------------------------|----------|----------|---------|---------|----------|
| Small Reinforced Concrete (Office/Commercial)       | 0.0052   | 0.3064   | 0.08964 | 1.79354 | 0.318    |
| Medium Reinforced Concrete (Office/Commercial)      | 0.0074   | 0.2282   | 0.09508 | 1.77894 | 0.2359   |
| Large Reinforced Concrete Tilt-up (Commercial)      | 0.0114   | 0.2681   | 0.09815 | 1.77256 | 0.277    |
| Small Reinforced Masonry (Office/Commercial)        | 0.0073   | 0.1829   | 0.09739 | 1.77418 | 0.189    |
| Medium Reinforced Masonry (Office/Commercial)       | 0.0084   | 0.2106   | 0.0972  | 1.77384 | 0.2175   |
| Small Unreinforced Brick (Office/Apartment)         | 0.0141   | 0.1729   | 0.10672 | 1.75264 | 0.17815  |
| Medium Unreinforced Masonry (Office/Apartment)      | 0.0105   | 0.1970   | 0.10066 | 1.76608 | 0.20325  |
| Large Unreinforced Masonry (Office)                 | 0.0100   | 0.1878   | 0.10073 | 1.76625 | 0.1938   |
| Small PEMB (Office/Storage)                         | 0.0125   | 0.1257   | 0.10975 | 1.74484 | 0.12935  |
| Medium PEMB (Office/Commercial)                     | 0.0143   | 0.1444   | 0.11009 | 1.74562 | 0.14872  |
| Large PEMB (Office/Storage/Hangar)                  | 0.0177   | 0.1785   | 0.1096  | 1.74481 | 0.18365  |
| Small Wood Frame (Residence)                        | 0.0087   | 0.1144   | 0.10546 | 1.75473 | 0.11785  |
| Medium Wood Frame (Residence/Apartment)             | 0.0107   | 0.1417   | 0.10541 | 1.75508 | 0.146    |
| Medium Steel Stud (Office/Commercial)               | 0.0159   | 0.1602   | 0.10987 | 1.74513 | 0.1649   |
| Modular Building/Trailer (Office/Residence/Storage) | 0.0096   | 0.1271   | 0.1054  | 1.75505 | 0.13095  |
| Vehicle                                             | 0.0009   | 0.1074   | 0.08434 | 1.80506 | 0.1117   |

**Table A-15. Close-in Adjustment Parameters for  $P_{f(bc)}$**

| ES Building Type                                 | $P_{f(bc)1}$ | $P_{f(bc)2}$                                                                                                               |
|--------------------------------------------------|--------------|----------------------------------------------------------------------------------------------------------------------------|
| Small Reinforced Concrete (Office/Commercial)    | 1.00         | $\text{EXP}(-330.43+100.96*(\ln(W_a))-11.618*(\ln(W_a))^2+0.59364*(\ln(W_a))^3-0.011345*(\ln(W_a))^4)$                     |
| Medium Reinforced Concrete (Office/Commercial)   | 1.00         | $\text{EXP}(-130.31+38.22*(\ln(W_a))-4.2566*(\ln(W_a))^2+0.21066*(\ln(W_a))^3-0.0039012*(\ln(W_a))^4)$                     |
| Large Reinforced Concrete Tilt-up (Commercial)   | 1.00         | $-0.1108+((0.38698*W_a)/(2330.4+W_a))$                                                                                     |
| Small Reinforced Masonry (Office/Commercial)     | 1.00         | $-0.0128+((0.20231*W_a)/(14754+W_a))$                                                                                      |
| Medium Reinforced Masonry (Office/Commercial)    | 1.00         | $-0.024+((0.24954*W_a)/(9160.1+W_a))$                                                                                      |
| Small Unreinforced Brick (Office/Apartment)      | 1.00         | 0.18                                                                                                                       |
| Medium Unreinforced Masonry (Office/Apartment)   | 1.00         | $-4.7904+((4.9933*W_a)/(29.996+W_a))$                                                                                      |
| Large Unreinforced Masonry (Office)              | 1.00         | $-4.8294+((5.0222*W_a)/(38.228+W_a))$                                                                                      |
| Small PEMB (Office/Storage)                      | 1.00         | $-3.2784+((3.4088*W_a)/(39.217+W_a))$                                                                                      |
| Medium PEMB (Office/Commercial)                  | 1.00         | $-0.037719+((0.22199*W_a)/(4840+W_a))$                                                                                     |
| Large PEMB (Office/Storage/Hangar)               | 1.00         | $-0.0341+((0.21859*W_a)/(5067.3+W_a))$                                                                                     |
| Small Wood Frame (Residence)                     | 1.00         | $-4.479+((4.5989*W_a)/(7.221+W_a))$                                                                                        |
| Medium Wood Frame (Residence/Apartment)          | 1.00         | $-4.6697+((4.8108*W_a)/(29.434+W_a))$                                                                                      |
| Medium Steel Stud (Office/Commercial)            | 1.00         | $\text{EXP}(274.49-173.58*(\ln(W_a))+36.146*(\ln(W_a))^2-3.426*(\ln(W_a))^3+0.15323*(\ln(W_a))^4-0.0026334*(\ln(W_a))^5)$  |
| Modular Building/Trailer(Office/Residence/Story) | 1.00         | 0.13                                                                                                                       |
| Vehicle                                          | 1.00         | $\text{EXP}(-1372.5+495.77*(\ln(W_a))-70.975*(\ln(W_a))^2+5.0232*(\ln(W_a))^3-0.17563*(\ln(W_a))^4+0.002425*(\ln(W_a))^5)$ |

**Table A-16. Close-in Adjustment Parameters for Building Collapse Region Boundaries**

| ES Building Type                                 | $R_1$<br>(ft/lbs <sup>1/3</sup> ) | $R_2$ (ft/lbs <sup>1/3</sup> )         |          |        |        |
|--------------------------------------------------|-----------------------------------|----------------------------------------|----------|--------|--------|
|                                                  |                                   | $R_{2min}$<br>(ft/lbs <sup>1/3</sup> ) | A        | B      | C      |
| Small Reinforced Concrete (Office/Commercial)    | 6                                 | 8                                      | -4.128   | 11.874 | 43114  |
| Medium Reinforced Concrete (Office/Commercial)   | 7                                 | 8                                      | -2.9501  | 10.661 | 56396  |
| Large Reinforced Concrete Tilt-up (Commercial)   | 8                                 | 11                                     | 0.16852  | 15.451 | 32550  |
| Small Reinforced Masonry (Office/Commercial)     | 8                                 | 10                                     | -0.13307 | 10.113 | 56344  |
| Medium Reinforced Masonry (Office/Commercial)    | 7                                 | 10                                     | 0.80385  | 11.677 | 47077  |
| Small Unreinforced Brick (Office/Apartment)      | 9                                 | 12                                     | 4.2209   | 11.907 | 776.41 |
| Medium Unreinforced Masonry (Office/Apartment)   | 9                                 | 12                                     | 0.5839   | 11.725 | 3761   |
| Large Unreinforced Masonry (Office)              | 9                                 | 12                                     | 0.25642  | 14.145 | 7926.6 |
| Small PEMB (Office/Storage)                      | 10                                | 13                                     | 0.92458  | 13.068 | 4821.9 |
| Medium PEMB (Office/Commercial)                  | 9                                 | 12                                     | 0.03521  | 13.618 | 6796.8 |
| Large PEMB (Office/Storage/Hangar)               | 9                                 | 12                                     | 0.14699  | 13.366 | 28431  |
| Small Wood Frame (Residence)                     | 8                                 | 11                                     | 1.0211   | 11.484 | 1453.8 |
| Medium Wood Frame (Residence/Apartment)          | 8                                 | 11                                     | 0.28302  | 12.153 | 9128.4 |
| Medium Steel Stud (Office/Commercial)            | 9                                 | 12                                     | -0.28856 | 11.951 | 17108  |
| Modular Building/Trailer(Office/Residence/Story) | 9                                 | 12                                     | 3.7687   | 11.621 | 997.25 |
| Vehicle                                          | 7                                 | 10                                     | 0.14699  | 13.366 | 28431  |



**Table A-17. Pressure / Impulse Coefficients – ES Building Percent Damage**

*Small R/C Office Building, 8" R/C Shearwalls with R/C Roof/Beams*

| Building Damage (%) | A (psi) | B (psi-ms) | C (psi <sup>2</sup> -ms) |
|---------------------|---------|------------|--------------------------|
| 100                 | 13.548  | 769.645    | 1540.17                  |
| 90                  | 12.319  | 581.692    | 1540.17                  |
| 80                  | 11.282  | 501.169    | 942.175                  |
| 70                  | 9.919   | 365.517    | 741.695                  |
| 60                  | 7.96    | 279.052    | 473.804                  |
| 50                  | 6.484   | 228.776    | 336.254                  |
| 40                  | 5.25    | 159.738    | 283.621                  |
| 30                  | 2.74    | 122.826    | 75.925                   |
| 20                  | 2.011   | 91.199     | 56.256                   |
| 10                  | 1.62    | 65.513     | 22.743                   |
| 5                   | 1.323   | 50.597     | 13.257                   |
| 1                   | 1.088   | 35.521     | 7.874                    |
| 0.5                 | 1.06    | 33.333     | 7.386                    |
| 0.1                 | 1.038   | 29.921     | 7.101                    |

*Medium R/C Office Building*

| Building Damage (%) | A (psi) | B (psi-ms) | C (psi <sup>2</sup> -ms) |
|---------------------|---------|------------|--------------------------|
| 100                 | 13.835  | 824.891    | 1388.51                  |
| 90                  | 11.612  | 574.348    | 742.369                  |
| 80                  | 8.14    | 482.244    | 445.328                  |
| 70                  | 7.161   | 353.564    | 444.486                  |
| 60                  | 6.409   | 255.592    | 326.069                  |
| 50                  | 5.093   | 199.011    | 194.472                  |
| 40                  | 3.942   | 126.715    | 118.888                  |
| 30                  | 1.879   | 98.417     | 14.955                   |
| 20                  | 1.222   | 80.109     | 9.33                     |
| 10                  | 1.047   | 61.047     | 4.828                    |
| 5                   | 0.873   | 48.883     | 2.982                    |
| 1                   | 0.73    | 34.915     | 1.881                    |
| 0.5                 | 0.697   | 32.63      | 1.576                    |
| 0.1                 | 0.671   | 29.672     | 1.36                     |

*Large Tilt-up Structure (~40,000 sq ft)*

| Building Damage (%) | A (psi) | B (psi-ms) | C (psi <sup>2</sup> -ms) |
|---------------------|---------|------------|--------------------------|
| 100                 | 4.336   | 326.124    | 48.313                   |
| 90                  | 2.23    | 259.322    | 48.313                   |
| 80                  | 1.575   | 215.228    | 48.313                   |
| 70                  | 1.316   | 147.447    | 48.313                   |
| 60                  | 1.193   | 118.912    | 36.178                   |
| 50                  | 1.072   | 99.9       | 25.804                   |
| 40                  | 0.924   | 76.5       | 24.456                   |
| 30                  | 0.797   | 58.898     | 19.87                    |
| 20                  | 0.683   | 44.951     | 14.59                    |
| 10                  | 0.565   | 33.467     | 9.037                    |
| 5                   | 0.492   | 28.325     | 5.391                    |
| 1                   | 0.348   | 21.754     | 3.274                    |
| 0.5                 | 0.304   | 20.191     | 2.891                    |
| 0.1                 | 0.267   | 18.281     | 2.011                    |

*Small Un-Reinforced Brick Structure (~2500 sq ft)*

| Building Damage (%) | A (psi) | B (psi-ms) | C (psi <sup>2</sup> -ms) |
|---------------------|---------|------------|--------------------------|
| 100                 | 3.991   | 64.87      | 39.819                   |
| 90                  | 3.477   | 47.25      | 26.763                   |
| 80                  | 3.025   | 39.154     | 21.055                   |
| 70                  | 2.578   | 33.13      | 14.68                    |
| 60                  | 2.211   | 28.744     | 9.999                    |
| 50                  | 2.034   | 25.697     | 7.704                    |
| 40                  | 1.86    | 23.171     | 6.652                    |
| 30                  | 1.708   | 20.922     | 5.429                    |
| 20                  | 1.557   | 18.285     | 4.451                    |
| 10                  | 1.2     | 13.298     | 2.379                    |
| 5                   | 1.044   | 11.41      | 1.439                    |
| 1                   | 0.848   | 9.271      | 0.6                      |
| 0.5                 | 0.801   | 8.867      | 0.548                    |
| 0.1                 | 0.763   | 8.539      | 0.504                    |

*Medium Un-Reinforced Masonry Structure (~10,000 sq ft)*

| Building Damage (%) | A (psi) | B (psi-ms) | C (psi <sup>2</sup> -ms) |
|---------------------|---------|------------|--------------------------|
| 100                 | 6.102   | 181.188    | 138.147                  |
| 90                  | 5.026   | 127.896    | 79.993                   |
| 80                  | 3.989   | 102.32     | 49.463                   |
| 70                  | 3.263   | 85.347     | 31.296                   |
| 60                  | 2.929   | 73.628     | 24.148                   |
| 50                  | 2.606   | 63.693     | 18.819                   |
| 40                  | 2.152   | 56.761     | 18.761                   |
| 30                  | 1.708   | 49.532     | 18.078                   |
| 20                  | 1.311   | 38.569     | 17.51                    |
| 10                  | 0.864   | 18.283     | 12.537                   |
| 5                   | 0.692   | 15.534     | 8.772                    |
| 1                   | 0.552   | 12.299     | 5.667                    |
| 0.5                 | 0.535   | 11.726     | 5.299                    |
| 0.1                 | 0.521   | 11.254     | 4.786                    |

*Large Un-Reinforced Masonry Structure (~40,000 sq ft)*

| Building Damage (%) | A (psi) | B (psi-ms) | C (psi <sup>2</sup> -ms) |
|---------------------|---------|------------|--------------------------|
| 100                 | 4.401   | 195.396    | 178.427                  |
| 90                  | 3.724   | 152.319    | 87.837                   |
| 80                  | 3.066   | 131.75     | 53.449                   |
| 70                  | 2.488   | 116.108    | 26.268                   |
| 60                  | 2.243   | 105.458    | 20.493                   |
| 50                  | 2.03    | 90.461     | 19.328                   |
| 40                  | 1.832   | 73.968     | 19.328                   |
| 30                  | 1.448   | 60.699     | 19.328                   |
| 20                  | 1.088   | 30.825     | 19.328                   |
| 10                  | 0.969   | 14.211     | 7.185                    |
| 5                   | 0.816   | 12.066     | 4.944                    |
| 1                   | 0.642   | 9.538      | 2.936                    |
| 0.5                 | 0.62    | 9.126      | 2.572                    |
| 0.1                 | 0.603   | 8.791      | 2.28                     |

*Small Reinforced Masonry Structure (~2500 sq ft)*

| Building Damage (%) | A (psi) | B (psi-ms) | C (psi <sup>2</sup> -ms) |
|---------------------|---------|------------|--------------------------|
| 100                 | 8.488   | 548.535    | 647.027                  |
| 90                  | 7.264   | 359.227    | 425.468                  |
| 80                  | 5.615   | 274.316    | 379.895                  |
| 70                  | 5.045   | 218.431    | 247.021                  |
| 60                  | 4.407   | 182.708    | 154.561                  |
| 50                  | 3.783   | 124.497    | 115.951                  |
| 40                  | 3.191   | 100.424    | 82.507                   |
| 30                  | 2.738   | 80.822     | 51.206                   |
| 20                  | 2.157   | 60.13      | 29.429                   |
| 10                  | 1.548   | 45.025     | 13.806                   |
| 5                   | 1.258   | 38.432     | 9.932                    |
| 1                   | 0.963   | 30.68      | 5.906                    |
| 0.5                 | 0.905   | 28.84      | 5.645                    |
| 0.1                 | 0.86    | 25.6       | 5.645                    |

*Medium Reinforced Masonry Structure (~10,000 sq ft)*

| Building Damage (%) | A (psi) | B (psi-ms) | C (psi <sup>2</sup> -ms) |
|---------------------|---------|------------|--------------------------|
| 100                 | 5.753   | 419.224    | 265.436                  |
| 90                  | 5.064   | 327.054    | 225.03                   |
| 80                  | 4.264   | 244.854    | 225.03                   |
| 70                  | 3.83    | 192.804    | 147.086                  |
| 60                  | 3.229   | 157.437    | 86.21                    |
| 50                  | 2.69    | 123.823    | 64.33                    |
| 40                  | 2.201   | 93.443     | 37.638                   |
| 30                  | 1.253   | 76.701     | 12.401                   |
| 20                  | 1.02    | 62.813     | 7.594                    |
| 10                  | 0.904   | 48.077     | 3.906                    |
| 5                   | 0.754   | 39.228     | 2.413                    |
| 1                   | 0.602   | 29.277     | 1.262                    |
| 0.5                 | 0.575   | 27.024     | 1.07                     |
| 0.1                 | 0.553   | 24.212     | 0.906                    |

*Small Metal Structure (~2500 sq ft)*

| Building Damage (%) | A (psi) | B (psi-ms) | C (psi <sup>2</sup> -ms) |
|---------------------|---------|------------|--------------------------|
| 100                 | 4.864   | 170.432    | 113.439                  |
| 90                  | 4.597   | 148.324    | 76.865                   |
| 80                  | 4.154   | 118.194    | 61.746                   |
| 70                  | 2.889   | 101.909    | 46.555                   |
| 60                  | 2.131   | 89.364     | 46.555                   |
| 50                  | 1.736   | 78.73      | 46.555                   |
| 40                  | 1.42    | 67.942     | 43.923                   |
| 30                  | 1.133   | 56.006     | 27.551                   |
| 20                  | 0.929   | 45.124     | 17.248                   |
| 10                  | 0.748   | 32.715     | 12.615                   |
| 5                   | 0.634   | 26.801     | 9.264                    |
| 1                   | 0.462   | 20.037     | 3.443                    |
| 0.5                 | 0.405   | 18.751     | 2.58                     |
| 0.1                 | 0.357   | 15.127     | 1.676                    |

*Medium Metal Structure (~10,000 sq ft)*

| Building Damage (%) | A (psi) | B (psi-ms) | C (psi <sup>2</sup> -ms) |
|---------------------|---------|------------|--------------------------|
| 100                 | 4.949   | 199.059    | 163.399                  |
| 90                  | 4.652   | 170.906    | 101.626                  |
| 80                  | 4.2     | 155.967    | 68.98                    |
| 70                  | 2.889   | 141.967    | 40.766                   |
| 60                  | 2.138   | 126.101    | 40.766                   |
| 50                  | 1.743   | 105.287    | 40.766                   |
| 40                  | 1.426   | 82.491     | 40.766                   |
| 30                  | 1.136   | 64.629     | 27.63                    |
| 20                  | 0.931   | 51.936     | 17.28                    |
| 10                  | 0.749   | 35.698     | 11.267                   |
| 5                   | 0.635   | 28.302     | 9.237                    |
| 1                   | 0.462   | 20.378     | 3.297                    |
| 0.5                 | 0.405   | 19.155     | 2.479                    |
| 0.1                 | 0.357   | 15.127     | 1.676                    |

*Medium Metal Stud Structure (~10,000 sq ft)*

| Building Damage (%) | A (psi) | B (psi-ms) | C (psi <sup>2</sup> -ms) |
|---------------------|---------|------------|--------------------------|
| 100                 | 6.425   | 318.938    | 319.479                  |
| 90                  | 6.144   | 254.791    | 239.142                  |
| 80                  | 5.905   | 223.619    | 190.457                  |
| 70                  | 5.304   | 202.971    | 141.023                  |
| 60                  | 4.65    | 186.178    | 76.942                   |
| 50                  | 2.785   | 171.043    | 76.942                   |
| 40                  | 2.382   | 153.3      | 76.942                   |
| 30                  | 2.107   | 131.829    | 76.942                   |
| 20                  | 1.783   | 95.462     | 76.942                   |
| 10                  | 1.217   | 70.219     | 54.612                   |
| 5                   | 0.979   | 49.235     | 39.515                   |
| 1                   | 0.789   | 33.056     | 24.174                   |
| 0.5                 | 0.766   | 29.952     | 21.733                   |
| 0.1                 | 0.747   | 27.363     | 19.729                   |

*High Bay Metal Structure (~40,000 sq ft)*

| Building Damage (%) | A (psi) | B (psi-ms) | C (psi <sup>2</sup> -ms) |
|---------------------|---------|------------|--------------------------|
| 100                 | 5.157   | 339.305    | 169.627                  |
| 90                  | 4.786   | 255.568    | 137.88                   |
| 80                  | 4.326   | 211.005    | 109.787                  |
| 70                  | 2.906   | 182.79     | 48.295                   |
| 60                  | 1.761   | 146.951    | 48.295                   |
| 50                  | 1.376   | 104.018    | 34.599                   |
| 40                  | 1.044   | 85.76      | 15.799                   |
| 30                  | 0.842   | 66.043     | 6.073                    |
| 20                  | 0.795   | 52.533     | 5.44                     |
| 10                  | 0.649   | 39.818     | 3.54                     |
| 5                   | 0.544   | 31.751     | 2.228                    |
| 1                   | 0.461   | 22.828     | 2.228                    |
| 0.5                 | 0.412   | 19.337     | 2.228                    |
| 0.1                 | 0.358   | 15.242     | 1.685                    |

*Small Wood Structure (~2500 sq ft)*

| Building Damage (%) | A (psi) | B (psi-ms) | C (psi <sup>2</sup> -ms) |
|---------------------|---------|------------|--------------------------|
| 100                 | 5.927   | 123.38     | 105.616                  |
| 90                  | 5.01    | 97.842     | 83.725                   |
| 80                  | 4.286   | 84.776     | 61.17                    |
| 70                  | 3.571   | 70.856     | 44.053                   |
| 60                  | 2.983   | 58.26      | 26.451                   |
| 50                  | 2.614   | 50.388     | 20.417                   |
| 40                  | 2.326   | 43.519     | 17.154                   |
| 30                  | 2.038   | 38.59      | 13.763                   |
| 20                  | 1.751   | 32.32      | 10.426                   |
| 10                  | 1.49    | 22.569     | 7.913                    |
| 5                   | 1.212   | 17.966     | 3.836                    |
| 1                   | 0.884   | 14         | 2.316                    |
| 0.5                 | 0.785   | 12.769     | 1.849                    |
| 0.1                 | 0.705   | 11.749     | 1.577                    |

*Medium Wood Structure (~10,000 sq ft)*

| Building Damage (%) | A (psi) | B (psi-ms) | C (psi <sup>2</sup> -ms) |
|---------------------|---------|------------|--------------------------|
| 100                 | 5.844   | 239.949    | 208.186                  |
| 90                  | 4.693   | 186.537    | 119.597                  |
| 80                  | 3.581   | 152.348    | 66.841                   |
| 70                  | 2.816   | 126.154    | 37.14                    |
| 60                  | 2.387   | 114.638    | 27.264                   |
| 50                  | 2.007   | 96.008     | 26.248                   |
| 40                  | 1.75    | 78.331     | 23.164                   |
| 30                  | 1.511   | 64.626     | 17.965                   |
| 20                  | 1.153   | 53.68      | 10.967                   |
| 10                  | 0.843   | 39.528     | 8.074                    |
| 5                   | 0.692   | 31.071     | 7.294                    |
| 1                   | 0.552   | 21.777     | 6.038                    |
| 0.5                 | 0.535   | 19.621     | 5.381                    |
| 0.1                 | 0.521   | 17.812     | 4.837                    |

*Small Trailer (~500 sq ft)*

| Building Damage (%) | A (psi) | B (psi-ms) | C (psi <sup>2</sup> -ms) |
|---------------------|---------|------------|--------------------------|
| 100                 | 4.31    | 75.862     | 46.335                   |
| 90                  | 3.586   | 62.907     | 33.363                   |
| 80                  | 2.873   | 50.998     | 22.605                   |
| 70                  | 2.348   | 40.57      | 14.679                   |
| 60                  | 2.044   | 33.728     | 12.738                   |
| 50                  | 1.819   | 31.077     | 10.014                   |
| 40                  | 1.595   | 27.653     | 8.18                     |
| 30                  | 1.371   | 24.26      | 6.408                    |
| 20                  | 1.175   | 20.733     | 4.939                    |
| 10                  | 0.933   | 16.561     | 2.974                    |
| 5                   | 0.78    | 14.346     | 2.233                    |
| 1                   | 0.635   | 12.193     | 1.612                    |
| 0.5                 | 0.611   | 11.115     | 1.32                     |
| 0.1                 | 0.549   | 10.201     | 1.144                    |

*Passenger Vehicle*

| Building Damage (%) | A (psi) | B (psi-ms) | C (psi <sup>2</sup> -ms) |
|---------------------|---------|------------|--------------------------|
| 100                 | 8.499   | 406.311    | 536.734                  |
| 90                  | 6.015   | 301.516    | 296.697                  |
| 80                  | 4.75    | 248.612    | 203.846                  |
| 70                  | 3.923   | 220.71     | 155.148                  |
| 60                  | 3.366   | 193.408    | 139.013                  |
| 50                  | 2.915   | 167.967    | 116.128                  |
| 40                  | 2.519   | 142.986    | 84.991                   |
| 30                  | 2.133   | 122.347    | 69.927                   |
| 20                  | 1.755   | 102.553    | 56.062                   |
| 10                  | 1.354   | 82.159     | 35.231                   |
| 5                   | 1.13    | 68.732     | 28.439                   |
| 1                   | 0.861   | 57.966     | 16.499                   |
| 0.5                 | 0.828   | 56.636     | 16.079                   |
| 0.1                 | 0.802   | 55.105     | 14.354                   |



**Table A-18. Pressure-impulse Coefficients – ES Roof Damage**

*4" Reinforced Concrete*

| Roof Damage | A (psi) | B (psi-ms) | C (psi <sup>2</sup> -ms) |
|-------------|---------|------------|--------------------------|
| 100%        | 1.4628  | 128.44     | 209.38365                |
| 50%         | 1.3165  | 64.22      | 75.03085                 |
| 0%          | 0.7314  | 20.81      | 14.139234                |

*14" Reinforced Concrete*

| Roof Damage | A (psi) | B (psi-ms) | C (psi <sup>2</sup> -ms) |
|-------------|---------|------------|--------------------------|
| 100%        | 9.6379  | 360.18     | 1005.7659                |
| 50%         | 8.6733  | 180.09     | 366.76792                |
| 0%          | 4.87183 | 58.35      | 71.000888                |

*Plywood / Wood Joists (2x10 @ 16")*

| Roof Damage | A (psi) | B (psi-ms) | C (psi <sup>2</sup> -ms) |
|-------------|---------|------------|--------------------------|
| 100%        | 3.3184  | 9.7963     | 6.7166472                |
| 50%         | 1.8553  | 6.4655     | 3.3943969                |
| 0%          | 0.92765 | 3.1348     | 1.1579693                |

*Gypsum / Fiberboard / Steel Joist*

| Roof Damage | A (psi) | B (psi-ms) | C (psi <sup>2</sup> -ms) |
|-------------|---------|------------|--------------------------|
| 100%        | 0.1044  | 1.047      | 0.1747247                |

*Plywood panelized (2x6 @ 24")*

| Roof Damage | A (psi) | B (psi-ms) | C (psi <sup>2</sup> -ms) |
|-------------|---------|------------|--------------------------|
| 100%        | 2.6219  | 11.31      | 7.3541168                |
| 50%         | 1.4881  | 7.47       | 3.7917427                |
| 0%          | 0.7441  | 3.62       | 1.2893091                |

*2" Lightweight Concrete/Steel Deck & Joists*

| Roof Damage | A (psi) | B (psi-ms) | C (psi <sup>2</sup> -ms) |
|-------------|---------|------------|--------------------------|
| 100%        | 1.4654  | 150.9      | 265.97727                |
| 50%         | 1.4051  | 99.6       | 143.55884                |
| 0%          | 1.1241  | 48.29      | 49.12373                 |

*Medium Steel Panel (18 gauge)*

| Roof Damage | A (psi) | B (psi-ms) | C (psi <sup>2</sup> -ms) |
|-------------|---------|------------|--------------------------|
| 100%        | 2.6749  | 72         | 91.259266                |
| 50%         | 2.5649  | 47.52      | 50.127404                |
| 0%          | 2.0519  | 23.04      | 17.775234                |

*Light Steel Panel (22 gauge)*

| Roof Damage | A (psi) | B (psi-ms) | C (psi <sup>2</sup> -ms) |
|-------------|---------|------------|--------------------------|
| 100%        | 1.5534  | 44.04      | 43.537949                |
| 50%         | 1.4895  | 29.07      | 23.891002                |
| 0%          | 1.1916  | 14.09      | 8.4482788                |

*Steel (automobile)*

| Roof Damage | A (psi)     | B (psi-ms)  | C (psi <sup>2</sup> -ms) |
|-------------|-------------|-------------|--------------------------|
| 100%        | 12.56361407 | 79.39296879 | 47.26898964              |
| 50%         | 9.607369918 | 46.50158021 | 21.03086164              |
| 0%          | 4.938735846 | 17.72752511 | 4.203991333              |

**Table A-19. Pressure-impulse Coefficients – Glass Breakage**

*Dual Pane Windows*

| Glass breakage (%) | A (psi) | B (psi-ms) | C (psi <sup>2</sup> -ms) |
|--------------------|---------|------------|--------------------------|
| 100                | 0.852   | 33.51      | 19.743                   |
| 90                 | 0.643   | 19.734     | 13.045                   |
| 70                 | 0.493   | 7.989      | 7.66                     |
| 50                 | 0.383   | 7.988      | 3.42                     |
| 30                 | 0.3     | 0.201      | 1                        |
| 10                 | 0.19    | 0.2        | 0.3                      |
| 1                  | 0.105   | 0.1        | 0.1                      |

*Annealed Windows*

| Glass breakage (%) | A (psi) | B (psi-ms) | C (psi <sup>2</sup> -ms) |
|--------------------|---------|------------|--------------------------|
| 100                | 0.853   | 26.976     | 39.765                   |
| 90                 | 0.717   | 20.34      | 15.382                   |
| 70                 | 0.547   | 9.886      | 8.177                    |
| 50                 | 0.424   | 3.885      | 4.752                    |
| 30                 | 0.316   | 3.456      | 1.316                    |
| 10                 | 0.21    | 0          | 0.8                      |

*Tempered Windows*

| Glass breakage (%) | A (psi) | B (psi-ms) | C (psi <sup>2</sup> -ms) |
|--------------------|---------|------------|--------------------------|
| 100                | 3.082   | 287.38     | 1117.9                   |
| 90                 | 3.007   | 224.92     | 626.41                   |
| 70                 | 2.702   | 131.12     | 389.13                   |
| 50                 | 2.477   | 8.325      | 197.8                    |
| 30                 | 1.727   | 8.324      | 29.077                   |
| 10                 | 1.343   | 8.323      | 8                        |
| 1                  | 1       | 0.102      | 7                        |
| 0.10               | 0.8     | 0.101      | 5                        |
| 0.01               | 0.65    | 0.1        | 3                        |

**Table A-20. Mass Distribution for PES Roof**

| PES #                    | Mass of PES roof (lbs) | Percent Material (%) |          | Percent Mass (%) |       |       |       |       |       |       |       |       |        |
|--------------------------|------------------------|----------------------|----------|------------------|-------|-------|-------|-------|-------|-------|-------|-------|--------|
|                          |                        | Steel                | Concrete | Bin 1            | Bin 2 | Bin 3 | Bin 4 | Bin 5 | Bin 6 | Bin 7 | Bin 8 | Bin 9 | Bin 10 |
| PEMB                     | 13,200                 | 100                  | 0        | 0                | 0     | 5     | 5     | 5     | 15    | 20    | 25    | 15    | 10     |
| Hollow Clay Tile         | 51,800                 | 5                    | 95       | 0                | 0     | 5     | 5     | 5     | 15    | 20    | 25    | 15    | 10     |
| HAS                      | 1,722,600              | 10                   | 90       | 20               | 15    | 7.5   | 7.5   | 10    | 10    | 10    | 10    | 5     | 5      |
| Large Concrete Arch ECM  | 584,600                | 5                    | 95       | 5                | 5     | 5     | 5     | 7.5   | 7.5   | 7.5   | 7.5   | 10    | 40     |
| Medium Concrete Arch ECM | 438,500                | 5                    | 95       | 5                | 5     | 5     | 5     | 7.5   | 7.5   | 7.5   | 7.5   | 10    | 40     |
| Small Concrete Arch ECM  | 292,300                | 5                    | 95       | 5                | 5     | 5     | 5     | 7.5   | 7.5   | 7.5   | 7.5   | 10    | 40     |
| Large Steel Arch ECM     | 31,400                 | 100                  | 0        | 5                | 5     | 5     | 5     | 7.5   | 7.5   | 7.5   | 7.5   | 10    | 40     |
| Medium Steel Arch ECM    | 23,600                 | 100                  | 0        | 5                | 5     | 5     | 5     | 7.5   | 7.5   | 7.5   | 7.5   | 10    | 40     |
| Small Steel Arch ECM     | 15,700                 | 100                  | 0        | 5                | 5     | 5     | 5     | 7.5   | 7.5   | 7.5   | 7.5   | 10    | 40     |
| Large AGBS               | 305,900                | 12                   | 88       | 7.5              | 12.5  | 20    | 12.5  | 7.5   | 7.5   | 7.5   | 7.5   | 7.5   | 10     |
| Medium AGBS              | 245,300                | 12                   | 88       | 7.5              | 12.5  | 20    | 12.5  | 7.5   | 7.5   | 7.5   | 7.5   | 7.5   | 10     |
| Small AGBS (Square)      | 126,400                | 12                   | 88       | 7.5              | 12.5  | 20    | 12.5  | 7.5   | 7.5   | 7.5   | 7.5   | 7.5   | 10     |
| Medium Concrete Building | 245,300                | 12                   | 88       | 7.5              | 12.5  | 20    | 12.5  | 7.5   | 7.5   | 7.5   | 7.5   | 7.5   | 10     |
| Small Concrete Building  | 126,400                | 12                   | 88       | 7.5              | 12.5  | 20    | 12.5  | 7.5   | 7.5   | 7.5   | 7.5   | 7.5   | 10     |
| Ship (large)             | 183,800                | 100                  | 0        | 5                | 5     | 5     | 5     | 5     | 5     | 5     | 5     | 20    | 40     |
| Ship (medium)            | 137,800                | 100                  | 0        | 5                | 5     | 5     | 5     | 5     | 5     | 5     | 5     | 20    | 40     |
| Ship (small)             | 61,300                 | 100                  | 0        | 5                | 5     | 5     | 5     | 5     | 5     | 5     | 5     | 20    | 40     |
| ISO Container            | 1,236 × NISO           | 100                  | 0        | 0                | 0     | 5     | 5     | 5     | 15    | 20    | 25    | 15    | 10     |

\*Mass distribution numbers in table are in percent (%)

**Table A-21. Mass Distribution for PES Front Wall**

| PES #                    | Mass of PES front wall (lbs) | Percent Material (%) |          | Percent Mass (%) |       |       |       |       |       |       |       |       |        |
|--------------------------|------------------------------|----------------------|----------|------------------|-------|-------|-------|-------|-------|-------|-------|-------|--------|
|                          |                              | Steel                | Concrete | Bin 1            | Bin 2 | Bin 3 | Bin 4 | Bin 5 | Bin 6 | Bin 7 | Bin 8 | Bin 9 | Bin 10 |
| PEMB                     | 2,201                        | 100                  | 0        | 0                | 0     | 5     | 5     | 5     | 15    | 20    | 25    | 15    | 10     |
| Hollow Clay Tile         | 25,920                       | 5                    | 95       | 2.5              | 5     | 7.5   | 10    | 12.5  | 15    | 20    | 15    | 10    | 2.5    |
| HAS                      | 277,530                      | 10                   | 90       | 2.5              | 5     | 5     | 7.5   | 15    | 15    | 15    | 10    | 10    | 15     |
| Large Concrete Arch ECM  | 48,737                       | 13                   | 87       | 5                | 5     | 5     | 5     | 7.5   | 7.5   | 7.5   | 7.5   | 10    | 40     |
| Medium Concrete Arch ECM | 48,737                       | 13                   | 87       | 5                | 5     | 5     | 5     | 7.5   | 7.5   | 7.5   | 7.5   | 10    | 40     |
| Small Concrete Arch ECM  | 48,737                       | 13                   | 87       | 5                | 5     | 5     | 5     | 7.5   | 7.5   | 7.5   | 7.5   | 10    | 40     |
| Large Steel Arch ECM     | 37,775                       | 16                   | 84       | 5                | 5     | 5     | 5     | 7.5   | 7.5   | 7.5   | 7.5   | 10    | 40     |
| Medium Steel Arch ECM    | 37,775                       | 16                   | 84       | 5                | 5     | 5     | 5     | 7.5   | 7.5   | 7.5   | 7.5   | 10    | 40     |
| Small Steel Arch ECM     | 37,775                       | 16                   | 84       | 5                | 5     | 5     | 5     | 7.5   | 7.5   | 7.5   | 7.5   | 10    | 40     |
| Large AGBS               | 176,473                      | 0                    | 100      | 0                | 5     | 5     | 10    | 40    | 10    | 5     | 5     | 5     | 15     |
| Medium AGBS              | 128,287                      | 0                    | 100      | 0                | 5     | 5     | 10    | 40    | 10    | 5     | 5     | 5     | 15     |
| Small AGBS (Square)      | 60,592                       | 0                    | 100      | 0                | 5     | 5     | 10    | 40    | 10    | 5     | 5     | 5     | 15     |
| Medium Concrete Building | 147,891                      | 2                    | 98       | 7.5              | 12.5  | 20    | 12.5  | 7.5   | 7.5   | 7.5   | 7.5   | 7.5   | 10     |
| Small Concrete Building  | 69,851                       | 2                    | 98       | 7.5              | 12.5  | 20    | 12.5  | 7.5   | 7.5   | 7.5   | 7.5   | 7.5   | 10     |
| Ship (large)             | 61,561                       | 100                  | 0        | 5                | 5     | 5     | 5     | 5     | 5     | 5     | 5     | 20    | 40     |
| Ship (medium)            | 61,561                       | 100                  | 0        | 5                | 5     | 5     | 5     | 5     | 5     | 5     | 5     | 20    | 40     |
| Ship (small)             | 30,627                       | 100                  | 0        | 5                | 5     | 5     | 5     | 5     | 5     | 5     | 5     | 20    | 40     |
| ISO Container            | 640 × NISO                   | 100                  | 0        | 0                | 0     | 5     | 5     | 5     | 15    | 20    | 25    | 15    | 10     |

\*Mass distribution numbers in table are in percent (%)

**Table A-22. Mass Distribution for PES Side Walls**

| PES #                    | Mass of PES side walls (lbs) | Percent Material (%) |          | Percent Mass (%) |       |       |       |       |       |       |       |       |        |
|--------------------------|------------------------------|----------------------|----------|------------------|-------|-------|-------|-------|-------|-------|-------|-------|--------|
|                          |                              | Steel                | Concrete | Bin 1            | Bin 2 | Bin 3 | Bin 4 | Bin 5 | Bin 6 | Bin 7 | Bin 8 | Bin 9 | Bin 10 |
| PEMB                     | 8,806                        | 100                  | 0        | 0                | 0     | 5     | 5     | 5     | 15    | 20    | 25    | 15    | 10     |
| Hollow Clay Tile         | 103,680                      | 5                    | 95       | 2.5              | 5     | 7.5   | 10    | 12.5  | 15    | 20    | 15    | 10    | 2.5    |
| HAS                      | 1,513,800                    | 10                   | 90       | 20               | 15    | 7.5   | 7.5   | 10    | 10    | 10    | 10    | 5     | 5      |
| Large Concrete Arch ECM  | 194,880                      | 5                    | 95       | 5                | 5     | 5     | 5     | 7.5   | 7.5   | 7.5   | 7.5   | 10    | 40     |
| Medium Concrete Arch ECM | 146,160                      | 5                    | 95       | 5                | 5     | 5     | 5     | 7.5   | 7.5   | 7.5   | 7.5   | 10    | 40     |
| Small Concrete Arch ECM  | 97,440                       | 5                    | 95       | 5                | 5     | 5     | 5     | 7.5   | 7.5   | 7.5   | 7.5   | 10    | 40     |
| Large Steel Arch ECM     | 31,400                       | 100                  | 0        | 5                | 5     | 5     | 5     | 7.5   | 7.5   | 7.5   | 7.5   | 10    | 40     |
| Medium Steel Arch ECM    | 23,550                       | 100                  | 0        | 5                | 5     | 5     | 5     | 7.5   | 7.5   | 7.5   | 7.5   | 10    | 40     |
| Small Steel Arch ECM     | 15,700                       | 100                  | 0        | 5                | 5     | 5     | 5     | 7.5   | 7.5   | 7.5   | 7.5   | 10    | 40     |
| Large AGBS               | 255,484                      | 0                    | 100      | 0                | 5     | 5     | 10    | 40    | 10    | 5     | 5     | 5     | 15     |
| Medium AGBS              | 256,574                      | 0                    | 100      | 0                | 5     | 5     | 10    | 40    | 10    | 5     | 5     | 5     | 15     |
| Small AGBS (Square)      | 121,184                      | 0                    | 100      | 0                | 5     | 5     | 10    | 40    | 10    | 5     | 5     | 5     | 15     |
| Medium Concrete Building | 295,782                      | 2                    | 98       | 7.5              | 12.5  | 20    | 12.5  | 7.5   | 7.5   | 7.5   | 7.5   | 7.5   | 10     |
| Small Concrete Building  | 139,702                      | 2                    | 98       | 7.5              | 12.5  | 20    | 12.5  | 7.5   | 7.5   | 7.5   | 7.5   | 7.5   | 10     |
| Ship (large)             | 547,210                      | 100                  | 0        | 5                | 5     | 5     | 5     | 5     | 5     | 5     | 5     | 20    | 40     |
| Ship (medium)            | 410,408                      | 100                  | 0        | 5                | 5     | 5     | 5     | 5     | 5     | 5     | 5     | 20    | 40     |
| Ship (small)             | 204,183                      | 100                  | 0        | 5                | 5     | 5     | 5     | 5     | 5     | 5     | 5     | 20    | 40     |
| ISO Container            | 2,599 × NISO                 | 100                  | 0        | 0                | 0     | 5     | 5     | 5     | 15    | 20    | 25    | 15    | 10     |

\*Mass distribution numbers in table are in percent (%)

**Table A-23. Mass Distribution for PES Rear Wall**

| PES #                    | Mass of PES rear wall (lbs) | Percent Material (%) |          | Percent Mass (%) |       |       |       |       |       |       |       |       |        |
|--------------------------|-----------------------------|----------------------|----------|------------------|-------|-------|-------|-------|-------|-------|-------|-------|--------|
|                          |                             | Steel                | Concrete | Bin 1            | Bin 2 | Bin 3 | Bin 4 | Bin 5 | Bin 6 | Bin 7 | Bin 8 | Bin 9 | Bin 10 |
| PEMB                     | 2,201                       | 100                  | 0        | 0                | 0     | 5     | 5     | 5     | 15    | 20    | 25    | 15    | 10     |
| Hollow Clay Tile         | 25,920                      | 5                    | 95       | 2.5              | 5     | 7.5   | 10    | 12.5  | 15    | 20    | 15    | 10    | 2.5    |
| HAS                      | 832,590                     | 10                   | 90       | 20               | 20    | 15    | 10    | 10    | 5     | 5     | 5     | 5     | 5      |
| Large Concrete Arch ECM  | 32,176                      | 5                    | 95       | 5                | 5     | 5     | 5     | 7.5   | 7.5   | 7.5   | 7.5   | 10    | 40     |
| Medium Concrete Arch ECM | 32,176                      | 5                    | 95       | 5                | 5     | 5     | 5     | 7.5   | 7.5   | 7.5   | 7.5   | 10    | 40     |
| Small Concrete Arch ECM  | 32,176                      | 5                    | 95       | 5                | 5     | 5     | 5     | 7.5   | 7.5   | 7.5   | 7.5   | 10    | 40     |
| Large Steel Arch ECM     | 36,920                      | 5                    | 95       | 5                | 5     | 5     | 5     | 7.5   | 7.5   | 7.5   | 7.5   | 10    | 40     |
| Medium Steel Arch ECM    | 36,920                      | 5                    | 95       | 5                | 5     | 5     | 5     | 7.5   | 7.5   | 7.5   | 7.5   | 10    | 40     |
| Small Steel Arch ECM     | 36,920                      | 5                    | 95       | 5                | 5     | 5     | 5     | 7.5   | 7.5   | 7.5   | 7.5   | 10    | 40     |
| Large AGBS               | 176,473                     | 0                    | 100      | 0                | 5     | 5     | 10    | 40    | 10    | 5     | 5     | 5     | 15     |
| Medium AGBS              | 128,287                     | 0                    | 100      | 0                | 5     | 5     | 10    | 40    | 10    | 5     | 5     | 5     | 15     |
| Small AGBS (Square)      | 60,592                      | 0                    | 100      | 0                | 5     | 5     | 10    | 40    | 10    | 5     | 5     | 5     | 15     |
| Medium Concrete Building | 147,891                     | 2                    | 98       | 7.5              | 12.5  | 20    | 12.5  | 7.5   | 7.5   | 7.5   | 7.5   | 7.5   | 10     |
| Small Concrete Building  | 69,851                      | 2                    | 98       | 7.5              | 12.5  | 20    | 12.5  | 7.5   | 7.5   | 7.5   | 7.5   | 7.5   | 10     |
| Ship (large)             | 61,561                      | 100                  | 0        | 5                | 5     | 5     | 5     | 5     | 5     | 5     | 5     | 20    | 40     |
| Ship (medium)            | 61,561                      | 100                  | 0        | 5                | 5     | 5     | 5     | 5     | 5     | 5     | 5     | 20    | 40     |
| Ship (small)             | 30,627                      | 100                  | 0        | 5                | 5     | 5     | 5     | 5     | 5     | 5     | 5     | 20    | 40     |
| ISO Container            | 640 × NISO                  | 100                  | 0        | 0                | 0     | 5     | 5     | 5     | 15    | 20    | 25    | 15    | 10     |

\*Mass distribution numbers in table are in percent (%)

**Table A-24. Roof Component Characteristics**

| PES                      | Initial Breakout Value<br>$Y_0$ (lbs) | Total Destruction Value<br>$Y_{100}$ (lbs) | PES Volume<br>$V$ (ft <sup>3</sup> ) |
|--------------------------|---------------------------------------|--------------------------------------------|--------------------------------------|
| PEMB                     | 3                                     | 40                                         | 31,104                               |
| Hollow Clay Tile         | 1                                     | 8                                          | 31,104                               |
| HAS                      | 1,000                                 | 2,000                                      | 229,680                              |
| Large Concrete Arch ECM  | 15                                    | 250                                        | 25,000                               |
| Medium Concrete Arch ECM | 15                                    | 250                                        | 18,750                               |
| Small Concrete Arch ECM  | 15                                    | 250                                        | 12,500                               |
| Large Steel Arch ECM     | 15                                    | 250                                        | 25,000                               |
| Medium Steel Arch ECM    | 15                                    | 250                                        | 18,750                               |
| Small Steel Arch ECM     | 15                                    | 250                                        | 12,500                               |
| Large AGBS               | 1                                     | 16                                         | 135,258                              |
| Medium AGBS              | 1                                     | 16                                         | 107,440                              |
| Small AGBS (Square)      | 1                                     | 16                                         | 36,864                               |
| Medium Concrete Building | 1                                     | 16                                         | 107,440                              |
| Small Concrete Building  | 1                                     | 16                                         | 36,864                               |
| Ship (large)             | 100                                   | 5,000                                      | 603,000                              |
| Ship (medium)            | 100                                   | 5,000                                      | 452,250                              |
| Ship (small)             | 100                                   | 5,000                                      | 150,000                              |
| ISO Container            | 3                                     | 40                                         | 1,360                                |

**Table A-25. Front Wall Component Characteristics**

| PES                      | Initial Breakout Value<br>$Y_0$ (lbs) | Total Destruction Value<br>$Y_{100}$ (lbs) | PES Volume<br>$V$ (ft <sup>3</sup> ) |
|--------------------------|---------------------------------------|--------------------------------------------|--------------------------------------|
| PEMB                     | 3                                     | 40                                         | 31,104                               |
| Hollow Clay Tile         | 1                                     | 8                                          | 31,104                               |
| HAS                      | 40                                    | 2,000                                      | 229,680                              |
| Large Concrete Arch ECM  | 1                                     | 10                                         | 25,000                               |
| Medium Concrete Arch ECM | 1                                     | 10                                         | 18,750                               |
| Small Concrete Arch ECM  | 1                                     | 10                                         | 12,500                               |
| Large Steel Arch ECM     | 1                                     | 10                                         | 25,000                               |
| Medium Steel Arch ECM    | 1                                     | 10                                         | 18,750                               |
| Small Steel Arch ECM     | 1                                     | 10                                         | 12,500                               |
| Large AGBS               | 1                                     | 8                                          | 135,258                              |
| Medium AGBS              | 1                                     | 8                                          | 107,440                              |
| Small AGBS (Square)      | 1                                     | 8                                          | 36,864                               |
| Medium Concrete Building | 3                                     | 100                                        | 107,440                              |
| Small Concrete Building  | 3                                     | 100                                        | 36,864                               |
| Ship (large)             | 100                                   | 5,000                                      | 603,000                              |
| Ship (medium)            | 100                                   | 5,000                                      | 452,250                              |
| Ship (small)             | 100                                   | 5,000                                      | 150,000                              |
| ISO Container            | 3                                     | 40                                         | 1,360                                |

**Table A-26. Side Wall Component Characteristics**

| PES                      | Initial Breakout Value<br>$Y_0$ (lbs) | Total Destruction Value<br>$Y_{100}$ (lbs) | PES Volume<br>$V$ (ft <sup>3</sup> ) |
|--------------------------|---------------------------------------|--------------------------------------------|--------------------------------------|
| PEMB                     | 1                                     | 40                                         | 31,104                               |
| Hollow Clay Tile         | 1                                     | 8                                          | 31,104                               |
| HAS                      | 1,000                                 | 2,000                                      | 229,680                              |
| Large Concrete Arch ECM  | 2,000                                 | 10,000                                     | 25,000                               |
| Medium Concrete Arch ECM | 2,000                                 | 10,000                                     | 18,750                               |
| Small Concrete Arch ECM  | 2,000                                 | 10,000                                     | 12,500                               |
| Large Steel Arch ECM     | 2,000                                 | 10,000                                     | 25,000                               |
| Medium Steel Arch ECM    | 2,000                                 | 10,000                                     | 18,750                               |
| Small Steel Arch ECM     | 2,000                                 | 10,000                                     | 12,500                               |
| Large AGBS               | 1                                     | 8                                          | 135,258                              |
| Medium AGBS              | 1                                     | 8                                          | 107,440                              |
| Small AGBS (Square)      | 1                                     | 8                                          | 36,864                               |
| Medium Concrete Building | 3                                     | 100                                        | 107,440                              |
| Small Concrete Building  | 3                                     | 100                                        | 36,864                               |
| Ship (large)             | 100                                   | 5,000                                      | 603,000                              |
| Ship (medium)            | 100                                   | 5,000                                      | 452,250                              |
| Ship (small)             | 100                                   | 5,000                                      | 150,000                              |
| ISO Container            | 1                                     | 40                                         | 1,360                                |

**Table A-27. Rear Wall Component Characteristics**

| PES                      | Initial Breakout Value<br>$Y_0$ (lbs) | Total Destruction Value<br>$Y_{100}$ (lbs) | PES Volume<br>$V$ (ft <sup>3</sup> ) |
|--------------------------|---------------------------------------|--------------------------------------------|--------------------------------------|
| PEMB                     | 1                                     | 40                                         | 31,104                               |
| Hollow Clay Tile         | 1                                     | 8                                          | 31,104                               |
| HAS                      | 2,000                                 | 10,000                                     | 229,680                              |
| Large Concrete Arch ECM  | 2,000                                 | 10,000                                     | 25,000                               |
| Medium Concrete Arch ECM | 2,000                                 | 10,000                                     | 18,750                               |
| Small Concrete Arch ECM  | 2,000                                 | 10,000                                     | 12,500                               |
| Large Steel Arch ECM     | 2,000                                 | 10,000                                     | 25,000                               |
| Medium Steel Arch ECM    | 2,000                                 | 10,000                                     | 18,750                               |
| Small Steel Arch ECM     | 2,000                                 | 10,000                                     | 12,500                               |
| Large AGBS               | 1                                     | 8                                          | 135,258                              |
| Medium AGBS              | 1                                     | 8                                          | 107,440                              |
| Small AGBS (Square)      | 1                                     | 8                                          | 36,864                               |
| Medium Concrete Building | 3                                     | 100                                        | 107,440                              |
| Small Concrete Building  | 3                                     | 100                                        | 36,864                               |
| Ship (large)             | 100                                   | 7,500                                      | 603,000                              |
| Ship (medium)            | 100                                   | 7,500                                      | 452,250                              |
| Ship (small)             | 100                                   | 7,500                                      | 150,000                              |



|               |   |    |       |
|---------------|---|----|-------|
| ISO Container | 1 | 40 | 1,360 |
|---------------|---|----|-------|

**Table A-28. Secondary Fragment Initial Velocity**

| PES                      | Roof     |            | Front wall |            | Side wall |            | Rear wall |            | Cut-off values<br>$IV_{max}$ (ft/s) |
|--------------------------|----------|------------|------------|------------|-----------|------------|-----------|------------|-------------------------------------|
|                          | $a_{iv}$ | $exp_{iv}$ | $a_{iv}$   | $exp_{iv}$ | $a_{iv}$  | $exp_{iv}$ | $a_{iv}$  | $exp_{iv}$ |                                     |
| PEMB                     | 700      | 0.45       | 700        | 0.45       | 700       | 0.45       | 700       | 0.45       | 1,500                               |
| Hollow Clay Tile         | 700      | 0.45       | 700        | 0.45       | 700       | 0.45       | 700       | 0.45       | 1,500                               |
| HAS                      | 6550     | 0.8        | 11900      | 0.8        | 6550      | 0.8        | 4990      | 0.8        | 1,500                               |
| Large Concrete Arch ECM  | 141.8    | 0.365      | 678.9      | 0.49       | 70.6      | 0.482      | 61.7      | 0.495      | 3,000                               |
| Medium Concrete Arch ECM | 142.8    | 0.396      | 746.4      | 0.571      | 70.2      | 0.536      | 68.2      | 0.586      | 3,000                               |
| Small Concrete Arch ECM  | 139.4    | 0.444      | 863.3      | 0.657      | 68        | 0.585      | 78.3      | 0.662      | 3,000                               |
| Large Steel Arch ECM     | 234.9    | 0.361      | 295.7      | 0.313      | 88.3      | 0.489      | 39.9      | 0.313      | 3,000                               |
| Medium Steel Arch ECM    | 237.4    | 0.389      | 384.7      | 0.409      | 89.3      | 0.521      | 51.7      | 0.413      | 3,000                               |
| Small Steel Arch ECM     | 237.1    | 0.431      | 402.5      | 0.441      | 87.6      | 0.567      | 54.3      | 0.441      | 3,000                               |
| Large AGBS               | 1711     | 0.405      | 1731       | 0.47       | 2011      | 0.5074     | 1731      | 0.47       | 3,000                               |
| Medium AGBS              | 1575     | 0.4        | 2300       | 0.539      | 2300      | 0.539      | 2300      | 0.539      | 3,000                               |
| Small AGBS (Square)      | 1211     | 0.404      | 2004       | 0.6        | 2004      | 0.6        | 2004      | 0.6        | 3,000                               |
| Medium Concrete Building | 1604     | 0.3975     | 2007       | 0.535      | 2007      | 0.535      | 2007      | 0.535      | 3,000                               |
| Small Concrete Building  | 1223     | 0.401      | 1746       | 0.596      | 1746      | 0.596      | 1746      | 0.596      | 3,000                               |
| Ship (large)             | 2130     | 0.45       | 2130       | 0.45       | 2130      | 0.45       | 2130      | 0.45       | 3,000                               |
| Ship (medium)            | 2130     | 0.45       | 2130       | 0.45       | 2130      | 0.45       | 2130      | 0.45       | 3,000                               |
| Ship (small)             | 2130     | 0.45       | 2130       | 0.45       | 2130      | 0.45       | 2130      | 0.45       | 3,000                               |
| ISO Container            | 700      | 0.45       | 700        | 0.45       | 700       | 0.45       | 700       | 0.45       | 1,500                               |

**Table A-29. Secondary Fragment Maximum Throw Cutoff Values**

| PES                      | Maximum Throw Cutoff Values |                 |                |                |
|--------------------------|-----------------------------|-----------------|----------------|----------------|
|                          | Roof (ft)                   | Front wall (ft) | Side wall (ft) | Rear wall (ft) |
| PEMB                     | Primary max.                | Primary max.    | Primary max.   | Primary max.   |
| Hollow Clay Tile         | Primary max.                | 3600            | 3600           | 3600           |
| HAS                      | 3000                        | 3600            | 3000           | 3000           |
| Large Concrete Arch ECM  | 3600                        | 5100            | 3600           | 3600           |
| Medium Concrete Arch ECM | 3600                        | 5100            | 3600           | 3600           |
| Small Concrete Arch ECM  | 3600                        | 5100            | 3600           | 3600           |
| Large Steel Arch ECM     | 3600                        | 5100            | 3600           | 3600           |
| Medium Steel Arch ECM    | 3600                        | 5100            | 3600           | 3600           |
| Small Steel Arch ECM     | 3600                        | 5100            | 3600           | 3600           |
| Large AGBS               | 3600                        | 4700            | 4700           | 4700           |
| Medium AGBS              | 3600                        | 4700            | 4700           | 4700           |
| Small AGBS (Square)      | 3600                        | 4700            | 4700           | 4700           |
| Medium Concrete Building | 3600                        | 4700            | 4700           | 4700           |
| Small Concrete Building  | 3600                        | 4700            | 4700           | 4700           |
| Ship (small)             | 4400                        | 4400            | 4400           | 4400           |
| Ship (medium)            | 4400                        | 4400            | 4400           | 4400           |
| Ship (large)             | 4400                        | 4400            | 4400           | 4400           |
| ISO Container            | 4400                        | 4400            | 4400           | 4400           |

## Attachment 1 - Thermal

## PURPOSE

This memorandum addresses major technical and analytical decisions made as part of the SAFER 3.1 Thermal branch. Specific questions addressed are:

1. Why are thermal effects only considered for 1.3 events?
2. Why aren't other effects/consequences considered in 1.3 events?
3. Why is an adjustment made if a PES is present?
4. What is the PES adjustment based on?
5. Why is PES damage not considered?
6. Why is an adjustment made if an ES is present?
7. What is the ES adjustment based on?
8. How were the fatality (as a function of the inverse of the adjusted scaled range) curves derived?
9. Why is the maximum probability of fatality for thermal effects only 0.5?

## REFERENCES

1. Swisdak, M. M., "DDESB Blast Effects Computer User's Manual And Documentation (Revision 1)," DDESB Technical Paper 17, 1 January 2005.
2. Edmondson, J. N. and Prescott, B. L., "The Thermal Radiation Effects From The Initiation Of HD 1.3 Explosives," RANN/2/49/00119/90, AEA Technology, March 1992
3. Briefings to RBESCT

## DISCUSSIONS

1. Why are thermal effects only considered for 1.3 events?

The assumption was made that the thermal effects from a high-explosives event would be insignificant (compared to other effects) if 1.3 items were not present.

2. Why aren't other effects/consequences considered in 1.3 events?

The assumption was made that the blast-related effects (direct pressure and impulse, glass hazards, ES building failure, and debris) from a 1.3 event would be insignificant compared to thermal.

3. Why is an adjustment made if a PES is present?

The adjustment to the yield is made in order to account for the effect the presence of the PES has on the yield "seen" outside of the PES.

4. What is the PES adjustment based on?

In SAFER 3.1, the yield adjustment in the thermal branch is made based on the logic for the yield adjustment in the pressure and impulse branch. The algorithms for determining the adjusted weight are based on the Blast Effects Computer (ref 1).

5. *Why is PES damage not considered?*

In SAFER, building damage is not a design goal. PES damage is used to determine effects external to the building, and they are considered in sequence with thermal being the last. There is no provision in SAFER that the PES may actually contain an event and there are no other effects to be considered “after” thermal effects, therefore the damage to the PES does not need to be determined.

6. *Why is an adjustment made if an ES is present?*

The protection afforded by the ES against thermal effects is considered in SAFER, unless the ES is “open.”

7. *What is the ES adjustment based on?*

The Science Panel determined the nominal thermal blocking factors based on the material type of the building and expert opinion.

8. *How were the fatality (as a function of the inverse of the adjusted scaled range) curves derived?*

The Science Panel created the curves based on available literature (ref 2) describing the probability of third-degree burns as a function of the quantity of explosives. A relationship was developed to translate third-degree burns into probability of fatality and then the Science Panel plotted data points from the existing and developed equations. These data points were then used to fit a standard normal distribution describing the probability of fatality as a function of the inverse of the scaled adjusted range

9. *Why is the maximum probability of fatality for thermal effects only 0.5?*

The information available (ref 2) predicted a maximum probability of fatality of approximately 0.5 and the Science Panel did not alter this value.

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## Attachment 2 – Simplified Close-In Fatality Mechanisms (SCIFM)

## ***Simplified Close-In Fatality Mechanisms (SCIFM)***

*Prepared by – John Tatom (APT)*

*Mike Swisdak (NSWC)*

*Revision Date – May 2009*

### **PURPOSE**

This memorandum addresses the rationale and development of the Simplified Close-In Fatality Mechanisms (SCIFM).

Specific questions include:

1. What is SCIFM and why is it necessary?
2. How does SCIFM work?
3. What are the ( $X_1$ ,  $Y_1$ ) and ( $X_2$ ,  $Y_2$ ) parameters based on?
4. How was the shape of the transition region curve determined?
5. How were the plateau values established?
6. Are there step-functions in the SCIFM logic?
7. Does SCIFM affect injury determination?
8. Why doesn't SCIFM apply to direct blast fatality mechanisms?
9. Why are there fixed minimum values for  $X_2$  in the building failure SCIFM logic?
10. Why does  $X_1=X_2$  in the debris SCIFM logic?
11. Why aren't the  $X_1$  and  $X_2$  debris SCIFM values based on scaled range?
12. Why does  $X_1=X_2$  in the thermal SCIFM logic?
13. Why aren't the  $X_1$  and  $X_2$  thermal SCIFM values based on scaled range?

### **REFERENCES (ATTACHED)**

1. "SAFER 3 Algorithm Poster Session," DDESB Seminar 2004, APT CE1-09900, 13 August 2004.
2. "SAFER 3 Range of Validity Technical Memorandum," APT CE1-16000, 25 February 2005.
3. Briefings to RBESCT

### **DISCUSSION**

1. *What is SCIFM and why is it necessary?*

SCIFM is a conservative methodology designed to allow the use of SAFER at shorter distances than the original/nominal logic was intended.

2. *How does SCIFM work?*

With the introduction of the SCIFM logic, SAFER 3.1 has three distinct regions in which the probability of fatality is determined:

Region 1 (close to the PES): plateau region with a constant value of  $P_{fle}$

Region 2 (transition): Beyond the plateau, a region where  $P_{fle}$  value is determined by a stored curve



Region 3: At ranges large enough to be in the range of validity for the normal SAFER equations, the  $P_{fle}$  value is calculated using the standard SAFER logic for each branch

As shown in Figure 1, SCIFM Region Visualization, these three regions are delineated by the two points  $X_1$  and  $X_2$ .

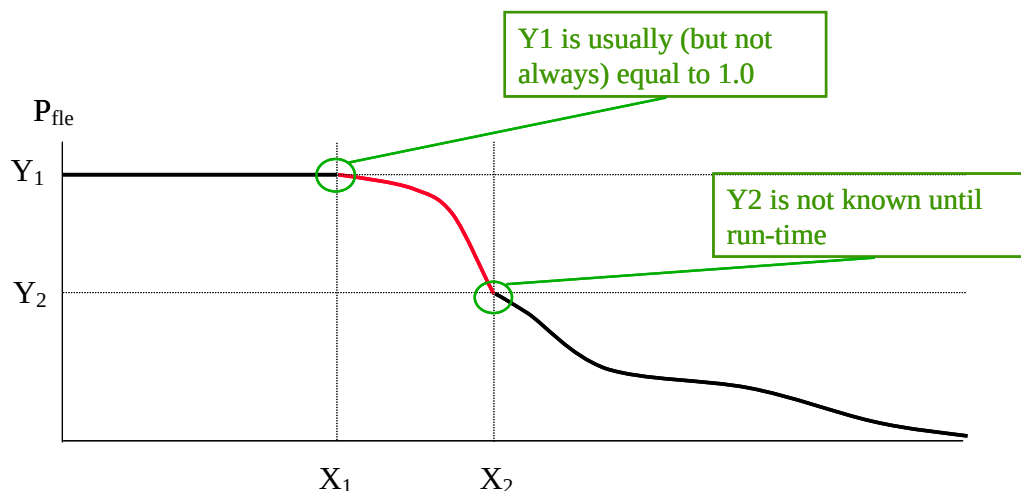


Figure 1. SCIFM Region Visualization

The values for  $X_1$  and  $X_2$  are stored or calculated for each branch of the SAFER logic, as shown in Table 1. The values for  $X_1$  are considered placeholders and will be refined in future versions of SAFER.

Table 1. SCIFM Range Parameters

| Mechanism                                      | $X_1$ | $X_2$                                          |
|------------------------------------------------|-------|------------------------------------------------|
| <i>Pressure and Impulse</i>                    |       |                                                |
| Lung Rupture                                   | N/A   | N/A                                            |
| Whole Body Displacement                        | N/A   | N/A                                            |
| Skull Fracture                                 | N/A   | N/A                                            |
| <i>Glass</i>                                   |       |                                                |
| Annealed                                       | K6    | K12                                            |
| Dual Pane                                      | K6    | K12                                            |
| Tempered                                       | K6    | K12                                            |
| <i>Building Failure</i>                        |       |                                                |
| Small Reinforced Concrete (Office/Commercial)  | K6    | $X_2 = A + ((B * NEW) / (C + NEW)) \{min=8\}$  |
| Medium Reinforced Concrete (Office/Commercial) | K7    | $X_2 = A + ((B * NEW) / (C + NEW)) \{min=8\}$  |
| Large Reinforced Concrete Tilt-up (Commercial) | K8    | $X_2 = A + ((B * NEW) / (C + NEW)) \{min=11\}$ |
| Small Reinforced Masonry (Office/Commercial)   | K8    | $X_2 = A + ((B * NEW) / (C + NEW)) \{min=10\}$ |
| Medium Reinforced Masonry (Office/Commercial)  | K7    | $X_2 = A + ((B * NEW) / (C + NEW)) \{min=10\}$ |

|                                                  |                  |                                     |
|--------------------------------------------------|------------------|-------------------------------------|
| Small Unreinforced Brick (Office/Apartment)      | K9               | $X2=A+((B*NEW)/(C+NEW)) \{min=12\}$ |
| Medium Unreinforced Masonry (Office/Apartment)   | K9               | $X2=A+((B*NEW)/(C+NEW)) \{min=12\}$ |
| Large Unreinforced Masonry (Office)              | K9               | $X2=A+((B*NEW)/(C+NEW)) \{min=12\}$ |
| Small PEMB (Office/Storage)                      | K10              | $X2=A+((B*NEW)/(C+NEW)) \{min=13\}$ |
| Medium PEMB (Office/Commercial)                  | K9               | $X2=A+((B*NEW)/(C+NEW)) \{min=12\}$ |
| Large PEMB (Office/Storage/Hangar)               | K9               | $X2=A+((B*NEW)/(C+NEW)) \{min=12\}$ |
| Small Wood Frame (Residence)                     | K8               | $X2=A+((B*NEW)/(C+NEW)) \{min=11\}$ |
| Medium Wood Frame (Residence/Apartment)          | K8               | $X2=A+((B*NEW)/(C+NEW)) \{min=11\}$ |
| Medium Steel Stud (Office/Commercial)            | K9               | $X2=A+((B*NEW)/(C+NEW)) \{min=12\}$ |
| Modular Building/Trailer(Office/Residence/Story) | K9               | $X2=A+((B*NEW)/(C+NEW)) \{min=12\}$ |
| Vehicle                                          | K7               | $X2=A+((B*NEW)/(C+NEW)) \{min=10\}$ |
| <i>Debris</i>                                    |                  |                                     |
| High Angle                                       | 2* crater radius | 2* crater radius                    |
| Low Angle                                        | 2* crater radius | 2* crater radius                    |
| <i>Other</i>                                     |                  |                                     |
| Thermal                                          | Fireball radius  | Fireball radius                     |

The building failure  $X_2$  equations use stored parameters as shown in Table 2.

Table 2.  $X_2$  Equation Parameters

| ES Building Type                                 | A        | B      | C      |
|--------------------------------------------------|----------|--------|--------|
| Small Reinforced Concrete (Office/Commercial)    | -4.128   | 11.874 | 43114  |
| Medium Reinforced Concrete (Office/Commercial)   | -2.9501  | 10.661 | 56396  |
| Large Reinforced Concrete Tilt-up (Commercial)   | 0.16852  | 15.451 | 32550  |
| Small Reinforced Masonry (Office/Commercial)     | -0.13307 | 10.113 | 56344  |
| Medium Reinforced Masonry (Office/Commercial)    | 0.80385  | 11.677 | 47077  |
| Small Unreinforced Brick (Office/Apartment)      | 4.2209   | 11.907 | 776.41 |
| Medium Unreinforced Masonry (Office/Apartment)   | 0.5839   | 11.725 | 3761   |
| Large Unreinforced Masonry (Office)              | 0.25642  | 14.145 | 7926.6 |
| Small PEMB (Office/Storage)                      | 0.92458  | 13.068 | 4821.9 |
| Medium PEMB (Office/Commercial)                  | 0.03521  | 13.618 | 6796.8 |
| Large PEMB (Office/Storage/Hangar)               | 0.14699  | 13.366 | 28431  |
| Small Wood Frame (Residence)                     | 1.0211   | 11.484 | 1453.8 |
| Medium Wood Frame (Residence/Apartment)          | 0.28302  | 12.153 | 9128.4 |
| Medium Steel Stud (Office/Commercial)            | -0.28856 | 11.951 | 17108  |
| Modular Building/Trailer(Office/Residence/Story) | 3.7687   | 11.621 | 997.25 |
| Vehicle                                          | 0.14699  | 13.366 | 28431  |

The values for  $Y_1$  and  $Y_2$  are stored or calculated for each branch of the SAFER logic, as shown in Table 3. %Glass and FA are user inputs: the percentage of glass on the structure and the floor area of the structure.

Table 3. Y1 and Y2 Parameters

| Mechanism                                         | Y1  | Y2                                                                                                                                                                                |
|---------------------------------------------------|-----|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <i>Pressure and Impulse</i>                       |     |                                                                                                                                                                                   |
| Lung Rupture                                      | N/A | N/A                                                                                                                                                                               |
| Whole Body Displacement                           | N/A | N/A                                                                                                                                                                               |
| Skull Fracture                                    | N/A | N/A                                                                                                                                                                               |
|                                                   |     |                                                                                                                                                                                   |
| <i>Glass</i>                                      |     |                                                                                                                                                                                   |
| Annealed                                          | 0.1 | $Y2 = [-0.00019264 + 0.00051619(\text{LOG}(\text{NEW}))] * [\% \text{Glass}/10\%] * [5000/\text{FA}]^{1/2}$                                                                       |
| Dual Pane                                         | 0.1 | $Y2 = [-0.00010599 + 0.00078248(\text{LOG}(\text{NEW}))] * [\% \text{Glass}/10\%] * [5000/\text{FA}]^{1/2}$                                                                       |
| Tempered                                          | 0.1 | $Y2 = [-0.00024899 + 0.00014097(\text{LOG}(\text{NEW}))] * [\% \text{Glass}/10\%] * [5000/\text{FA}]^{1/2}$                                                                       |
|                                                   |     |                                                                                                                                                                                   |
| <i>Building Failure</i>                           |     |                                                                                                                                                                                   |
| Small Reinforced Concrete (Office/Commercial)     | 1.0 | $Y2 = \text{EXP}(-330.43 + 100.96 * (\text{LN}(W_a)) - 11.618 * (\text{LN}(W_a))^2 + 0.59364 * (\text{LN}(W_a))^3 - 0.011345 * (\text{LN}(W_a))^4)$                               |
| Medium Reinforced Concrete (Office/Commercial)    | 1.0 | $Y2 = \text{EXP}(-130.31 + 38.22 * (\text{LN}(W_a)) - 4.2566 * (\text{LN}(W_a))^2 + 0.21066 * (\text{LN}(W_a))^3 - 0.0039012 * (\text{LN}(W_a))^4)$                               |
| Large Reinforced Concrete Tilt-up (Commercial)    | 1.0 | $Y2 = -0.1108 + ((0.38698 * W_a) / (2330.4 + W_a))$                                                                                                                               |
| Small Reinforced Masonry (Office/Commercial)      | 1.0 | $Y2 = -0.0128 + ((0.20231 * W_a) / (14754 + W_a))$                                                                                                                                |
| Medium Reinforced Masonry (Office/Commercial)     | 1.0 | $Y2 = -0.024 + ((0.24954 * W_a) / (9160.1 + W_a))$                                                                                                                                |
| Small Unreinforced Brick (Office/Apartment)       | 1.0 | $Y2 = 0.18$                                                                                                                                                                       |
| Medium Unreinforced Masonry (Office/Apartment)    | 1.0 | $Y2 = -4.7904 + ((4.9933 * W_a) / (29.996 + W_a))$                                                                                                                                |
| Large Unreinforced Masonry (Office)               | 1.0 | $Y2 = -4.8294 + ((5.0222 * W_a) / (38.228 + W_a))$                                                                                                                                |
| Small PEMB (Office/Storage)                       | 1.0 | $Y2 = -3.2784 + ((3.4088 * W_a) / (39.217 + W_a))$                                                                                                                                |
| Medium PEMB (Office/Commercial)                   | 1.0 | $Y2 = -0.037719 + ((0.22199 * W_a) / (4840 + W_a))$                                                                                                                               |
| Large PEMB (Office/Storage/Hangar)                | 1.0 | $Y2 = -0.0341 + ((0.21859 * W_a) / (5067.3 + W_a))$                                                                                                                               |
| Small Wood Frame (Residence)                      | 1.0 | $Y2 = -4.479 + ((4.5989 * W_a) / (7.221 + W_a))$                                                                                                                                  |
| Medium Wood Frame (Residence/Apartment)           | 1.0 | $Y2 = -4.6697 + ((4.8108 * W_a) / (29.434 + W_a))$                                                                                                                                |
| Medium Steel Stud (Office/Commercial)             | 1.0 | $Y2 = \text{EXP}(274.49 - 173.58 * (\text{LN}(W_a)) + 36.146 * (\text{LN}(W_a))^2 - 3.426 * (\text{LN}(W_a))^3 + 0.15323 * (\text{LN}(W_a))^4 - 0.0026334 * (\text{LN}(W_a))^5)$  |
| Modular Building/Trailer (Office/Residence/Story) | 1.0 | $Y2 = 0.13$                                                                                                                                                                       |
| Vehicle                                           | 1.0 | $Y2 = \text{EXP}(-1372.5 + 495.77 * (\text{LN}(W_a)) - 70.975 * (\text{LN}(W_a))^2 + 5.0232 * (\text{LN}(W_a))^3 - 0.17563 * (\text{LN}(W_a))^4 + 0.002425 * (\text{LN}(W_a))^5)$ |
|                                                   |     |                                                                                                                                                                                   |
| <i>Debris</i>                                     |     |                                                                                                                                                                                   |
| High Angle                                        | 1.0 | SAFER 3.1.0 result                                                                                                                                                                |

|           |     |                    |
|-----------|-----|--------------------|
| Low Angle | 1.0 | SAFER 3.1.0 result |
|           |     |                    |
| Other     |     |                    |
| Thermal   | 1.0 | SAFER 3.1.0 result |

3. *What are the  $(X_1, Y_1)$  and  $(X_2, Y_2)$  parameters based on?*

The  $X_2$  parameters are largely based on the range of validity of the algorithms, as described in a separate document (ref 2). The  $Y_2$  values are generally a function of  $X_2$ . The  $(X_1, Y_1)$  values were conservatively established based on expert opinion.

4. *How was the shape of the transition region curve determined?*

The curve was created to conservatively transition the  $P_{fle}$  values from  $(X_1, Y_1)$  to  $(X_2, Y_2)$  and is based on expert opinion.

5. *How were the plateau values established?*

For purposes of conservatism, the value was set to 1.0 for all mechanisms other than glass. For glass, historical precedent suggested that glass hazards would never kill all occupants of normal ES types. The value of 0.1 for glass was based on expert opinion.

6. *Are there step-functions in the SCIFM logic?*

In general, there are not. However, in cases where  $X_1$  equals  $X_2$  and  $Y_2$  is less than  $Y_1$ , step-function results will occur.

7. *Does SCIFM affect injury determination?*

Yes, in some cases (when injury levels are dependent on fatality levels and the fatality level has been affected by SCIFM).

8. *Why doesn't SCIFM apply to direct blast fatality mechanisms?*

The direct blast fatality mechanisms were already designed to generate  $P_{fle}$  results as high as 1.0 if the scaled range was small enough. Therefore, the SCIFM logic was not necessary.

9. *Why are there fixed minimum values for  $X_2$  in the building failure SCIFM logic?*

Certain assumptions concerning the response of the ES were not considered accurate at scaled ranges smaller than the fixed minima; therefore the fixed minimum values were included for conservatism.

10. *Why does  $X_1=X_2$  in the debris SCIFM logic?*

The SAFER debris density function accounts for most ranges relatively well, but was not intended to apply inside the crater itself. Thus, the  $X_2$  value (which represents the minimum range at which the standard algorithms can be used) could have been set to value as small as the crater radius, but was doubled for conservatism. The plateau region extends out to the same value.

11. *Why aren't the  $X_1$  and  $X_2$  debris SCIFM values based on scaled range?*

The crater radius is not expressed as a scaled range, so  $X_1$  and  $X_2$  cannot be, either.

*12. Why does  $X_1=X_2$  in the thermal SCIFM logic?*

The SAFER thermal logic was not intended to apply inside the fireball itself. Thus, the  $X_2$  value (which represents the minimum range at which the standard algorithms can be used) was set to the fireball radius.

*13. Why aren't the  $X_1$  and  $X_2$  thermal SCIFM values based on scaled range?*

The fireball radius is not expressed as a scaled range, so  $X_1$  and  $X_2$  cannot be, either.

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## Attachment 3 – Input Section

## **PURPOSE**

This memorandum addresses major technical and analytical decisions made as part of the SAFER 3.1 input section. Specific questions addressed are:

1. Why were the weapon types shown in Table 1 chosen?
2. What guidance is there for choosing weapon types when the actual weapon is not a choice?
3. What are the weapon models based on?
4. Why were these PES types chosen?
5. What guidance is there for choosing PES types when the actual PES is unknown or not available as a choice?
6. What are the PES blast and debris parameters based on?
7. Why were these activity types chosen?
8. Why were these ES types chosen?
9. What guidance is there for choosing ES types when the actual ES is unknown or not available as a choice?
10. What are the ES models based on?
11. What guidance is there for choosing ES roof types when the actual ES roof is unknown or not available as a choice?
12. How were the methods for determining maximum/expected yields (by HD) derived?
13. How were the TNT conversion factors determined?

## **REFERENCES**

1. Swisdak, M. M. and Ward, J. M., “DDESB Blast Effects Computer Users Manual and Documentation (Revision 1),” DDESB Technical Paper 17 (Revision 1), 1 January 2005.
2. Crull, Michelle and Swisdak, Michael, “Methodologies For Calculating Primary Fragment Characteristics,” DDESB Technical Paper 16 (Revision 2), 17 October 2005.
3. Briefings to RBESCT
4. Chrostowski, Jon; Wilde, Paul and Gan, Wenshui, “Blast Damage, Serious Injury and Fatality Models for Structures and Windows”, ACTA, Torrance, CA, July 2001.

## **DISCUSSIONS**

1. Why were the weapon types shown in Table 1 chosen?

The weapon choices available in SAFER are based on a philosophy developed for the Army’s “Worst Case Donor/Acceptor” Program: If testing or analysis is performed using a “worst case” donor munition as the explosion source, then the results would be applicable to all other munitions that present a lesser hazard.

For HD 1.1 munitions, several different items were identified as being potential worst cases from both a blast and fragmentation standpoint; it being up to the user to select the type that most closely represents the actual item. MK 80 series bombs (MK 82, MK 83,



or MK 84) represent all large, robust munitions; M107 projectiles represent all small, robust munitions. The AIM-7 warhead represents all fragmenting or thin-skinned items.

For HD 1.2, the M1 projectile represents all HD 1.2.1 items, while the 40 mm projectile represents all HD 1.2.2 projectiles.

Thus, by using items that represent “worst” cases, the results can be applied to other, similar weapons in class. If calculations made for an item that was not “worst case”, then the results obtained would only apply to that particular item. If SAFER analyses were performed with weapons that did not represent worst-case situations, then the results would be weapon specific and could not be applied to other weapons or situations.

2. *What guidance is there for choosing weapon types when the actual weapon is not a choice?*

The user should know if his/her weapons are robust/non-robust, bombs/projectiles, lightly cased items, bare explosives, etc. With this general knowledge, choices can be made. As a rule, if the NEW is made up of a mixture of different types of items, select the “worst” case. If this cannot be easily determined, make multiple runs by varying the input weapon selection and then use the one that gives the highest probability of fatality.

3. *What are the weapon models based on?*

The blast models use the same algorithms as the DDESB Blast Effects Computer<sup>1</sup>.

The fragmentation models use the algorithms and information described in DDESB TP 16<sup>2</sup>.

4. *Why were these PES types chosen?*

The intent was to provide as many options as possible under the following constraints: (1) either test data were available or (2) the buildings are typical of DOD storage and operational facilities even if no test data were available.

5. *What guidance is there for choosing PES types when the actual PES is unknown or not available as a choice?*

As a rule, the debris hazard will dominate and therefore the user should select the closest match in terms of debris type and generation potential. If this cannot be easily determined, make multiple runs by varying the PES selection (between reasonable choices) and then use the one that produces the most conservative result.

If the PES does not contribute significantly to the debris hazard, consider Table 1.

Table 1. PES Selection Criteria

| PES Type | Blast Attenuation | Secondary Debris Mass |
|----------|-------------------|-----------------------|
| Open     | None              | None                  |
| PEMB     | None              | Minor                 |
| HCT      | None              | Moderate              |

Additional guidance is provided in DDESB Technical Paper #19.

6. *What are the PES blast and debris parameters based on?*

Where available, test data were used to anchor the SAFER models. When test data were not available, the consensus expert opinion of the Science Panel was used. See Table 2 for a summary of the basis of the PES parameters for blast and debris hazards.

Table 2. PES Parameter Basis

| PES Type                 | Blast                   | Debris                           |
|--------------------------|-------------------------|----------------------------------|
| Open                     | N/A                     | N/A                              |
| PEMB                     | N/A                     | Expert Opinion                   |
| HCT                      | N/A                     | Expert Opinion                   |
| HAS                      | Distant Runner (E4, E5) | Distant Runner (E4, E5)          |
| Large Concrete Arch ECM  | Compiled test results   | Inferred from Eskimo test series |
| Medium Concrete Arch ECM | Compiled test results   | Inferred from Eskimo test series |
| Small Concrete Arch ECM  | Compiled test results   | Inferred from Eskimo test series |
| Large Steel Arch ECM     | Compiled test results   | Inferred from Eskimo 1           |
| Medium Steel Arch ECM    | Compiled test results   | Eskimo 1                         |
| Small Steel Arch ECM     | Compiled test results   | Inferred from Eskimo 1           |
| Large AGBS               | Compiled test results   | Inferred from 40 Tonne Trial     |
| Medium AGBS              | Compiled test results   | Correlated to 40 Tonne Trial     |
| Small AGBS               | Compiled test results   | Inferred from 40 Tonne Trial     |
| Medium Concrete Ops Bldg | Compiled test results   | Inferred from SciPan 1           |
| Small Concrete Ops Bldg  | Compiled test results   | SciPan 1                         |
| Large Ship               | Compiled test results   | Inferred from MPS test           |
| Medium Ship              | Compiled test results   | Inferred from MPS test           |
| Small Ship               | Compiled test results   | Inferred from MPS test           |
| ISO Containers           | Compiled test results   | Expert Opinion                   |

See the Pressure and Impulse Tech Memo (CE1-15800) for more details on the blast attenuation models and the Debris Tech Memo (CE1-15900) for further background on the PES debris models.

7. *Why were these activity types chosen?*

In 1997 when the probability of event task was undertaken, the RBESCT reviewed the DDESB accident database. The DDESB database used the activity types now in SAFER, to categorize the activity occurring when an accident occurred. The same activities are currently used in the Army maintained accident database ESMAM.

8. *Why were these ES types chosen?*

ES types were chosen to represent typical building construction and size. Previous consequence programs that modeled typical building types were consulted (e.g. BDAM, FACEDAP, and ERASDAC). Sizes were chosen to represent typical occupancies and uses. The highest priority for describing the building type in SAFER is the wall material (e.g. reinforced concrete, tilt-up reinforced concrete, wood frame, unreinforced masonry, pre-engineered metal). High priority was also placed on the size of the building. Most building types are provided with 3 floor area options (small = 2500 sf, medium = 10,000 sf, and large = 40,000 sf). An attempt was made to use the most typical roof construction for the type and size of building that was being modeled. Fifteen unique buildings and one automobile were chosen to represent the most common building types. Overall building response to overpressure is based on these unique building designs. See Reference 4 for a detailed description of the building types used in SAFER.

*9. What guidance is there for choosing ES types when the actual ES is unknown or not available as a choice?*

When the ES type is unknown or unavailable then typically weak or high-risk ES types should be evaluated and the worst case used to determine risk. Medium wood, large reinforced concrete, unreinforced masonry, and large metal building types should be considered in the evaluation unless it is known that the specific building type is not applicable. Because of its atypical strength, the small reinforced concrete building should only be chosen for a reinforced concrete building with a reinforced concrete roof. Also, because of its high risk, the large reinforced concrete building should only be used when the ES is known to be a tilt-up reinforced concrete structure.

*10. What are the ES models based on?*

The ES models are each based on specific designs. Structural damage, serious injury, and fatality are related to blast loads in P-I diagrams. The designs and procedures are described in Reference 4.

*11. What guidance is there for choosing ES roof types when the actual ES roof is unknown or not available as a choice?*

The selection of roof type will not affect the structural response fatality mechanism. Therefore, the user should select the closest match in terms of debris protection. If this cannot be easily determined, make multiple runs by varying the roof selection (between reasonable choices) and then use the one that produces the most conservative results.

*12. How were the methods for determining maximum/expected yields (by HD) derived?*

For HD 1.2, there is a reasonable amount of data upon which to base part of the yield uncertainty. For all of the following discussion, let  $N$  be the total number of rounds in the stack.

- a. HD 1.2 items are non-mass detonating when stored alone; based on this definition, no more than  $0.5 \cdot N$  can react at one time.
- b. Based on tests conducted for the 105 mm round, the average number of rounds participating in the total event is  $0.29 \cdot N$  (with a standard deviation of  $0.14 \cdot N$ ; N.B., this is based on 2,753 events).
- c. If it is assumed that the full output of an HD 1.2 round is  $Y$ , then the average yield for an HD 1.2 event is  $0.11 \cdot Y$  with a standard deviation of  $0.15 \cdot Y$  (based on 559 points), where  $Y$  represents full output.

Similar, hard information for accidental detonations involving only HD 1.1 is less common, although some anecdotal evidence available. At several accidents (Roseville & Benson) in the U.S. and a Russian accident at Severmorsk, the total number of rounds participating is not 100%, but something less (intact rounds have been thrown out). The opinion of the Science Panel based on experience is that the number participating for HD 1.1 might be  $0.9 \cdot N$ . When they do participate, the yield is generally high -- perhaps the yield is  $0.9 \cdot Y$ , where  $Y$  represents full output.

For mixed storage of HD 1.1 with HD 1.2 and HD 1.3, the amount participating probably drops to as low as  $0.8 \cdot N$ , based on the results of the MPS test and also the USS Mount Hood accident (1944). For the MPS test, the yield was  $0.6 \cdot Y$ .

*13. How were the TNT conversion factors determined?*

The equivalent weights that are assumed for each of the explosives are the same as those used in the Blast Effects Computer. An energetic material will have several equivalent weights—depending on the airblast parameter upon which the equivalence is determined. Usually, equivalences are reported for peak pressure and positive impulse and these two values may differ significantly. Moreover, the equivalence will vary with the range at which it is computed. The values used are based on peak pressure and are average values taken from numerous sources. Equivalent weights based on impulse are generally less than those based on peak pressure. Therefore, by using peak pressure values, a degree of conservatism is built into the impulse estimates.

## Attachment 4 – SAFER 3.1 Pressure and Impulse Branch

## **SAFER 3.1 Pressure and Impulse Branch**

*Prepared by – John Tatom (APT)*

*Mike Swisdak (NSWC)*

*Revision Date – May 2009*

### **PURPOSE**

This memorandum addresses major technical and analytical decisions made as part of the SAFER 3.1 pressure and impulse branch. Specific questions addressed are:

1. Why were simplified Kingery-Bulmash equations used?
2. Have the open-air pressure and impulse predictions been validated?
3. Why is no adjustment made for open, PEMB, or HCT?
4. Why are orientation effects not considered for PES types other than ECM and HAS?
5. Why are weapon effects on pressure and impulse not considered if a PES is present?
6. Why are some pressure and impulse predictions higher when buildings are present as opposed to open-air predictions?
7. Have the adjusted (due to the presence of the PES) pressure and impulse predictions been validated?
8. How was the PES damage/intact algorithm derived?
9. How were the  $Y_0$ ,  $Y_{100}$ , and  $b$  parameters chosen?
10. What is the pressure and impulse reduction (due to the ES) based on?
11. How was the average venting area percentage chosen?
12. Why is the percent glass involved in the pressure and impulse reduction (due to the ES) calculation?
13. Why do the parameters in the pressure and impulse reduction (due to the ES) calculation not vary by ES type?
14. Why isn't reflected impulse considered?
15. How does the SAFER 3.1 method for determining fatality due to whole body displacement differ from the TNO probit function for that consequence?
16. Why does the SAFER 3.1 method for determining fatality due to whole body displacement differ from the TNO probit function for that consequence?
17. How does the SAFER 3.1 method for determining fatality due to lung rupture differ from the TNO probit function for that consequence?
18. Why does the SAFER 3.1 method for determining fatality due to lung rupture differ from the TNO probit function for that consequence?
19. How does the SAFER 3.1 method for determining fatality due to skull fracture differ from the TNO probit function for that consequence?
20. Why does the SAFER 3.1 method for determining fatality due to skull fracture differ from the TNO probit function for that consequence?
21. Does the SAFER 3.1 method for determining fatality due to whole body displacement treat people in the open differently than people inside structures?
22. Does the SAFER 3.1 method for determining fatality due to lung rupture treat people in the open differently than people inside structures?
23. Does the SAFER 3.1 method for determining fatality due to skull fracture treat people in the open differently than people inside structures?

24. *Why are the fatalities due to whole body displacement, lung rupture, and skull fracture considered (and summed) independently?*

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## DISCUSSIONS

1. *Why were simplified Kingery-Bulmash equations used?*

The complete Kingery-Bulmash (ref 1) curves/equations were considered to be too complex to include in SAFER, given that the simplified equations produce results within 2%. Also, the simplified equations were used in the Blast Effects Computer (ref 2), with which SAFER is intended to be in agreement with. The simplified Kingery-Bulmash equations are widely accepted and have been corroborated by numerous tests.

2. *Have the open-air pressure and impulse predictions been validated?*

Yes. Figures 1-5 show a comparison between SAFER output and data for the following weapons detonated in the open (NB: These data are taken from Reference 2):

- MK 82, MK 83, and MK 84 bombs
- M107 155-mm projectiles
- WAU-17 warhead

Comparisons are not shown for two weapons: M1 105-mm projectile and MK 2 40-mm projectile. The data for these two items were derived using the methodologies of Reference 3; therefore, there is insufficient test data for these two items.

The algorithms in the Blast Effects Computer and thus in SAFER are generally based upon and derived from empirical data. The algorithms were selected to “match” the empirically predicted pressures and impulses within a few percent (generally less than 5%).

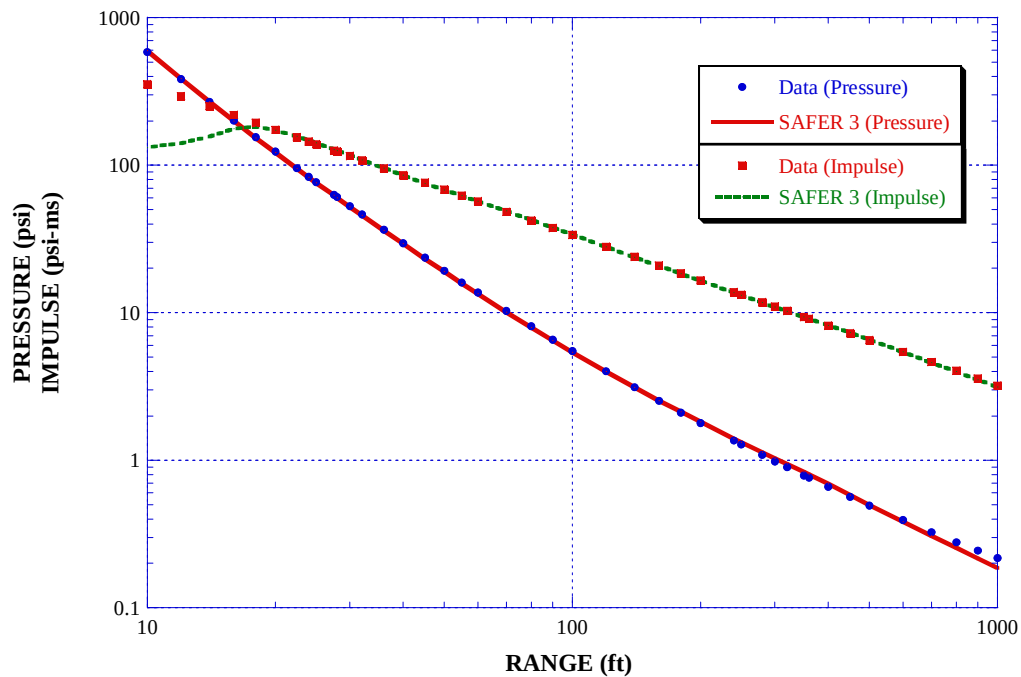


Figure 1. MK 82 Bomb



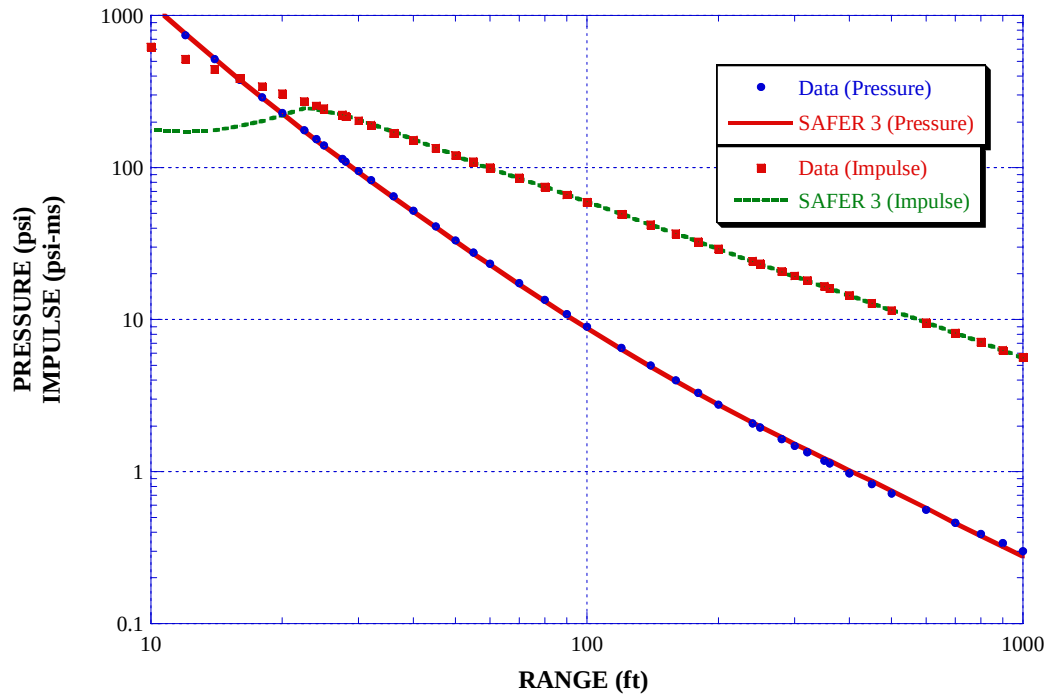


Figure 2. MK 83 Bomb

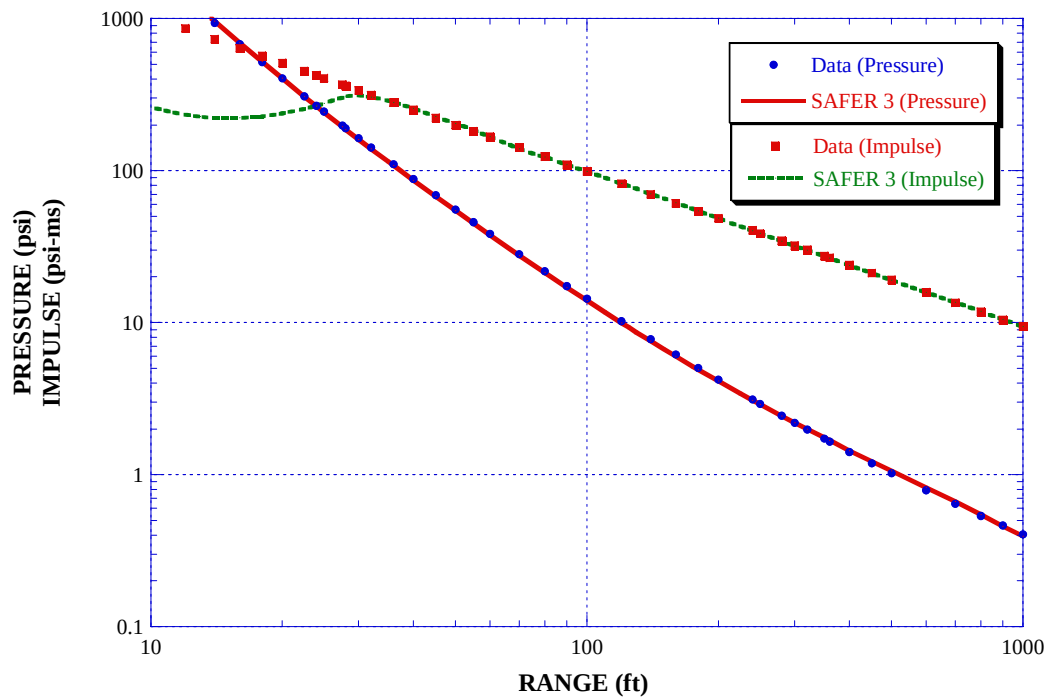


Figure 3. MK 84 Bomb

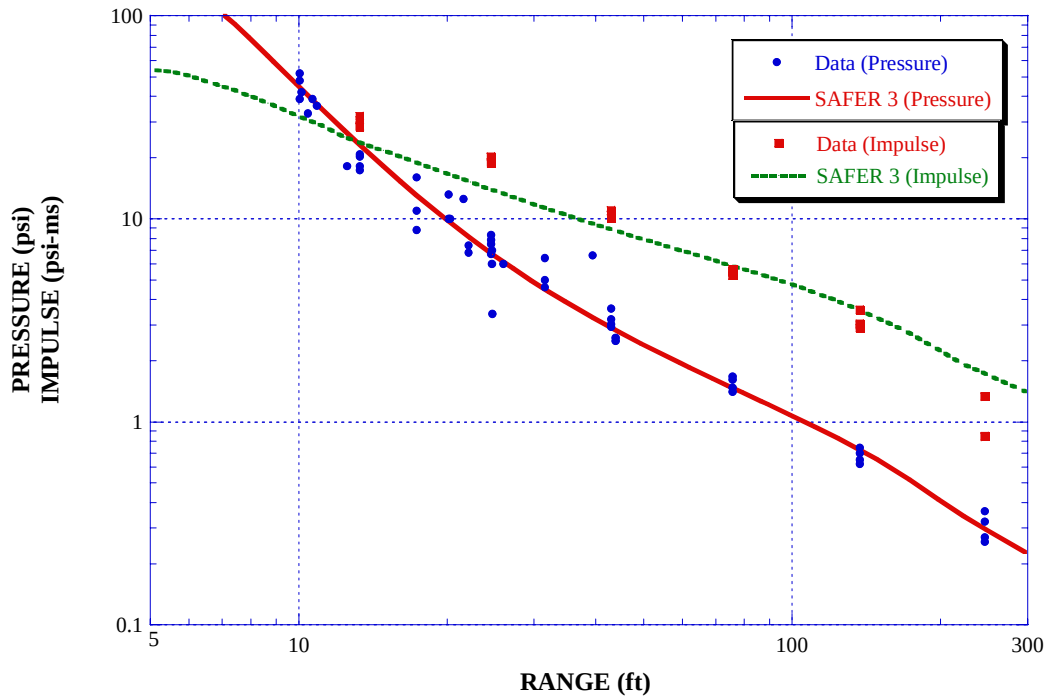


Figure 4. M107 155 mm Projectile

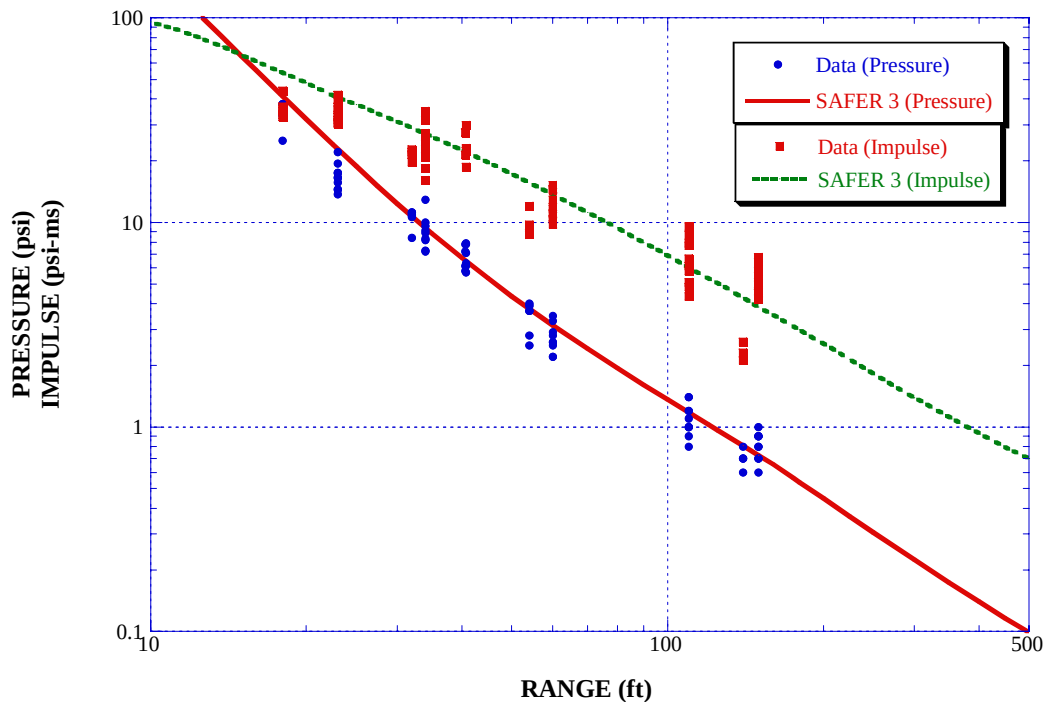


Figure 5. WAU-17 Warhead

### 3. Why is no adjustment made for open, PEMB, or HCT?

There is no adjustment made to consider the effects of the presence of the PES if there is no PES structure, or if that structure is so light as to be treated as if there were no containment effects. This is the case for pre-engineered metal buildings and hollow clay

tile PES types. The secondary debris from these buildings is still considered; thus the absence of an adjustment (for a building without orientation) is conservative.

4. *Why are orientation effects not considered for PES types other than ECM and HAS?*

The “focusing” or “channeling” of pressure and impulse is based on test data. At this time, the only comprehensive data sets available are for earth-covered magazines and hardened aircraft shelters. Furthermore, PES types that have a square footprint (such as above-ground brick structures and operating buildings in SAFER) would not be expected to have orientation effects unless asymmetrical venting conditions were present.

5. *Why are weapon effects on pressure and impulse not considered if a PES is present?*

As part of a study performed for the DDESB in 1995 (ref 4), it was found that type of weapon and/or type of explosive had no effect on reducing the scatter in the observed data. The only variable that seemed to have an effect was the total weight of energetic material.

6. *Why are some pressure and impulse predictions higher when buildings are present as opposed to open-air predictions?*

This is due to “focusing” or “channeling” of pressure and impulse.

7. *Have the adjusted (due to the presence of the PES) pressure and impulse predictions been validated?*

Yes, see Figures 6-13 taken from Reference 2.

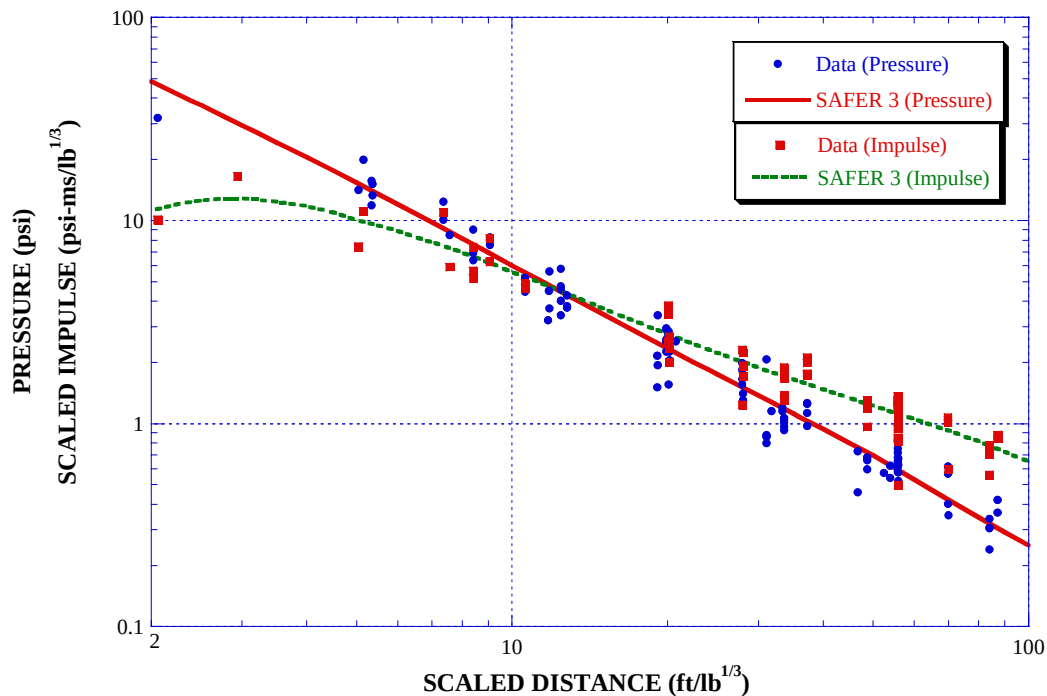


Figure 6. Aboveground Structure)

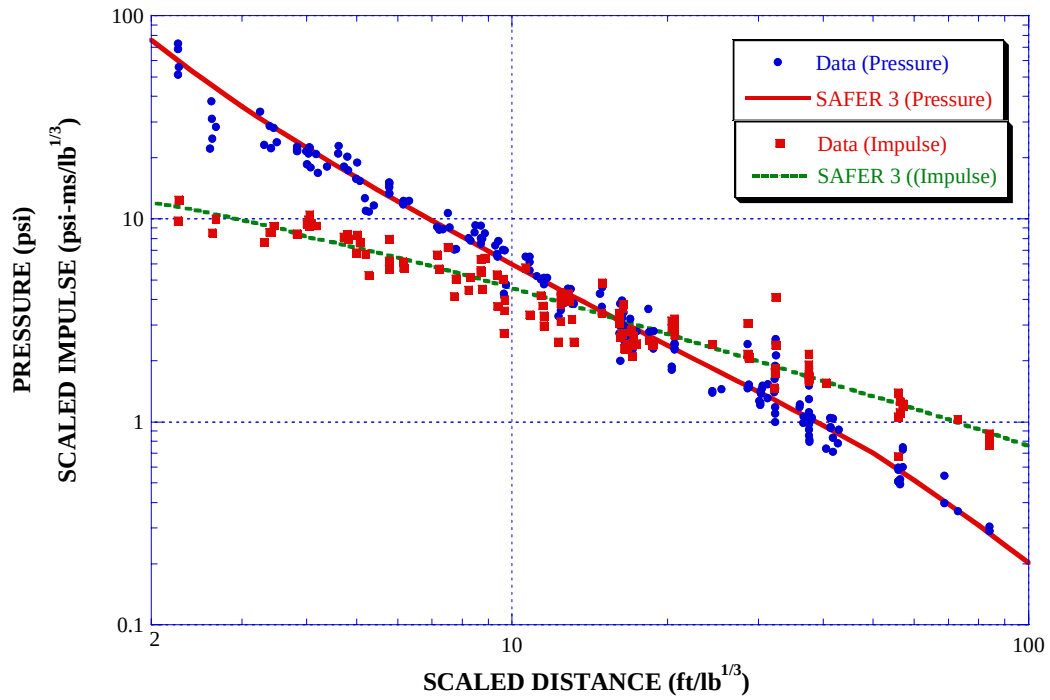


Figure 7. ISO Container & Ship

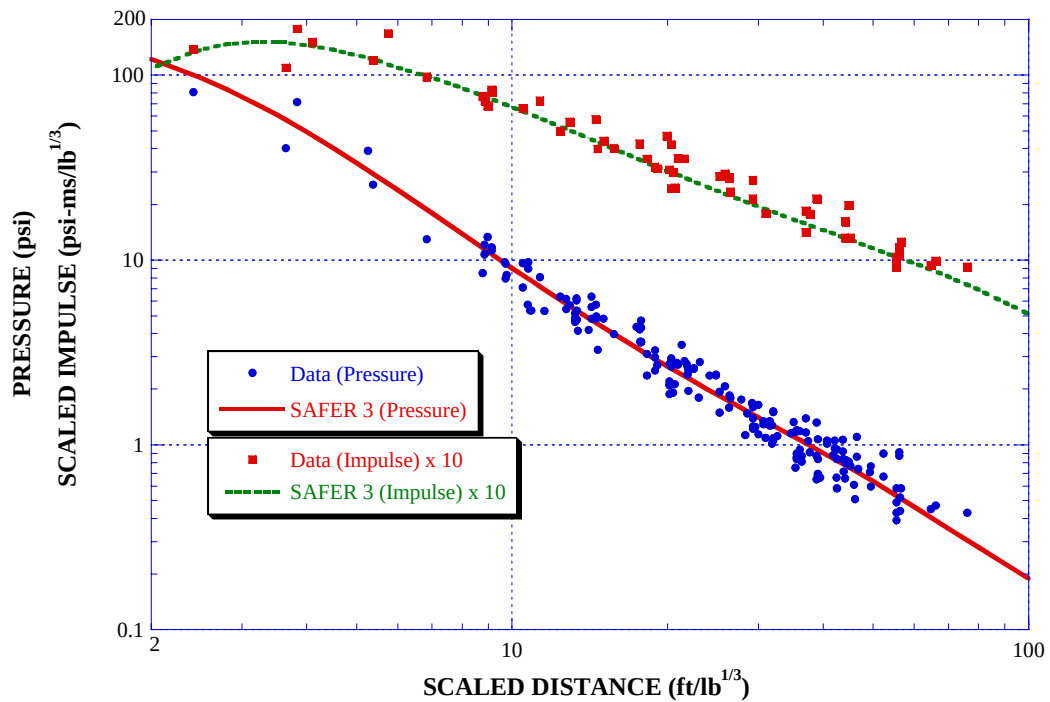


Figure 8. ECM Front

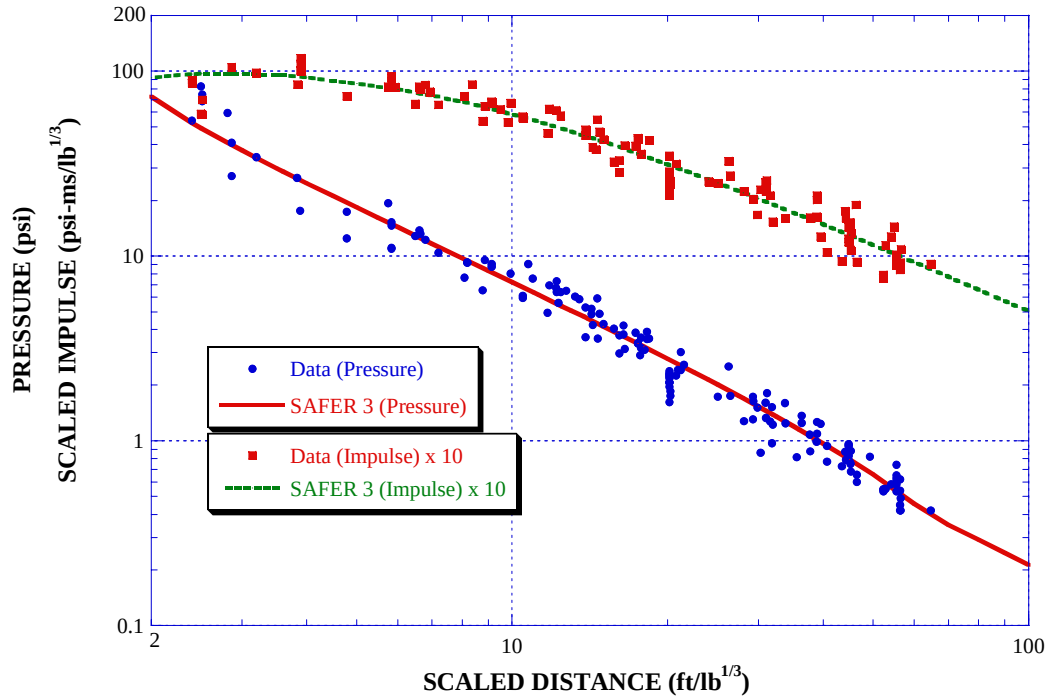


Figure 9. ECM Side

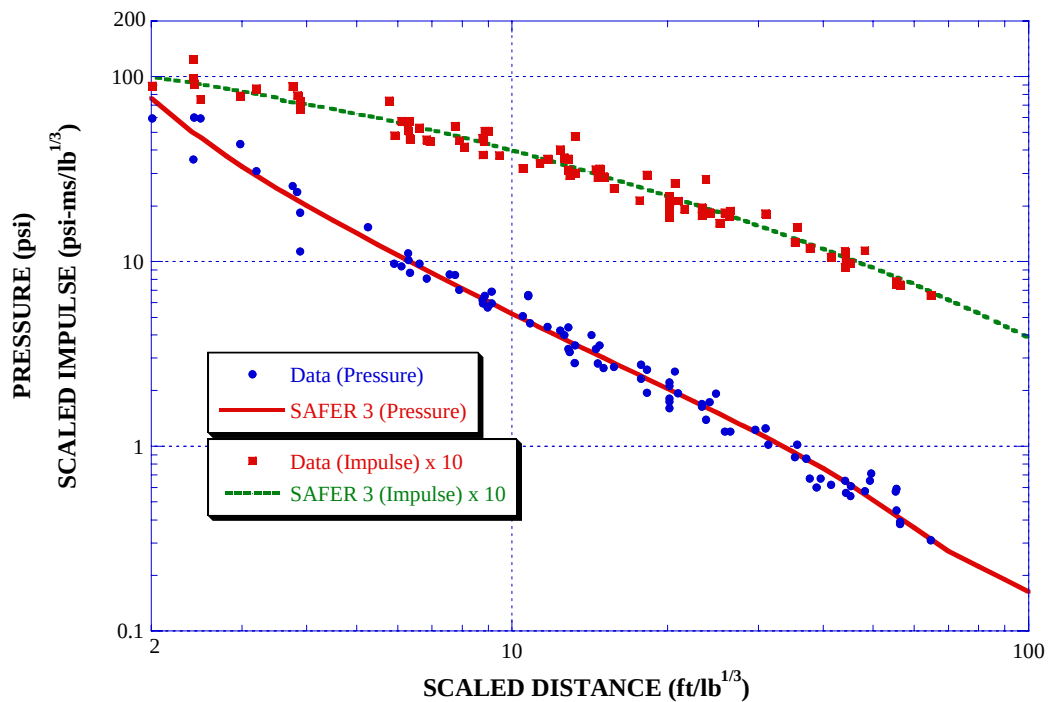


Figure 10. ECM Rear

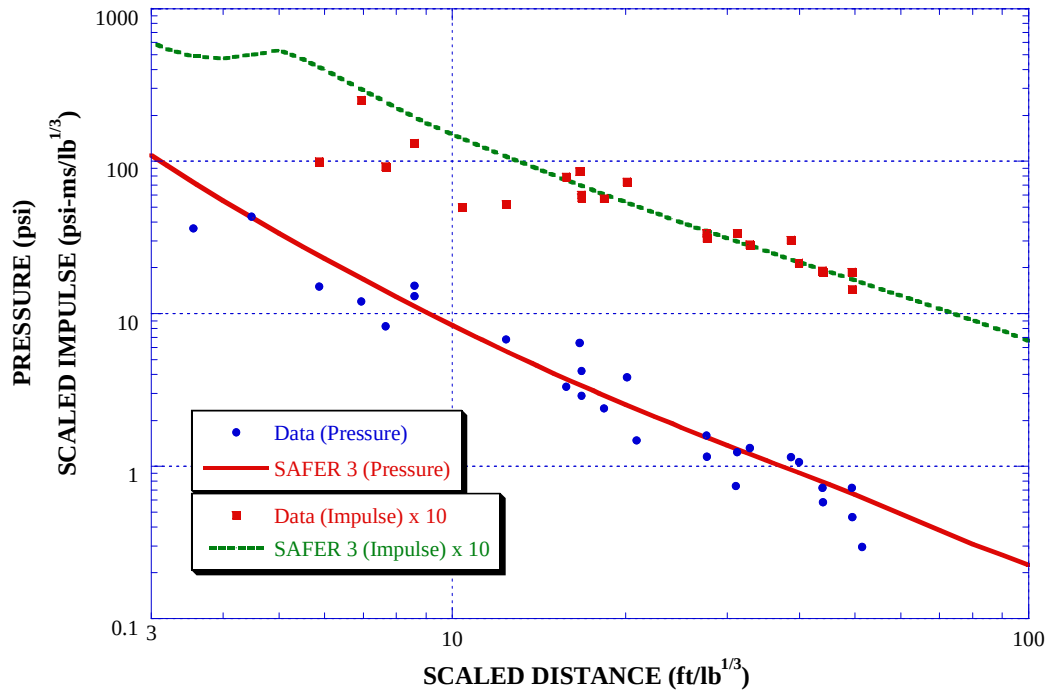


Figure 11. HAS Front

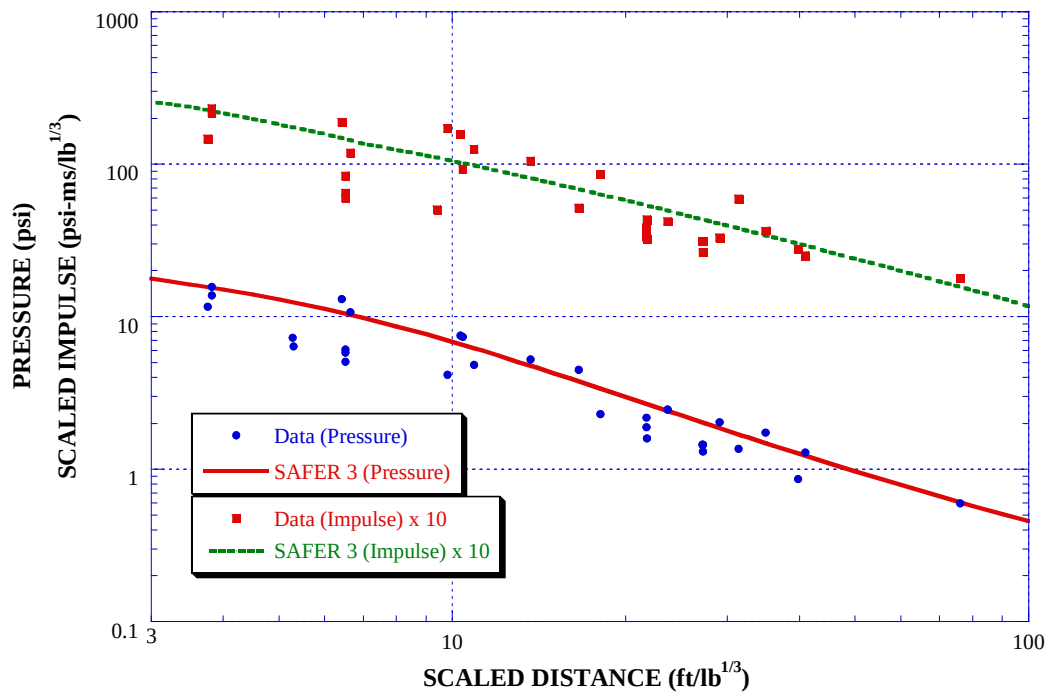


Figure 12. HAS Side

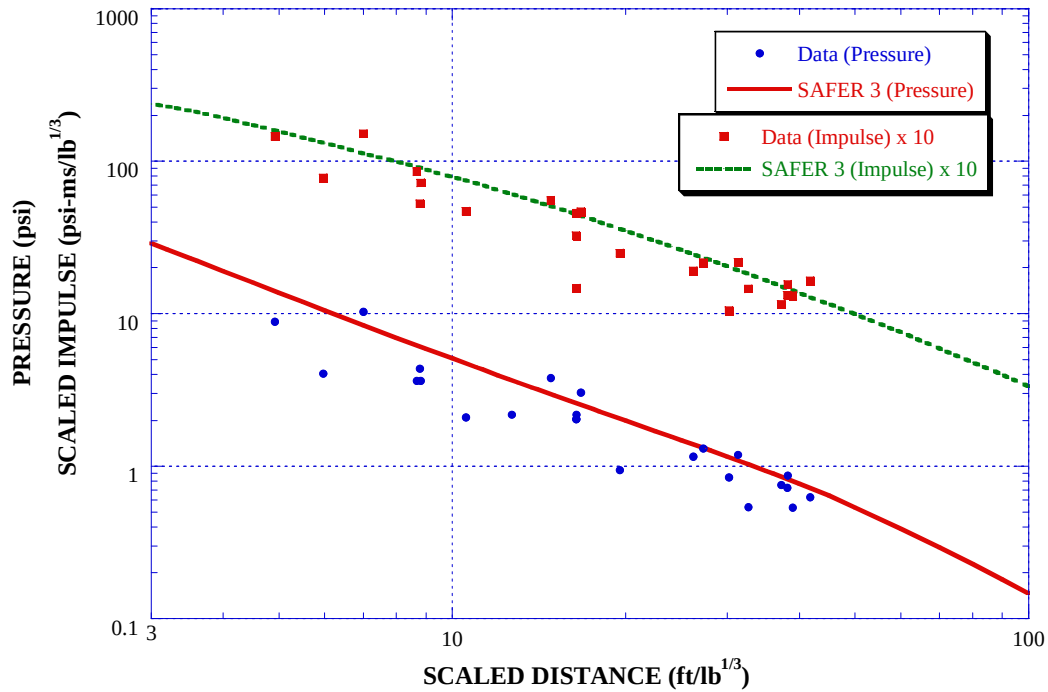


Figure 13. HAS Rear

#### 8. How was the PES damage/intact algorithm derived?

The main reason for calculating the PES damage is to be able to determine the amount of PES mass in the air – in other words, secondary debris. In SAFER 3.1, this is done by analyzing the damage to four components of the PES: roof, front wall, side walls, and rear wall. The algorithm needed to be able to determine at what point any mass from a PES component became secondary debris, at what point the entire component becomes secondary debris, and what happens in between these two points. The Science Panel created an algorithm based on three parameters ( $Y_0$ ,  $Y_{100}$ , and  $b$ ) for each PES type and component, as shown in Figure 14.

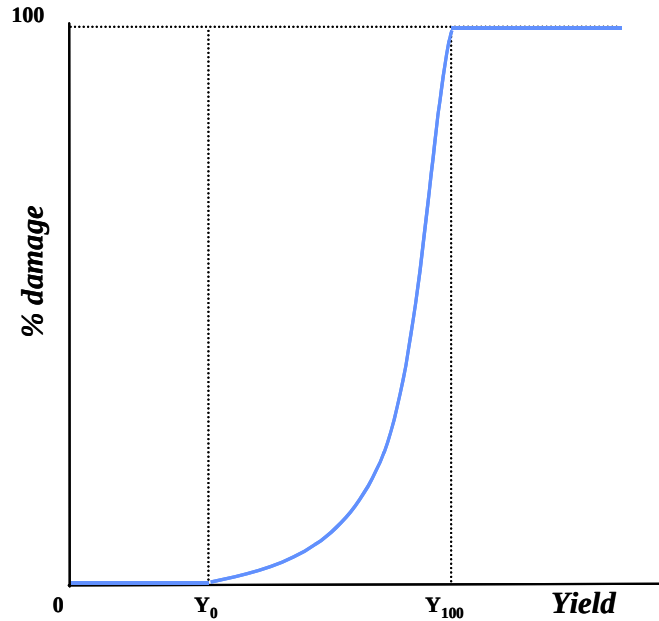


Figure 14. PES Damage Function

The curve is represented by the equation

$$PES_{damage(i)} = a * (W_2 - Y_0)^b$$

where  $a = 1/(Y_{100} - Y_0)^b$ ,  $W_2$  = Equivalent NEW (lbs), [from Step 4], and the constants  $Y_0$ ,  $Y_{100}$ , and  $b$  are provided in the appropriate table for the PES component: Table 1, Damage Coefficients for the PES Roof; Table 2, Damage Coefficients for the PES Front Wall; Table 3, Damage Coefficients for the PES Side Walls; Table 4, Damage Coefficients for the PES Rear Wall. Coefficients in the tables are based on the PES building type and were chosen to predict failure at conservative loads.

Table 1. Percent Damage Coefficients for the PES Roof

| PES (roof)                    | $Y_0$ [lbs] | $Y_{100}$ [lbs] | $b$  |
|-------------------------------|-------------|-----------------|------|
| Pre-engineered metal building | 3           | 40              | 0.4  |
| Earth-covered magazine        | 15          | 250             | 1.0  |
| Hardened aircraft shelter     | 1000        | 2000            | 0.9  |
| Aboveground brick structure   | 1           | 16              | 0.5  |
| Operating building            | 1           | 16              | 0.5  |
| Hollow Clay Tile              | 1           | 8               | 0.25 |
| Ship (small)                  | 100         | 5000            | 1.1  |
| Ship (medium)                 | 100         | 5000            | 1.1  |
| Ship (large)                  | 100         | 5000            | 1.1  |



Table 2. Percent Damage Coefficients for the PES Front Wall

| PES (front wall)              | $Y_0$ [lbs] | $Y_{100}$ [lbs] | b    |
|-------------------------------|-------------|-----------------|------|
| Pre-engineered metal building | 3           | 40              | 0.4  |
| Earth-covered magazine        | .5          | 10              | 0.6  |
| Hardened aircraft shelter     | 40          | 2000            | 0.9  |
| Aboveground brick structure   | 1           | 8               | 0.25 |
| Operating building            | 3           | 100             | 0.4  |
| Hollow Clay Tile              | 1           | 8               | 0.25 |
| Ship (small)                  | 100         | 5000            | 1.1  |
| Ship (medium)                 | 100         | 5000            | 1.1  |
| Ship (large)                  | 100         | 5000            | 1.1  |

Table 3. Percent Damage Coefficients for the PES Side Walls

| PES (side walls)              | $Y_0$ [lbs] | $Y_{100}$ [lbs] | b    |
|-------------------------------|-------------|-----------------|------|
| Pre-engineered metal building | 1           | 40              | 0.4  |
| Earth-covered magazine        | 2000        | 10000           | 0.9  |
| Hardened aircraft shelter     | 1000        | 2000            | 0.9  |
| Aboveground brick structure   | 1           | 8               | 0.25 |
| Operating building            | 3           | 100             | 0.4  |
| Hollow Clay Tile              | 1           | 8               | 0.25 |
| Ship (small)                  | 100         | 5000            | 1.1  |
| Ship (medium)                 | 100         | 5000            | 1.1  |
| Ship (large)                  | 100         | 5000            | 1.1  |

Table 4. Percent Damage Coefficients for the PES Rear Wall

| PES (rear walls)              | $Y_0$ [lbs] | $Y_{100}$ [lbs] | b    |
|-------------------------------|-------------|-----------------|------|
| Pre-engineered metal building | 1           | 40              | 0.4  |
| Earth-covered magazine        | 2000        | 10000           | 0.9  |
| Hardened aircraft shelter     | 2000        | 10000           | 0.9  |
| Aboveground brick structure   | 1           | 8               | 0.25 |
| Operating building            | 3           | 100             | 0.4  |
| Hollow Clay Tile              | 1           | 8               | 0.25 |
| Ship (small)                  | 100         | 7500            | 1.1  |
| Ship (medium)                 | 100         | 7500            | 1.1  |
| Ship (large)                  | 100         | 7500            | 1.1  |

9. How were the  $Y_0$ ,  $Y_{100}$ , and b parameters chosen?

The parameters used in the determination of PES component damage were determined based on test data, partially-confined internal loads and structural analysis, and Science Panel expert opinion. Values for the buildings were based on conservative calculations for internal loads and structural loads in representative PES building designs.

10. What is the pressure and impulse reduction (due to the ES) based on?

The protection afforded by the ES against direct pressure and impulse effects is based on techniques found in TM5-1300, Section 2-15.5 (ref 5), and was compared to test data (ref 6) and compared to another computer model, BlastX (ref 7).

*11. How was the average venting area percentage chosen?*

The value of 2.5% was chosen for all ES types based on expert opinion of the Science Panel. This value is intended to represent vents, ducts, pipes, doorway “leakage”, etc. – essentially all openings other than windows.

*12. Why is the percent glass involved in the pressure and impulse reduction (due to the ES) calculation?*

It is assumed that the windows of a building provide no reduction in pressure and impulse, so the nominal venting area of the ES is combined with the percent glass of the ES to determine the total venting area of the ES.

*13. Why do the parameters in the pressure and impulse reduction (due to the ES) calculation not vary by ES type?*

At the time the algorithms were created, there was no available test data or other basis to determine parameter variations among ES types. However, it was assumed that such variations might well exist. Therefore, the values were left in the form of a parameter table so that eventually such variations could be introduced by simply changing the parameter value.

*14. Why isn't reflected impulse considered?*

It was not clear to the Science Panel how the term “reflected impulse” would be defined or derived and then used in conjunction with reflected pressure. The term was not expressly called for in the TNO literature (ref 8,9), either.

*15. How does the SAFER 3.1 method for determining fatality due to whole body displacement differ from the TNO probit function (ref 8,9) for that consequence?*

After determining the S and z values, SAFER uses a normal distribution rather than a probit function to determine fatality levels.

*16. Why does the SAFER 3.1 method for determining fatality due to whole body displacement differ from the TNO probit function (ref 8,9) for that consequence?*

SAFER requires higher fidelity than the probit function was designed for, especially at the extreme low end.

*17. How does the SAFER 3.1 method for determining fatality due to lung rupture differ from the TNO probit function (ref 8,9) for that consequence?*

After determining the S and z values, SAFER uses a normal distribution rather than a probit function to determine fatality levels.

*18. Why does the SAFER 3.1 method for determining fatality due to lung rupture differ from the TNO probit function (ref 8,9) for that consequence?*

SAFER requires higher fidelity than the probit function was designed for, especially at the extreme low end.

*19. How does the SAFER 3.1 method for determining fatality due to skull fracture differ from the TNO probit function (ref 8,9) for that consequence?*

After determining the S and z values, SAFER uses a normal distribution rather than a probit function to determine fatality levels.

20. *Why does the SAFER 3.1 method for determining fatality due to skull fracture differ from the TNO probit function (ref 8,9) for that consequence?*

SAFER requires higher fidelity than the probit function was designed for, especially at the extreme low end.

21. *Does the SAFER 3.1 method for determining fatality due to whole body displacement treat people in the open differently than people inside structures?*

No, except that there will be no pressure and impulse reduction in Step 7 if there is no ES and the nominal pressure will be determined differently (as described in Tech Paper 14). This forces the conservative assumption that people in the open are near trees, sidewalks, benches, tables, etc. – something that could cause blunt trauma wounds.

22. *Does the SAFER 3.1 method for determining fatality due to lung rupture treat people in the open differently than people inside structures?*

No, except that there will be no pressure and impulse reduction in Step 7 if there is no ES and the nominal pressure will be determined differently (as described in Tech Paper 14).

23. *Does the SAFER 3.1 method for determining fatality due to skull fracture treat people in the open differently than people inside structures?*

No, except that there will be no pressure and impulse reduction in Step 7 if there is no ES and the nominal pressure will be determined differently (as described in Tech Paper 14). This forces the conservative assumption that people in the open are near trees, sidewalks, benches, tables, etc. – something that could cause blunt trauma wounds.

24. *Why are the fatalities due to whole body displacement, lung rupture, and skull fracture considered (and summed) independently?*

The separate mechanisms are considered independently to avoid double-counting of fatalities.

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## Attachment 5 - Injury

## PURPOSE

This memorandum addresses the rationale and development of the injury algorithms in SAFER 3.1.

Specific questions include:

1. What is the best technique for classifying injuries?
2. Is the AIS method widely accepted?
3. Is a more applicable method available?
4. Are there subjectivity issues associated with "hospitalization" that might prevent a fair comparison of the results from a predictive tool (such as SAFER) to real world data?
5. How does SAFER sequence the calculation/accounting of mechanisms and conditions?
6. How does SAFER account for multiple injuries from the same mechanism?
7. How does SAFER account for injuries from multiple mechanisms?
8. Does SAFER consider someone injured by one mechanism more susceptible to an injury from a different mechanism?
9. How does SAFER account for injuries from all mechanisms?
10. Should you report this condition and greater, or this condition and not greater?
11. What does SAFER calculate and report: The number of people injured or the number of injuries?
12. How is a major injury defined?
13. How is a minor injury defined?
14. What are the sources for the injury models in SAFER?
15. How does SAFER add insult to injury?

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8. Briefings to RBESCT

## DISCUSSION

### 1. *What is the best technique for classifying injuries?*

The RBESCT decided to classify injuries based on AIS (Abbreviated Injury Scale) level (ref 1, 2).

| AIS Level | Severity                | Type of Injury                                               |
|-----------|-------------------------|--------------------------------------------------------------|
| 0         | None                    | None                                                         |
| 1         | Minor                   | Superficial                                                  |
| 2         | Moderate                | Reversible, Medical Attention Required                       |
| 3         | Serious                 | Reversible, Hospitalization Required                         |
| 4         | Severe                  | Life-threatening, Not fully recoverable with Medical Care    |
| 5         | Critical                | Non-reversible, Not fully recoverable even with Medical Care |
| 6         | Virtually Un-survivable | Fatal                                                        |

### 2. *Is the AIS method widely accepted?*

The method seems to be used by many in risk analysis efforts, but medical professionals do not necessarily commonly use it.

### 3. *Is a more applicable method available?*

None has been found.

### 4. *Are there subjectivity issues associated with "hospitalization" that might prevent a fair comparison of the results from a predictive tool (such as SAFER) to real world data?*

Yes, but that is to be expected. SAFER is expected to represent generic rather than specific situations.

### 5. *How does SAFER sequence the calculation/accounting of mechanisms and conditions?*

SAFER considers fatalities from all mechanisms before considering injuries. Similarly, SAFER determines all major injuries before considering minor injuries (ref 1).

### 6. *How does SAFER account for multiple injuries from the same mechanism?*

SAFER counts multiple injuries from a single mechanism to an individual as a single injury (ref 1).

### 7. *How does SAFER account for injuries from multiple mechanisms?*

SAFER counts injuries from a multiple mechanisms to an individual as a single injury (i.e., considers only the most severe injury from any mechanism)(ref 1).

### 8. *Does SAFER consider someone injured by one mechanism more susceptible to an injury from a different mechanism?*

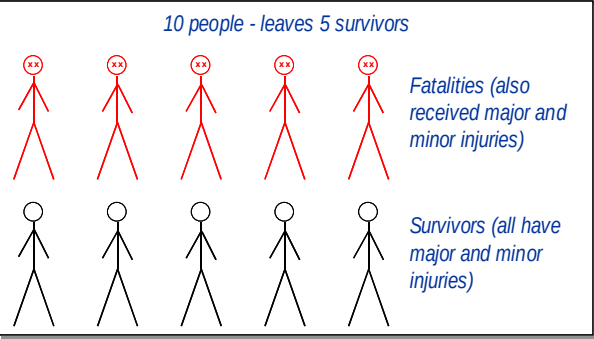
No, SAFER considers each mechanism independently and then reports only the most severe single injury (ref 1).

9. *How does SAFER account for injuries from all mechanisms?*

SAFER does not “accumulate” injuries; i.e., some number of minor injuries does not equate to a major injury (ref 1).

10. *Does SAFER report (A) This condition and greater, or (B) This condition and not greater?*

Example: An ES has 10 people in it. Assume an event leaves 5 survivors, all of whom have major injuries. Should the results be reported as A or B?

|                                          | A         | B        |  |
|------------------------------------------|-----------|----------|------------------------------------------------------------------------------------|
| <b>Expected number of fatalities</b>     | <b>5</b>  | <b>5</b> |                                                                                    |
| <b>Expected number of major injuries</b> | <b>10</b> | <b>5</b> |                                                                                    |
| <b>Expected number of minor injuries</b> | <b>10</b> | <b>0</b> |                                                                                    |

SAFER reports (B) (ref 1).

11. *What does SAFER calculate and report: The number of people injured or the number of injuries?*

SAFER may calculate more than one injury for a given person; however, it only reports the number of people injured (ref 1).

12. *How is a major injury defined?*

In SAFER, a major injury is AIS Level 3 or 4. This can be thought of as an injury requiring admittance to the hospital. (Note: AIS Levels 5 and 6 are considered a fatality by SAFER.)

13. *How is a minor injury defined?*

In SAFER, a minor injury is AIS Level 1 or 2. This injury level can include emergency room treatment, but not admittance to the hospital.

14. *What are the sources for the injury models in SAFER?*

The Science Panel reviewed existing injury models (when possible) and adapted them for use in SAFER (ref 3). Depending on the source and nature of the existing model, varying degrees of model modification was required. Some significant model sources include the DIRE software program (ref 4, 5), ACTA work (ref 6), and published UK MoD papers (ref 7).

15. *How does SAFER add insult to injury?*

SAFER does not add insult to injury. SAFER is a follower of the principle: “Rebar and stones may break my bones, but words can never hurt me!”



## Attachment 6 - Glass

**PURPOSE**

This memorandum addresses major technical and analytical decisions made as part of the SAFER 3.1 glass methodology. Specific questions addressed are:

1. How/why is the SAFER 3.1 method different from the GLASS-CF method?
2. What assumptions are made about window coverings (blinds, curtains, drapes, etc.)?
3. What is the PWHFA and why are the corner areas “double-counted” in the hazard area calculation?
4. How was the perimeter distance chosen?
5. How were the parameters associated with the serious injury as a function of glass breakage derived?
6. Why is the yield adjustment made?
7. How were the parameters associated with the yield adjustment derived?
8. How was the relationship between fatality and serious injury determined?
9. What assumptions are made about emergency response?
10. Why are medium windows used rather than having a user-selectable size?
11. What are the assumptions on the dimensions of the window?
12. Can SAFER distinguish between the following cases?
  - a. Case 1: An event with a yield and distance that generates 100% glass breakage
  - b. Case 2: An event with a higher yield than Case 1 but the same distance
  - c. Case 3: An event with the same yield as Case 1 but a lesser distance
13. What is the “beyond 100% breakage” algorithm and what is it based on?
14. Why not use an impulse-based algorithm for all cases?
15. Is there a transition region where answers “jump” when the “beyond 100% breakage” algorithm is used?

**REFERENCES**

1. “Blast Damage, Serious Injury and Fatality Models for Structures and Windows.” Chrostowski, Jon D., Wilde, Paul D., Gan, Wenshiu. ACTA Report, March 2001.
2. Briefings to RBESCT

**DISCUSSIONS**

1. *How/why is the SAFER 3.1 method different from the GLASS-CF (ref 1) method?*

The glass model in SAFER is intended to allow the introduction of additional data sets as they become available. However, the primary data set currently relied on is the output of the GLASS-CF model. The SAFER model is more generic than the GLASS-CF model, based on the assumption that the SAFER user will generally not know the design specifics of the windows in the ES buildings involved in the SAFER run.

2. *What assumptions are made about window coverings (blinds, curtains, drapes, etc.)?*

No direct factor is used to represent window coverings in SAFER 3.1. However, the methodology beyond K24 is based on models that assume approximately 50% of windows are protected by coverings of some type. Inside K12, SAFER considers window coverings to have no glass hazard mitigation capability. Between K24 and K12, the window protection is gradually removed (see Equations 79 & 80 in Technical Paper 14).

3. *What is the PWHFA and why are the corner areas “double-counted” in the hazard area calculation?*

The potential window hazard floor area (PWHFA) represents the portion of the ES floor that would be hazarded by glass fragments. The corner areas are double-counted intentionally because the windows on more than one wall could affect those regions.

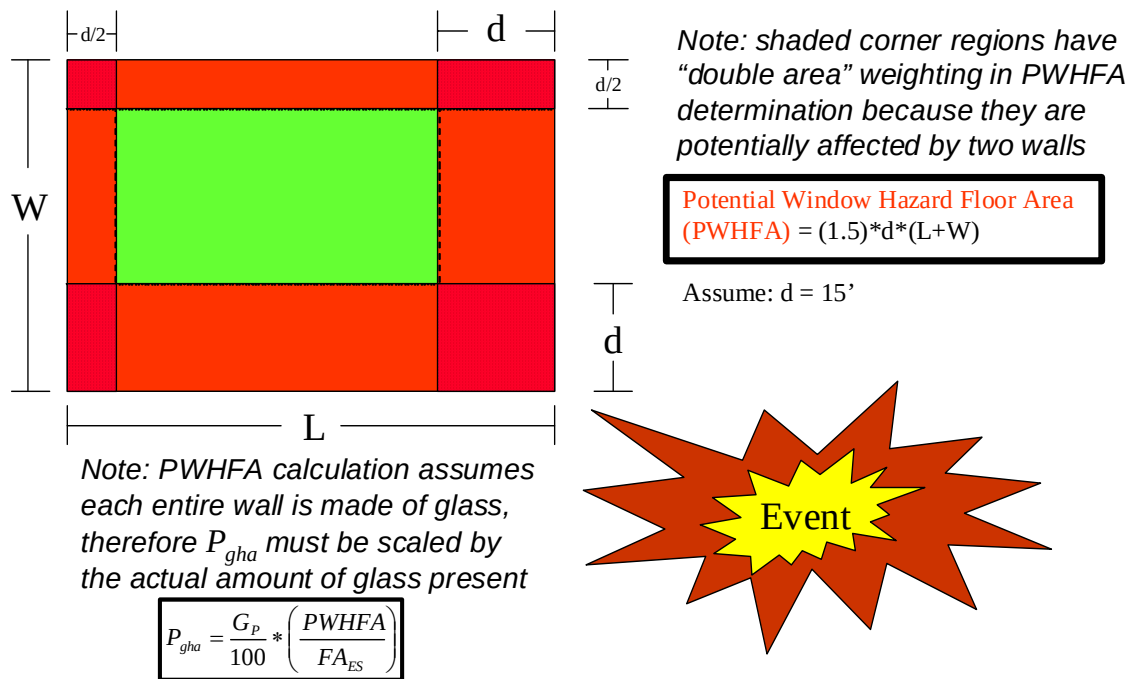


Figure 1. Glass Methodology

4. *How was the perimeter distance chosen?*

The perimeter distance was set to 15 feet, which was intended to represent different buildings with varying floor areas. This value was chosen based on an initial assessment of typical buildings and available literature on a conservative average distance to the nearest interior wall.

5. *How were the parameters associated with the serious injury as a function of glass breakage derived?*

The Science Panel used pressure-impulse diagrams for both glass breakage (Figures 2-4) and serious injury to create an equation for serious injury as a function of glass breakage.

After all the test points had been plotted, the Science Panel created a curve to match the data, as shown in Figure 5. This curve is then represented in SAFER by the stored parameters.

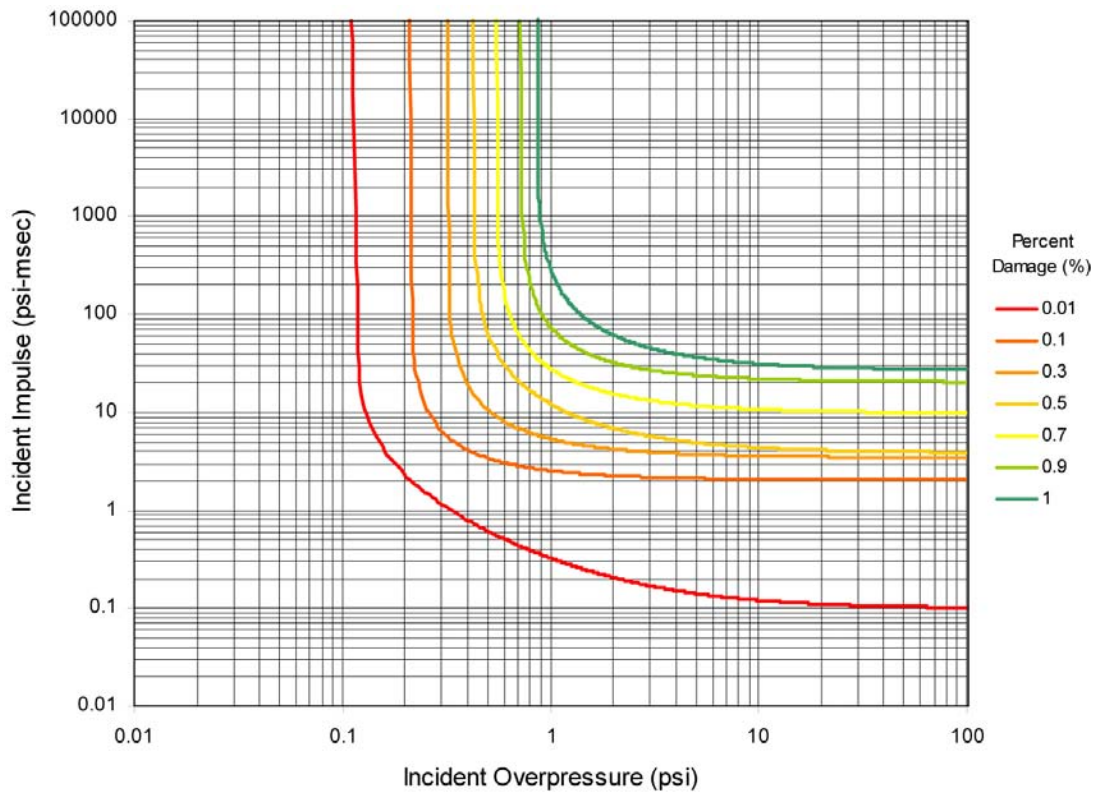


Figure 2. Annealed

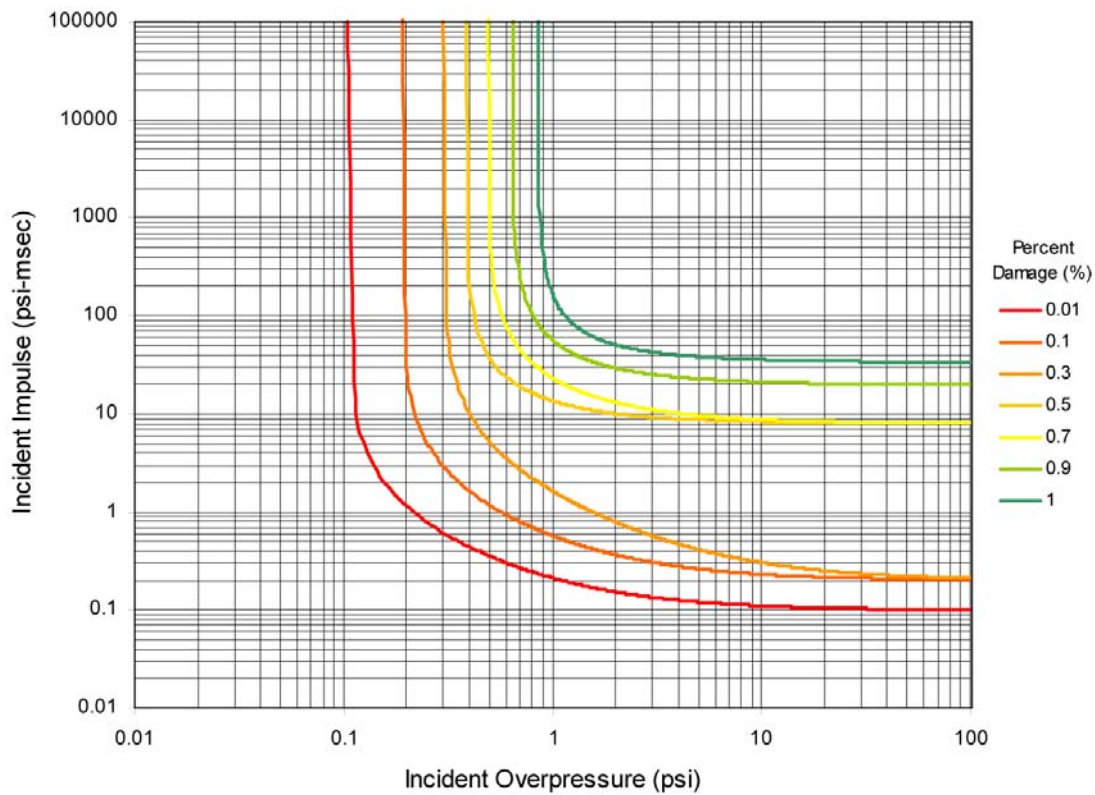


Figure 3. Dual Pane

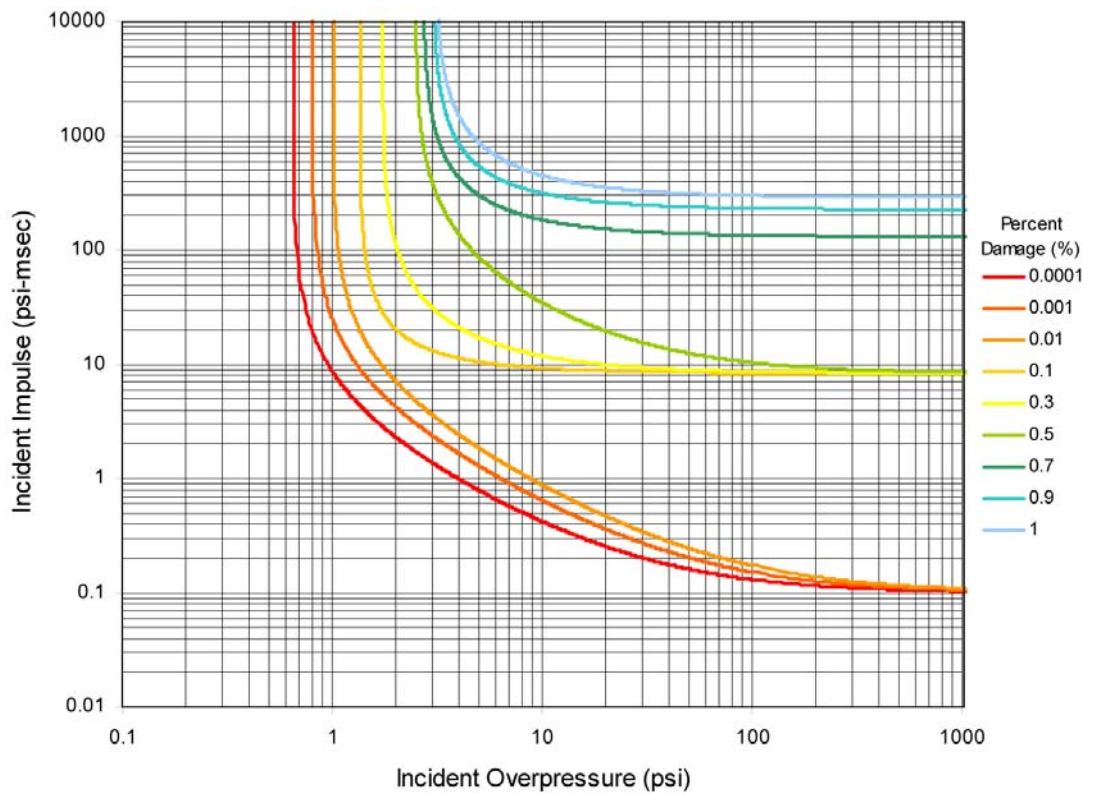
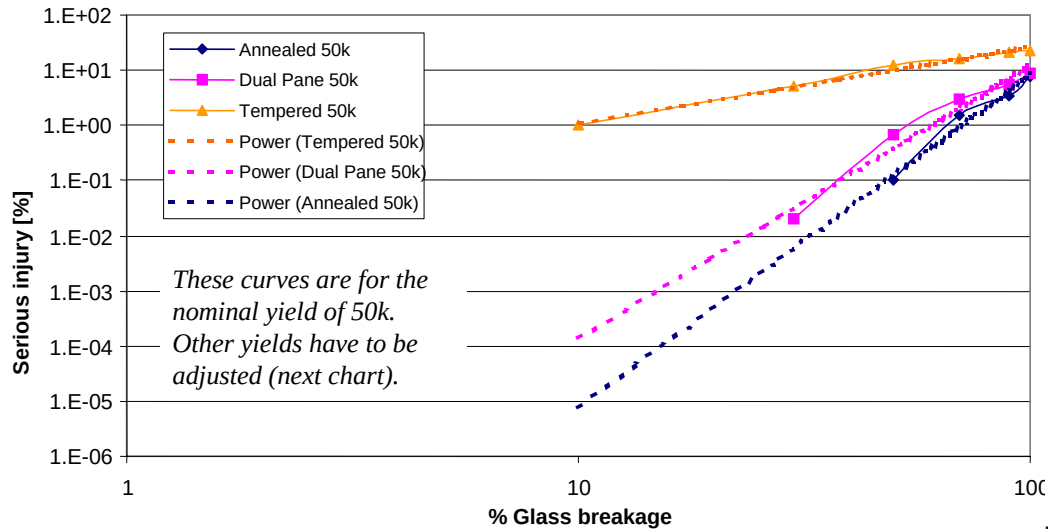


Figure 4. Tempered



Note: Solid lines are data points from the Wilde model. Dashed lines represent the SAFER 3.1 equations.

Figure 5. Serious Injury Given Breakage

#### 6. Why is the yield adjustment made?

The model prediction data used by the Science Panel (see Question 5) are yield dependant. The yield is not known until run-time, therefore a dynamic yield adjustment function needed to be created. The baseline curve used data points associated with a 50,000 lb yield, so the yield adjustment is made based on the ratio of the actual run yield to the baseline (or nominal) yield. The yield dependency can be seen in Figure 6.

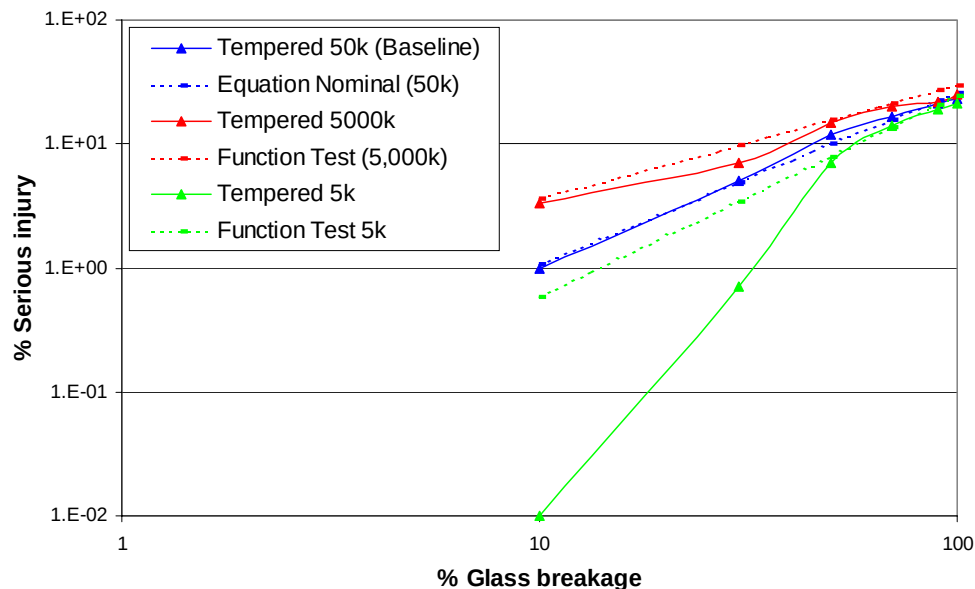


Figure 6. Yield Adjustment Test @ 5,000,000 lbs. & 5,000 lbs.

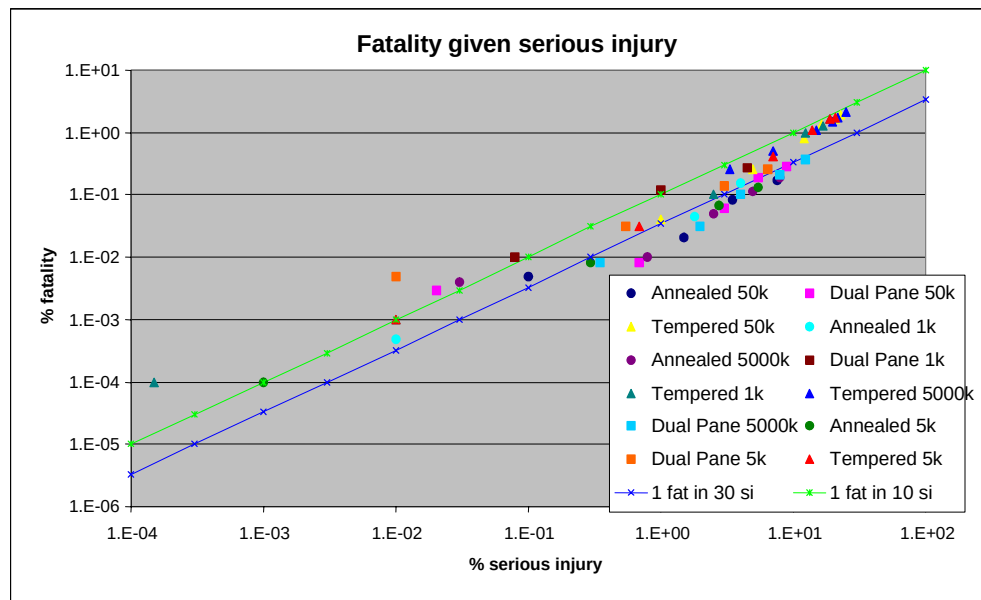
#### 7. How were the parameters associated with the yield adjustment derived?

By plotting data sets from multiple yields, the Science Panel could then create an equation for adjusting from the nominal yield to the desired value. This adjustment is

dependant on the percentage of glass broken as well as the yield. The parameters that describe this adjustment equation are then stored in SAFER.

8. *How was the relationship between fatality and serious injury determined?*

The Science Panel used pressure-impulse diagrams for fatalities [ref 1] along with the previously derived serious injury function to estimate a ratio of 1 fatality for every 30 serious glass injuries, as shown in Figure 7, for ranges beyond K24. This estimate was compared to other known data sources and discussed with the author of GLASS-CF, Paul Wilde. Inside K24, an adjustment function gradually increases the number of fatalities per serious injury to 1 in 15 at K12. Inside K12, the Simplified Close-In Fatality Mechanisms (SCIFM) logic applies (see Separate SCIFM Technical Memorandum APTCE1-16500).



**SAFER Version 3.0: 1 fatality / 30 serious injuries**

$$Pf(glass) = P_{sinj} / 30$$

Figure 7. Glass Fatality to Serious Injury Ratio

9. *What assumptions are made about emergency response?*

No direct factor was used in the development of the model (nor may be input by the user) to represent emergency response in SAFER 3.1. However, the data sets and validation effort on which the methodology is based (beyond K24) assumes approximately 67% of injuries serious enough to cause fatalities are averted by “average” emergency response conditions. Inside K12, SAFER considers emergency response to have no effect on the ratio of fatality to serious injury.

*10. Why are medium windows used rather than having a user-selectable size?*

Because the user, in most applications of SAFER, will not know all of the design details of the windows (e.g. size, thickness and type of glazing, strength and stiffness of supports) a medium window size (4' x 5') was chosen to provide an average estimate of window response. Also, the step-functions associated with discrete modeling (such as 3 distinct window sizes) can produce undesirable results when transitioning from one option to another. Therefore a single window size was chosen until such time as a continuous function allowing for variation in glass specifics – including dimensions – can be developed and/or incorporated.

*11. What are the assumptions on the dimensions of the window?*

The approximate dimensions of the window are 4'X5'.

*12. Can SAFER distinguish between the following cases?*

Case 1: An event with a yield and distance that generates 100% glass breakage

Case 2: An event with a higher yield than Case 1 but the same distance

Case 3: An event with a the same yield as Case 1 but a lesser distance

Yes, SAFER 3.1 can distinguish between all 3 cases. Case 2 would be different from Case 1 in two ways: the yield adjustment function (as previously described) and a “beyond 100% breakage” algorithm. This algorithm is used at scaled ranges that are less than the scaled range required to create 100% breakage. Case 3 would only be affected by the “beyond 100% breakage” algorithm (see Question 13).

*13. What is the “beyond 100% breakage” algorithm and what is it based on?*

SAFER 3.1 uses a separate algorithm to determine probability of serious injury (due to glass breakage) when the pressure and impulse exceed the levels required to create 100% breakage. This algorithm is based on the impulse and the yield, rather than the breakage level and the yield. This removes the restriction of not being able to “go beyond” 100% breakage.

The logic for this algorithm is shown in Figure 8.



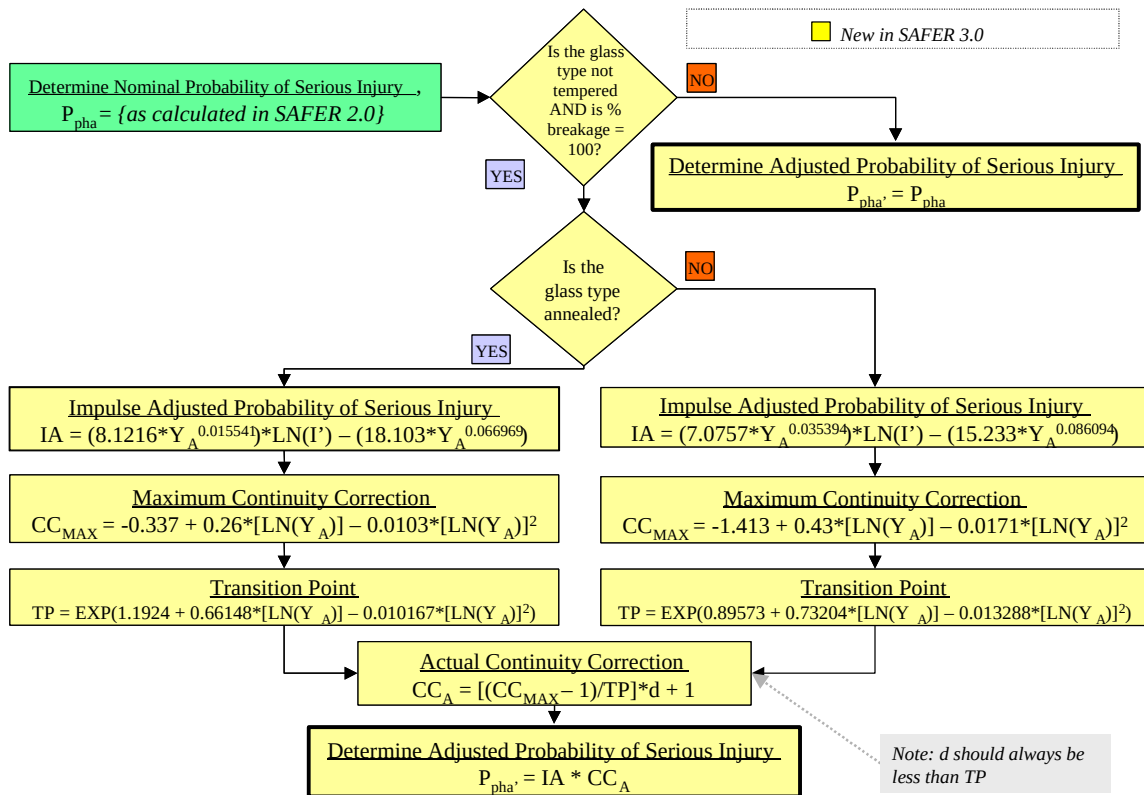


Figure 8. SAFER 3.1 Glass Logic

14. Why not use an impulse-based algorithm for all cases?

While it would be possible to determine serious injury (due to glass) for all scenarios using an impulse-based routine, SAFER 3.1 only uses such an algorithm in the “beyond 100% breakage” regime. This is because the existing (breakage-based) routine appears to work well for cases involving less than 100% breakage. In a future version of SAFER, a single routine for all cases could be developed, if desired.

15. Is there a transition region where answers “jump” when the “beyond 100% breakage” algorithm is used?

SAFER 3.1 has a continuity correction routine to reduce such an effect in the transition region, as shown in Figure 8.

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## Attachment 7 – Structural Response

## PURPOSE

This memorandum addresses major technical and analytical decisions made as part of the SAFER 3.1 structural response methodology. Specific questions addressed are:

1. How is the ES damage/intact value determined for both the roofs and walls?
2. How/why is the SAFER method different from the ACTA method?
3. How were the SAFER curves derived?
4. How is the cumulative log-normal distribution used to convert building damage to probability of fatality?
5. Why is the probability of fatality less than 1.0 when building damage equals 100%?
6. What does 100% building damage mean?
7. How are cases that would cause “beyond 100% damage” handled?
8. Is the roof type entered by the user accounted for in the building failure models?
9. Is the ES floor area entered by the user accounted for in the building failure models?

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2. Briefings to RBESCT.

## DISCUSSION

1. *How is the ES damage/intact value determined for both the roofs and walls?*

The ACTA building failure model (Ref. 1) uses pressure-impulse diagrams, Figures 1-16, to predict ES damage. SAFER refers to this ES damage as “composite damage” and is used in Step 10 to determine the number of fatalities. The separate values of wall and roof damage are needed to determine the protection the damaged ES provides against debris. Because the roof is user-selectable (for debris protection purposes), the method for determining damage to the roof needs to reflect the roof type chosen by the user at run-time. The building failure model does not consider the roof selected, but instead uses the default roof type for that ES. Therefore, a separate set of PI diagrams, Figures 17-24, is used to determine the damage to the roof selected by the user. The wall type is not a parameter the user can alter once an ES type is selected, thus the wall damage is based on the composite damage.

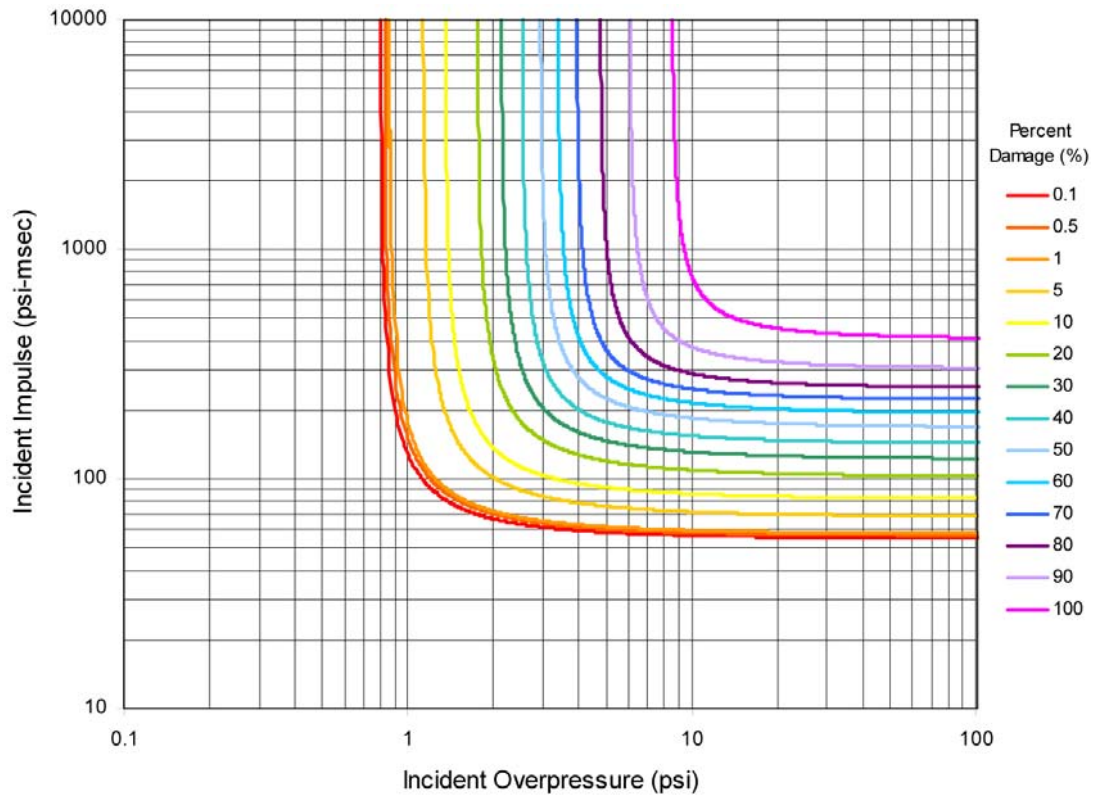


Figure 1. Passenger Vehicle

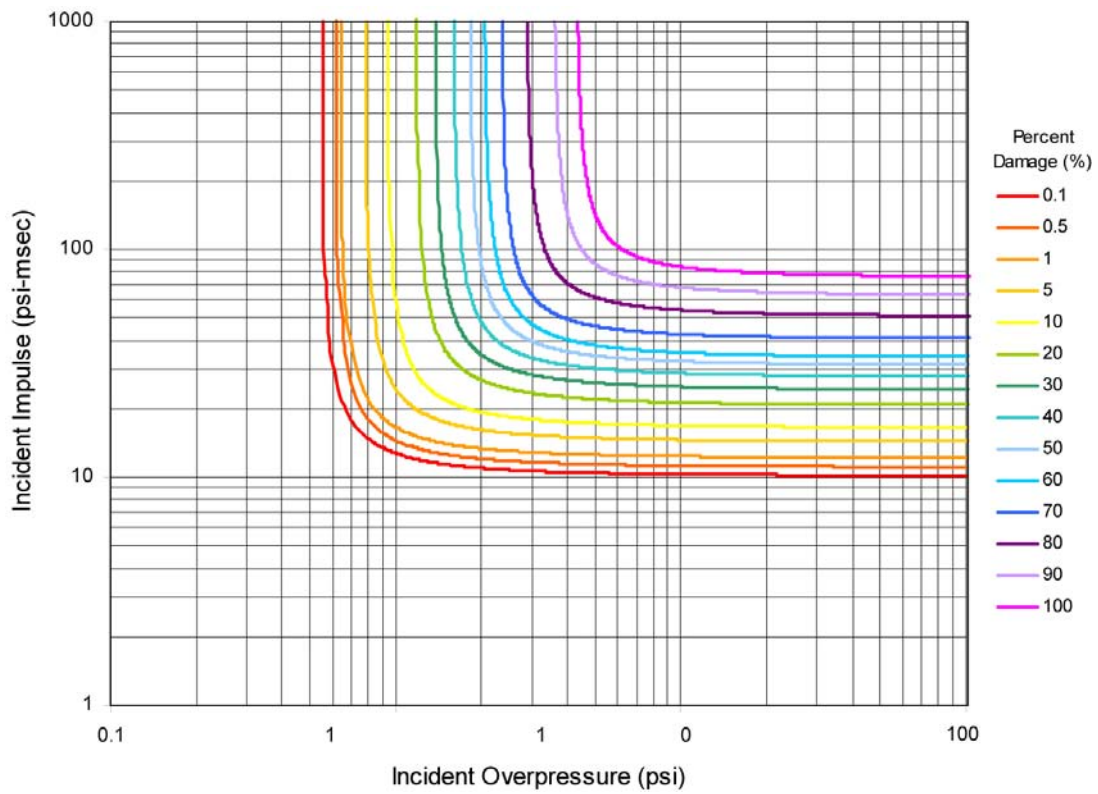


Figure 2. Small Trailer (~500 sq ft)

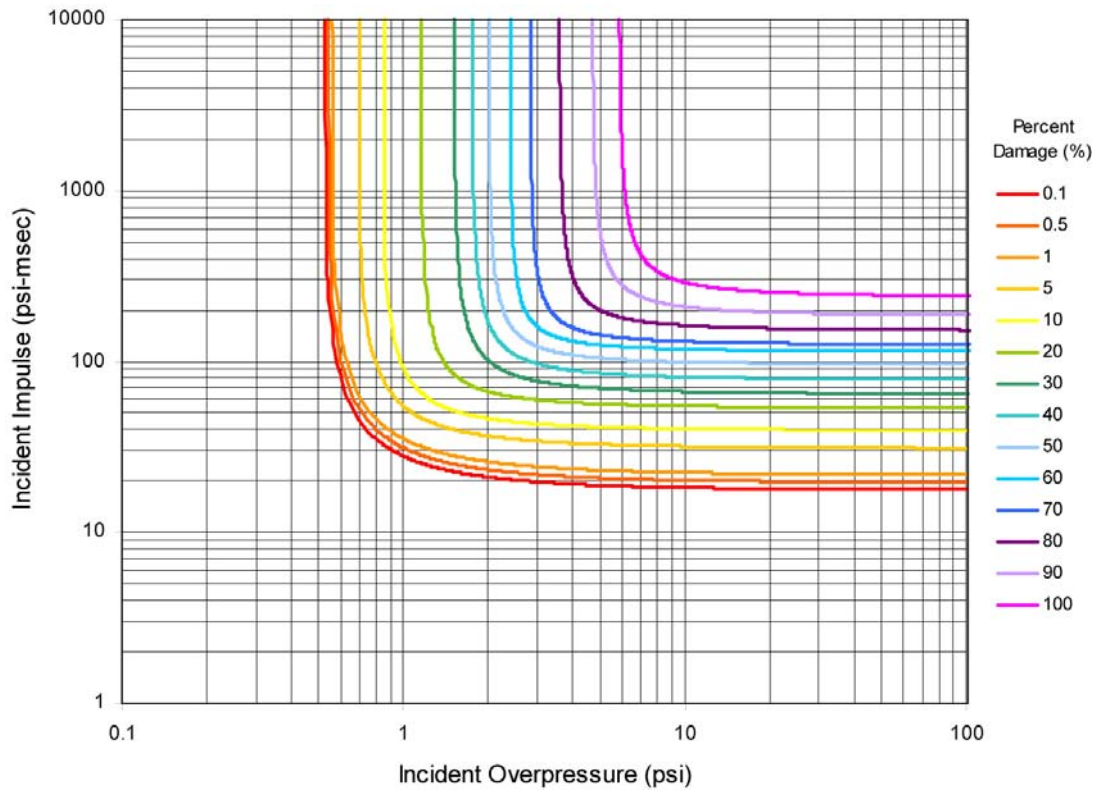


Figure 3. Medium Wood Structure (~10,000 sq ft)

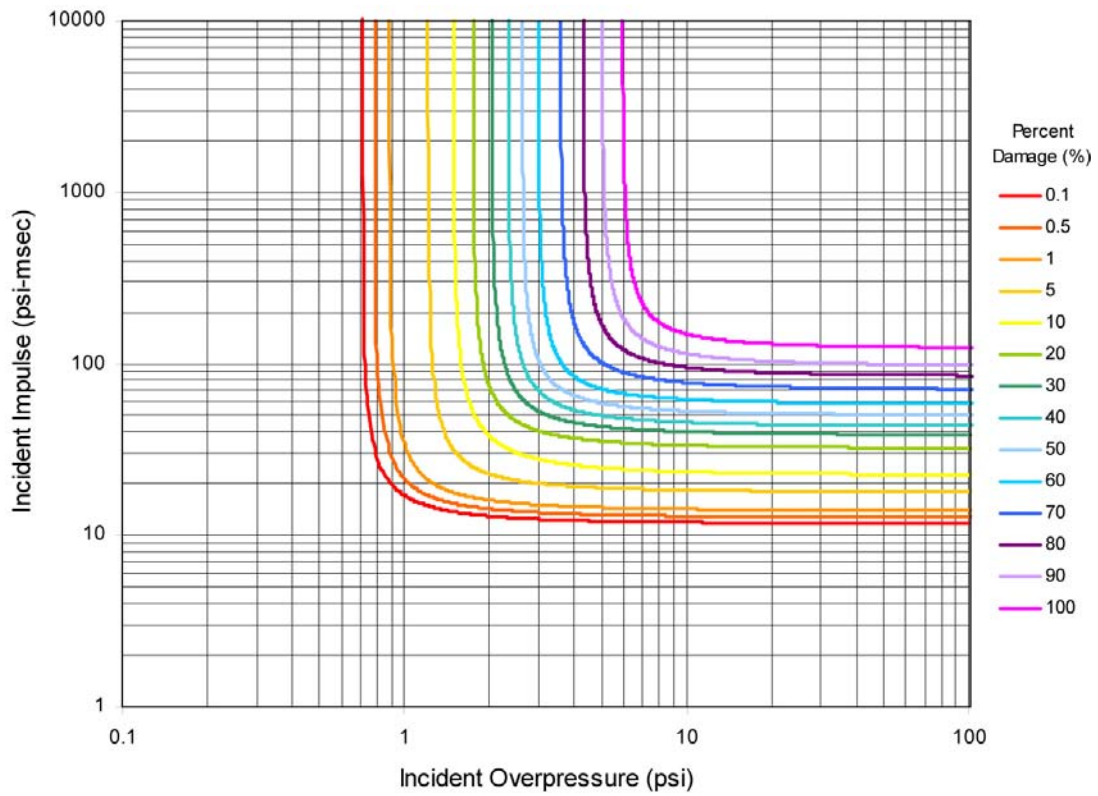


Figure 4. Small Wood Structure (~2500 sq ft)

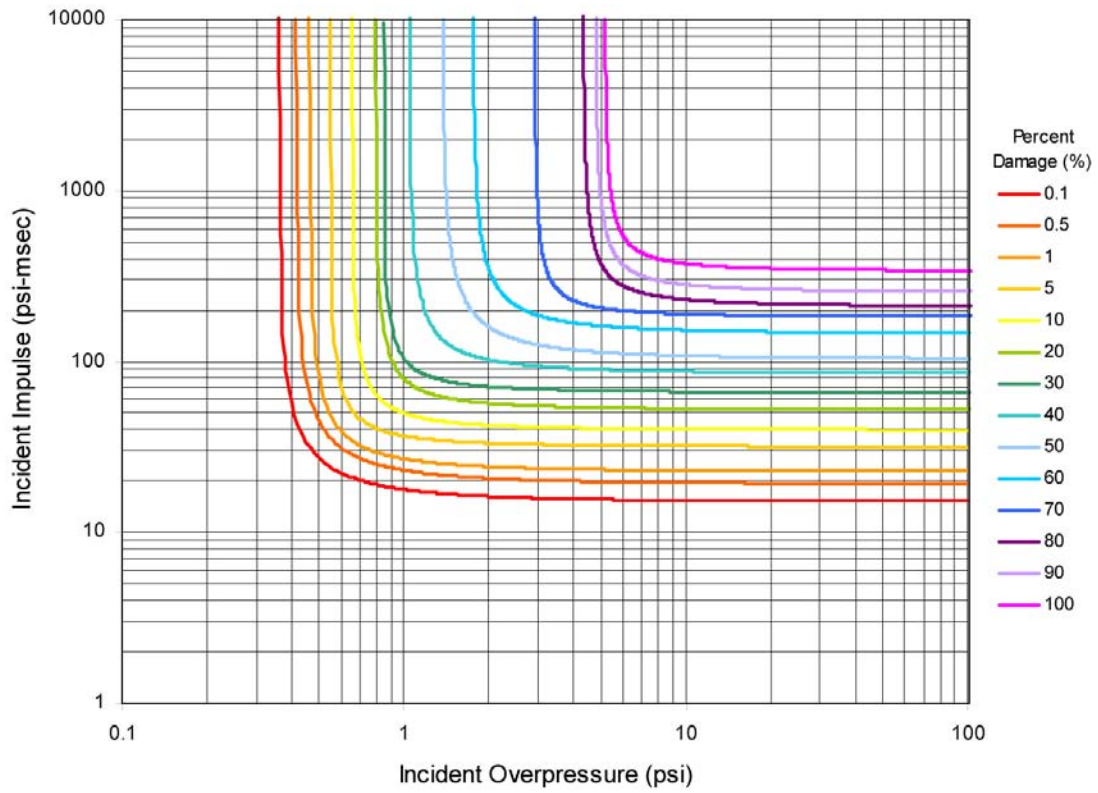


Figure 5. High Bay Metal Structure (~40,000 sq ft)

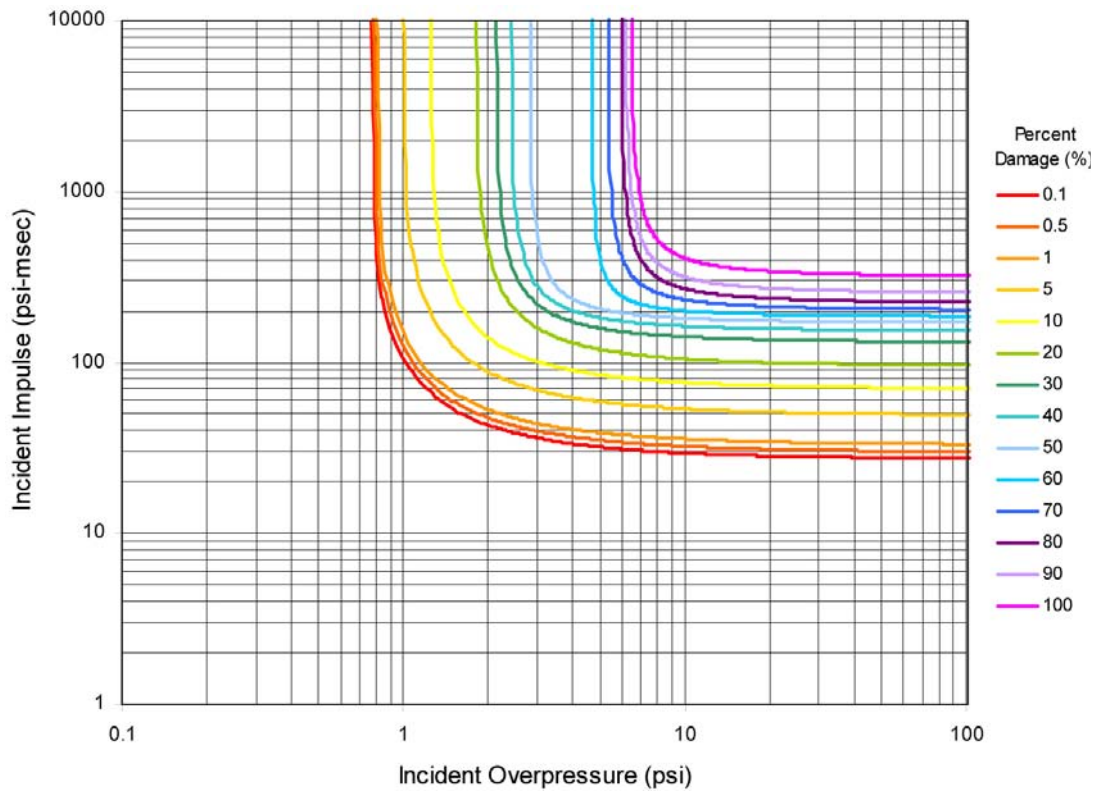


Figure 6. Medium Metal Stud Structure (~10,000 sq ft)



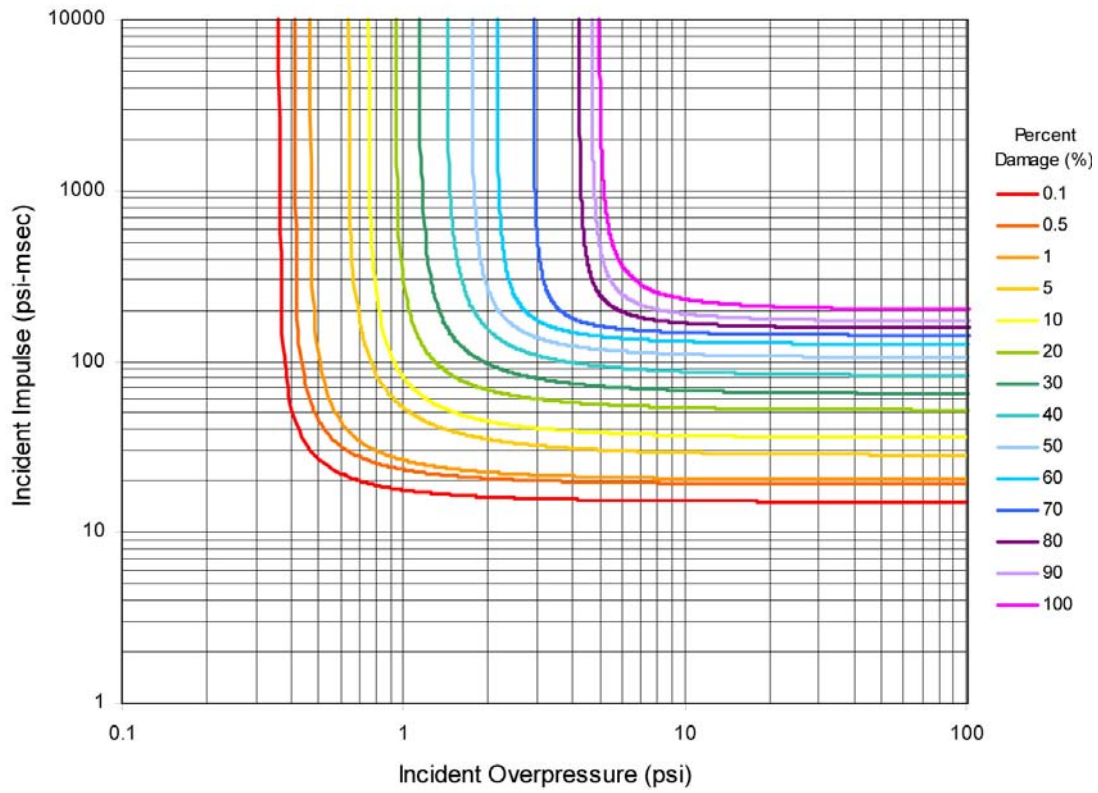


Figure 7. Medium Metal Structure (~10,000 sq ft)

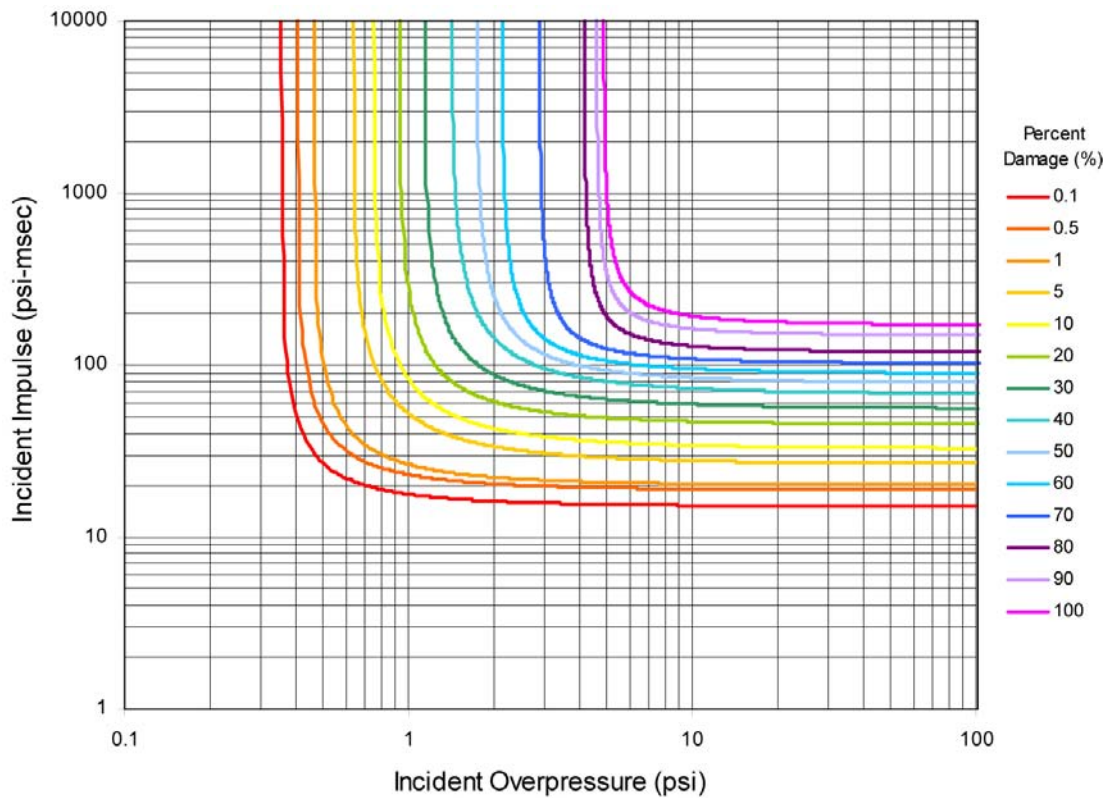


Figure 8. Small Metal Structure (~2500 sq ft)



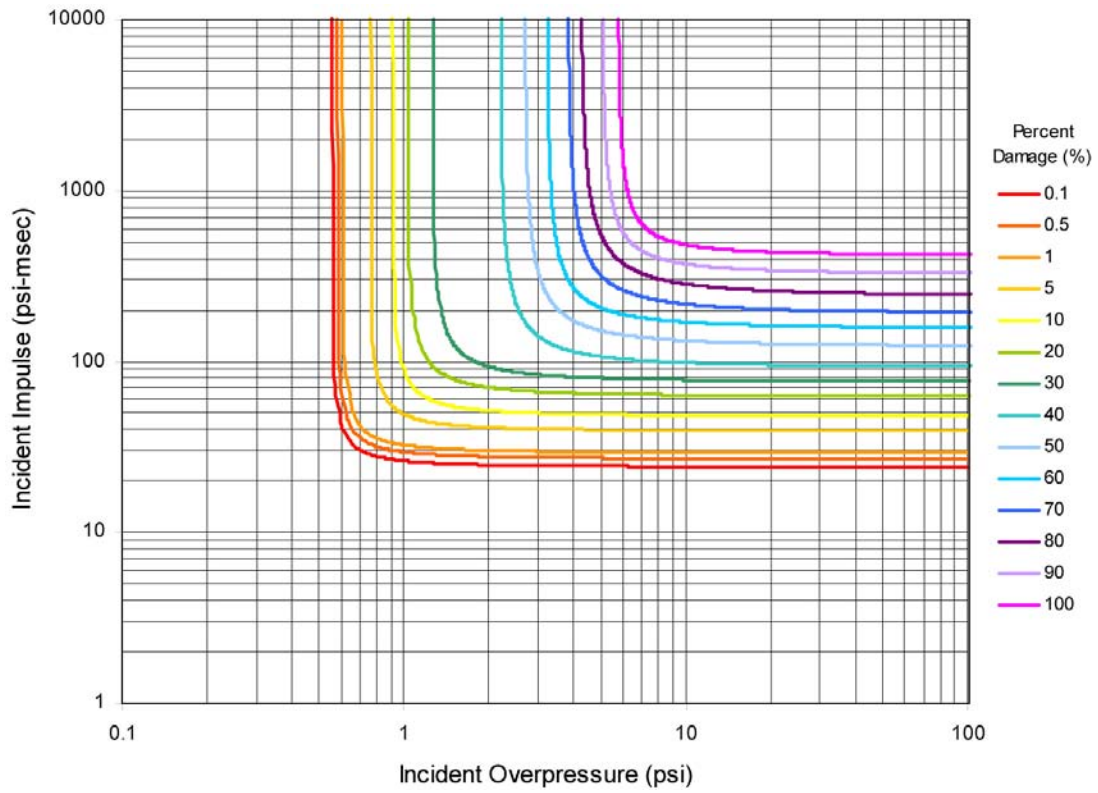


Figure 9. Medium Reinforced Masonry Structure (~10,000 sq ft)

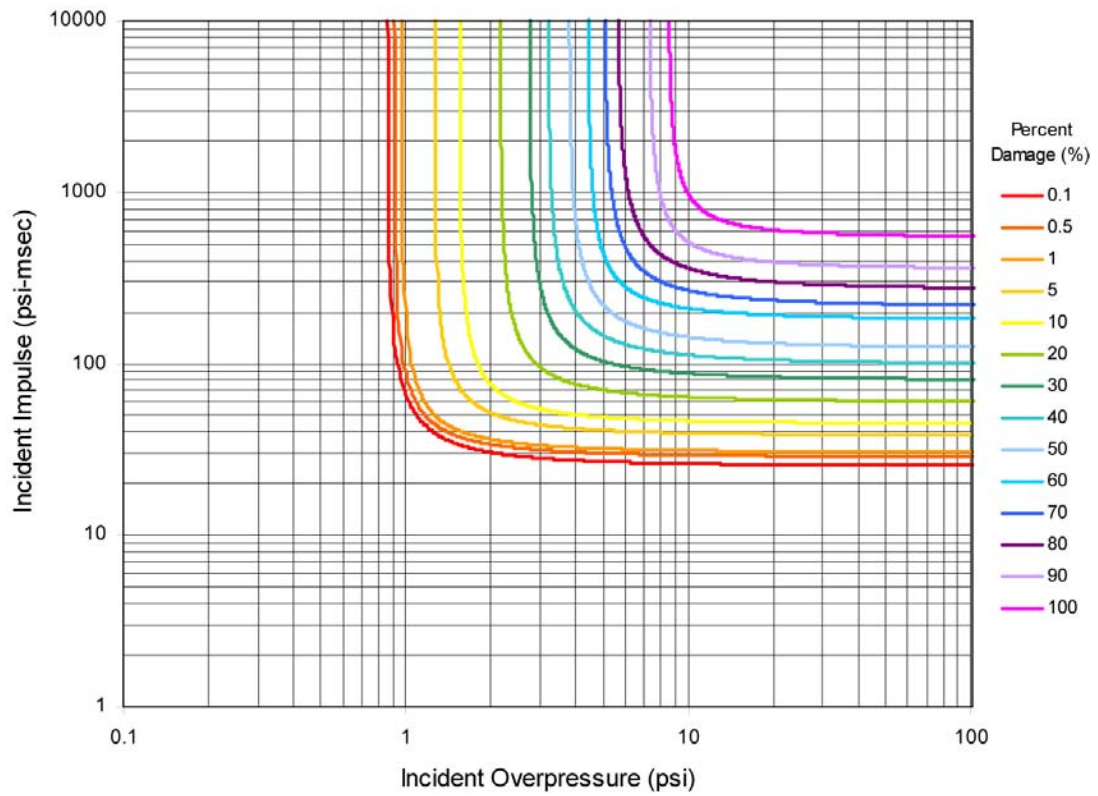


Figure 10. Small Reinforced Masonry Structure (~2500 sq ft)

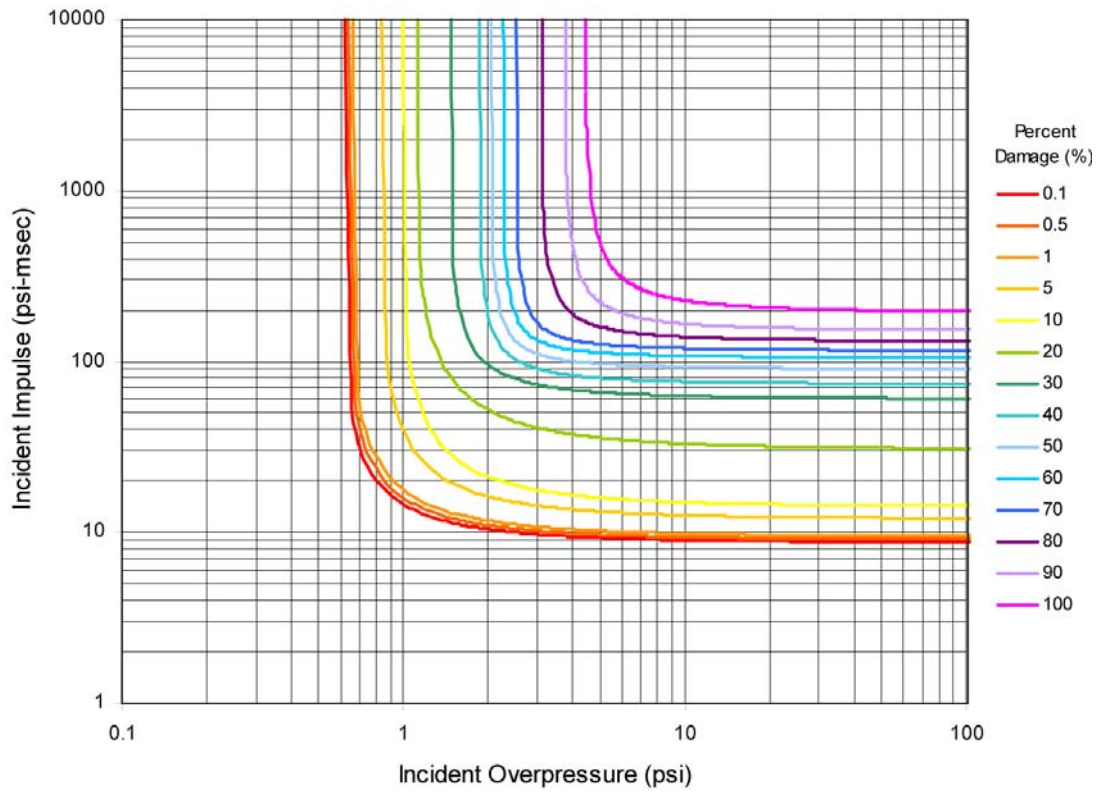


Figure 11. Large Un-Reinforced Masonry Structure (~40,000 sq ft)

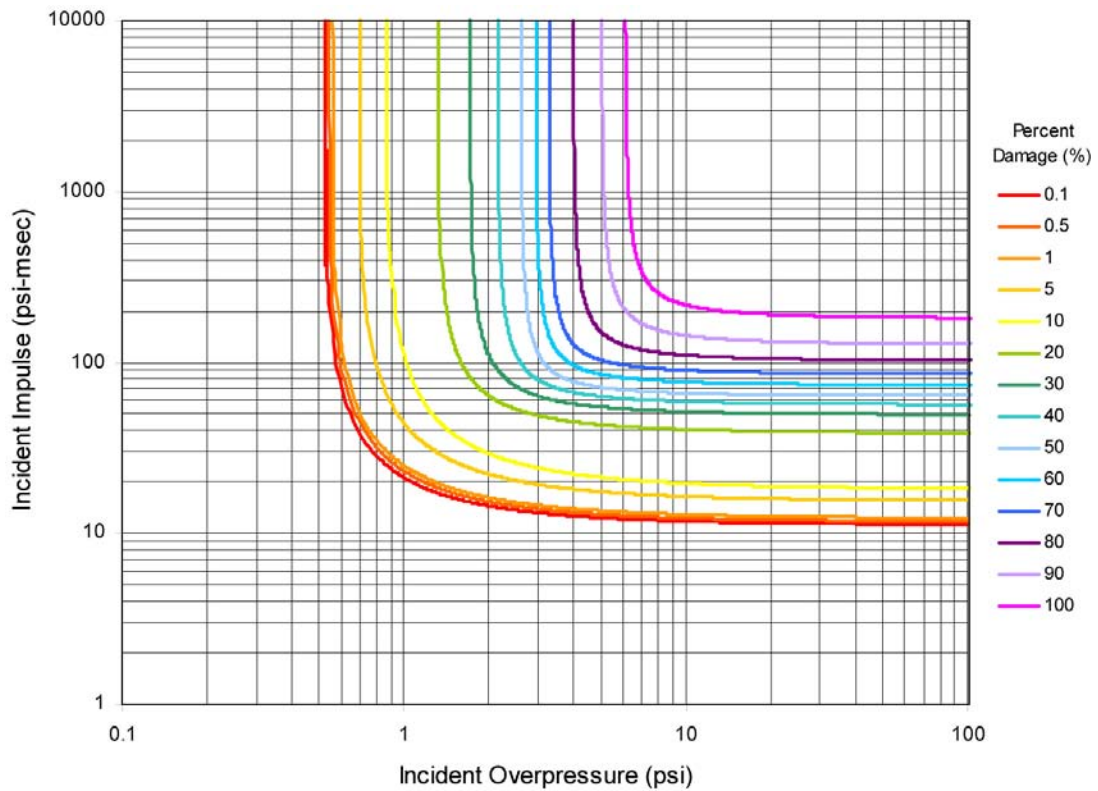


Figure 12. Medium Un-Reinforced Masonry Structure (~10,000 sq ft)

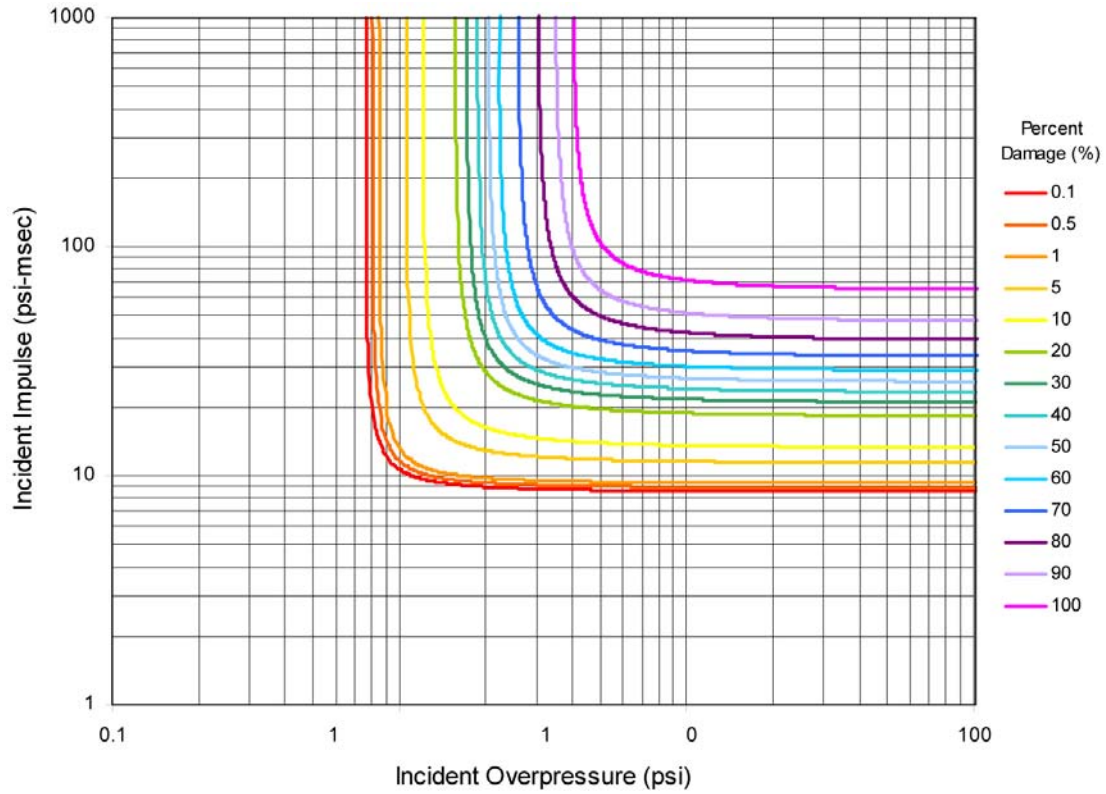


Figure 13. Small Un-Reinforced Brick Structure (~2500 sq ft)

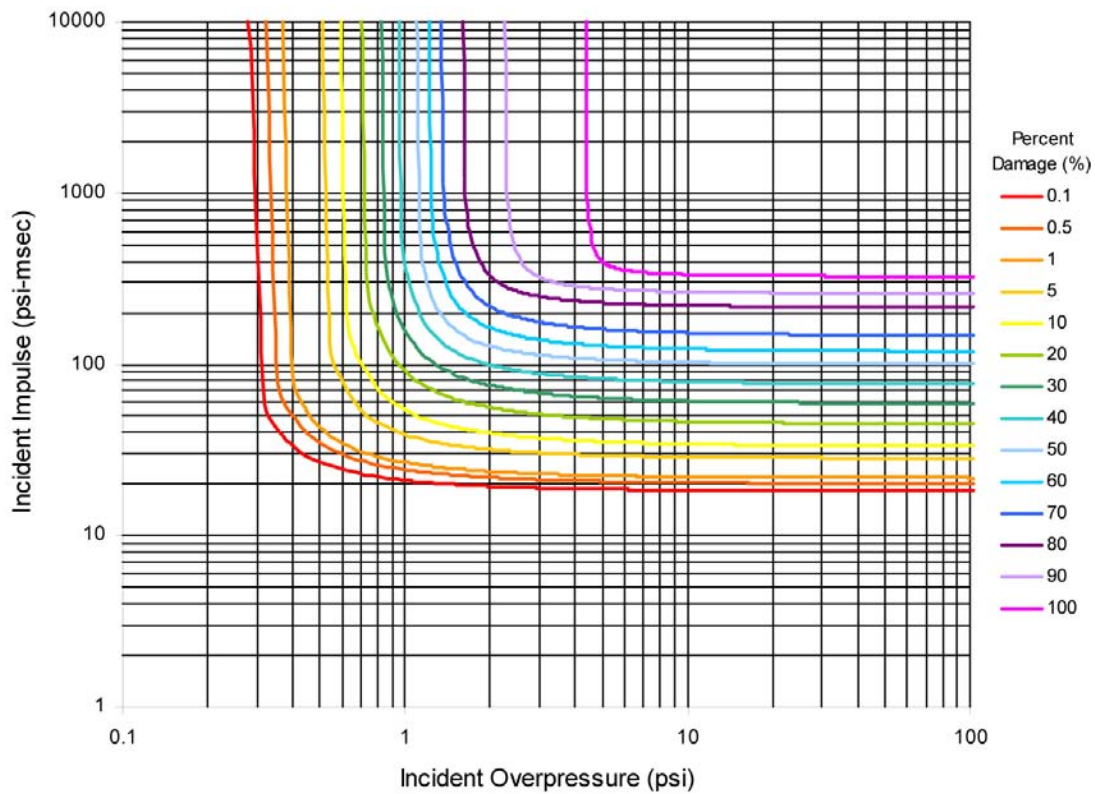


Figure 14. Large Tilt-up Structure (~40,000 sq ft)

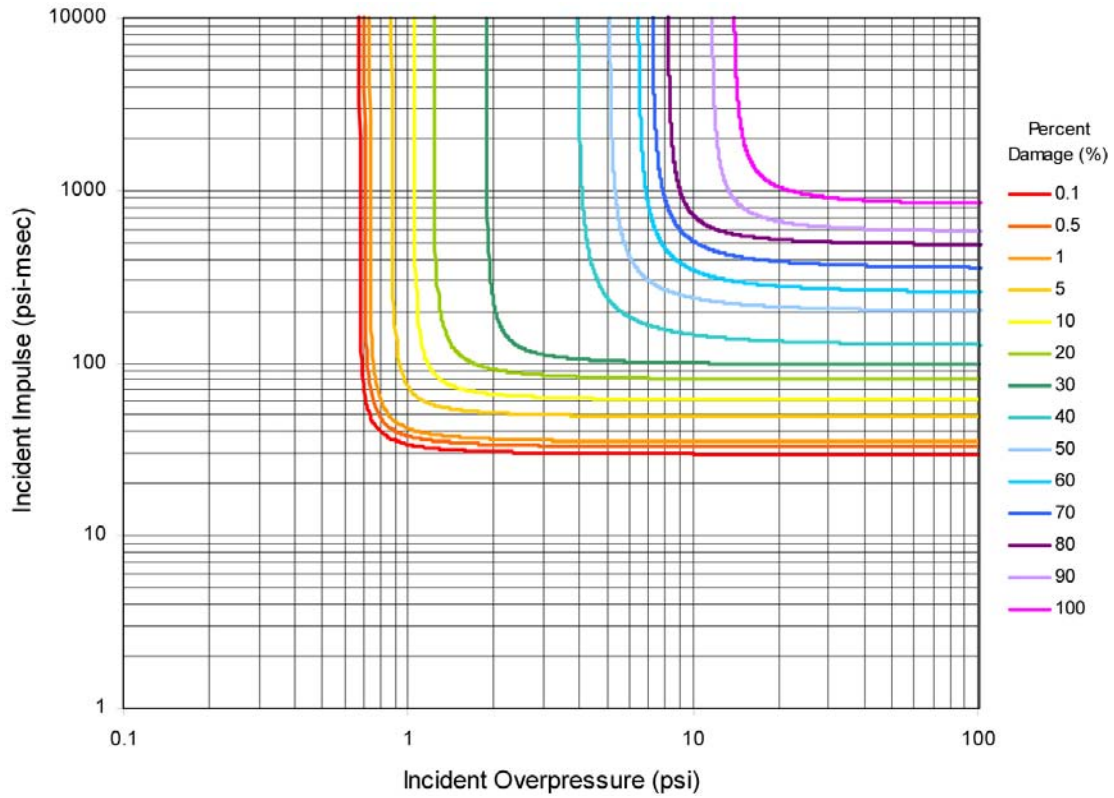


Figure 15. Medium R/C Office Building

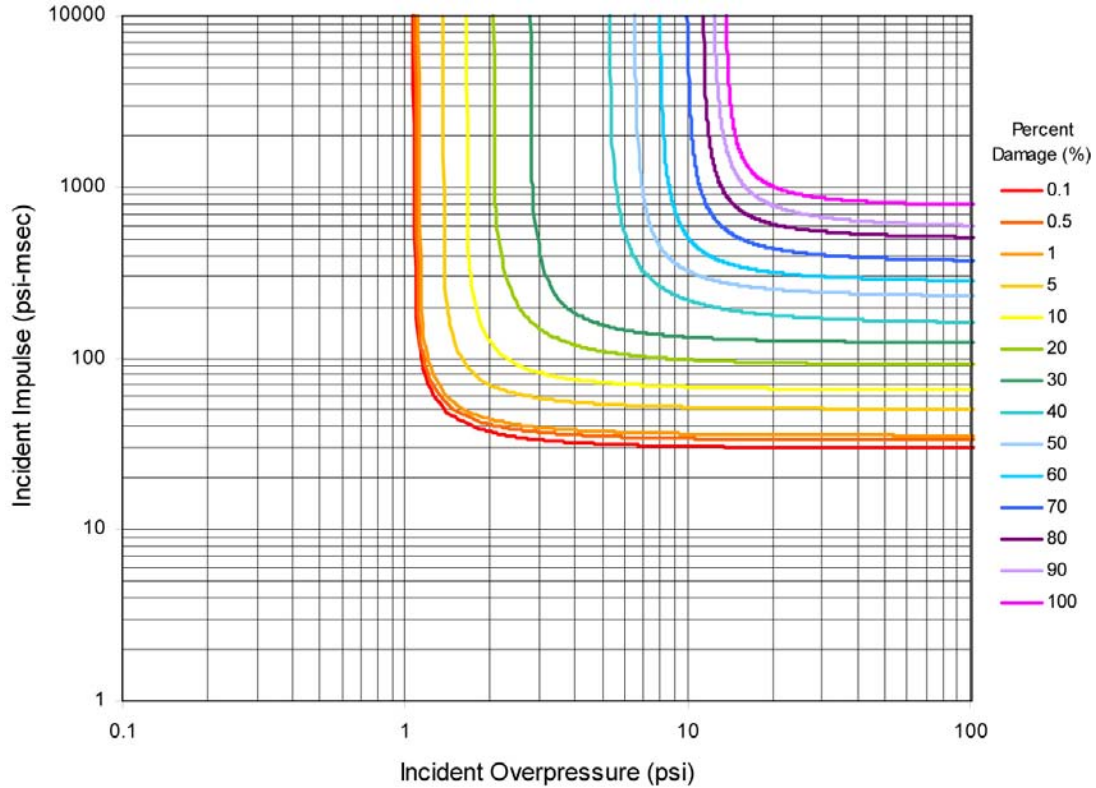


Figure 16. Small R/C Office Building, 8" R/C Shearwalls with R/C Roof/Beams



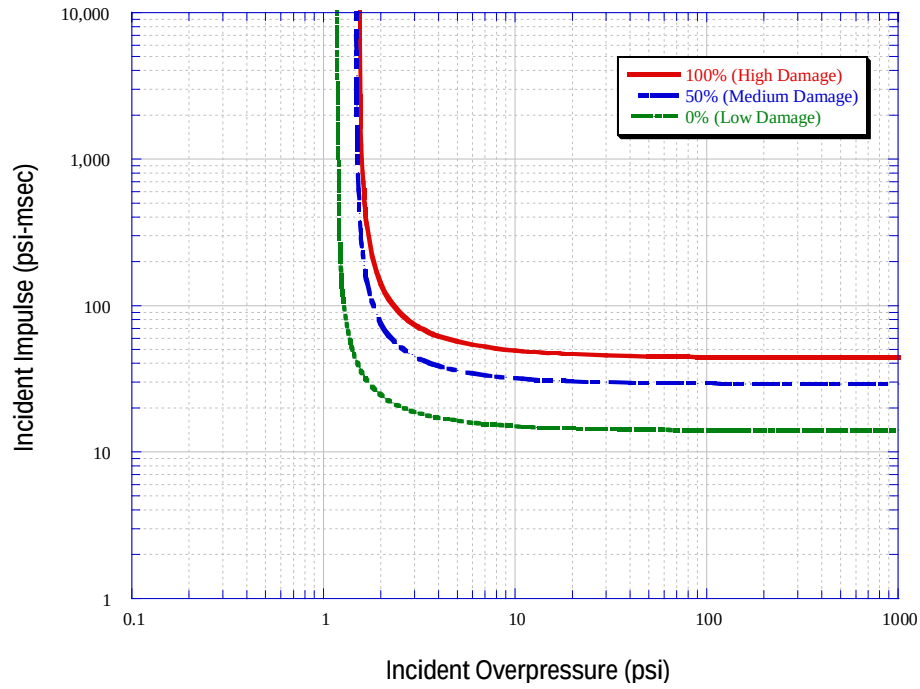


Figure 17. Light Steel Panel (22 gauge) Roof

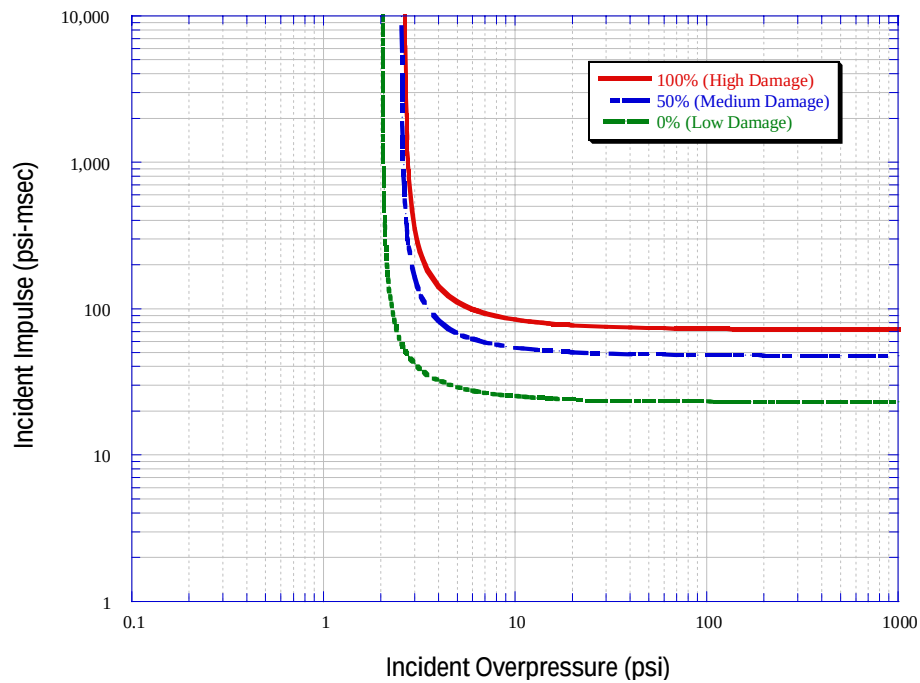


Figure 18. Medium Steel Panel (18 gauge) Roof

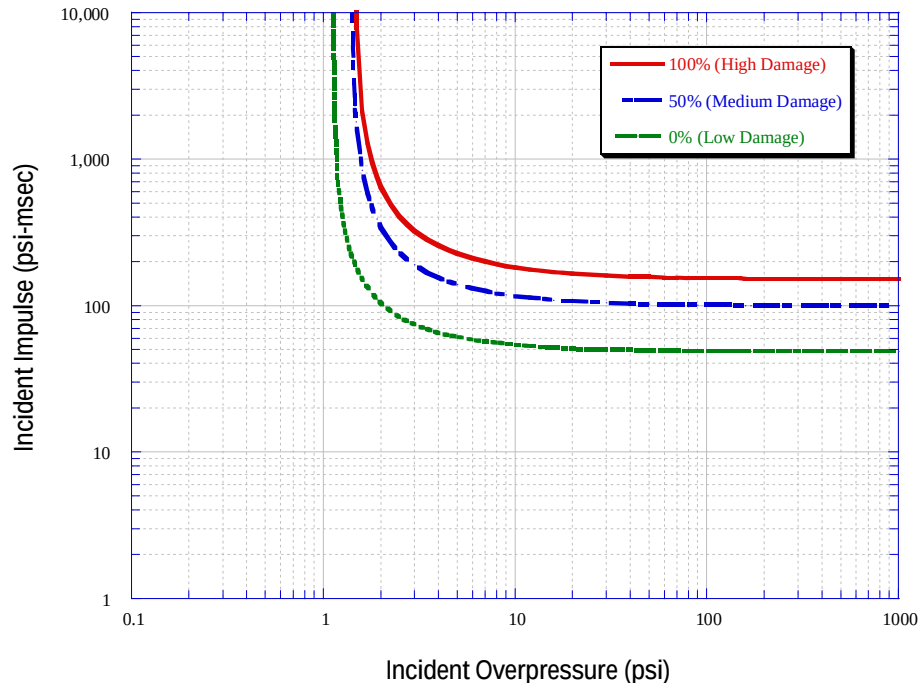


Figure 19. 2" Lightweight Concrete / Steel Deck and Joists Roof

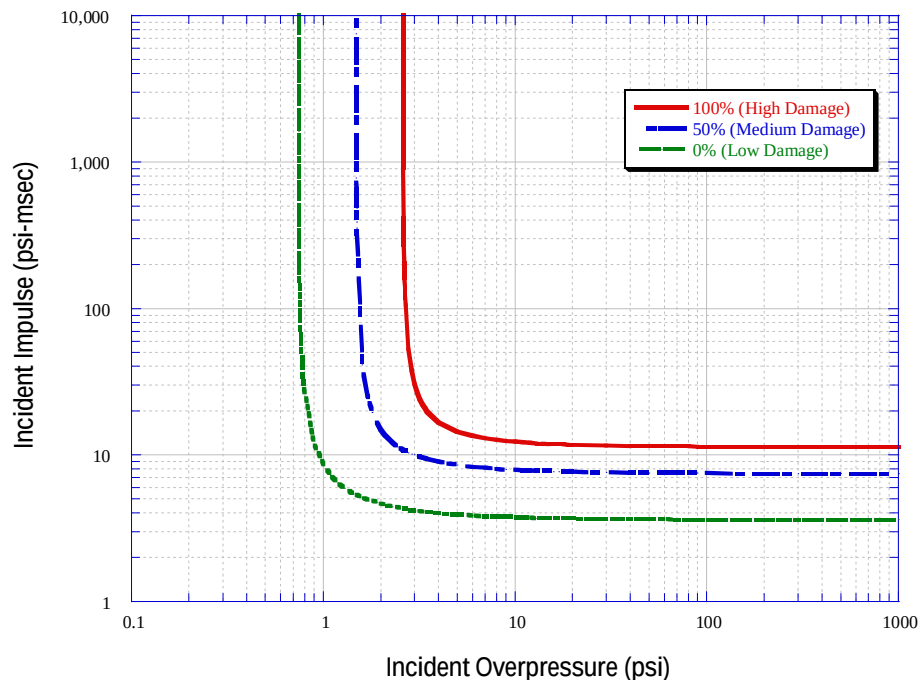


Figure 20. Plywood Panelized (2 x 6 @ 24") Roof



Figure 21. Gypsum / Fiberboard / Steel Joists Roof

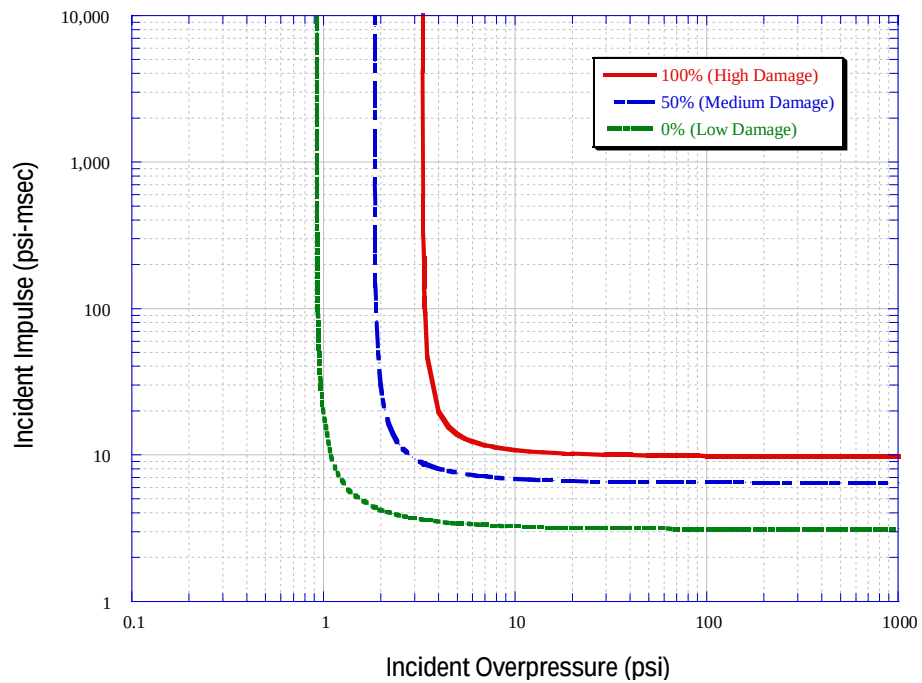


Figure 22. Plywood / Wood Joists (2 x 10 @ 16") Roof

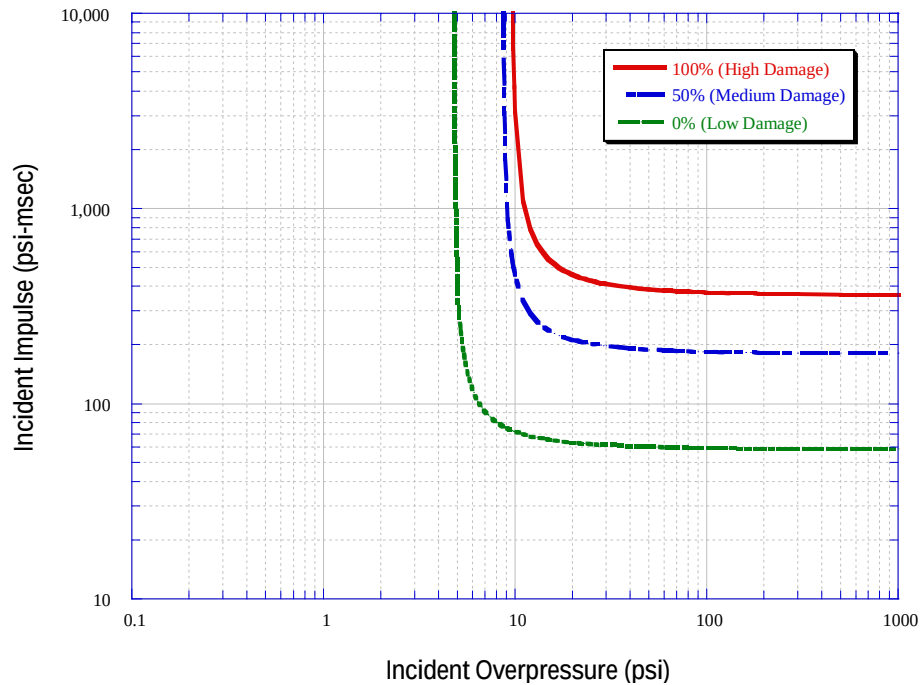


Figure 23. 14" Reinforced Concrete Roof

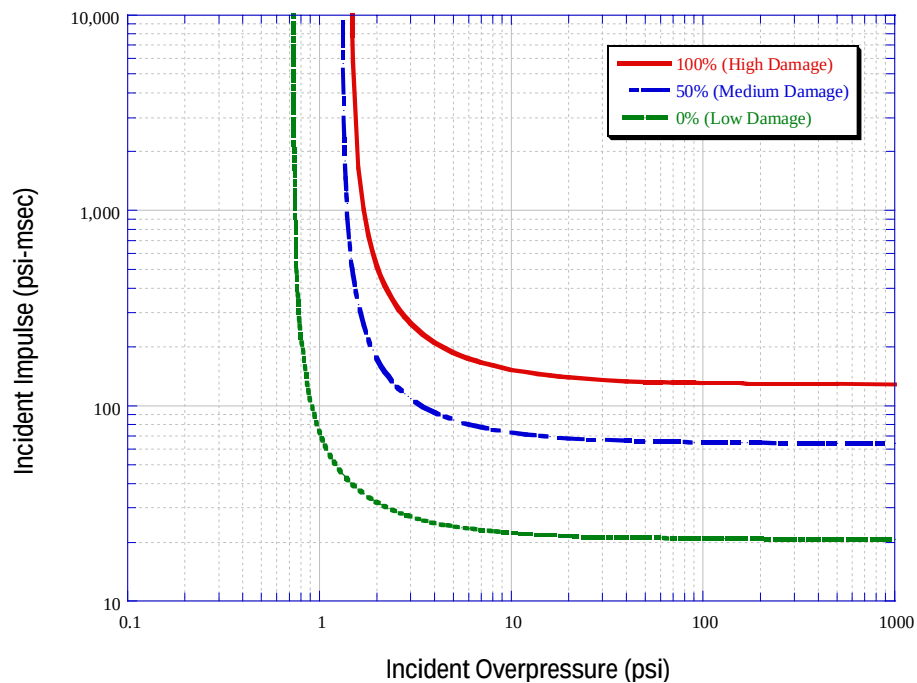


Figure 24. 4" Reinforced Concrete Roof

## 2. How/why is the SAFER method different from the ACTA curves?

The ACTA P-I curves predict fatality as a function of pressure and impulse. The SAFER method represents probability of fatality as a function of building damage. SAFER 3.1



uses a normal distribution, therefore the ACTA curves could not be directly used to determine the probability of fatality. Instead, data points from the ACTA curves that do consider structural response were used to help anchor the normal distributions.

### 3. How were the SAFER curves derived?

The Science Panel used the ACTA data points and relationships derived by NFESC and ACTA to determine the probability of fatality at two damage levels, 40% and 90%. A lognormal distribution (adjusted for a maximum set at less than 1.0) was then created to pass through the two points obtained from the data for each ES type. This process is depicted in Figure 25 and described in Question 4 below.

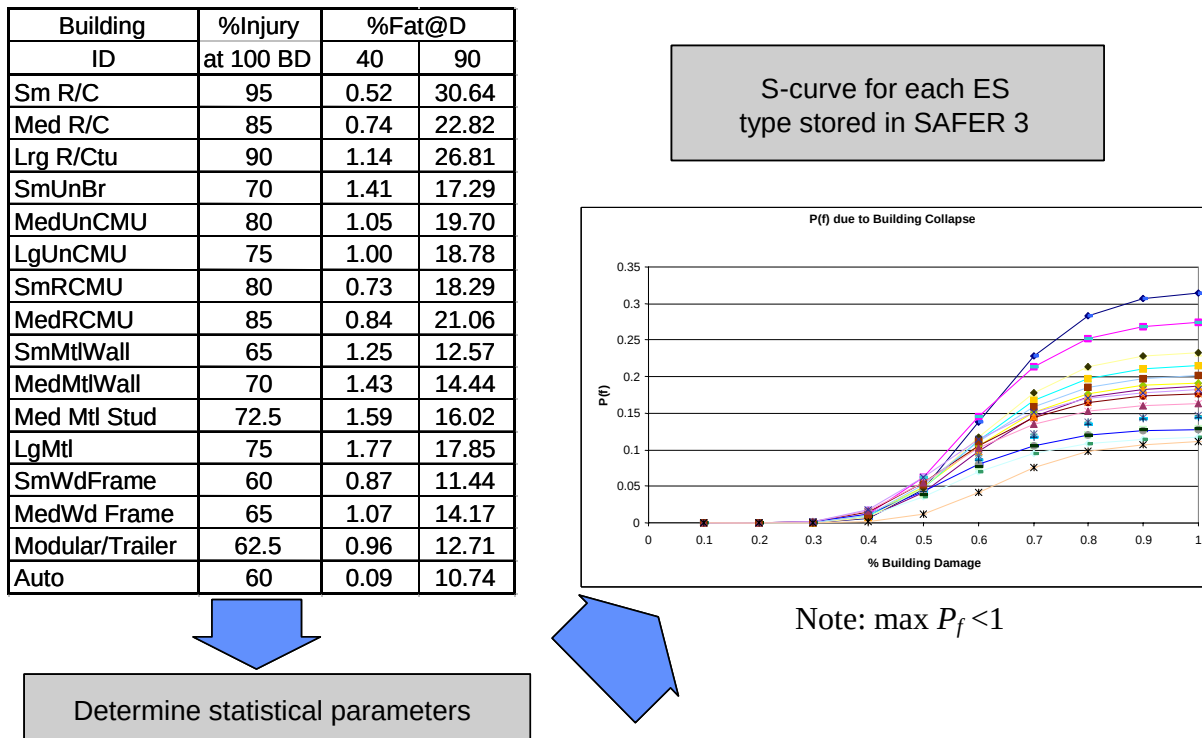


Figure 25. SAFER Probability of Fatality Curve Creation Process

### 4. How is the cumulative log-normal distribution used to convert building damage to probability of fatality?

The lognormal distribution for each ES type is computed to match three data points: the probability of fatality at 40% building damage,  $P_{f40}$ , the probability of fatality at 90% building damage,  $P_{f90}$ , and an assumed maximum probability of fatality ( $P_{f_{max}}$ ). The paragraphs below describe the process used to compute the parameters of the lognormal distribution using these three data points.

First, the probability of fatality parameters are scaled by  $P_{f_{max}}$  as follows:

$$P_{f40s} = P_{f40} / P_{f_{max}} \quad \text{and} \quad P_{f90s} = P_{f90} / P_{f_{max}}$$

Next,  $n\sigma_{40}$  and  $n\sigma_{90}$  are defined as the number of sigma above (+) or below (-) the mean that the probabilities  $Pf_{40s}$  and  $Pf_{90s}$  represent. The standard deviation,  $\sigma$ , of the distribution [in units of  $\log(\%BldgDam)$ ] is computed by:

$$\sigma = [\log(90) - \log(40)] / [n\sigma_{90} - n\sigma_{40}]$$

and the mean of the distribution [again in  $\log(\%BldgDam)$ ] is:

$$\mu = \log(40) + n\sigma_{40} * \sigma = \log(90) - n\sigma_{90} * \sigma$$

As an example, the following computes the distribution parameters  $\mu$  and  $\sigma$  for the Small Reinforced Concrete (RC) ES type. The input data and scaled probabilities for the Small RC ES are:

$$\begin{aligned} Pf_{40} &= 0.0052 & Pf_{40s} = Pf_{40}/Pf_{max} &= 0.0052 / 0.318 = 0.01635 \\ Pf_{90} &= 0.3064 & Pf_{90s} = Pf_{90}/Pf_{max} &= 0.3064 / 0.318 = 0.96352 \\ Pf_{max} &= 0.318 \end{aligned}$$

Using a standard statistical table, one can find the sigma levels to which the scaled probabilities correspond.

$$\begin{aligned} Pf_{40s} = 0.01635 &\Rightarrow n\sigma_{40} = -2.13625 \text{ sigma, and} \\ Pf_{90s} = 0.96352 &\Rightarrow n\sigma_{90} = +1.7925 \text{ sigma} \end{aligned}$$

The mean and standard deviation for the Small RC ES are then computed as:

$$\begin{aligned} \sigma &= [\log(90) - \log(40)] / [1.7925 - (-2.13625)] = 0.35218 / 3.92875 = 0.08964 \\ \text{and} \\ \mu &= \log(40) - n\sigma_{40} * \sigma = 1.60206 - (-2.13625) * 0.08964 = 1.7935 \\ &= \log(90) - n\sigma_{90} * \sigma = 1.95424 - (+1.7925) * 0.08964 = 1.7935 \end{aligned}$$

Finally, the value of  $Pf_{max}$  is varied to force the value of  $Pf_{100}$  to be 99% of the value of  $Pf_{max}$ . While this could be accomplished via trial and error by executing the above process a large number of times, use of the “Goal Seek” function in MS Excel™ accomplishes the task with minimal effort.

#### 5. *Why is the probability of fatality less than 1.0 when building damage equals 100%?*

This is because of two reasons:

- a. 100% damage does not necessarily mean that the building has completely collapsed. 100% damage does mean that the building is a complete loss economically and functionally. A building with 100% damage would have many elements that have collapsed but could also have structural elements that still support dead loads but could not support live loads.
- b. even if most or all of the ES has collapsed, accidents have shown that there can be survivors.

6. *What does 100% building damage mean?*

100% damage, as a minimum, indicates that the major structural components have exceeded the design failure load and that many have failed and may have collapsed. The building is not functional and must be replaced.

7. *How are cases that would cause "beyond 100% damage" handled?*

Such cases are addressed by the Simplified Close-In Fatality Mechanisms (SCIFM) logic (see CE1-16500).

8. *Is the roof type entered by the user accounted for in the building failure models?*

No. The building failure models always use the default roof type. A change in roof type (from the default) only affects the predicted PES debris hazard and risk.

9. *Is the ES floor area entered by the user accounted for in the building failure models?*

No. The building failure models assume a default floor area because they are based on specific representative designs. The floor area only affects the glass hazard risk.

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## Attachment 8 - Debris

**PURPOSE**

This memorandum addresses major technical and analytical decisions made as part of the SAFER 3.1 debris branch. Specific questions addressed are:

1. How were the numbers of fragments for each weapon type determined?
2. What is the rationale for the choice of average mass values?
3. What is the basis for the equation that determines the number of weapons on the outer surface?
4. What is the basis for the nominal maximum throw range for each weapon?
5. Why do the smaller mass bins have lesser max throw ranges?
6. Why aren't additional weapon types included?
7. How were the nominal fragment blocking factors determined?
8. Why is the PES damage considered before the primary fragments are blocked by the PES?
9. How were the relative component areas calculated?
10. How were the nominal mass distributions determined for each PES component?
11. What are the nominal maximum throw ranges for each PES component based on?
12. How were the steel/concrete ratios for each PES component determined?
13. What is the reasoning behind the dynamic mass distribution adjustment?
14. On what are the weight-to-volume considerations based?
15. Why aren't all PES components dependent on weight-to-volume considerations?
16. How were the volumes for each PES determined?
17. Why aren't crater ejecta considered for all PES types?
18. What are the crater ejecta parameters based on?
19. What is the basis for the high/low angle separation?
20. Why is there a distinction among low-angle fragments?
21. Why was the bivariate normal distribution chosen as the probability density function for high-angle and low-angle (side impact) debris?
22. Have the arriving fragment tables been compared to test data?
23. How were the " $f$ " values derived and why are they not always equal for HAS and ECM?
24. How are the maximum throw values and  $\sigma$  related?
25. How are the mass-based fragment tables converted to kinetic energy tables?
26. Why is terminal velocity assumed?
27. What are the  $\Delta KE$  values for walls and roofs based on?
28. How were the invulnerable areas determined?
29. What is the basis for the probability of a hit?

30. Why was the fatality versus kinetic energy curve that is used by SAFER chosen?
31. What is the basis of the barricade logic?

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## DISCUSSIONS

### *1. How were the numbers of fragments for each weapon type determined?*

Where available, the numbers were taken from available reports (ref 1). The Science Panel performed a weapon analysis using the methodology of Reference 1 to determine the numbers for the MK82 and M107.

Although other data sources, such as the Joint Munitions Effectiveness Manual (JMEM), have unclassified data for the MK 82 and the M107 (ref 2), the data may not be unclassified for the WAU-17 (Sparrow). In addition, the data for other weapons that might be added later might also be classified in the JMEM. For this reason, in order to have consistent numbers for all weapons, it was decided to use the Reference 1 methodology (Gurney). An initial comparison made between the Reference 1 estimates and the JMEM measurements showed that the Reference 1 estimates are the more conservative.

### *2. What is the rationale for the choice of average mass values?*

The average mass values were chosen because they create a direct correlation from mass bins to kinetic energy bins when terminal velocity is assumed. That is, a fragment from mass bin 1 at terminal velocity will belong in kinetic energy bin 1.

### *3. What is the basis for the equation that determines the number of weapons on the outer surface?*

The equations (taken from Ref 3) represent the number of items on the outer surface of a rectangular stack. Let  $N_w$  equal the total number of munitions in a rectangular stack with dimensions  $3n \times n \times n$  (See Figure 1). This stack shape is approximately the one that would fit into a standard earth covered magazine.



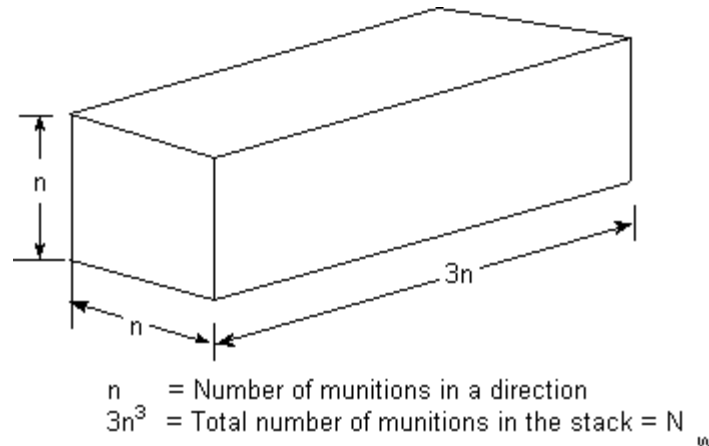


Figure 1. Theoretical Stack Geometry

Off the side of the stack:

$$N_{eff} = 3n^2$$

$$N_{pos} = \frac{3n^2}{3n^3} = 1.442 N_w^{-1/3}$$

Note:  $N_{pos}$  is the percentage of weapons on the outer surface of the stack

4. *What is the basis for the nominal maximum throw range for each weapon?*

The values are based on available published literature (ref 4, 5).

5. *Why do the smaller mass bins have lesser max throw ranges?*

Trajectory analysis shows that larger pieces have a higher ballistic coefficient and are expected to travel the furthest. Therefore, a trajectory analysis tool, TRAJ (ref 4), was used to estimate the nominal max throw for smaller mass bins. This assumption appears to be supported by SciPan1 test data (ref 19).

6. *Why aren't additional weapon types included?*

The weapon choices available in SAFER are based on a philosophy developed for the Army's "Worst Case Donor/Acceptor" Program: If testing or analysis is performed using a "worst case" donor munition as the explosion source, then the results would be applicable to all other munitions that present a lesser hazard.

For HD 1.1 munitions, several different items were identified as being potential worst cases; it being up to the user to select the type that most closely represents the actual item. MK 80 series bombs (MK 82, MK 83, or MK 84) represent all large, robust

munitions; M107 projectiles represent all small, robust munitions. The AIM-7 warhead represents all fragmenting or thin-skinned items.

For HD 1.2, the M1 projectile represents all HD 1.2.1 items, while the 40 mm projectile represents all HD 1.2.2 projectiles.

Thus, by using items that represent “worst” cases, the results can be applied to other, similar weapons in class. If calculations were made for an item that was not “worst case,” then the results obtained would only apply to that particular item. If SAFER analyses were performed with weapons that did not represent worst-case situations, then the results would be weapon specific and could not be applied to other weapons or situations.

*7. How were the nominal fragment blocking factors determined?*

The values are based on expert opinion by the Science Panel.

*8. Why is the PES damage considered before the primary fragments are blocked by the PES?*

This sequencing ensures that the predictions are never non-conservative.

*9. How were the relative component areas calculated?*

The relative component areas were determined by comparing the surface area of the component to the overall outer surface of the PES.

*10. How were the nominal mass distributions determined for each PES component?*

Some test data have been analyzed (SciPan1, Distant Runner Event 4, Distant Runner Event 5, Eskimo 1, 40/27 Tonne Trials). Where no test data were available, SAFER uses expert opinion by the Science Panel based on their years of experience.

*11. What are the nominal maximum throw ranges for each PES component based on?*

The nominal maximum throw ranges are based on available empirical data for:

- ISO Containers, Ships (ref 6)
- Concrete Operating Buildings (ref 7)
- ECM types (ref 8)
- HAS (ref 9)
- AGBS types (ref 10)

The maximum throw ranges for open, PEMB, and HCT are controlled by the primary fragment maximum throw range.

*12. How were the steel/concrete ratios for each PES component determined?*

Expert opinion by the Science Panel based on typical design of each PES type. In PES components where both steel and concrete are present, a conservative (high) estimate for the percentage of steel was made.

*13. What is the reasoning behind the dynamic mass distribution adjustment?*

There is a certain yield ( $Y_{100}$  in SAFER) at which all of the mass of a PES component becomes potential secondary debris. However, at yield levels beyond  $Y_{100}$ , the component would be expected to break-up in a different manner. As the yield gets higher, the component will tend to break up into smaller pieces. Therefore, the dynamic mass distribution allows SAFER to adjust the nominal mass distribution assigned to each PES component based on the yield entered by the user.

*14. On what are the weight-to-volume considerations based?*

Computer models, including SHOCK and FRANG (ref 11, 12), were used to account for the effects of weight-to-volume (W/V) on loads and initial debris velocity, and also to calculate a conservative estimate of debris throw distance. The Science Panel then used empirical data to establish maximum debris range.

*15. Why aren't all PES components dependent on weight-to-volume considerations?*

If a PES had no supporting test data, no weight-to-volume considerations were made. Test data are generally available for all heavier PES types.

*16. How were the volumes for each PES determined?*

The PES volumes were based on the component dimensions (volume = length \* width \* height), using rectilinear approximations when necessary.

*17. Why aren't crater ejecta considered for all PES types?*

Crater ejecta are not considered for ships, because it is assumed that the ship is in water. Ejecta are considered for all other PES types.

*18. What are the crater ejecta parameters based on?*

The Science Panel created equations based on available models and data. The parameters for these curves are stored in SAFER. The majority of the information was taken from recent literature (ref 13), CONWEP (ref 14), and test results. SAFER crater dimension estimates were shown to be reasonable (slightly on the conservative side) in a validation effort (see Figures 2- 10).

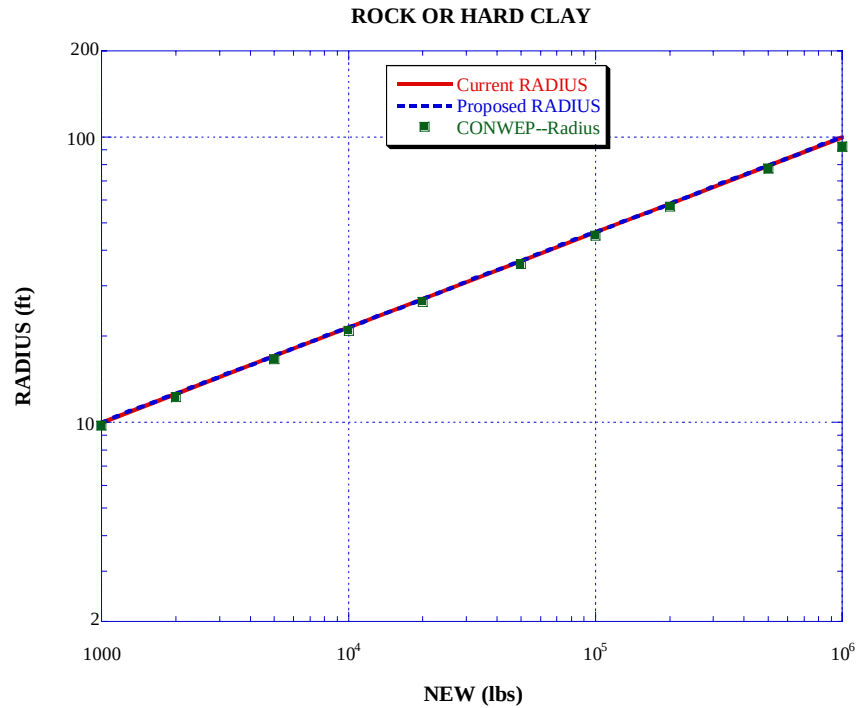


Figure 2. SAFER Crater Radius Prediction Validation (Rock or Hard Clay)

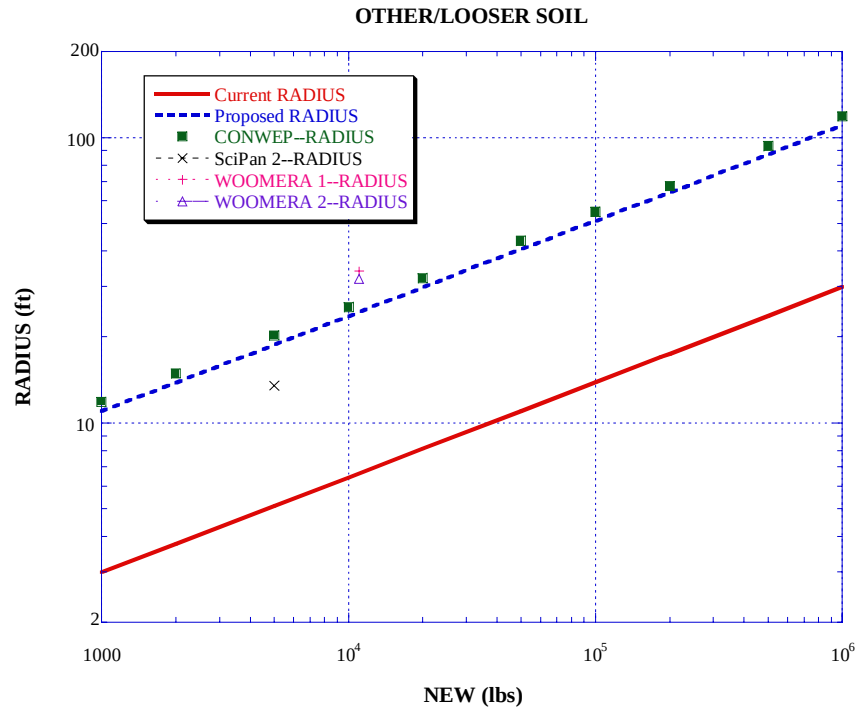


Figure 3. SAFER Crater Radius Prediction Validation (Looser Soils)

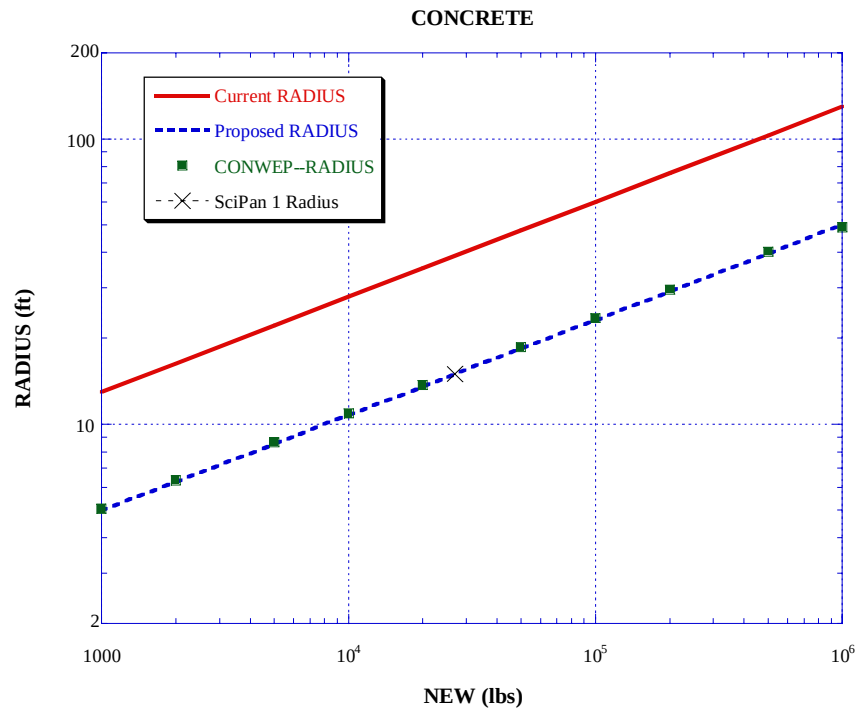


Figure 4. SAFER Crater Radius Prediction Validation (Concrete)

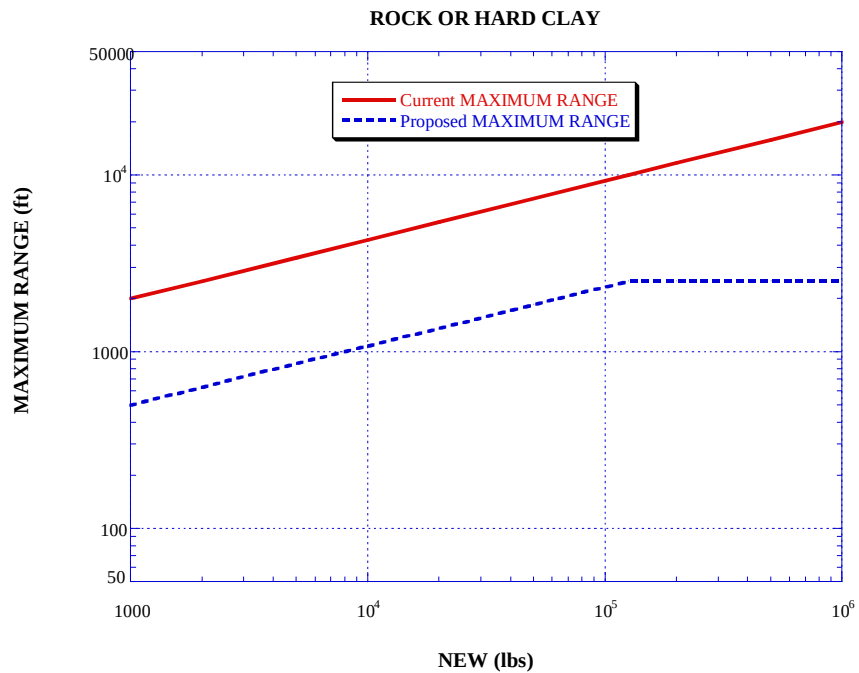


Figure 5. SAFER Maximum Crater Ejecta Range Prediction Validation (Rock or Hard Clay)

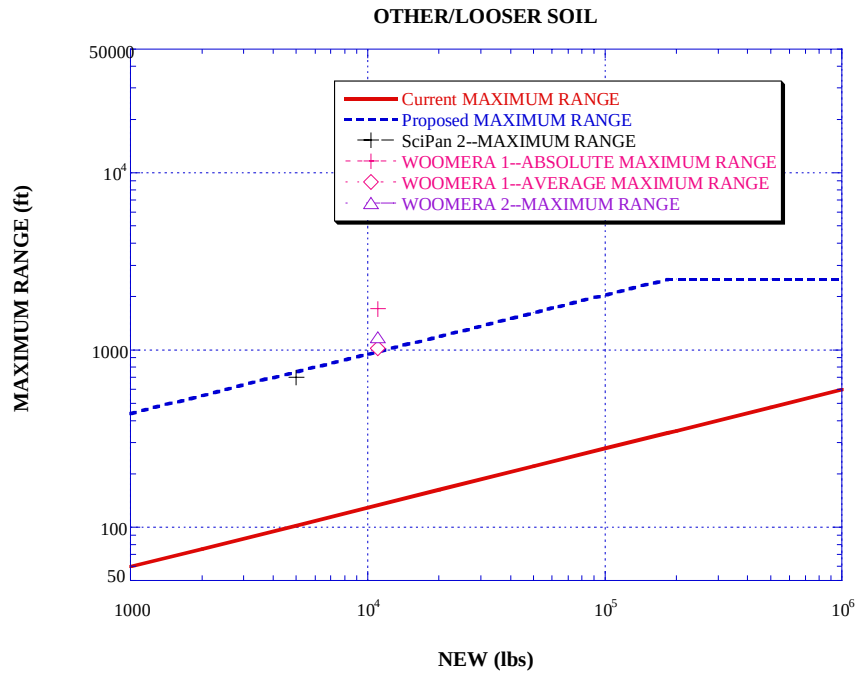


Figure 6. SAFER Maximum Crater Ejecta Range Prediction Validation (Looser Soil)

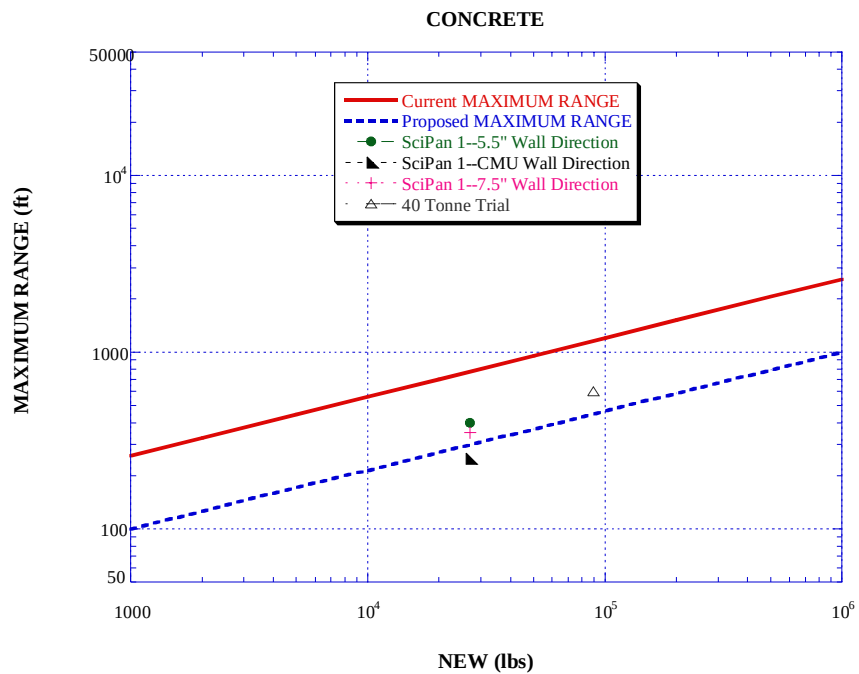


Figure 7. SAFER Maximum Crater Ejecta Range Prediction Validation (Concrete)

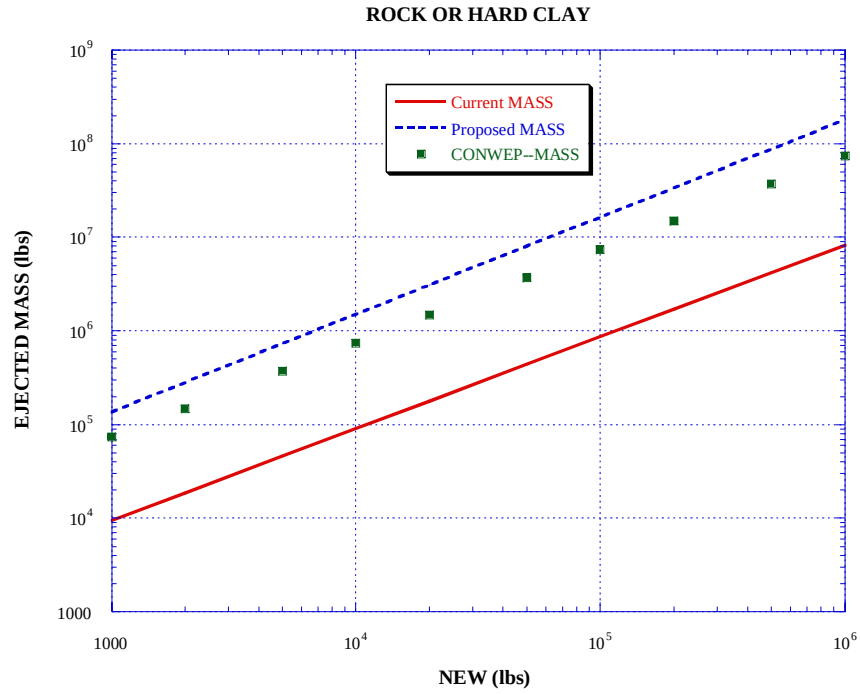


Figure 8. SAFER Crater Ejecta Mass Prediction Validation (Rock or Hard Clay)

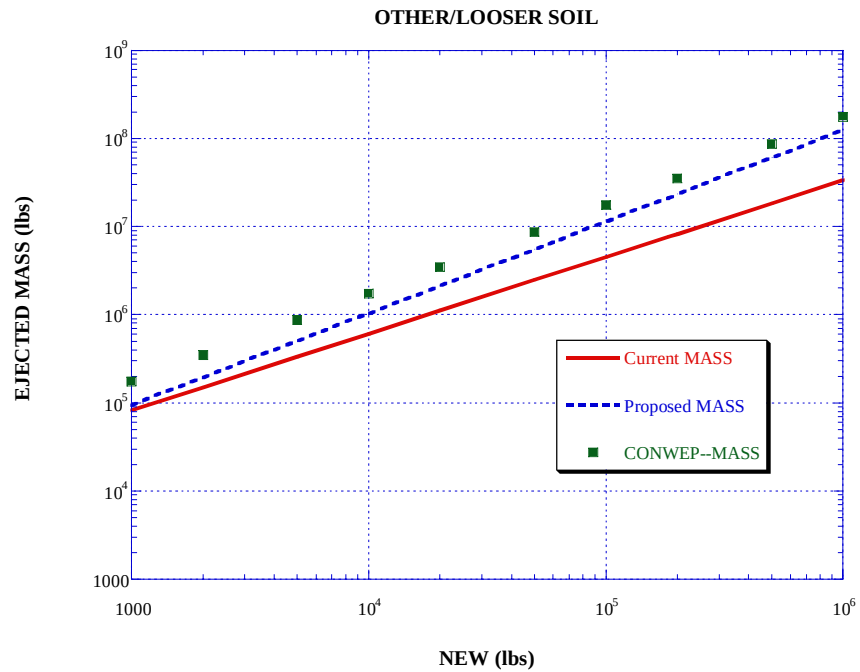


Figure 9. SAFER Crater Ejecta Mass Prediction Validation (Looser Soil)

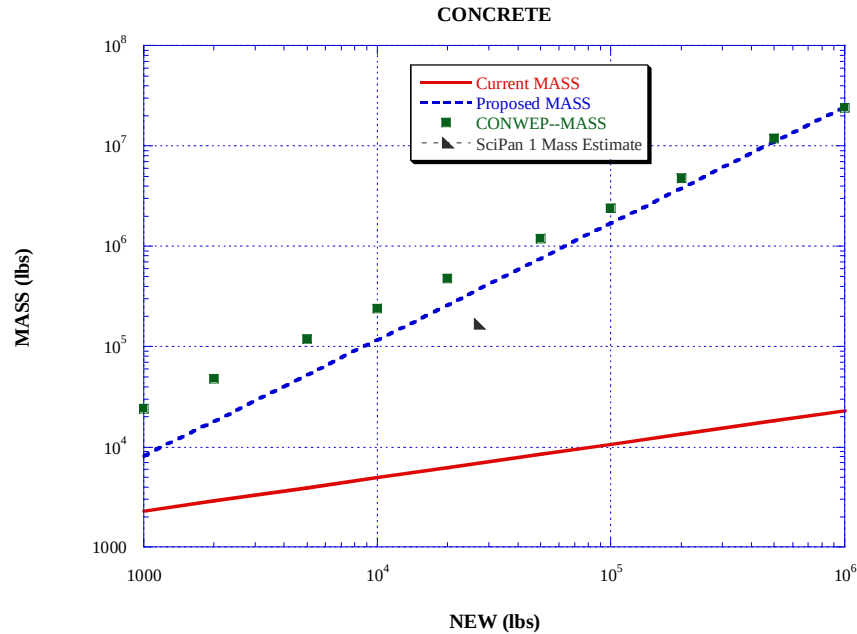


Figure 10. SAFER Crater Ejecta Mass Prediction Validation (Concrete)

19. *What is the basis for the high/low angle separation?*

For primary fragments, the Science Panel performed an initial trajectory analysis study using TRAJ (ref 4), and then revised the curves based on expert opinion and test data.

The Maximum Throw Range represents the  $3\sigma$  value. This means that there is a small, but finite, probability that there will be debris landing beyond the Maximum Throw Range when the ratio (Distance/Maximum Throw) is greater than 1. Because there is a finite probability that there will be debris beyond the Maximum Throw Range, the high/low angle separation of the total number of fragments at these extreme ranges still must be calculated (small for low angle trajectories and, consequently, large for high angle trajectories).

SAFER 3.1 assumes all secondary debris from the roof and all crater ejecta are high angle fragments. SAFER 3.1 further assumes that all fragments from the PES walls are low angle hazards. These assumptions are based on trajectory analysis and observation of test videos.

20. *Why is there a distinction among low-angle fragments?*

Some fragments that are falling at or near terminal velocity (but still have a horizontal component to their trajectory) will impact the walls of an ES rather than the roof. These are considered “side-impact” fragments. The remaining low-angle fragments are traveling with a dominant horizontal trajectory component and strike the ES walls at a potentially higher velocity. These are considered “fly-through” fragments.

21. *Why was the bivariate normal distribution chosen as the probability density function for high-angle and low-angle (side impact) debris?*



The use of the bivariate normal is the most common assumption that is used to model debris originating from an isotropic source. The ability to vary the dispersion makes it a versatile choice. The choice of a distribution for SAFER is very different than the choice of a distribution for a site-specific analysis. If the orientation of the building is known, for example, the characteristic “maltese cross” or cruciform pattern can be modeled. The problem is that the model is being developed for any site and therefore site-specific knowledge should not drive the choice of distributions. The fact that a specific set of debris data has visible patterns is an interesting point; to justify the use of some other distribution for that site, however, the proper data to evaluate for selecting the SAFER distribution would be debris from a large set of events with a random orientation in azimuth. The RBESCT Science Panel believes this would show that a bivariate normal is the most utilitarian choice.

22. *Have the arriving fragment tables been compared to test data?*

Yes. The arriving fragment densities predicted (ref 15) by SAFER have been compared against several test debris data sets. Figure 11 show a sample of the comparisons that are found in the reference.

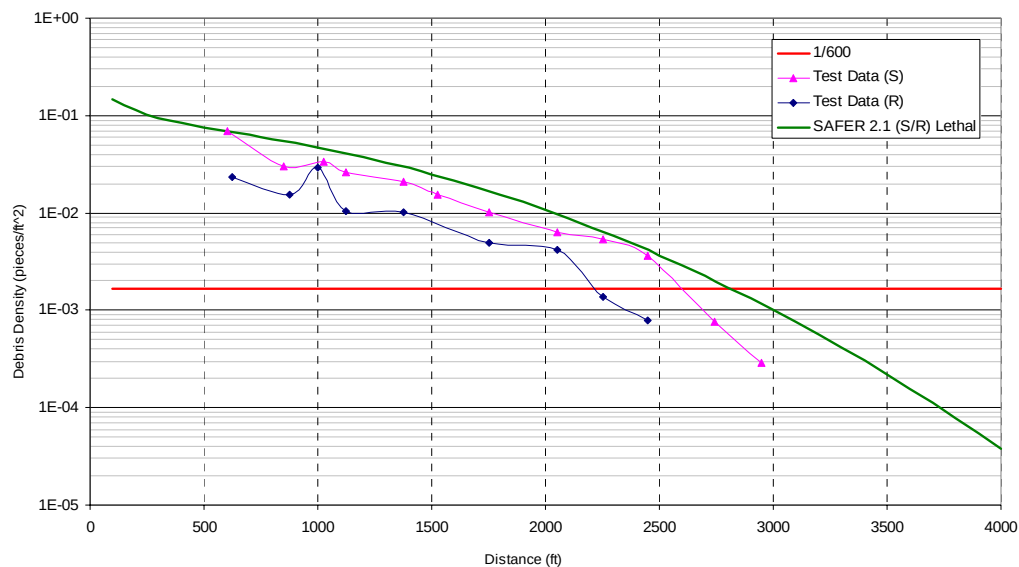


Figure 11. SAFER Debris Density Prediction Comparison to ESKIMO 1 Data

Note: The data in Figure 11 was compiled using SAFER Version 2.1.

23. *How were the “f” values derived and why are they not always equal for HAS and ECM?*

The “f” value allows SAFER to account for orientation effects. Essentially, it prevents most fragments from one side of a building from traveling across the event and out the other side. For example, pieces from the front wall of a PES would not be expected to fly in the rearward direction, and vice-versa. The Science Panel assessed the “f” values on a component-by-component basis that accounted for the PES volume, PES component dimensions, and asymmetry considerations. Therefore, HAS component “f” values and ECM components “f” values would not necessarily be the same.

24. *How are the maximum throw values and  $\sigma$  related?*

They are related by the equation: maximum throw =  $n * \sigma$ . The “n” value is thus a measure of the spread of the data.

The n values were selected based on test data and expert opinion. The value of 3 (for all fragment types other than crater ejecta) is the standard value. The value of 4 (for crater ejecta) reduces the calculated sigma and is based on test data (ref 16) that indicates a higher close-in density and the occasional "rogue" fragment found in testing that was not representative of the typical ejecta.

25. *How are the mass-based fragment tables converted to kinetic energy tables?*

For high-angle fragments and side-impact low-angle fragments, the mass-based fragment tables are converted to KE tables by using the terminal velocity for the material type in question. Concrete fragments and crater ejecta convert directly from mass to KE bins, whereas steel fragments are one bin higher because of their increased terminal velocity.

For fly-through low-angle fragments, the mass-based fragment tables are converted to KE tables by using the calculated impact velocity for the material type in question at that range.

26. *Why is terminal velocity assumed?*

Terminal velocity is assumed for high-angle fragments and side-impact low-angle fragments because they are considered to be falling from a sufficient elevation to achieve such a velocity (due to being lobbed from the donor to the ES).

27. *What are the  $\Delta KE$  values for walls and roofs based on?*

These values were provided by ACTA (ref 15) and are being tested as part of the SPIDER program (ref 17).

28. *How were the invulnerable areas determined?*

These values were provided by ACTA (ref 18) and expert opinion by the Science Panel.

29. *What is the basis for the probability of a hit?*

When fragments and/or debris are ejected it is often necessary to calculate the probability of their impacting a particular target. Work by Klein and Hackett (ref 19, 20) give the hit probability equation as:

$$P = 1 - \exp^{(-q * A_T)}$$

where,

P = Probability of hit

q = Areal density of fragments (number of fragments per area) at the range and direction of the target

$A_T$  = Area of target

Note: q and  $A_T$  must be in consistent units

30. Why was the fatality versus kinetic energy curve that is used by SAFER chosen?

The primary reason is that another government agency (the Range Commanders Council) had previously considered this issue in some detail. Their research had established a commonality method that has been adopted by several agencies as an industry standard (ref 21). After the RBESCT reviewed their research, the same approach was adopted.

31. What is the basis of the barricade logic?

The purpose of the barricade logic is to determine the percentage of low angle (PES wall) fragments that are blocked by the barricade. This is done by determining the percentage of fragments ejected at even increments of PES height that are blocked assuming that all ejected fragments would hit the ES if not for the presence of the barricade.

At each height increment, a number of angles are computed as shown in **Error! Reference source not found.** (all are measured from zenith). These angles are used for two purposes: first, to determine the shift required to focus all low angle (PES wall) fragments onto the ES, and then to compute the percentage of the possible ejection angles that would be blocked by the barricade. After the blocked percentage is computed for each height increment, the percentage blocked is averaged over the entire height of the PES to determine the barricade effectiveness at blocking low angle PES fragments. The section below provides the equations used.

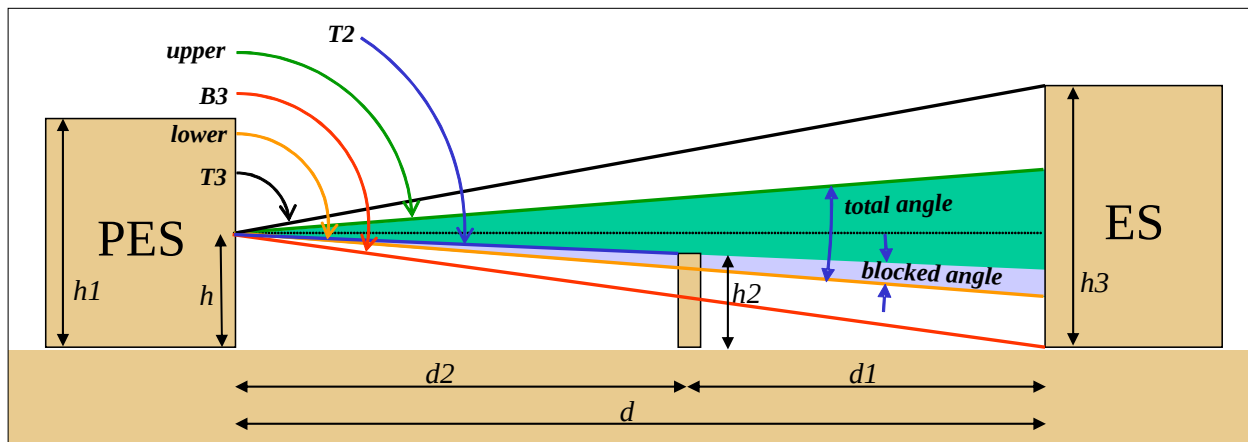


Figure 12. Question 31 – Parameters used by Blocking Algorithm

Starting at  $h=0$  and proceeding until the height of the PES ( $h_1$ ) is reached, compute:

$$T3 = \text{ACOS}[ (h_3-h) / \sqrt{d^2 + (h_3-h)^2} ] = \text{angle to the top of the ES}$$

$$B3 = \text{ACOS}[ -h / \sqrt{d^2 + h^2} ] = \text{angle to the base of the ES}$$

$$T2 = \text{ACOS}[ (h_2 - h) / \sqrt{d^2 + (h_2 - h)^2} ] = \text{angle to the top of the barricade}$$

$$\text{upper} = \text{IF}[ B3 < 90 + \frac{1}{2}\text{angle}, \text{Max}(B3 - 2 * \frac{1}{2}\text{angle}, T3), \text{Max}(90 - \frac{1}{2}\text{angle}, T3) ]$$

= upper projection angle of fragments from the PES to the ES

$$\text{lower} = \text{IF}[ T3 > 90 - \frac{1}{2}\text{angle}, \text{Min}(T3 + 2 * \frac{1}{2}\text{angle}, B3), \text{Min}(90 + \frac{1}{2}\text{angle}, B3) ]$$

= lower projection angle of fragments from the PES to the ES

total angle = lower – upper = equals the span of angles at which fragments are ejected

$$\text{blocked angle} = \text{Max}[ 0, \text{lower} - \text{max}(T2, \text{upper}) ]$$

$$\text{local reduction} = \text{Max}[ 0, \text{blocked angle} / \text{total angle} ]$$

When the top of the PES ( $h_1$ ) is reached, the Total Reduction due to the barricade is calculated by:

$$\text{Total Reduction} = [ \sum \text{local reductions} ] / \# \text{ height increments}$$

= the average local reduction

The Total Reduction is then used to reduce the number of fly-through fragments departing the PES by:

For  $j = 1$  to 7

Arriving debris mass table  $j$ :

For  $n = 1$  to 10

$$\text{Bin } n: N_{af}' = N_{af} * (1 - \text{Total Reduction})$$

Next  $n$ ,

Next  $j$ .

## Attachment 9 - Uncertainty

## **An Analytic Approach for Treating Uncertainty in Probabilistic Risk Assessments**

*Presenter: Richard W. Mensing, Ph.D., Analytics International Corp., P. O. Box 35,  
Mount Vernon, VA 22121-0035, 916.408.1531, fax 703.360.1342, rwmensing@prodigy.net*

### **Abstract**

When performing probabilistic risk assessments and estimating Risk, it is necessary to recognize and properly account for both random variations (aleatory uncertainties) and epistemic uncertainties. To do this, the analysis generally involves extensive computer calculations and simulations including sampling from probability and uncertainty distributions. Occasionally, such extensive computations can be avoided if some simplifying assumptions can reasonably be made. This paper outlines a statistically rigorous analytical approach for estimating Risk and Risk uncertainty when such assumptions are justifiable. The approach, albeit tedious, can be executed on a spreadsheet without the use of simulations. It is illustrated for a risk analysis of fatalities for operations involving explosives in structures at military facilities.

Dr. Mensing has more than 30 years of experience in educational and research environments in theoretical and applied statistics and probability. For more than 15 years, his primary focus has been in risk/safety/ hazard analysis, including methods, model development and applications. He also was involved in the development and application of formal expert elicitation techniques, when little or no data is available, for deriving model inputs for risk analyses.

### **Introduction**

The principal element of a quantitative probabilistic risk assessment (PRA) of a potential catastrophic situation is the estimation of Risk, i.e., the expected value of loss due to the occurrence of a catastrophic event. An example is the estimation of the expected number of fatalities at exposed sites (ESs) due to the occurrence of an explosive event at a potential explosion site (PES) within a military facility. Recognizing that the occurrence of the catastrophic event (explosive event) and the loss (number of fatalities) are aleatory (random) variables, Risk (R) is commonly quantified by:

$$R = (\text{Expected number of occurrences of the catastrophic event per risk period}) \times (\text{Expected value of loss per occurrence}).$$

When quantifying Risk, it is important to recognize that the expected values in the definition of Risk are generally not known with certainty. Hence, it is important that this knowledge, or epistemic, uncertainty be identified and quantified as part of the Risk estimation process. In a previous paper,<sup>1</sup> a two-phased simulation methodology for estimating Risk, which accounted for both the inherent random variations of the risk environment and the epistemic uncertainties inherent to the estimation process, was outlined. If simulations are not practical, it may be possible, if

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<sup>1</sup> Mensing, R. W. and A. D. Barondes, "Treatment of Uncertainty in the Estimation of Risk," *Proceedings of the 30<sup>th</sup> U. S. DoD Explosives Safety Seminar*, Atlanta, GA, 2002. Distribution Statement A: Approved for public release; distribution is unlimited.

reasonable assumptions can be made, to develop an analytical approach to estimating Risk. This paper outlines such an analytical approach, recognizing both aleatory (random) variation and epistemic (knowledge and modeling) uncertainties, for developing point and bounding estimates of Risk. The approach is illustrated for estimating the Risk, i.e., expected number of fatalities at exposed sites (ESs), associated with the occurrence of an explosive event at a potential explosion site (PES).

## **Risk Estimation**

The process of estimating Risk involves a number of steps when both the random variations inherent to the risk scenario and the uncertainties associated with modeling such a scenario are recognized. The first step in the Risk estimation process is development of a mathematical/probabilistic model of the environment and risk source of interest, i.e., to develop a model of the physical situation of interest, referred to as the model of the world (MOW). The MOW includes deterministic models, e.g., structural models, as well as probabilistic models, e.g., occurrence of the catastrophic event, magnitude of the event, extent of structural damage, magnitude of loss, etc. Such an MOW forms the basis for estimating Risk. An example of a risk scenario is the risk associated with operations, e.g., storage or maintenance, involving explosives at sites within a military facility. For this scenario one risk of interest is the number of fatalities at exposed sites (ESs) within the vicinity of a potential explosion site (PES). For this case, the MOW would include models of:

- Physical characteristics of the ES and PES structures,
- Temporal distributions of the quantity of explosives at the PES and the number of personnel at the ES,
- Occurrence and magnitude of explosive events at the PES,
- Severity of the explosive effects at the ES,
- Occurrence of fatalities at the ES.

A reasonable MOW could be based on the following assumptions:

1. Risk period:

Generally, the risk period of interest is a 'typical' calendar year (365 days or 8760 hours). Because explosive materials may not be present at a PES during the entire year, the time explosives are present in the PES in a 'typical' year will vary between different types of sites and facilities. For example, a 'typical' year for a long-term storage site is likely to involve explosive materials being in the site all year. On the other hand, for a maintenance site in which operations may go on only 8 hours a day, 5 days a week, explosives may only be present approximately 24 percent of the year.

2. The quantity of explosive materials or net explosive weight (NEW) at a PES and the number of exposures (E) at an ES:

When present, the operational quantity of explosives at a PES, denoted NEW, is assumed to be constant. However, for some sites, it is assumed that there could be some day-to-

day variation in the NEW involved in the operations. It is assumed that the amount of NEW will affect both the probability of an explosive event occurring and, given the event occurs, the probability that an individual at an ES is a fatality. The effect of the day-to-day variation on the probability an explosive event occurs is assumed to be described by a lognormal distribution  $(0, \sigma_{\text{NEW1}})$  [see Item 3 below]. The effect of the day-to-day variation on the probability of a fatality, when an explosive event occurs, is also assumed to be described by a lognormal distribution  $(0, \sigma_{\text{NEW2}})$  [see Item 5 below].

The number of exposures,  $E$ , in an ES is assumed to be constant throughout the fraction of the operating year when exposures are present except for some day-to-day variation. The temporal random variation in  $E$  between days is assumed to have a lognormal probability distribution. The parameters of the distribution are a fixed number of exposures, considered to be the median daily number of exposures,  $E_o$ , and the standard deviation,  $\sigma_e$ , of the logarithm of a multiplicative factor,  $\delta_e$ , describing the day-to-day variation in the number of daily exposures,  $E$ . Thus  $E$  is modeled as

$$E = E_o * \delta_e$$

where  $\delta_e$  is a lognormal random variable with parameters  $(0, \sigma_e)$ . It is assumed that, in some situations, the day-to-day variation of  $E$  would affect the expected number of explosive events,  $\lambda$ . The effect of this day-to-day variation on the probability an explosive event occurs is assumed to be described by a lognormal distribution  $(0, \sigma_{e1})$  [see Item 3 below].

The effects of the random variation of the quantity of explosives at the PES and the number of exposures at the ES are assumed to be correlated random variables [see Item 3 below].

### 3. Occurrence of an explosive event at a PES:

Explosive events at a PES are assumed to occur at ‘random’ throughout the ‘operating’ year of a PES (where operating time refers to time when explosives are present at the PES and the potential exists for an explosive event to occur). Thus, the number of explosive events per operating year is assumed to follow a Poisson distribution with parameter  $\lambda$ , the expected number of explosive events per operating year. [Note: Given the Poisson assumption, the probability that exactly one event occurs per year is  $\lambda e^{-\lambda}$  ( $\approx \lambda$ )] If explosives are present for only a fraction of a calendar year, the expected number of explosive events per ‘typical’ year would be the fraction times  $\lambda$ . It is assumed that the expected number of explosive events per year, denoted by  $\lambda$ , refers to the adjusted value of  $\lambda$ , i.e., the expected number of explosive events per ‘typical’ year.

For each type of site, e.g., maintenance or storage, there may be circumstances that would cause the expected number of explosive events at a particular site to vary from the nominal expected number. This is modeled by a multiplicative scaling factor,  $S$ , applied to the nominal  $\lambda$  for the appropriate facility type. Examples are facilities located outside the CONUS or facilities at which the explosives are exposed to the environment.

If loss is the number of fatalities among an exposed population (exposures) at an ES, the consequence of the explosive event is significant, i.e., fatalities may occur, only if the exposures are present at the time of the explosive event. Thus, if exposures are present



for a fraction,  $\Delta t$ , of time explosives are present at a PES,  $\Delta t$  represents the portion of the operating year when the loss could be greater than zero. For example, suppose the PES is a maintenance site operating 8 hours a day, 5 days of the week, and exposures are present in the ES during the same hours of the year. Then,  $\Delta t = 1$ . Alternatively, if explosives are present at the PES 16 hours a day, 5 days a week, and exposures are present at an ES for 8 hours a day, 5 days a week, then,  $\Delta t = 0.5$ . Note that it is assumed that  $\lambda$  has been adjusted to account for the 24 percent of the year the explosives are present in the PES.

During the portion of the year when explosives are present at the PES and exposures are present at the ES, the expected number of explosive events,  $\lambda$ , is assumed to be a function of NEW and E, and hence a temporal random variable. It is assumed that the random variation in  $\lambda$  is modeled by a lognormal distribution. Hence,  $\lambda$  is modeled as:

$$\lambda = \lambda_o * \delta_{NEW1} * \delta_{e1}$$

where  $\lambda_o$  is the nominal value of the expected number of explosive events per typical year, assumed to be the median value of  $\lambda$  and  $\delta_{NEW1}$ ,  $\delta_{e1}$  are the joint random effects of NEW and E, modeled by a joint lognormal distribution  $[(0,0); \sigma_{NEW1}, \sigma_{e1}, \rho_{Ne}]$ , where  $\rho_{Ne}$  represents the correlation between the logarithms of  $\delta_{NEW1}$  and  $\delta_{e1}$

#### 4. Effects of the Explosive Event at an ES

Given an explosive event, the yield and all effects, i.e., overpressure and impulse, glass breakage, building collapse and debris, are random variables. The effect of the random variation in yield and individual effects on the probability of a fatality, when an explosive event occurs, is assumed described by lognormal distributions [See Item 5 below]

#### 5. Number of Fatalities at an ES

Given an explosive event, the number of fatalities at an ES is assumed to be a binomial random variable with parameters  $n = E$ ,  $p = p_{fle}$ , which is a function of the probabilities of a fatality,  $p_{f|k}$ ,  $k=1,2,3,4$ , associated with the four effects. The probability  $p_{fle}$  is the probability that an individual is a fatality due to at least one of the effects, i.e.,

$$\begin{aligned} p_{fle} &= p_{f|1} + (1 - p_{f|1}) * p_{f|2} + (1 - p_{f|1}) * (1 - p_{f|2}) * p_{f|3} + (1 - p_{f|1}) * (1 - p_{f|2}) * (1 - p_{f|3}) * p_{f|4} \\ &= \sum_k p_{f|k} - \sum_{i \neq k} p_{f|i} p_{f|k} + \sum_{i \neq j \neq k} p_{f|i} p_{f|j} p_{f|k} - \prod_k p_{f|k} \end{aligned}$$

Each of the probabilities,  $p_{f|k}$ , is a function of NEW, yield and the corresponding effect. The variation in each of the probabilities,  $p_{f|k}$ , due to the random variation in yield and the corresponding effect, as well as the day-to-day variation in NEW, is assumed to have a distribution, which is approximated by a lognormal probability distribution. Specifically, it is assumed that:

$$p_{f|k} = p_{f|ko} * \delta_k * \delta_y * \delta_{NEW2}$$

where  $p_{f|ko}$  is the median value of  $p_{f|k}$ ,  $\delta_k$  is the variation due to the random variation in the  $k^{th}$  effect,  $\delta_y$  is the variation due to the random variation in yield and  $\delta_{NEW2}$  is the variation due to the day-to-day variation in NEW. The multiplicative factor,  $\delta_k$  has a lognormal distribution with parameters  $(0, \sigma_k)$ ,  $\delta_y$  has a lognormal distribution with parameters  $(0, \sigma_y)$  and  $\delta_{NEW2}$  has a lognormal distribution with parameters  $(0, \sigma_{NEW2})$ . The three multiplicative factors are assumed to be independent.

## 6. Correlations

Because  $\lambda$  and  $p_{f|k}$  are both functions of the random variable NEW, it is possible that these random variables are themselves correlated. This would be modeled by assuming that the effects of the random variation of NEW on  $\lambda$  and  $p_{f|k}$ ,  $\delta_{NEW1}$  and  $\delta_{NEW2}$ , respectively, are correlated. However, the variable  $\lambda$  characterizes the occurrence of an explosive event, whereas  $p_{f|k}$  relates to the probability of a fatality given an event occurs. It seems reasonable that the effect of the temporal random variation in NEW will not necessarily translate in a linearly related way relative to the random variation in  $\lambda$  and  $p_{f|k}$ . Thus, the model assumes the effects of the random variation in NEW on  $\lambda$  and  $p_{f|k}$ , respectively, are independent.

Since  $\lambda$  is a function of the random variable E, it is assumed that, as random variables,  $\lambda$  and E are correlated. The correlation is modeled by assuming that there is a linear relation between the logarithm of the  $\delta$  terms characterizing the effects of the random temporal variation in the number of exposures at an ES. Specifically, it is assumed that  $\ln \delta_{e1} = r \ln \delta_e$ , where  $r$  is the ratio of the standard deviations of the two logarithms, i.e.,  $r = \sigma_{e1}/\sigma_e$ .

The above assumptions form the basis for developing the MOW.

The second step of the risk estimation process is quantifying the MOW. The MOW involves a number of probability distributions each with its appropriate parameters. Thus, quantification of the MOW involves specifying models and values for the model parameters. Generally there is uncertainty associated with specifying the models and values of the parameters due to incomplete information. Therefore, in addition to specifying the MOW, it is necessary to quantify the knowledge or epistemic uncertainties associated with creating the MOW. This could include allowance for more than one version of a deterministic model (e.g., structure) or for an expression of the uncertainties associated with specifying the values of the model parameters (e.g., the parameters of the probability distributions describing the random variation modeled in the MOW).

The following assumptions are made regarding epistemic uncertainties associated with developing the MOW for the risk analysis of explosive events at a PES. The illustration is limited to assuming the principal uncertainty in specifying the probability models in the MOW is the state of knowledge about values of parameters and values of the median of a lognormal random variable:

1. The epistemic uncertainty associated with evaluating  $\lambda_o$ , the median expected number of explosive events per 'typical' year, is reasonably described by a lognormal distribution. The parameters of the uncertainty distribution are the median,  $\lambda_{oo}$ , and the standard deviation,  $\sigma_{\lambda o}$ , of the logarithm of a multiplicative factor,  $\delta_{\lambda o}$ . Thus, the uncertainty in  $\lambda_o$  is described in terms of the identity:

$$\lambda_o = \lambda_{oo} * \delta_{\lambda o}$$

where  $\delta_{\lambda o}$  has a lognormal uncertainty distribution with parameters (0,  $\sigma_{\lambda o}$ ).

2. The epistemic uncertainty associated with assessing the appropriate value of the scaling factor,  $S$ , is reasonably described by a lognormal distribution. The parameters of the uncertainty distribution are the median of  $S$ ,  $S_o$ , and the standard deviation,  $\sigma_s$ , of the logarithm of a multiplicative factor,  $\delta_s$ . Thus, the uncertainty in  $S$  is described in terms of the identity:

$$S = S_o * \delta_s$$

where  $\delta_s$  has a lognormal uncertainty distribution with parameters  $(0, \sigma_s)$ .

3. The epistemic uncertainty associated with evaluating  $\Delta t$ , the fraction of the operating year that exposures are present in the ES, is reasonably described by a lognormal distribution. The parameters of the uncertainty distribution are the median of  $\Delta t$ ,  $\Delta t_o$ , and the standard deviation,  $\sigma_{\Delta t}$ , of the logarithm of a multiplicative factor,  $\delta_{\Delta t}$ . Thus, the uncertainty in  $\Delta t$  is described in terms of the identity:

$$\Delta t = \Delta t_o * \delta_{\Delta t}$$

where  $\delta_{\Delta t}$  has a lognormal uncertainty distribution with parameters  $(0, \sigma_{\Delta t})$ .

4. The epistemic uncertainty associated with evaluating the median number of daily exposures in an ES,  $E_o$ , is reasonably described by a lognormal distribution. The parameters of the uncertainty distribution are the median value,  $E_{oo}$ , and the standard deviation,  $\sigma_{E_o}$ , of the logarithm of a multiplicative factor,  $\delta_{E_o}$ . Thus, the uncertainty in the median  $E_o$  is de-scribed in terms of the identity:

$$E_o = E_{oo} * \delta_{E_o}$$

where  $\delta_{E_o}$  has a lognormal uncertainty distribution with parameters  $(0, \sigma_{E_o})$ .

5. For each of the four effects,  $k = 1,2,3,4$ , the epistemic uncertainty associated with evaluating the median of the probability of a fatality due to effect  $k$ ,  $p_{f|k,o}$ , is assumed to be based on uncertainty in modeling the effects as well as uncertainty in assessing the median yield of the explosive event. The overall epistemic uncertainty in  $p_{f|k,o}$  is reasonably described by a lognormal distribution. The parameters of the uncertainty distribution are the medians of  $p_{f|k,o}$ ,  $p_{f|k,oo}$ , and the standard deviations,  $\sigma_{k_o}$  and  $\sigma_{y_o}$ , of the logarithm of multiplicative factors,  $\delta_{k_o}$  and  $\delta_{y_o}$ , respectively. That is, the epistemic uncertainty in specifying the median  $p_{f|k,o}$  can be described in terms of the identity:

$$p_{f|k,o} = p_{f|k,oo} * \delta_{k_o} * \delta_{y_o}$$

where  $\delta_{k_o}$  has a lognormal uncertainty distribution with parameters  $(0, \sigma_{k_o})$  and  $\delta_{y_o}$  has a lognormal uncertainty distribution with parameters  $(0, \sigma_{y_o})$ . It is assumed that the effects of the uncertainties in assessing the median yields on the median probabilities of a fatality, modeled by  $\delta_{y_o}$ , are independent between the different effects.

## Analytical Approach

Given the MOW and descriptions of the epistemic uncertainties, the third step of the Risk estimation process is evaluation of the estimate of Risk. Because of the complexity of the analysis, the most common approach is based on sampling from epistemic uncertainty distributions and MOW models and performing computer simulations to estimate Risk. Alternatively, based on the reasonableness of the simplifying assumptions, an analytical expression may be developed.

The analytical approach to estimating Risk is based on starting with the generally accepted definition of Risk or the expected value of loss, e.g., the expected number of fatalities per risk period. For example, consider a scenario in which a catastrophic event occurs as a Poisson ( $\lambda$ ) event over time and, given an event occurs, the number of fatalities due to the event is reasonably modeled as a binomial ( $n, p$ ) random variable. The parameter  $n$  is the number of exposures and  $p$  is the probability that an individual is a fatality. In this scenario the Risk,  $F$ , i.e., the expected number of fatalities per risk period is

$$F = \lambda * n * p$$

Since  $F$  is a function of the parameters of the probability distributions describing the random variation, it can be evaluated if the values of the parameters are known with certainty. However, these values are seldom known with certainty. They are generally subject to knowledge (epistemic) uncertainty. Given the uncertainty associated with the models and model parameters,  $F$  can be treated as an epistemic uncertain variable. That is,  $F$  can be treated as a Risk estimator. The epistemic uncertainty distribution of  $F$ , comparable to the sampling distribution of an estimator in statistical estimation, provides a basis for developing point and bounding estimates of Risk. In particular, the epistemic expected value and standard deviation of  $F$  can be assessed. These parameters, along with specification of an appropriate distribution family for the uncertainty distribution, provide point and uncertainty bound estimates of Risk for PRAs. Specifically, the expected value of the epistemic uncertainty distribution of  $F$  provides a point estimate of Risk and the appropriate percentiles of the uncertainty distribution provide bounding estimates of Risk.

To illustrate development of such estimates, consider the estimation of Risk at ES due to explosive events at a PES containing explosives, as modeled in the previous section. Based on the assumptions outlined in the previous section, for fixed values of the random variables,  $E$ ,  $NEW$ , yield and effects, the conditional expected number of fatalities per year is

$$F = \Delta t * S * \lambda(NEW, E) * p_{fle}(NEW, \text{yield}, \text{effects}) * E \quad (1)$$

Risk, i.e., the (unconditional) expected number of fatalities per year, is the expected value of  $F$ , taken with respect to the distributions of the random variables. Thus, Risk is

$$EF = \Delta t * S * E(\lambda * E) * E(p_{fle}) \quad (2)$$

The notation  $E(.)$  refers to the expected value of the respective random variable (or uncertain model parameter). Based on the assumptions outlined in the previous section,

$$E(\lambda * E) = \lambda_o * E_o * \exp[0.5(\sigma_{NEW1}^2 + (r+1)^2 * \sigma_e^2 + 2(r+1) * \rho_{Ne} * \sigma_{NEW1} * \sigma_e)] \quad (3)$$

$$E(p_{f|e}) = \sum_k p_{f|k,o} \exp(0.5 \sigma_{k1}^2) - \sum_{i \neq k} p_{f|i,o} p_{f|k,o} \exp(0.5 \sigma_{ik}^2) + \sum_{i \neq j \neq k} p_{f|i,o} p_{f|j,o} p_{f|k,o} \exp(0.5 \sigma_{ijk}^2) - \{\prod_k p_{f|k,o}\} \exp(0.5 \sigma_{1234}^2) \quad (4)$$

Notationally,

$$\begin{aligned} \sigma_{k1}^2 &= \sigma_k^2 + \sigma_y^2 + \sigma_{NEW2}^2 \\ \sigma_{ik}^2 &= \sigma_i^2 + \sigma_k^2 + 4(\sigma_y^2 + \sigma_{NEW2}^2) \\ \sigma_{ijk}^2 &= \sigma_i^2 + \sigma_j^2 + \sigma_k^2 + 9(\sigma_y^2 + \sigma_{NEW2}^2) \\ \sigma_{1234}^2 &= \sum_k \sigma_k^2 + 16(\sigma_y^2 + \sigma_{NEW2}^2). \end{aligned}$$

If the values of the parameters in Equations (2) through (4) are known without (epistemic) uncertainty, these identities provide the value of Risk. Given this is not the case, it is appropriate to develop estimates of Risk, which recognize the uncertainties associated with assessing Risk.

Given that the parameters,  $\Delta t$ ,  $S$  and the median values  $\lambda_o$ ,  $E_o$ , and the  $p_{f|k,o}$ ;  $k=1,2,3,4$  are subject to epistemic uncertainty, the expression of  $EF$  in Equation (2) through (4) identifies an (epistemic) estimator of Risk. The epistemic uncertainty is quantified by the uncertainty distribution of the estimator  $EF$ . Based on risk estimation with uncertainty, a point estimate of Risk is the expected value of the estimator  $EF$ , i.e., the expected value of the uncertainty distribution. The epistemic variance of  $EF$  provides a basis for developing uncertainty bound/interval estimates of Risk. The following are the expected value and variance of the uncertainty distribution based on assuming epistemic uncertainty in the parameters  $\Delta t$ ,  $S$ ,  $\lambda_o$ ,  $E_o$  and the  $p_{f|k,o}$ ;  $k=1,2,3,4$  as outlined in the previous section.

## 1. Expected Value

Based on the epistemic uncertainty models outlined in the previous section and assuming independence between the epistemic uncertainties of the four terms in  $EF$ , the expected value of the uncertainty distribution of the epistemic estimator  $EF$ , denoted,  $E_{ep}(EF)$ , is

$$\begin{aligned} E_{ep}(EF) &= E_{ep}(\Delta t) * E_{ep}(S) * E_{ep}[E(\lambda * E)] * E_{ep}[E(p_{f|e})] \\ &= \Delta t_o * \exp(0.5 \sigma_{\Delta t}^2) * S_o * \exp(0.5 \sigma_S^2) * E_{ep}[E(\lambda * E)] * E_{ep}[E(p_{f|e})]. \end{aligned}$$

The individual expected values are

$$\begin{aligned} E_{ep}(\Delta t) &= \Delta t_o * \exp(0.5 \sigma_{\Delta t}^2) \\ E_{ep}(S) &= S_o * \exp(0.5 \sigma_S^2) \\ E_{ep}[E(\lambda * E)] &= \lambda_{oo} * E_{oo} * \exp[0.5(\sigma_{\lambda_o}^2 + \sigma_{E_o}^2 + \sigma_{NEW1}^2 + (r+1)^2 \sigma_e^2 + \\ &2(r+1) * \rho_{Ne} * \sigma_{NEW1} * \sigma_e)] \\ E_{ep}[E(p_{f|e})] &= \sum_k p_{f|k,oo} * \exp[0.5(\sigma_{k1}^2 + \sigma_{ko1}^2)] - \sum_{i \neq k} p_{f|i,oo} * p_{f|k,oo} \\ &* \exp[0.5(\sigma_{ik}^2 + \sigma_{iko}^2)] + \sum_{i \neq j \neq k} p_{f|i,oo} * p_{f|j,oo} * p_{f|k,oo} * \exp[0.5(\sigma_{ijk}^2 + \sigma_{ijk_o}^2)] - \\ &(\prod_k p_{f|k,oo}) * \exp[0.5(\sigma_{1234}^2 + \sigma_{1234_o}^2)]. \end{aligned}$$

The variances in the identity for  $E_{ep}[E(p_{f|e})]$  are respectively

$$\begin{aligned}\sigma_{k1}^2 &= \sigma_k^2 + \sigma_y^2 + \sigma_{NEW2}^2 \\ \sigma_{ko1}^2 &= \sigma_{ko}^2 + \sigma_{yo}^2 \\ \sigma_{ik}^2 &= \sigma_i^2 + \sigma_k^2 + 4(\sigma_y^2 + \sigma_{NEW2}^2) \\ \sigma_{iko}^2 &= \sigma_{io}^2 + \sigma_{ko}^2 + 4\sigma_{yo}^2 \\ \sigma_{ijk}^2 &= \sigma_i^2 + \sigma_j^2 + \sigma_k^2 + 9(\sigma_y^2 + \sigma_{NEW2}^2) \\ \sigma_{ijko}^2 &= \sigma_{io}^2 + \sigma_{jo}^2 + \sigma_{ko}^2 + 9\sigma_{yo}^2 \\ \sigma_{1234}^2 &= \sum_k \sigma_k^2 + 16(\sigma_y^2 + \sigma_{NEW2}^2) \\ \sigma_{1234o}^2 &= \sum_k \sigma_{ko}^2 + 16\sigma_{yo}^2\end{aligned}$$

## 2. Variance

Based on the epistemic uncertainty models outlined in the previous section and assuming independence between the epistemic uncertainties of the four terms in  $EF$ , the variance of the epistemic estimator  $EF$ , denoted,  $V_{ep}(EF)$ , is

$$\begin{aligned}V_{ep}(EF) &= V_{ep}[\Delta t * S * E(\lambda * E) * E(p_{f|e})] \\ &= E_{ep}^2(\Delta t) * E_{ep}^2(S) * E_{ep}^2[E(\lambda * E)] * E_{ep}^2[E(p_{f|e})] * \{CV_{\Delta t}^2 + CV_S^2 + CV_{E(\lambda * E)}^2 + \\ &\quad CV_{E(p_{f|e})}^2 + CV_{\Delta t}^2 * CV_S^2 + CV_{\Delta t}^2 * CV_{E(\lambda * E)}^2 + CV_{\Delta t}^2 * CV_{E(p_{f|e})}^2 + CV_S^2 * CV_{E(\lambda * E)}^2 + \\ &\quad CV_S^2 * CV_{E(p_{f|e})}^2 + CV_{E(\lambda * E)}^2 * CV_{E(p_{f|e})}^2 + CV_{\Delta t}^2 * CV_S^2 * CV_{E(\lambda * E)}^2 + CV_{\Delta t}^2 * CV_S^2 * \\ &\quad CV_{E(p_{f|e})}^2 + CV_{\Delta t}^2 * CV_{E(\lambda * E)}^2 * CV_{E(p_{f|e})}^2 + CV_S^2 * CV_{E(\lambda * E)}^2 * CV_{E(p_{f|e})}^2 + CV_{\Delta t}^2 * CV_S^2 * \\ &\quad CV_{E(\lambda * E)}^2 * CV_{E(p_{f|e})}^2\}.\end{aligned}$$

For any term  $X$ :

$$CV_X^2 = V_{ep}(X)/E_{ep}^2(X).$$

The individual variances are

$$\begin{aligned}V_{ep}(\Delta t) &= \Delta t_o^2 * \exp(\sigma_{\Delta t}^2) * [\exp(\sigma_{\Delta t}^2) - 1] \\ V_{ep}(S) &= S_o^2 * \exp(\sigma_s^2) * [\exp(\sigma_s^2) - 1] \\ V_{ep}[E(\lambda * E)] &= \exp[\sigma_{NEW1}^2 + (r+1)^2 * \sigma_e^2 + 2(r+1) * \rho_{Ne} * \sigma_{NEW1} * \sigma_e] * E_{ep}^2(\lambda_o) * E_{ep}^2(E_o) \\ &\quad * [CV_{\lambda_o}^2 + CV_{E_o}^2 + CV_{\lambda_o}^2 * CV_{E_o}^2] \\ -E_{ep}(\lambda_o) &= \lambda_{oo} * \exp(0.5\sigma_{\lambda_o}^2) \\ -E_{ep}(E_o) &= E_{oo} * \exp(0.5\sigma_{E_o}^2) \\ -V_{ep}(\lambda_o) &= \lambda_{oo}^2 * \exp(\sigma_{\lambda_o}^2) * [\exp(\sigma_{\lambda_o}^2) - 1] \\ -V_{ep}(E_o) &= E_{oo}^2 * \exp(\sigma_{E_o}^2) * [\exp(\sigma_{E_o}^2) - 1] \\ V_{ep}(E(p_{f|e})) &\cong V_{ep}\{\sum_k p_{f|k,o} * \exp(0.5\sigma_{k1}^2)\} + V_{ep}\{\sum_{i \neq k} p_{f|i,o} * p_{f|k,o} * \exp(0.5\sigma_{ik}^2)\} + V_{ep}\{\sum_{i \neq j \neq k} p_{f|i,o} * p_{f|j,o} * p_{f|k,o} * \exp(0.5\sigma_{ijk}^2)\} + V_{ep}\{\prod_k p_{f|k,o} * \exp(0.5\sigma_{1234}^2)\}.\end{aligned}$$

The individual terms in the identity for  $V_{ep}(E(p_{f|e}))$  are

$$V_{ep}\{\sum_k p_{f|k,o} * \exp(0.5\sigma_{k1}^2)\} = \sum_k p_{f|k,oo}^2 * \exp(\sigma_{k1}^2 + \sigma_{ko1}^2) * [\exp(\sigma_{ko1}^2) - 1] + 2\sum_{i \neq k} p_{f|i,oo} *$$

$$p_{f|k,oo} \exp(0.5(\sigma_{i1}^2 + \sigma_{io1}^2 + \sigma_{k1}^2 + \sigma_{ko1}^2)) [\exp(\sigma_{yo}^2) - 1]$$

$$V_{ep}\{\sum_{i \neq k} p_{f|i,o} p_{f|k,o} \exp(0.5\sigma_{ik}^2)\} = \sum_{i \neq k} p_{f|i,oo}^2 p_{f|k,oo}^2 \exp(\sigma_{ik}^2 + \sigma_{iko}^2) [\exp(\sigma_{iko}^2) - 1]$$

$$+ 2 \sum_{i \neq k, j \neq l} \exp(0.5(\sigma_{ik}^2 + \sigma_{jl}^2)) \text{COV}(p_{f|i,o} p_{f|k,o}; p_{f|j,o} p_{f|l,o}).$$

The covariance,  $\text{COV}(\cdot)$ , has one of two forms:

- $i \neq k, j \neq l$ :  $\text{COV}(p_{f|i,o} p_{f|k,o}; p_{f|j,o} p_{f|l,o}) = (\prod_k p_{f|k,oo}) \exp(0.5(\sum_k \sigma_{ko}^2 + 4\sigma_{yo}^2)) [\exp(4\sigma_{yo}^2) - 1]$
- $i \neq k, i \neq l$ ; i.e., two subscripts are the same:  $\text{COV}(p_{f|i,o} p_{f|k,o}; p_{f|i,o} p_{f|l,o}) = p_{f|i,oo}^2 p_{f|k,oo}^2 p_{f|l,oo}^2 \exp(0.5(2\sigma_{io}^2 + \sigma_{ko}^2 + \sigma_{lo}^2 + 4\sigma_{yo}^2)) [\exp(\sigma_{io}^2 + 3\sigma_{yo}^2) - 1]$

$$V_{ep}\{\sum_{i \neq j \neq k} p_{f|i,o}^2 p_{f|j,o}^2 p_{f|k,o}^2 \exp(0.5\sigma_{ijk}^2)\} = \sum_{i \neq j \neq k} p_{f|i,oo}^2 p_{f|j,oo}^2 p_{f|k,oo}^2 \exp(\sigma_{ijk}^2 + \sigma_{ijko}^2) [\exp(\sigma_{ijko}^2) - 1]$$

$$+ 2 \sum_{i \neq j \neq k, i \neq l} p_{f|i,oo}^2 p_{f|j,oo}^2 p_{f|k,oo}^2 p_{f|l,oo}^2 \exp(0.5(\sigma_{ijk}^2 + \sigma_{ijl}^2)) \exp(0.5(2\sigma_{io}^2 + 2\sigma_{jo}^2 + \sigma_{ko}^2 + \sigma_{lo}^2 + 12\sigma_{yo}^2)) [\exp(\sigma_{io}^2 + \sigma_{jo}^2 + 7\sigma_{yo}^2) - 1]$$

$$V_{ep}\{\prod_k p_{f|k,o} \exp(0.5\sigma_{1234}^2)\} = \prod_k p_{f|k,oo}^2 \exp(\sigma_{1234}^2 + \sigma_{1234o}^2) [\exp(\sigma_{1234o}^2) - 1].$$

Given the expected value and variance of the uncertainty distribution, the expected value provides a point estimate of Risk. Given a choice of a distribution family for the uncertainty distribution, the percentiles of the distribution, which are functions of the expected value and standard deviation, provides a basis for developing uncertainty bounds for Risk. For example, suppose it is reasonable to treat  $EF$  as a lognormal uncertain variable. Given the uncertainty information, calculate  $E_{ep}(EF)$  and  $V_{ep}(EF)$ . Using the identities for the lognormal distribution for a lognormal variable  $X$ :

$$E(X) = \exp[E(\ln X) + 0.5V(\ln X)]$$

$$V(X) = E^2(X) [\exp(V(\ln X)) - 1],$$

solve for:

$$V(\ln X) = \ln[(V(X)/E^2(X)) + 1]$$

$$E(\ln X) = \ln[E(X)] - 0.5V(\ln X).$$

The  $\alpha$ th percentile for  $X$  is

$$X_\alpha = \exp[E(\ln X) + U_\alpha SD(\ln X)]$$

where  $U_\alpha$  is the  $\alpha$ th percentile of the standard normal distribution and  $SD(\cdot)$  refers to the standard deviation.

## Discussion

The analytical approach is based on:

- 1 identifying the epistemic estimator of Risk as the expected value of loss, evaluated with respect to the inherent random variation,
- 2 developing point and bounding estimates of Risk based on evaluating the epistemic

expected value and variance of the epistemic estimator of risk, along with a model of the uncertainty distribution of the estimator.

Successful application of the methodology relies, significantly, on development of the MOW and modeling of the epistemic uncertainties associated with the MOW. The quality of the Risk estimator and its ability to provide useful estimates for Risk decision making will be limited to how well the MOW depicts the actual physical environment being analyzed. The more the MOW deviates from reality, the less useful the analysis will be. This is always a concern with using mathematical/probability models to model reality, whether an analytical or computational/simulation approach to risk assessments is used.

Similarly, the uncertainty distributions, describing the current state of knowledge in developing and quantifying the MOW, are critical to the quality of both analytical and computational risk analyses. Whereas the computational approach requires each of the uncertainty distributions to be identified, the analytical approach only requires the epistemic expected values and variances of the parameters of the MOW to be identified. However, as discussed in the previous section of the paper, to construct bounding estimates of Risk, an appropriate type of distributional family depicting the epistemic uncertainty of the Risk estimator must be identified. Due to the complexity of the Risk estimator and the mixing of a large number of uncertainty distributions, no one family of distributions is obvious. Certainly, the distribution must be defined over positive space and one might expect the distribution to be skewed, i.e., have a long tail toward higher values. Some potential candidate distributions might include the lognormal, gamma, Weibull and extreme value distributions, which are all fairly robust distributional families. Choice of the uncertainty distribution is critical to providing useful bounding estimates of Risk and the successful application of the analytical approach.

## Acronyms and Symbols

CONUS continental United States  
COV covariance  
CV coefficient of variation  
E exposures (personnel)  
 $E$  expected value  
e explosive event  
ES exposed site  
exp(.) exponential function  
F fatalities  
i,j,k indices of fatality causing effects  
ln natural logarithm  
MOW model of the world  
n number of occurrences  
NEW net explosive weight  
 $p_{fle}$  probability of a fatality given an explosive event occurs  
 $p_{flk}$  probability of a fatality given the  $k^{th}$  effect  
PES potential explosion site  
R Risk  
S scaling factor



$SD$  standard deviation  
 $t$  time  
 $U_{\alpha}$   $\alpha$ th percentile of the standard normal distribution  
 $V$  variance  
 $X$  random variable  
 $\delta$  variation multiplicative factor  
 $\lambda$  expected frequency of occurrence  
 $\sigma^2$  variance of random variable  $X$   
 $\rho$  correlation  
 $\Pi$  product function  
 $\Sigma$  summation function

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## Attachment 10 – P(e) Matrix

## **PURPOSE**

This memorandum addresses major technical and analytical decisions made as part of the SAFER Version 3.1 P(e) matrix. Specific questions addressed are:

1. Where did the data come from?
2. Did all the Services provide data?
3. Why do we not have different matrixes for each Service?
4. How were the activity types selected?
5. Why are there different probabilities of event based on storage and transportation compatibility group?
6. How were the groups of CGs chosen?
7. Why were environmental factors developed?
8. How were the environmental factor categories chosen?
9. How were environmental factor numbers determined?

## **REFERENCES**

1. Final IOC Risk Report Volumes I, II, and III, "Industrial Operations Command Safety and Security Risk Analysis," prepared by Quantitech, Inc. for the U.S. Army Industrial Operations Command (IOC), 28 February 1997.
2. Final Phase I report, "Risk-Based Explosives Safety Criteria," prepared by APT Research, Inc., 15 September 1998.
3. RBESCT Minutes.
4. Statistical analyses of background P(e) data presented at RBESCT meetings

## **DISCUSSIONS**

### **WHAT IS THE P(E) MATRIX?**

A P(e) Matrix is used by SAFER to determine the probability of an explosive event, P(e), at a Potential Explosive Site (PES). The matrix is based on the type of explosive involved, the type of operation being performed and other environmental factors that affect the likelihood of an unplanned explosive event occurring.

1. Where did the data come from?

Two data sources were used as the original foundation for the P(e) estimates. They are the DDESB accident database and the Army Industrial Operations Command (IOC) Risk Report. The SAFER Version 3.0 matrix contained additional information from the Army, Navy, Air Force, and Marine Corps. These data are shown following the questions and responses in this memo.

2. Did all the Services provide data?

Yes. After the original matrix was developed the Air Force questioned if the data were applicable to the Air Force, Navy and Marines because the majority of the data used to develop the matrix came from the Army and reference 1. Therefore, the Services were

tasked to research their Services' specific accident databases and number of PESs by activity type. The Services' data were used to determine if a new matrix needed to be developed.

3. *Why do we not have different matrixes for each Service?*

The RBESCT considered developing Service unique matrixes. After reviewing the accident data provided by each of the Services, it was determined that there were insignificant differences in the accident rates by PES activity type, so unique matrices were not warranted.

4. *How were the activity types selected?*

Activity types were chosen based on the activities used in the DDESB database. Some of the activities were similar and therefore the RBESCT decided to group some of these activities to eliminate confusion. The final list of activities were reviewed by the RBESCT and approved.

5. *Why are there different probabilities of event based on storage and transportation compatibility group (CG)?*

The RBESCT realized that not all explosives have the same sensitivities to external stimuli. It was decided by the RBESCT to use the explosives' Storage Compatibility Groups (CG) to account for different sensitivities. The CG was chosen because:

- a. All explosives have a CG assigned during the Hazard Classification process,
- b. CGs are well defined and should be understood by the persons using SAFER, and
- c. CGs can be grouped by sensitivity as described in question 6.

6. *How were the groups of CGs chosen?*

The CGs were divided into three sensitivity groups. Group I was considered the most sensitive to external stimuli and includes CGs L, A, B, G, H, J, and F. Group II is considered having an average sensitivity. Group II includes CG C and includes all propellants. In storage, Group II (propellants) is considered the most sensitive because propellants having depleted stabilizer can autoignite. Group III was considered the least sensitive and includes CGs D, E and N.

7. *Why were scaling factors developed?*

Environmental factors were developed to account for circumstances that increased the probability of event. (e.g. hostile environments, initial testing, inclement weather.)

8. *How were the environmental factor categories chosen?*

The Services developed situations that activities might be performed in that would increase the probability of an event occurring. This list was divided into two categories. The first group was considered to have a major effect on the probability of event and was assigned an environmental factor of 10 (representing 1 order of magnitude increase in risk). The second group was considered to have a minor effect on the probability of event and was assigned an environmental factor of 3 (representing ½ order of magnitude increase in risk).

9. *How were environmental factor numbers determined?*

The RBESCT determined the magnitude of the environmental factors based on experience.

***FY97 – FY02 Army Explosive Mishap Summary***

| PES used primarily for                          | Paragraph | Number of Mishaps |
|-------------------------------------------------|-----------|-------------------|
|                                                 |           | A, B, C, D & H    |
| Assembly/Disassembly/LAP/Maintenance/Renovation | 1 – 12    | 12                |
| Burning Ground/Demil/Demolition/Disposal        | 13 – 14   | 2                 |
| Lab/Test/Training                               |           |                   |
| Loading/Unloading                               |           |                   |
| Inspection/Painting/Packing                     | 15        | 1                 |
| Manufacturing                                   | 16 – 18   | 3                 |
| Deep Storage (longer than 1 month)              | 19        | 1                 |
| Temporary Storage (1 day to 1 month)            |           |                   |
| <b>TOTAL A, B, C, D &amp; H MISHAPS</b>         |           | <b>19</b>         |

Paragraphs 1 – 19 are class A, B, C, D & H mishaps.

1. Assembly - Lathing LX-19 bullet liner. No injuries.
2. Assembly - Consolidation of explosives into sub-munition. No injuries.
3. Assembly - Warhead pressing. No injuries.
4. Assembly - Warhead pressing. No injuries.
5. Assembly - Fire destroyed (?) plus buildings. No injuries.
6. Assembly - Blending operation. No injuries.
7. Assembly - M55 detonator detonation. 1 injury.
8. Assembly - Detonation during M55 detonator production. 1 injury.
9. Assembly - Flash fire during 120MM mortar illumination mix production. No injuries.
10. Assembly - .50 caliber discharge in packing area. 1 injury.
11. Assembly - Defuzing M67 fragmentation grenades. 2 injuries.
12. Assembly - Rocket motor ignited during removal from M155MM RAP round. No injuries.
13. Burning Ground - Bulldozer ran over 60 mm causing detonation on OD range. No injuries.
14. Burning Ground - Low order explosion during burning of primers. No injuries.
15. Inspection - Fire/explosion in conditioning chamber (60 mm). No injuries.
16. Manufacturing - Fire during propellant extrusion. No injuries.
17. Manufacturing - Explosion during nitroglycerin mixing. No injuries.
18. Manufacturing - Detonation during pre-mix NG2. 3 injuries.
19. Deep Storage - Igloo fire involving stored propellant. No injuries.

**FY87 – FY02 Air Force Explosive Mishap Summary**

These data will be used to determine the Probability of Event ( $P_e$ ) table for the Department of Defense Explosives Safety Board (DDESB) sponsored Risk-Based Explosives Safety Criteria Team project, Safety Assessment for Explosives Risk (SAFER). These data are for FY87 through FY02.

| PES used primarily for                          | Paragraph | Number of Mishaps |     |
|-------------------------------------------------|-----------|-------------------|-----|
|                                                 |           | A-C               | D&H |
| Assembly/Disassembly/LAP/Maintenance/Renovation | 1 – 5     | 3                 | 2   |
| Burning Ground/Demil/Demolition/Disposal        | 6 – 20    | 13                | 2   |
| Lab/Test/Training                               | 21 – 29   | 3                 | 6   |
| Loading/Unloading                               | 30 – 34   | 3                 | 2   |
| Inspection/Painting/Packing                     |           | 0                 | 0   |
| Manufacturing                                   | 35        | 1                 | 0   |
| Deep Storage (longer than 1 month)              | 36        | 1                 | 0   |
| Temporary Storage (1 day to 1 month)            |           | 0                 | 0   |
| TOTAL A, B, C, D & H MISHAPS                    |           | 24                | 12  |

Paragraphs 1 – 36 are class A, B, C, D & H mishaps.

1. C – MJU-7/B flare ignited during build-up.
2. A – Inadvertent actuation of MJU-7 flares in munitions storage area.
3. C – LCBAS forced bgg out due to excess pressure.
4. D – Fire consumed 5000 lbs of propellant.
5. D – Pressure blew ballistic gas generator to floor.
6. C – Safety fuse contacted blasting caps.
7. C – Worker used unauthorized method to detonate GBS-4 LWD.
8. B – Titan 34D booster propellant ignited.
9. B – Jammed 30mm round detonated.
10. C – Functioning of BDU-33 spotting charge.
11. C – Pre-ignition of magnesium/aluminum during demolition.
12. C – Worker burned while improperly disposing black powder.
13. C – MK-199 exploded and injured worker.

14. C – Fuzes detonated while being moved.
15. C – Worker was disposing of powder from dud grenade and was burned.
16. C – Ignition of rocket motor during disposal of Minuteman II countermeasure rockets.
17. D – Dud BDU-33 detonated in truck.
18. H – Demolition explosive detonated prematurely on disposal range (16 Feb 99).
19. C – Secondary explosion occurred after destruction of target identification bomb during range clearance of unexploded ordnance (7 Apr 99).
20. C – Black powder flashed during unauthorized disposal on disposal range (25 Jun 99).
21. D – Inadvertent firing of gas generator.
22. D – Inadvertent functioning of MAU-169 gas grain generator during test.
23. D – Thermal battery fired during testing.
24. C – Inadvertent flare activation from aircraft on the flightline (18 Oct 96).
25. D – Inadvertent flexible confined detonating cord on drone during checkout (26 Nov 96).
26. D – Inadvertent flexible confined detonating cord on drone during checkout (28 Jan 97).
27. C – Inadvertent flare activation from aircraft on the flightline (16 Mar 98).
28. D – Inadvertent flare activation from aircraft on the flightline (2 Aug 99).
29. C – AIM-9 missile exploded during aging and surveillance test firing (30 Jun 00).
30. C – Ale-40 system activated during ops check.
31. C – Inadvertent jettison of flare from A-10A aircraft in HAS.
32. C – M-206 flares inadvertently ignited during load.
33. D – Battery firing device inadvertently activated.
34. D – GBU-12 battery firing device fired during install.
35. A – Peacekeeper motor ignited and destroyed AF property.
36. C – 40,000 lb of propellant ignited in storage igloo.



***FY87 – FY02 Air Force PES Summary***

These data will be used to determine the Probability of Event ( $P_e$ ) table for the Department of Defense Explosives Safety Board (DDESB) sponsored Risk-Based Explosives Safety Criteria Team project, Safety Assessment for Explosives Risk (SAFER). These data are for FY87 through FY02.

| Primary Activity at PES                                 | Time Period | No. of Facilities |
|---------------------------------------------------------|-------------|-------------------|
| Assembly / Disassembly / LAP / Maintenance / Renovation | FY87 – FY02 | 397               |
| Burning Ground / Demil / Demolition / Disposal          | FY87 – FY02 | 50                |
| Lab / Test / Training                                   | FY87 – FY02 | 111               |
| Loading / Unloading                                     | FY87 – FY02 | 800               |
| Inspection / Painting / Packing                         | FY87 – FY02 | 206               |
| Manufacturing                                           | FY87 – FY02 | 0                 |
| Deep Storage (longer than 1 month)                      | FY87 – FY02 | 4,340             |
| Temporary Storage (1 day to 1 month)                    | FY87 – FY02 | -                 |
| In-Transit Storage (hrs to a few days)                  | FY87 – FY02 | -                 |

## NAVY EXPLOSIVE MISHAP SUMMARY

**FY97-02 NAVY EXPLOSIVE MISHAP SUMMARY**

The following descriptions of 27 class A, B and C explosive mishaps were gleaned from COMNAVSAFCEM Letter 8020 Serial 43/0675 of 4 May 1999 and a follow-on email generated 18 class D explosive mishaps. These data were used to establish the Probability of Event ( $P_e$ ) table for the Department of Defense Explosives Safety Board (DDESB) sponsored Risk-Based Explosives Safety Criteria Team project.

|   | PES used primarily for                          | Paragraph                                                    | Number of Mishaps<br>A-C D |    |
|---|-------------------------------------------------|--------------------------------------------------------------|----------------------------|----|
| A | Assembly/Disassembly/LAP/Maintenance/Renovation | 13, 15, 20, 21, 22, 28, 29, 45                               | 5                          | 3  |
| B | Burning Ground/Demil/Demolition/ Disposal       | 2, 8, 10, 23, 24, 27, 33, 34, 35, 41                         | 6                          | 4  |
| C | Lab/Test/Training                               | 1, 3, 4, 5, 6, 9, 16, 18, 26, 30, 31, 36, 39, 40, 42, 43, 44 | 9                          | 8  |
| D | Loading/Unloading                               | 12                                                           | 1                          | 0  |
| E | Inspection/Painting/Packing                     | 7, 19                                                        | 2                          | 0  |
| F | Manufacturing                                   | 17, 32, 37, 38                                               | 1                          | 3  |
| G | Deep Storage (1 month - year)                   | 11, 14                                                       | 2                          | 0  |
| H | Temporary Storage (1 day - 1 month)             | 25                                                           | 1                          | 0  |
|   | TOTAL A, B, C & D MISHAPS = 45                  |                                                              | 27                         | 18 |

Paragraphs 1-27 are class A, B & C mishaps, 28-45 are class D.

1. C - A premature detonation of a MK 37 arming device occurred during a functional test.
2. B - The black powder in a dud saluting charge ignited during the demilitarization process.
3. C - MJU-22/B flares ignited in test fixture during environmental testing.
4. C - Explosive material detonated while being processed into a suitable configuration for a test.
5. C - A MK66 detonator detonated during the demilitarization process.
6. C - A black powder train was improperly initiated during training exercise.

7. E - A decoy flare was intentionally initiated at a segregation site.
8. B - Premature initiation of scrap propellant at a burning site.
9. C - Premature warhead detonation at a test facility.
10. B - Detonation of improperly marked material at a burning site.
11. G - Magazine detonation.
12. D - Tractor trailer ignited while being blocked and braced.
13. A - A CXU-3 CAD detonated during a MK 76 practice bomb buildup.
14. G - Magazine deflagration/detonation.
15. A - Initiator detonated during disassembly.
16. C - Torpedo after body exploded during testing.
17. F - Explosion in manufacturing facility.
18. C - Inadvertent firing of a MK-6 MOD 4 gas generator during testing.
19. E - Ejection seat inadvertently fired during receipt inspection.
20. A - Inadvertent CAD firing during seat assembly.
21. A - Rocket motor ignited during disassembly.
22. A - Chaff counter measure ignited during disassembly.
23. B - Rocket propellant ignited during demilitarization.
24. B - Detonation of item during preparation for demilitarization.
25. H - Sonobuoys ignited in ready service locker.
26. C - A MK 30 MOD 0 arming firing device initiated during testing.
27. B - Explosive material inadvertently mixed with inert scrap for burning.
28. A - A sonobouy squib was activated during disassembly.
29. A - A mine lanyard was improperly removed during maintenance.

- 30. C - Cartridges heated in conditioning oven ignited due to improper temperature setting.
- 31. C - Igniter material ignited due to rough handling.
- 32. F - Improper equipment setup caused ignition of propellant during machining operation.
- 33. B - Material exploded during thermal treatment.
- 34. B - Small arms round thrown off station during thermal treatment.
- 35. B - Canopy ejected during seat removal while prepping aircraft for salvage.
- 36. C - Assumed spent cartridge ignited during disassembly for test analysis.
- 37. F - Improper equipment setup caused ignition of propellant during machining operation.
- 38. F - Molding powder ignited during pressing operation.
- 39. C - Rockets with warheads jettisoned onto runway prior to takeoff.
- 40. C - Rockets with warheads jettisoned onto runway prior to takeoff.
- 41. B - Premature detonation of material at thermal treatment area.
- 42. C - Test sample ignited due to improper grounding.
- 43. C - Firing system malfunctioned during test demonstration.
- 44. C - Rockets with warheads jettisoned onto runway prior to takeoff.
- 45. A - Torpedo starter cartridge ignited during maintenance.

**FY97-02 NAVY EXPLOSIVE MISHAP SUMMARY**

The following descriptions of 10 class A, B and C explosive mishaps and 23 Class D explosive mishaps were gleaned from COMNAVSAFCEN Letter 8020 Serial 43/0215 of 6 Mar 2003, which provided FY97-FY02 explosive mishap data for Navy mishaps and Marine Corps Aviation mishaps (Marine Corps Ground mishaps are being provided separately to the Marine Corps RBESCT member). This information is to be used to update the Probability of Event (P<sub>e</sub>) Matrix for the Safety Assessment for Explosives Risk (SAFER) Model. This summary does not include explosive mishaps that occurred on ships, in moving aircraft, or on range. C/D 1.4 mishaps in parked aircraft, in test cells, on flight lines, in paralofts (e.g., CAD initiation resulting in deployed parachutes, fire extinguishing agent release, actuating guillotine cartridges; signal cartridges in practice bombs) were not included; however, C/D 1.4 events that resulted in injuries or that that occurred during Lab/Test or Assembly/Disassembly operations were included.

|   | PES used primarily for                          | Paragraph                                                                                    | Number of Mishaps |    |
|---|-------------------------------------------------|----------------------------------------------------------------------------------------------|-------------------|----|
|   |                                                 |                                                                                              | A-C               | D  |
| A | Assembly/Disassembly/LAP/Maintenance/Renovation | 17, 18, 19, 20, 21, 23, 26, 28, <b>29</b>                                                    | 1                 | 8  |
| B | Burning Ground/Demil/Demolition/ Disposal       | <b>5</b> , 6, <b>13</b> , <b>16</b> , 22                                                     | 3                 | 2  |
| C | Lab/Test/Training                               | 1, <b>2</b> , <b>3</b> , <b>4</b> , 8, 9, 10, 12, <b>14</b> , 15, 24, 25, 27, 30, 31, 32, 33 | 4                 | 13 |
| D | Loading/Unloading                               |                                                                                              | 0                 | 0  |
| E | Inspection/Painting/Packing                     | <b>7</b>                                                                                     | 1                 | 0  |
| F | Manufacturing                                   | <b>11</b>                                                                                    | 1                 | 0  |
| G | Deep Storage (1 month - year)                   |                                                                                              | 0                 | 0  |
| H | Temporary Storage (1 day - 1 month)             |                                                                                              | 0                 | 0  |
|   | TOTAL A, B, C & D MISHAPS                       |                                                                                              | 10                | 23 |

Note: In the table above, paragraph numbers for Class A, B, & C mishaps are in bold print; paragraph numbers for Class D mishaps are not in bold print.

1. D – Mk 104 rocket motor sustainer propellant ignited during remote machining operation. No injuries.
2. C – At grenade training range, pin was pulled from grenade; grenade was dropped (before it was thrown); it detonated. Two injuries.

3. **C** – Propellant being removed from rocket motor by remotely operated lathe ignited and burned. Smoke entered control room – two operators were treated for smoke inhalation.
4. **C** – During breakdown of AN/ALQ-190(V) Chaff Countermeasure (**1.4S**) for surveillance testing, 18<sup>th</sup> round (of 18 total) initiated. One injury (thumb laceration required reconstructive surgery).
5. **C** – Mixed load of rocket motor casings and empty metal barrels were heated as a final explosives decontamination step, and an explosion occurred in the furnace. No injuries.
6. **D** – During thermal treatment of hydrazine mononitrate and nitrocellulose in the same treatment pan (remotely ignited), the material exploded. No injuries.
7. **C** – While performing inventory prior to shipment, technician dropped item (**1.4B**) on metal floor (4-foot drop). Item detonated when he picked it up. One injury.
8. **D** – 12 CADs (**1.4C**) loaded with squibs and percussion primers, but not output charges, were electrically and mechanically fired; after inspection to ensure items had fully functioned, they were cut with a hacksaw for primer seal inspection; primer ignited on 3<sup>rd</sup> cartridge. No injuries.
9. **D** – During dissection (using a piano wire) of a section of a foreign rocket motor, the propellant ignited. No injuries.
10. **D** – During remote pellet pressing operation of an experimental explosive (39 pellets); 31<sup>st</sup> pellet deflagrated as press ram was advanced to ejected pellet from die. No injuries.
11. **A** – During remote RDX grinding operation in 150-gallon horizontal mixer, a detonation occurred. No injuries.
12. **D** – During preparation for laboratory test, ignition occurred during transfer of a sample of A1A ignition material from a conductive container to a metal cup, due to lack of proper grounding. No injuries.
13. **C** – Detonation occurred during burning of trash and explosive packaging left from demolition operations. One injury.
14. **C** – During electrical resistance testing of armed MK-30 Mod 0 Arming Firing Device (**1.4D**), initiation occurred after removal of shorting plug during attachment of electrical connector. One injury.
15. **D** – Helo-launched exercise torpedo that failed to run was recovered and brought to torpedo facility. In washdown area, fresh water applied from a flushing hose entered battery compartment; exercise torpedo battery powered up and cause igniter and propellant grain (**1.4S**) to activate. One injury.

16. **C** – During disposal operations, ignition occurred while operator was manually transferring catocene-based propellant (1.3) from vehicle to disposal site. One injury.

17. **D** – During assembly of Mk 76 Practice Bomb (**1.4G**), an obstruction hampered insertion of firing pin assembly into bomb body, the operator attempted to force it, and the MK 4 signal cartridge initiated. One injury.

18. **D** – During preparation for assembly of fire extinguisher cartridges, when operator removed tray of BBU-43/A detonators (**1.4B**) from the oven, an initiation occurred. Investigation identified excessive oven temperature as cause. One injury.

19. **D** – Operator noticed aft canopy jettison control handle sitting on desk, unpinned, he picked item up and JAU/25A mechanical initiator (**1.4C**) detonated. One injury.

20. **D** – During disassembly of M257 warhead (1.3G), operator was removing the igniter system per SOP, and the igniter and candle functioned. Igniter did not have an out-of-line design configuration in violation of Navy Policy, but in 1979 the warhead had erroneously been assigned the same stock number as warheads with out-of-line igniters. One injury.

21. **D** – During final assembly of red smoke signals as part of a product improvement program, initiation of a signal occurred while operator was manually installing striker assembly. No injuries.

22. **D** – Army ammunition manager conducted unauthorized demilitarization of 5.5 pounds of explosives (1.2.1): placed explosive on ground next to a building, ignited the explosive, ran around corner and waited for it to burn – detonation occurred. No injuries.

23. **D** – During refurbishment of WGU-4A/B G&C section, thermal battery and gas generator were initiated during servo test. Technician inadvertently soldered 27-volt internal test line to thermal battery circuit board terminal vice attaching wires from servo unit to circuit board in umbilical base block. No injuries.

24. **D** - Propellant being machined by vertical band saw (remote operation) from wedges of dissected rocket motor slipped in vise; this created metal-to-metal contact between band saw blade and metal case of wedge, and caused ignition. No injuries.

25. **D** – During inerting operation, remotely operated lathe was used to remove PBXN-109 from IM test assembly; operator misestimated depth of cavity; cutting tool contacted bottom end of test assembly fill cavity; and heat from cutter ignited explosive. No injuries.

26. **D** – Ignition occurred during loading of CCU-36/A delay cartridge (**1.4C**). Operator did not successfully seat three-hole orifice disc in top of delay column before attempting to stake disc in place. No injuries.

27. **D** - During cleaning of residual felt “whiskers” from surface of MTV pellet with acetone-dampened rag, pellet ignited. One injury.

28. D – LUU-2B/B Flare (1.3G) was being loaded in SUU-25 Flare Pod, Tube 2. When large amount of resistance was encountered, operator used flare tool to try to unload tube, and timer was activated on forward flare. No injuries.

29. C – During removal of signal cartridges (**1.4G**) from practice bombs and subsequent bomb storage operations, an operator inadvertently picked up bomb with cartridge still installed and placed it in storage crate nose first. The cartridge detonated as firing pin hit bottom of crate. The operator, who had removed his PPE prior to the mishap, was injured.

30. D – During machining operation of MK4 Low Voltage Initiator (pyrotechnic material), operator did not follow SOP (neglected to turn on cooling air flow), resulting in initiation. Lathe shield enclosure contained effects of explosion - no injuries or equipment damage.

31. D – BQM-74E was being prepared for launch in support of missile exercise. During M-117 JATO resistance check, a JATO bottle was inadvertently fired, BQM-74E impacted ground 25 feet from launcher and sustained structural damage. No injuries.

32. D – Detonation occurred while drilling out a lead azide pellet from a Mk 32 Arming Device - due to procedural non-compliance (cleaning steps not conducted in SOP sequence). Minor injury (operator wore face shield, but being tall - he had to look down and turn his head in such a way that his ear was exposed).

33. D – Ignition occurred during remote compression molding of developmental composition as billet was being ejected from the die. No injuries.



**FY00-03 MARINE CORPS EXPLOSIVE MISHAP SUMMARY**

|   | PES used primarily for                          | Paragraph | Number of Mishaps<br>A-C D |  |
|---|-------------------------------------------------|-----------|----------------------------|--|
| A | Assembly/Disassembly/LAP/Maintenance/Renovation |           |                            |  |
| B | Burning Ground/Demil/Demolition/ Disposal       |           |                            |  |
| C | Lab/Test/Training                               |           | 5                          |  |
| D | Loading/Unloading                               |           |                            |  |
| E | Inspection/Painting/Packing                     |           |                            |  |
| F | Manufacturing                                   |           |                            |  |
| G | Deep Storage (1 month - year)                   |           |                            |  |
| H | Temporary Storage (1 day - 1 month)             |           |                            |  |
|   | TOTAL A, B, C & D MISHAPS                       |           | 5                          |  |

| Primary Activity at PES                                 | Time Period | No. of Facilities |
|---------------------------------------------------------|-------------|-------------------|
| Assembly / Disassembly / LAP / Maintenance / Renovation | FY00 – FY03 |                   |
| Burning Ground / Demil / Demolition / Disposal          | FY00 – FY03 |                   |
| Lab / Test / Training                                   | FY00 – FY03 | 338               |
| Loading / Unloading                                     | FY00 – FY03 |                   |
| Inspection / Painting / Packing                         | FY00 – FY03 |                   |
| Manufacturing                                           | FY00 – FY03 |                   |
| Deep Storage (longer than 1 month)                      | FY00 – FY03 |                   |
| Temporary Storage (1 day to 1 month)                    | FY00 – FY03 |                   |
| In-Transit Storage (hrs to a few days)                  | FY00 – FY03 |                   |

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## Attachment 11 - Bibliography

## **Bibliography of Published Papers**

Prepared by – Meredith Hardwick (APT)

Revision Date – May 2009

### **Purpose**

This memorandum provides a bibliography of the papers that have been published in support of the Risk-Based Explosives Safety Criteria Team.

| Date          | Title                                                                                                                                      | Author(s)                                                                   | Symposium/Report                                       |
|---------------|--------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------|--------------------------------------------------------|
| August 1998   | Risk-Based Explosives Safety Criteria Overview                                                                                             | Paul Price, Tom Pfitzer                                                     | DoD Explosives Safety Seminar, Orlando, FL             |
| August 1998   | Risk-Based Explosives Safety Methods                                                                                                       | Tom Pfitzer, Meredith Hardwick                                              | DoD Explosives Safety Seminar, Orlando, FL             |
| November 1999 | Status of the Risk-Based Explosives Safety Criteria Team                                                                                   | Jerry Ward, Tom Pfitzer, Paul Price, Meredith Hardwick                      | Parari '99, Canberra, Australia                        |
| November 1999 | Risk-Based Explosives Safety Modeling                                                                                                      | Meredith Hardwick, John Tatom, Mike Swisdak                                 | Parari '99, Canberra, Australia                        |
| November 1999 | Criteria Selection for Risk-Based Explosives Safety Standards                                                                              | Tom Pfitzer, Jerry Rufe, Jerry Ward                                         | Parari '99, Canberra, Australia                        |
| August 2000   | Governing Safety Using Risk-Based Methods                                                                                                  | Tom Pfitzer, Meredith Hardwick                                              | International System Safety Conference, Orlando, FL    |
| July 2000     | Status of Risk-Based Explosives Safety Criteria Team                                                                                       | Tom Pfitzer, Meredith Hardwick, Jerry Ward, Paul Price                      | DoD Explosives Safety Seminar, New Orleans, LA         |
| July 2000     | Comparison of International QRA models on the basis of the "Setup and Results of The Joint UK / Australian 40 tonne Donor / Acceptor Trial | Philip van Dongen, Meredith Hardwick, David Hewkin, Peter Kummer, Hans Oiom | DoD Explosives Safety Seminar, New Orleans, LA         |
| July 2000     | Risk-Based Explosives Safety Modeling                                                                                                      | John Tatom, Meredith Hardwick                                               | DoD Explosives Safety Seminar, New Orleans, LA         |
| August 2001   | Criteria Selection for Risk-Based Explosives Safety Standards                                                                              | Tom Pfitzer, Jerry Rufe                                                     | International System Safety Conference, Huntsville, AL |
| October 2001  | Assessing Risk at Ports, A Risk-Based Approach to evaluating port operations using the SAFER model                                         | Meredith Hardwick, Pete Yutmeyer, Tom Pfitzer                               | Parari '01, Canberra, Australia                        |
| October 2001  | Assessing Risks from Explosives, An Overview of Methods Developed for use by NATO Countries                                                | Jerry Ward, Tom Pfitzer, Meredith Hardwick                                  | Parari '01, Canberra, Australia                        |
| October 2001  | Comparison of 40 Tonne Test Debris Data to the SAFER Model Predictions                                                                     | John Tatom, Kristy Newton, Tom Pfitzer, Mike Swisdak                        | Parari '01, Canberra, Australia                        |
| August 2002   | SAFER Analysis for Shannon Explosives LTD.                                                                                                 | Meredith Hardwick, Pete Yutmeyer, Tom Pfitzer, John Tatom                   | DoD Explosives Safety Seminar, Atlanta, GA             |
| August 2002   | Siting of Explosives Storage at Kwajalein Missile Range Using SAFER Version 2.0                                                            | Kenyon Williams, Bruce Harris, Meredith Hardwick                            | DoD Explosives Safety Seminar, Atlanta, GA             |
| August 2002   | Uncertainty as Modeled in SAFER Version 2.0                                                                                                | Bob Baker, Kristy Newton, John Hall, Tom Pfitzer                            | DoD Explosives Safety Seminar, Atlanta, GA             |
| August 2002   | SAFER Analysis for Shannon Explosives                                                                                                      | Meredith Hardwick,                                                          | DoD Explosives Safety                                  |

## Bibliography of Published Papers

Prepared by – Meredith Hardwick (APT)

Revision Date – May 2009

| Date         | Title                                                                                                                   | Author(s)                                                  | Symposium/Report                               |
|--------------|-------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------|------------------------------------------------|
|              | LTD.                                                                                                                    | Tom Pfitzer, Pete Yutmeyer, John Tatom                     | Seminar, Atlanta, GA                           |
| August 2002  | SAFER Version 1.0 Analysis of Minuteman III Silos                                                                       | Lea Ann Cotton, John Tatom                                 | DoD Explosives Safety Seminar, Atlanta, GA     |
| August 2002  | Comparison of SAFER Debris Predictions with Various Test Data                                                           | Mike Swisdak, John Tatom, Kristy Newton                    | DoD Explosives Safety Seminar, Atlanta, GA     |
| August 2002  | SAFER 2 Algorithms                                                                                                      | John Tatom                                                 | DoD Explosives Safety Seminar, Atlanta, GA     |
| August 2002  | SAFER 2 Demonstration                                                                                                   | Meredith Hardwick                                          | DoD Explosives Safety Seminar, Atlanta, GA     |
| October 2003 | RBESCT Program Plan / Vision                                                                                            | Eric Olson, Jerry Ward, Meredith Hardwick, Tom Pfitzer     | Parari '03, Canberra, Australia                |
| October 2003 | Safety Assessment for Explosives Risk (SAFER) Model Status                                                              | Jerry Ward, Tom Pfitzer, Meredith Hardwick                 | Parari '03, Canberra, Australia                |
| October 2003 | Sequential Operations Protocol                                                                                          | Meredith Hardwick, Danielle DeBraccio, Pete Yutmeyer       | Parari '03, Canberra, Australia                |
| October 2003 | NATO Model Comparison – SAFER/US Perspective                                                                            | Tom Pfitzer, Meredith Hardwick                             | Parari '03, Canberra, Australia                |
| October 2003 | Status of Testing Program to Benefit Explosives Safety Standards Development in the United States Department of Defense | John Tatom, Mike Swisdak, Jim Tancreto                     | Parari '03, Canberra, Australia                |
| October 2003 | SCIPAN I — Test Description and Debris Characterization For Typical Aboveground Non-Earth-Covered Structures            | John Tatom, Mike Swisdak, Jim Tancreto                     | Parari '03, Canberra, Australia                |
| July 2004    | SciPan 1 and SciPan 2 Response of Reinforced Concrete Tiltup Construction to Blast Loading                              | Michael Swisdak, James Tancreto, John Tatom                | NAVFAC TM-2371-SHR                             |
| August 2004  | SAFER 3 Algorithms                                                                                                      | John Tatom, Michael Swisdak, James Tancreto                | DoD Explosives Safety Seminar, San Antonio, TX |
| August 2004  | An Analytical Approach For Treating Uncertainty In Probabilistic Risk Assessments                                       | Richard Mensing                                            | DoD Explosives Safety Seminar, San Antonio, TX |
| August 2004  | Are All Risk Criteria Created Equal And Used Equally?                                                                   | Tom Pfitzer, Meredith Hardwick, Bill Pfitzer               | DoD Explosives Safety Seminar, San Antonio, TX |
| August 2004  | RBESCT Program Plan /Vision                                                                                             | Eric Olson, Dr. Jerry Ward, Tom Pfitzer, Meredith Hardwick | DoD Explosives Safety Seminar, San Antonio, TX |
| August 2004  | Universal Risk Scales – A Tool For Developing Risk Criteria By Consensus                                                | Tom Pfitzer, Meredith Hardwick, Bill Pfitzer               | DoD Explosives Safety Seminar, San Antonio, TX |
| August 2004  | Safety Assessment For Explosives Risk (SAFER) Model Status                                                              | Meredith Hardwick, Tom Pfitzer, Dr. Jerry Ward             | DoD Explosives Safety Seminar, San Antonio, TX |
| August 2004  | Comparison Of SAFER Debris Density Results To Test Data                                                                 | John Tatom, Mike Swisdak, Kristy Newton                    | DoD Explosives Safety Seminar, San Antonio, TX |
| August 2004  | Status Of Testing Program To Benefit Explosives Safety Standards Development In The United States Department Of Defense | John Tatom, Mike Swisdak, Jim Tancreto                     | DoD Explosives Safety Seminar, San Antonio, TX |

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Prepared by – Meredith Hardwick (APT)

Revision Date – May 2009

| Date          | Title                                                                                                                             | Author(s)                                                  | Symposium/Report                                |
|---------------|-----------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------|-------------------------------------------------|
| August 2004   | Spider - A Test Program To Determine The Response Of Typical Wall And Roof Panels To Debris Impact                                | Jim Tancreto, John Tatom, Mike Swisdak                     | DoD Explosives Safety Seminar, San Antonio, TX  |
| August 2004   | SCIPAN 1 and SCIPAN 2—Response of Reinforced Concrete Tiltup Construction To Blast Loading                                        | Mike Swisdak, Jim Tancreto, John Tatom                     | DoD Explosives Safety Seminar, San Antonio, TX  |
| August 2004   | Uncertainty As Modeled In SAFER 3                                                                                                 | Bob Baker, Dr. John Hall, Tom Pfitzer, Kristy Newton       | DoD Explosives Safety Seminar, San Antonio, TX  |
| October 2005  | SciPan—A Program To Determine The Effects Of Blast Loading On Typical Structures--Update                                          | Michael Swisdak, John Tatom, James Tancreto                | Parari 05, Melbourne, Australia                 |
| October 2005  | SPIDER—A Test Program To Determine The Response Of Typical Wall and Roof Panels To Debris Impact                                  | John Tatom, James Tancreto, Michael Swisdak                | Parari 05, Melbourne, Australia                 |
| October 2005  | Comparison Of Risk Based Explosives Safety Criteria Team (RBESCT) Predictions With UK/Australian Defence Trial ADF 845/03 Results | Robert Conway, James Tancreto, Michael Swisdak, John Tatom | Parari 05, Melbourne, Australia                 |
| October 2005  | Status of the RBESCT                                                                                                              | Eric Olson, Tom Pfitzer, Meredith Hardwick                 | Parari '05, Melbourne, Australia                |
| January 2006  | Status Of Testing Program to Benefit Explosives Safety Standards In The United States Department of Defense                       | John Tatom, Michael Swisdak, James Tancreto                | ISEE, Dallas, TX                                |
| August 2006   | Status Of Testing Program to Benefit Explosives Safety Standards In The United States Department of Defense                       | Michael Swisdak, John Tatom, Jim Tancreto                  | DoD Explosives Safety Seminar, Philadelphia, PA |
| August 2006   | Debris Characterization Of An Explosion Inside An ISO Container Located On A Truck                                                | Michael Swisdak, John Tatom, Robert Conway, Jim Tancreto   | DoD Explosives Safety Seminar, Philadelphia, PA |
| August 2006   | DoD Risk-Based Explosives Safety Criteria Team – Report on Progress and Future Priorities                                         | Eric Olson, Meredith Hardwick                              | DoD Explosives Safety Seminar, Philadelphia, PA |
| February 2007 | Characterization Of An Explosion Inside An ISO Container Located On A Truck                                                       | Michael Swisdak, John Tatom                                | IHTR 2837                                       |
| February 2007 | The Science And Testing Behind Quantitative Risk Assessment Models                                                                | John Tatom, Michael Swisdak                                | ISEE, Nashville, TN                             |
| October 2007  | Procedures For The Collection, Analysis, and Interpretation Of Explosion-Produced Debris                                          | John Tatom, Michael Swisdak                                | Parari 07, Melbourne, Australia                 |
| October 2007  | Project ESKIMORE—The DDESB Long-Term Testing Initiative                                                                           | Jerry Ward, Michael Swisdak                                | Parari 07, Melbourne, Australia                 |
| October 2007  | ISO-2: Characterization Of A 4000 KG Explosion Inside An ISO Container Located On A Truck                                         | Michael Swisdak, John Tatom, David Kennedy                 | Parari 07, Melbourne, Australia                 |
| October 2007  | A Proposal For International Government/Industry Explosives Safety Testing Collaboration And Coordination                         | John Tatom, Michael Swisdak, David Kennedy, David Shatzer  | Parari 07, Melbourne, Australia                 |
| August 2008   | Project ESKIMORE—The DDESB Long-Term Testing Initiative                                                                           | Michael Swisdak, Robert Conway, Lea Ann Cotton             | DoD Explosives Safety Seminar, Palm Springs, CA |
| August 2008   | ISO-2: Program Description And Data Summary                                                                                       | Michael Swisdak, John Tatom, Robert Conway                 | DoD Explosives Safety Seminar, Palm Springs,    |

## ***Bibliography of Published Papers***

*Prepared by – Meredith Hardwick (APT)*

*Revision Date – May 2009*

| Date         | Title                                                                                   | Author(s)                                            | Symposium/Report                                |
|--------------|-----------------------------------------------------------------------------------------|------------------------------------------------------|-------------------------------------------------|
|              |                                                                                         |                                                      | CA                                              |
| August 2008  | ISO-2: Debris Catalogue Organization and Visualization                                  | John Tatom, Jesse Davis, Michael Swisdak             | DoD Explosives Safety Seminar, Palm Springs, CA |
| August 2008  | The Science Of SAFER 3.03                                                               | John Tatom, Michael Swisdak, Robert Conway           | DoD Explosives Safety Seminar, Palm Springs, CA |
| August 2008  | A Comparison Of Safety Levels Provided By Published Numerical Risk Criteria             | Tom Pfitzer                                          | DoD Explosives Safety Seminar, Palm Springs, CA |
| August 2008  | A Risk Management Concept Combining The Disciplines of System Safety, Range Safety      | Tom Pfitzer                                          | DoD Explosives Safety Seminar, Palm Springs, CA |
| August 2008  | DoD Risk-Based Explosives Safety Criteria Team—Report on Progress and Future Priorities | Jerry Ward, Meredith Hardwick                        | DoD Explosives Safety Seminar, Palm Springs, CA |
| October 2008 | Road Signs in Risk Space                                                                | Tom Pfitzer, Meredith Hardwick, Dr. Josephine Covino | 3 <sup>rd</sup> IAASS Conference, Rome, Italy   |

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Attachment 12 – URS

**Criteria Selection for Risk-Based Explosives Safety Standards  
Presented at PARARI 1999**

Tom Pfitzer, Jerry Rufe, and Dr. Jerry Ward

This document reviews one aspect of the work performed by the Risk-Based Explosives Safety Criteria Team (RBESCT) during fiscal year 1999 toward implementation of risk-based standards for explosives safety in the United States. In this paper, the authors summarize the research, precedents, and existing information that led to the selection of draft explosives safety criteria for use by the DoD Explosives Safety Board (DDESB). The review includes an assessment of comparable risks in other human endeavors, as well as a survey of comparable standards used in other areas of safety. The RBESCT developed the data under the sponsorship of the DDESB and the United States (U.S.) Army, Navy, Air Force, and Marines. The draft criteria are scheduled for trial implementation in fiscal year 2000. The RBESCT invites the international explosives safety community to provide additional data to help refine the criteria during fiscal year 2000. Such data can be provided electronically to [mhardwick@apt-research.com](mailto:mhardwick@apt-research.com).

## 1.0 Introduction

The work documented in this paper is sponsored by the Risk-Based Explosives Safety Criteria Team (RBESCT). The RBESCT is a team of government and industry professionals sponsored by the Department of Defense Explosives Safety Board (DDESB) and the four U.S. military services to develop and implement risk-based criteria for explosives safety in the U.S. An important part of their work is to gather background data and document the selected personnel protection criteria. This paper addresses the background data. Two other papers describing the work of the RBESCT are also being presented at PARARI '99.

## 2.0 Draft Criteria

The draft criteria shown in Figure 1 are for use as a supplement to the practice of applying quantity-distance (Q-D) measurements to determine explosives safety hazards. Nations participating in a The North Atlantic Treaty Organization (NATO) Risk Analysis Working Group are considering similar risk-based approaches.

| Risk to:                        | Draft Criteria                                                                                                                                                                                      |
|---------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Any 1 worker<br>(Annual $P_f$ ) | <ul style="list-style-type: none"><li>Limit maximum risk to <math>1 \times 10^{-4}</math></li></ul>                                                                                                 |
| All workers<br>(Annual $E_f$ )  | <ul style="list-style-type: none"><li>Attempt to lower risk to <math>1 \times 10^{-3}</math></li><li>Accept above <math>1 \times 10^{-2}</math> with significant national need only</li></ul>       |
| Any 1 person<br>(Annual $P_f$ ) | <ul style="list-style-type: none"><li>Limit maximum risk to <math>1 \times 10^{-6}</math></li></ul>                                                                                                 |
| All public<br>(Annual $E_f$ )   | <ul style="list-style-type: none"><li>Attempt to lower risk if above <math>1 \times 10^{-5}</math></li><li>Accept above <math>1 \times 10^{-3}</math> with significant national need only</li></ul> |

**Figure 1: Draft Criteria**

The goal of criteria selection is to establish a standard which will have broad based understanding, a strong legal precedence, and support within the technical community. The RBESCT used a combination of information from other regulations, historical precedence, and risk statistics to define each criterion chosen. The aim was to achieve a broad consensus of support for the criteria, recognizing that universal acceptance would not be initially possible. Figure 2 shows the different rationales that can be used to support criteria selection. As the number of rationales used to support a criterion increases, the level of acceptance also increases.

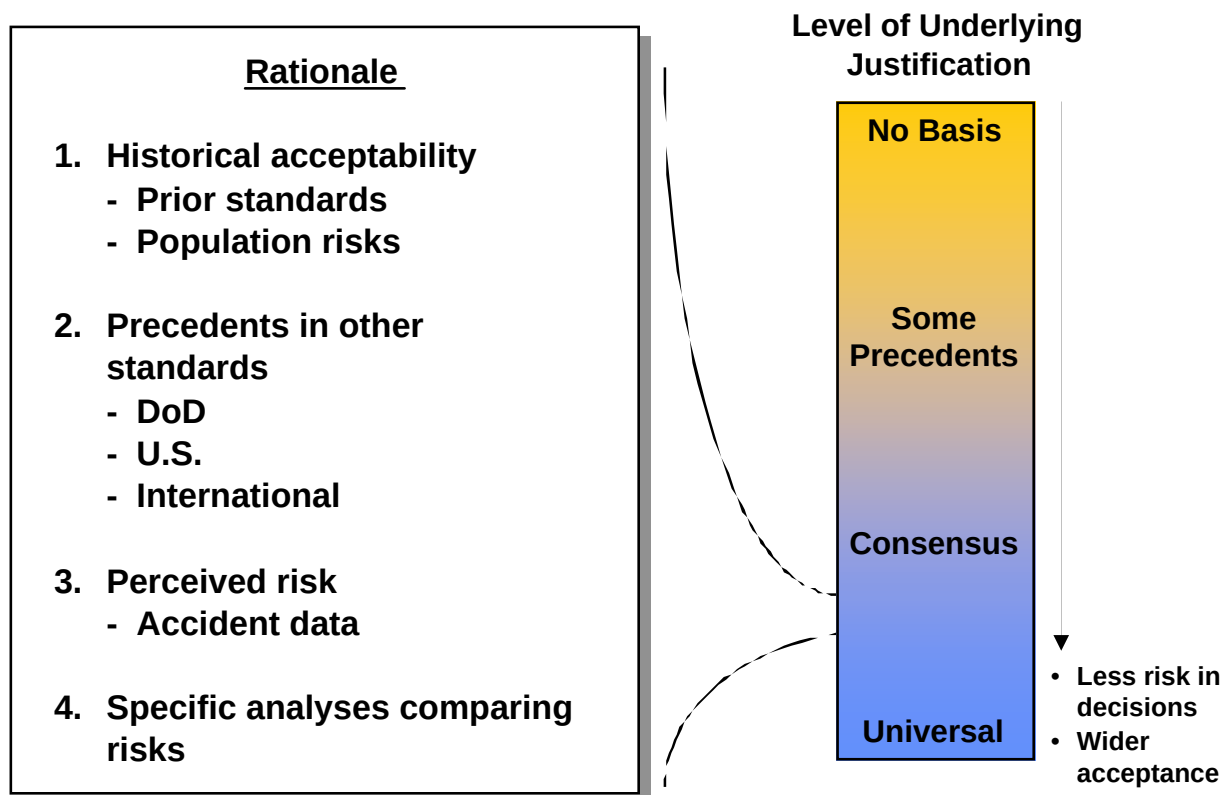


**Figure 2: Basis of Criteria**

Risk measures define who or what is at risk, the consequences of the risk, and the time period of the risk. As shown in Figure 3, numerous measures were considered by the RBESCT. Each measure has merit and would serve in varying degrees to achieve the desired purpose of assessing safety. The four measures that the RBESCT selected are as follows:

- The expected fatalities ( $E_f$ ) resulting from an explosive event at the potential explosion site (PES) on an annual basis assuming the annual average amount of explosive is present,
- Maximum expected fatalities, which are the same as (1) assuming that the explosive quantity present is at approved upper limit for the site,
- Individual probability of fatality ( $P_f$ ), which is the annual probability of fatality for any individual in the area surrounding the PES assuming that the annual average amount of explosive is present, and
- Peak individual probability of fatality, which is the same as (3) assuming that the explosive quantity present at the PES is at approved upper limit for the site.

Each measure focuses protection on a different set of persons or conditions. By using a combination of these four measures, the decision maker has a broader understanding of the risks. These measures are applied to three categories of personnel: those whose jobs relate to the potential explosion site (related), persons who are exposed by virtue of employment (non-related), and all others not included in the previous

definitions (public).

| Measure Selection         | Selected                                                                                                                                                                                    | Considered                                                                                                                                                                         |
|---------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Who or what is protected? | People (3 categories: related, non-related, public)                                                                                                                                         | <ul style="list-style-type: none"> <li>• High value facilities</li> <li>• Mission</li> </ul>                                                                                       |
| From what consequence?    | <ul style="list-style-type: none"> <li>• <math>E_f</math></li> <li>• Maximum <math>E_f</math></li> <li>• Individual <math>P_f</math></li> <li>• Peak Individual <math>P_f</math></li> </ul> | <ul style="list-style-type: none"> <li>• Probability of injury</li> <li>• Expected number of injured</li> <li>• Expected damage to facilities</li> <li>• Change in risk</li> </ul> |
| For what time period?     | Per year                                                                                                                                                                                    | <ul style="list-style-type: none"> <li>• Per day</li> <li>• Per operation</li> </ul>                                                                                               |

**Figure 3: Measures Considered**

### 3.0 Universal Risk Scale (URS)

Data were gathered relating to acceptable risk from a variety of sources. These data needed to be accumulated in a common format. This need led to the development of the Universal Risk Scales (URS), which are a byproduct of research undertaken by the RBESCT.

The scales have been used to compare relevant data to assist policy makers in selecting appropriate risk related criteria. During the past year the team has developed scales for each of the four criteria shown in Figure 1. *Note: These criteria are in draft form and have not been officially approved by the DoD Explosives Safety Board.*

The format chosen was important because it needed to 1) educate the reader as to the differences between the linear and logarithmic scale and 2) display a wide variety of sometimes disparate data. This format allows the aggregate weight of the individual data points to be viewed at the same time.

The center bar of the URS is the scale. The logarithmic format was specifically selected to highlight the huge differences in the amount of risk that exist in a very small numerical space. The difference between zero and one on a linear scale is small; in fact, most people think of it in terms of the linear measure of percent. The linear paradigm, however, does not adequately support the understanding and selection of risk criteria. Instead risk should be reviewed as orders of magnitude to achieve a proper perspective on relative risks.

The format shown in Figure 4 attempts to achieve that by allowing space for two types of precedents. On the right side is the actual accident experience. On the left side, governance precedents which regulate similar risks are shown in the same units of measure.

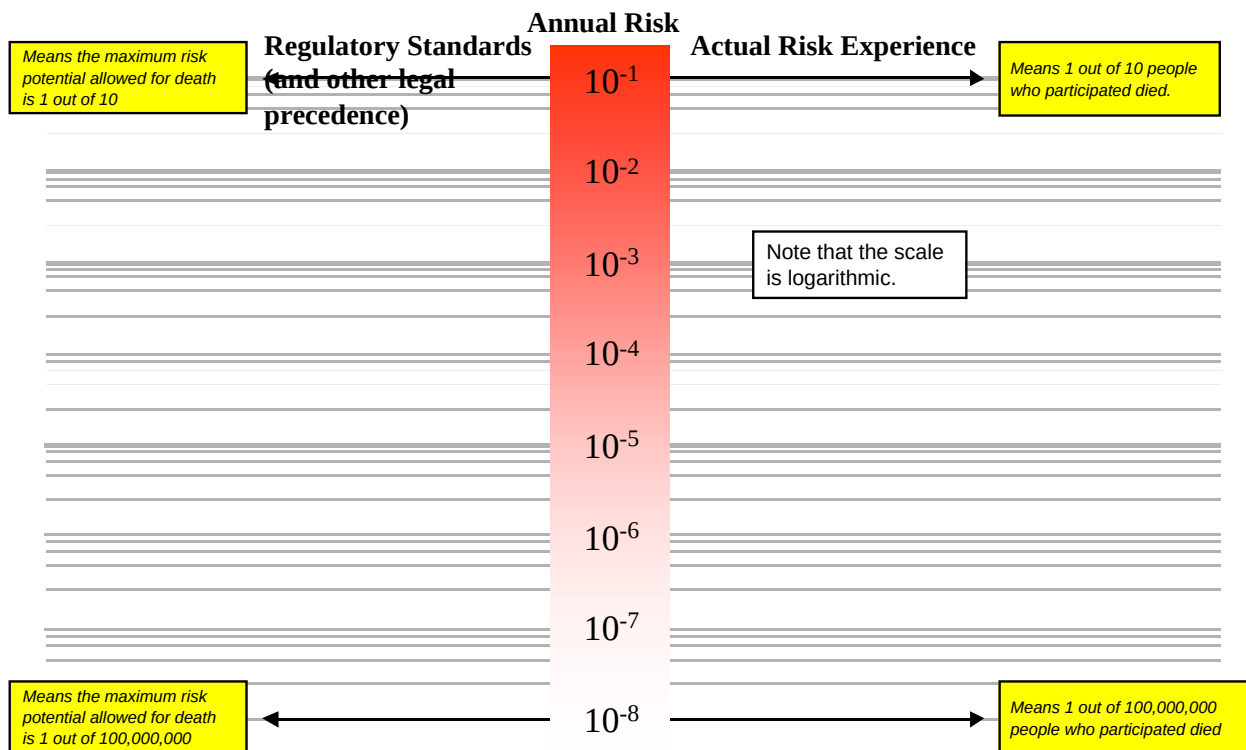


Figure 4: URS Format

## 4.0 Data Description

This section describes the data supporting the selection of the four criteria. In the figures which follow, all data are shown in terms of annual risk. Each figure contains a star indicating the level of risk associated with the draft criteria developed by the RBESCT. The surrounding data points are the product of research for relevant supporting data. Many data points are shown because individual readers may ascribe more or less relevance to each data point.

### 4.1 Risk to any One Worker

The scale supporting the protection criterion for any one worker is shown in Figure 5. This scale is labeled voluntary  $P_f$  because the risk associated with the action is accepted as a voluntary action taken by an individual. For example, when a person accepts a job with known risks it is "voluntary." Figure 5 plots the data on a URS and the following paragraphs describe each data point.



## INDIVIDUAL VOLUNTARY P<sub>flv</sub>

Risk  
Based  
Explosives  
Safety  
Criteria  
Team

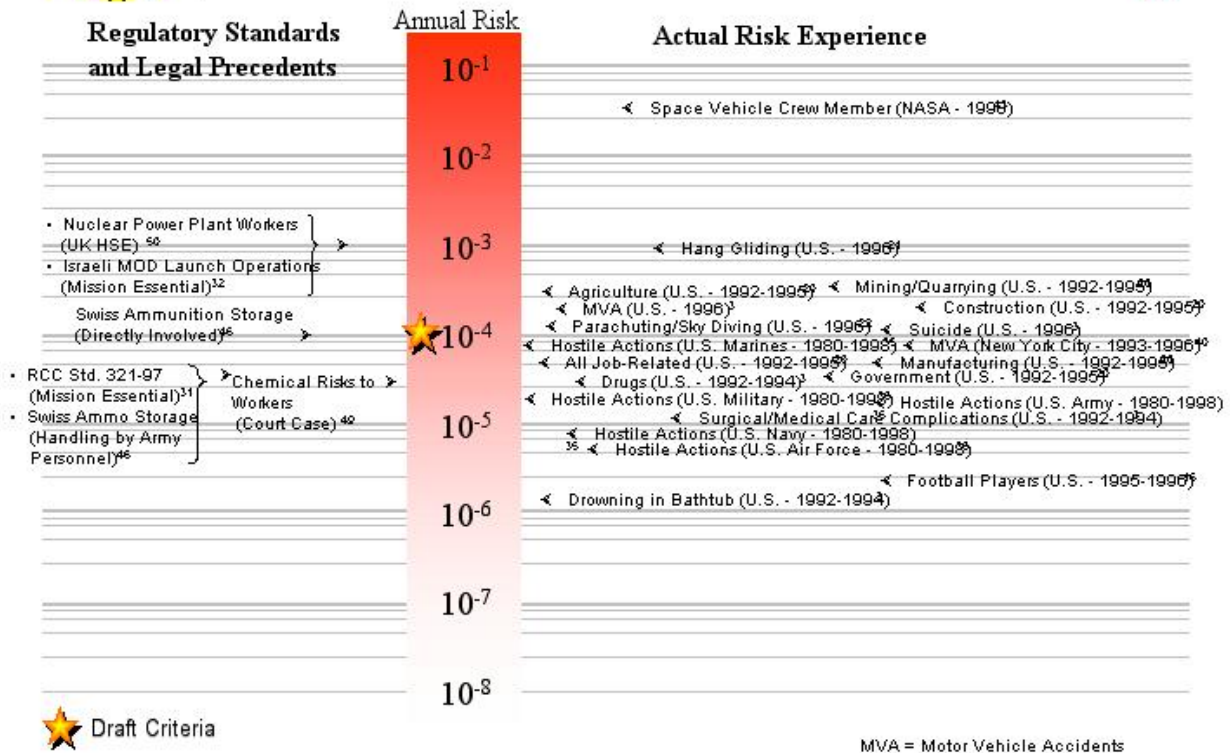


Figure 5: Voluntary Probability of Fatality

### Regulatory Standards

- Nuclear Power Plant Workers (UK HSE) – 1.00E-03. In the *UK Health and Safety Executive – The Tolerability of Risk from Nuclear Power Stations*, this is stated as the “suggested maximum tolerable risk to workers in any industry...about the most risk that is ordinarily accepted under modern conditions for workers in the UK and it seems reasonable to adopt it as the dividing line between what is just tolerable and what is intolerable.”
- Israeli MOD Launch Operations (Mission Essential) – 1.00E-03. From the *RCC Standard 321-97 Supplement, Common Risk Criteria for National Ranges: Inert Debris*, this is the number used by the Israeli Ministry of Defense as an annual individual risk criterion for mission essential workers.
- Swiss Ammunition Storage – 1.00E-04. From the *Swiss Technical Requirements for Storage of Ammunition (TLM 75), Part 2, Appendix 8-2*, this is the maximum allowable individual fatality risk per year for directly involved persons.
- Swiss Ammunition Storage (Handling by Army Personnel) – 3.00E-05. From the *Swiss Technical Requirements for Storage of Ammunition (TLM 75), Part 2, Appendix 8-2*, this is the maximum allowable individual fatality risk per year for Army personnel handling ammunition and explosives.
- RCC Standard 321-97 (Mission Essential) – 3.00E-05. From the *RCC Standard*

321-97, *Common Risk Criteria for National Ranges: Inert Debris*, this is the individual annual risk for mission essential personnel from the commonality criteria for national ranges, expressed in terms of expected fatalities.

- Chemical Risks to Workers (Court Case) –  $2.20E-05$ . The Occupational Safety and Health Administration regulates chemical risks when it can be shown that they pose a “significant risk.” In the Supreme Court decision from the case of *Industrial Union Department v. American Petroleum Institute*, 448 U.S. 607 (1980), Justice Stevens stated that “. . . if the odds are one in a thousand. . . a reasonable person might well consider the risk significant and take appropriate steps to decrease or eliminate it.” Based on a working lifetime of forty-five years, this translates into an annual individual risk of  $2.2 \times 10^{-5}$ . (Reproduced from the ACTA report to the Air Force, *Acceptable Risk Criteria for Launches from National Ranges: Rationale*.)

#### Actual Risk Experience

- Space Vehicle Crew Member (NASA) –  $2.76E-02$ . Obtained from a 1998 Knight Ridder, Associated Press report, this statistic is based on NASA deaths from 1967-1998. The average number of space vehicle crew member deaths per year has been 0.47 with an average annual population size of 17. 15 space vehicle crew members died during this period: 11 from accidents that occurred during space travel and 4 during preparations.
- Hang Gliding (U.S.) –  $8.48E-04$ . Based on statistics emailed to the author from the United States Hang Gliding Association, 7 of 8,250 reported hang gliders died in hang glider-related accidents in 1996.
- Mining/Quarrying (U.S.) –  $2.72E-04$ . From 1992-1995, the Bureau of Labor Statistics reported that each year, an average of 169 out of an average annual population of 621,100 miners and quarry workers died from job-related incidents.
- Agriculture (U.S.) –  $2.40E-04$ . From 1992-1995, the Bureau of Labor Statistics reported that each year, an average of 789 out of an average annual population of 3,289,583 agriculture workers died from job-related incidents.
- Motor Vehicle Accidents (U.S.) –  $1.63E-04$ . According to the National Center for Health Statistics, in 1996, 43,300 people died from Motor Vehicle Accidents (MVA) related accidents out of a reported population of 265,283,783.
- Construction (U.S.) –  $1.55E-04$ . From 1992-1995, the Bureau of Labor Statistics reported that each year, an average of 957 out of an average annual population of 6,172,581 construction workers died from job-related incidents.
- Parachuting/Sky Diving (U.S.) –  $1.26E-04$ . Based on statistics emailed to the author from the United States Parachute Association, 39 of 310,000 reported participants died in parachuting or sky diving accidents in 1996.
- Suicide (U.S.) –  $1.18E-04$ . According to the National Center for Health Statistics, during the years 1994 and 1996, an average of 31,022 people committed suicide out of an average population of 262,812,386.
- Hostile Actions (U.S. Marines) –  $7.65E-05$ . Based on data from the DoD Washington Headquarters Services – Directorate for Information Operations and Reports, from 1980-1998 an average of 14 out of an annual average of 188,251 active duty Marines died each year as a result of hostile actions.
- Motor Vehicle Accidents (New York City) –  $7.47E-05$ . According to the New York



State Department of Health, from 1993-1996 an annual average of 560 people died from MVA-related accidents out of an average annual population of 7,493,400 commuters.

- All Job-Related (U.S.) – 4.00E-05. From 1992-1995, the Bureau of Labor Statistics reported that each year, an average of 5,076 out of an average annual population of 126,906,250 workers died from job-related incidents.
- Manufacturing (U.S.) - 4.00E-05. From 1992-1995, the Bureau of Labor Statistics reported that each year, an average of 694 out of an average annual population of 17,356,250 manufacturing workers died from job-related incidents.
- Government (U.S.) - 3.00E-05. From 1992-1995, the Bureau of Labor Statistics reported that each year, an average of 543 out of an average annual population of 18,100,000 government workers died from job-related incidents.
- Drugs (U.S.) – 2.74E-05. According to the National Center for Health Statistics, from 1992-1994, an average of 7,054 people died each year from drug-related accidents out of an average annual population of 257,733,843.
- Hostile Actions (U.S. Military) – 1.55E-05. Based on data from the DoD Washington Headquarters Services – Directorate for Information Operations and Reports, from 1980-1998, an average of 30 out of an annual average of 1,908,078 active duty members of the armed forces died each year as a result of hostile actions.
- Hostile Actions (U.S. Army) – 1.29E-05. Based on data from the DoD Washington Headquarters Services – Directorate for Information Operations and Reports, from 1980-1998, an average of 9 out of an annual average of 680,291 active duty Army personnel died each year as a result of hostile actions.
- Surgical/Medical Care Complications (U.S.) – 1.04E-05. According to the National Center for Health Statistics, from 1992-1994, an average of 2,670 people died each year from surgical or medical care-related incidents out of an average annual population of 257,733,843.
- Hostile Actions (U.S. Navy) – 7.72E-06. Based on data from the DoD Washington Headquarters Services – Directorate for Information Operations and Reports, from 1980-1998, an average of 4 out of an annual average of 524,521 active duty naval personnel died each year as a result of hostile actions.
- Hostile Actions (U.S. Air Force) – 4.47E-06. Based on data from the DoD Washington Headquarters Services – Directorate for Information Operations and Reports, from 1980-1998, an average of 2 out of an annual average of 515,015 active duty Air Force personnel died each year as a result of hostile actions.
- Football Players (U.S.) – 1.71E-06. Based on statistics from the Annual Survey of Football Injury Research, 1931 – 1996 by F. O. Mueller and R.D. Schindler, an annual average of 14 football players die from directly-related football injuries out of an estimated 8,200,000 average annual participants. All of the deaths were high school students.
- Drowning in the Bathtub (U.S.) – 1.23E-06. According to the National Center for Health Statistics, from 1992-1994, an average of 317 people drowned each year while in the bathtub, out of an average annual population of 257,733,843.

## 4.2 Risk to any One Person

The scale supporting the protection criterion for any one person is shown in Figure 6. This scale is labeled involuntary  $P_f$  because the risk associated with the action is not accepted as a voluntary action taken by an individual. For example, victims of homicide, stroke or tornado generally do not die as the result of a voluntary decision to accept risk. These are “involuntary” actions. Figure 6 plots the data on a URS and the following paragraphs describe each data point.

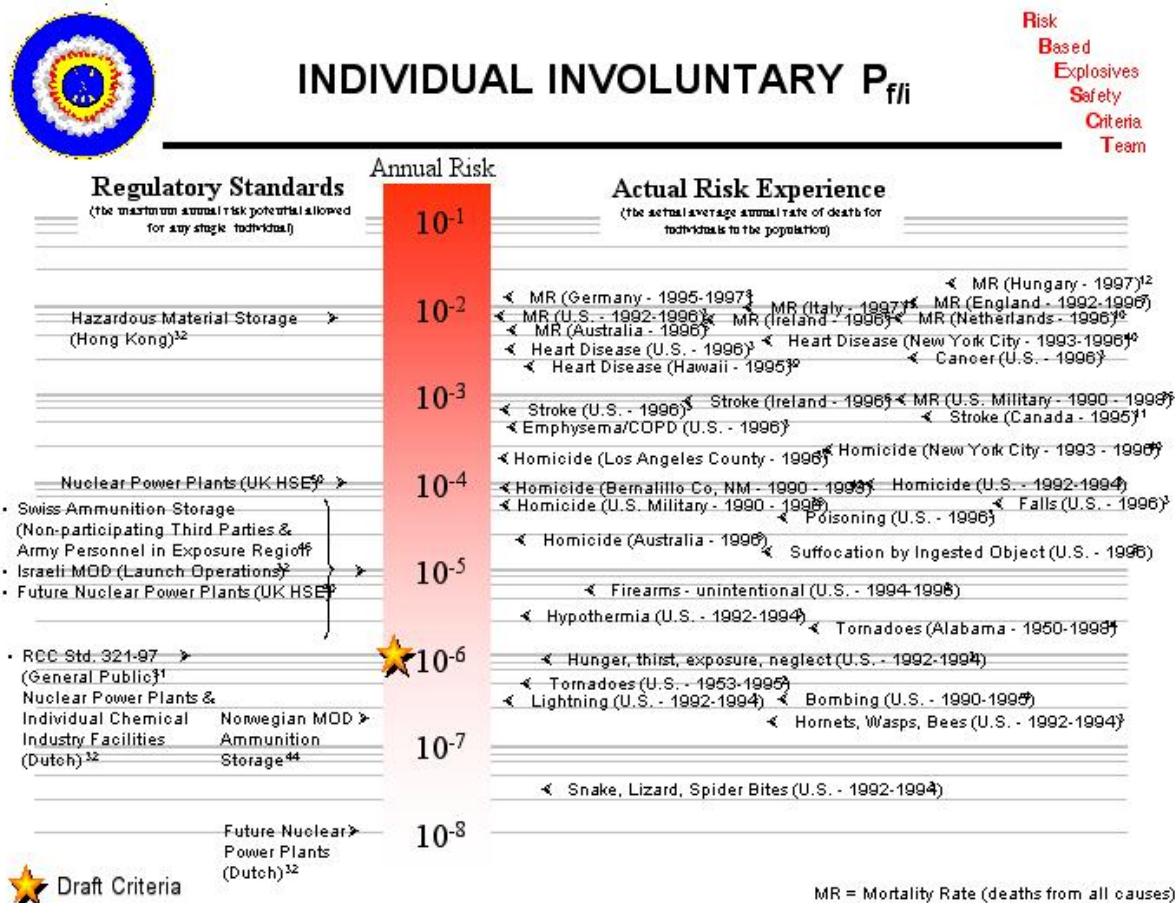


**Figure 6: Involuntary Probability of Fatality**

Note that mortality rates include all modes of fatality for the population reported. However, a mortality rate less than 1.00E-02 does not indicate that the people in that population live longer than 100 years. These numbers are affected by other statistics, including additions to the population through childbirth and increases or losses in population size due to immigration. With the exception of the mortality rate for the U.S. Military, each of the mortality rates includes and reflects the same elements in its derivation. (The U.S. Military mortality rate is not affected by childbirth and the average age and fitness level of the population is not comparable to the statistics for entire nations.) In other words, with the exception of the U.S. Military, this is a comparison of apples to apples. Relative to each other, these numbers are significant since they are a general indication of how probabilities of fatality are influenced by national and

geographic factors. Mortality rates include fatalities from both involuntary and voluntary actions.

### Regulatory Standards

- Nuclear Power Plants (UK HSE) –  $1.00E-04$ . In the *UK Health and Safety Executive – The Tolerability of Risk from Nuclear Power Stations*, it is stated that this is the “suggested maximum tolerable risk to any member of the public from any large-scale industrial hazard.” It is further explained that, “if the maximum tolerable risk for any worker is set at around 1 in 1000 per annum, it seems right to suggest that the maximum level that we [UK HSE] should be prepared to tolerate for any individual member of the public from any large-scale industrial hazard should be not less than ten times lower, i.e., 1 in 10,000 (1 in  $10^4$ ).”
- Swiss Ammunition Storage (Non-Participating Third Parties and Army Personnel in Exposure Region) –  $1.00E-05$ . From the *Swiss Technical Requirements for Storage of Ammunition (TLM 75), Part 2, Appendix 8-2*, this is the maximum allowable individual fatality risk per year for both non-participating third persons and for Army personnel in the exposure region of the facility dealing with ammunition and explosives.
- Israeli MOD Launch Operations (Uninformed General Public) –  $1.00E-05$ . From the *RCC Standard 321-97 Supplement, Common Risk Criteria for National Ranges: Inert Debris*, this is listed as the number established by the Israeli Ministry of Defense for the maximum annual individual fatality risk from launch operations for the non-participating, uninformed general public. Higher risk levels are tolerated for non-participating, uninformed workers in industrial facilities.
- Future Nuclear Power Plants (UK HSE) –  $1.00E-05$ . In the *UK Health and Safety Executive – The Tolerability of Risk from Nuclear Power Stations*, this is listed as the upper bound of the “range of risk to members of the public living near nuclear installation from normal operations.” It is also listed as “the risk of death in an accident at work in the very safest parts of industry.” In explanation, under the section, Safety in Operation, it is stated that “the annual risk of plant failure leading to an uncontrolled release at a modern station is of the order of 1 in a million. When we [UK HSE] reckon in the ‘unquantifiable’ sources of risk, we [UK HSE] must judge the chance overall to be in the region between 1 in 100,000 and 1 in 1 million per annum.”
- RCC Standard 321-97 (General Public) –  $1.00E-06$ . From the *RCC Standard 321-97, Common Risk Criteria for National Ranges: Inert Debris*, this is the individual annual risk for the general public from the commonality criteria for national ranges, expressed in terms of expected fatalities.
- Nuclear Power Plants (UK HSE – *de minimis*) Not Shown –  $1.00E-06$ . Although not specifically stated as *de minimis* in the *UK Health and Safety Executive – The Tolerability of Risk from Nuclear Power Stations*, this is stated as, “the level of risk below which, so long as precautions are maintained, it would not be reasonable to insist on expensive further improvements to standards.” It is otherwise stated as “a broadly acceptable risk to an individual of dying from some particular cause.” For determining *de minimis*, the question to ask is whether the risk level is high enough to warrant regulation. As such, this clearly qualifies as *de minimis*.

- Nuclear Power Plants & Individual Chemical Industry Facilities (Dutch) –  $1.00E-06$ . From the *RCC Standard 321-97 Supplement, Common Risk Criteria for National Ranges: Inert Debris*, this is listed as the acceptable risk standard used by Dutch industries for public individual fatality; applicable to established nuclear power plants and chemical industries.
- Norwegian MOD Ammunition Storage –  $2.00E-07$ . From *NO (ST) IWP 3-96, Storage of Ammunition – Quantitative Risk Assessment – Evaluation and Further Approach*, the Norwegian government has specified that this is the maximum permitted risk of death per year for a member of the public due to an accident in an ammunition storage area.
- Future Nuclear Power Plants (Dutch) –  $1.00E-08$ . From the *RCC Standard 321-97 Supplement, Common Risk Criteria for National Ranges: Inert Debris*, this is listed as the acceptable risk standard used by Dutch industries for public individual fatality; applicable to future nuclear power plants.

#### Actual Risk Experience

- Mortality Rate (Hungary) –  $1.38E-02$ . The Hungarian Central Statistical Office reported that in 1997, 139,434 people died out of a population of 10,135,000. This includes all modes of fatality.
- Mortality Rate (England) –  $1.09E-02$ . The UK Office for National Statistics reported that from 1992-1996, an average of 529,525 people died each year out of an annual population average of 48,630,475. This includes all modes of fatality.
- Mortality Rate (Germany) –  $1.07E-02$ . The Federal Statistical Office of Germany reported that from 1995-1997, an average of 875,940 people died each year out of an annual population average of 81,962,366. This includes all modes of fatality.
- Mortality Rate (Italy) –  $9.59E-03$ . The Italian Istituto Nazionale in Statistics reported that in 1997, 564,679 people died out of a population of 58,882,065. This includes all modes of fatality.
- Mortality Rate (U.S.) –  $8.73E-03$ . The National Center for Health Statistics reported that from 1992-1996, an average of 2,271,966 people died each year, out of an annual population average of 260,248,117. This includes all modes of fatality.
- Mortality Rate (Netherlands) –  $8.70E-03$ . The Centraal Bureau voor de Statistiek reported that in 1996, 135,434 people died out of a population of 15,567,107. This includes all modes of fatality.
- Mortality Rate (Ireland) –  $8.69E-03$ . The Central Statistics Office of Ireland reported that in 1996, 31,514 people died out of a population of 3,626,050. This includes all modes of fatality.
- Mortality Rate (Australia) –  $7.03E-03$ . The Australian Bureau of Statistics reported that in 1996, 128,726 people died out of a population of 18,311,000. This includes all modes of fatality.
- Heart Disease (U.S.) –  $2.79E-03$ . According to the National Center for Health Statistics, in 1994 and 1996, an average of 732,885 Americans died from heart disease. This is out of an average population of 262,812,386.
- Cancer (U.S.) –  $2.04E-03$ . According to the National Center for Health Statistics, in 1994 and 1996, an average of 536,922 Americans died from cancer. This is out of an average population of 262,812,386.

- Heart Disease (Hawaii) –  $1.93E-03$ . The Hawaiian State Department of Health, Office of Health Status Monitoring reported that in 1995, 2,286 Hawaiians died from heart disease. The US Census Bureau reported that the Hawaiian population that same year was 1,183,066. This probability of fatality was significantly lower than the national average.
- Mortality Rate (U.S. Military) –  $8.87E-04$ . Based on data from the DoD Washington Headquarters Services – Directorate for Information Operations and Reports, from 1980-1998, an average of 1,692 out of an annual average of 1,183,066 active duty military personnel died each year. This includes all modes of fatality.
- Stroke (Ireland) –  $8.04E-04$ . The Central Statistics Office of Ireland reported that in 1996, 2,917 people out of a population of 3,626,050, died from stroke.
- Homicide (Washington D.C.) –  $5.98E-04$ . The District of Columbia Department of Health State Center for Health Statistics reported that in 1995, 325 people out of a population of 543,213 were the victims of homicide.
- Stroke (U.S.) –  $5.96E-04$ . According to the National Center for Health Statistics, in 1994 and 1996, an average of 156,624 Americans died from stroke. This is out of an average population of 262,812,386.
- Stroke (Canada) –  $4.81E-04$ . According to Statistics Canada, in 1995 15,537 people died from stroke. This is out of a reported population of 32,301,455.
- Emphysema/COPD (U.S.) –  $3.83E-04$ . According to the National Center for Health Statistics, in 1996, 101,628 Americans died from complications of emphysema (chronic obstructive pulmonary disease). This is out of a population of 265,283,783.
- Homicide (New York City) –  $1.86E-04$ . The New York State Department of Health reported that, from 1993-1996, an average of 1,397 people out of an annual average population of 7,493,400 were victims of homicide.
- Homicide (Los Angeles County) –  $1.49E-04$ . For 1980-1998, the California Department of Justice, Criminal Justice Statistics Center reported that an annual average of 1,398 people out of 9,382,550 were victims of homicide.
- Homicide (U.S.) –  $9.74E-05$ . According to the National Center for Health Statistics, from 1992-1994, an average of 25,115 Americans were the victims of homicide. This is out of an average population of 257,733,843.
- Homicide (Bernalillo County, NM) –  $9.14E-05$ . The Government Information Sharing Project – Oregon State University reported that, from 1990-1993, an annual average of 45 out of 489,664 were the victims of homicide each year.
- Homicide (U.S. Marines) *Not Shown* –  $6.91E-05$ . Based on data from the DoD Washington Headquarters Services – Directorate for Information Operations and Reports, from 1980-1998, an average of 13 out of an annual average of 188,251 active duty Marines were the victims of homicide each year.
- Homicide (U.S. Army) *Not Shown* –  $6.03E-05$ . Based on data from the DoD Washington Headquarters Services – Directorate for Information Operations and Reports, from 1980-1998, an average of 41 out of an annual average of 680,291 active duty Army personnel were the victims of homicide each year.
- Falls (U.S.) –  $5.32E-05$ . According to the National Center for Health Statistics, in 1996, 14,100 people died from falls. This is out of a population of 265,283,783.
- Homicide (U.S. Navy) *Not Shown* –  $4.96E-05$ . Based on data from the DoD Washington Headquarters Services – Directorate for Information Operations and

Reports, from 1980-1998, an average of 26 out of an annual average of 524,521 active duty Navy personnel were the victims of homicide each year.

- Homicide (U.S. Military) –  $4.87E-05$ . Based on data from the DoD Washington Headquarters Services – Directorate for Information Operations and Reports, from 1980-1998, an average of 93 out of an annual average of 1,908,078 active duty military personnel were the victims of homicide each year.
- Poisoning (U.S.) –  $3.92E-05$ . According to the National Center for Health Statistics, in 1996, 10,400 people died from poisoning. This is out of a population of 265,283,783.
- Homicide (U.S. Air Force) *Not Shown* –  $2.52E-05$ . Based on data from the DoD Washington Headquarters Services – Directorate for Information Operations and Reports, from 1980-1998, an average of 13 out of an annual average of 515,015 active duty Air Force personnel were the victims of homicide each year.
- Homicide (Australia) –  $1.80E-05$ . The Australian Bureau of Statistics reported that, in 1996, 330 people out of a population of 18,311,000 were the victims of homicide.
- Suffocation by Ingested Object (U.S.) –  $1.13E-05$ . According to the National Center for Health Statistics, in 1996, 3,000 people died from suffocation by ingested object. This is out of a population of 265,283,783.
- Firearms – unintentional (U.S.) –  $5.44E-06$ . In the National Safety Council's *Accident Facts – 1997 Edition*, the average number of people who died each year from unintentional firearm accidents, from 1994-1996, was 1,429. This was out of an average annual population of 262,793,348 as reported by the US Census Bureau.
- Hypothermia (U.S.) –  $2.37E-06$ . According to the National Center for Health Statistics, from 1992-1994, an average of 611 people died each year from hypothermia. This is out of an average annual population of 257,733,843.
- Tornadoes (Alabama) –  $1.81E-06$ . According to statistics published by the National Weather Services Forecast Office, the average number of people who died in Alabama each year from tornadoes, from 1950-1998, was 7. This was out of an average annual population of 3,863,155 as reported by the US Census Bureau.
- Hunger, thirst, exposure, neglect (U.S.) –  $8.15E-07$ . According to the National Center for Health Statistics, from 1992-1994, an average of 210 people died each year from hunger, thirst, exposure or neglect. This is out of an average annual population of 257,733,843.
- Tornadoes (U.S.) –  $4.08E-07$ . In the National Safety Council's *Accident Facts – 1997 Edition*, the average number of people who died each year from tornadoes, from 1953-1995, was 88. This was out of an average annual population of 215,686,274 as reported by the US Census Bureau.
- Bombing (U.S.) –  $2.77E-07$ . According to statistics published by the FBI Explosives Unit Bomb Data Center, from 1990-1995, an average of 71 Americans were killed each year by bombings. The average annual population was 256,140,612 as reported by the National Center for Health Statistics. It should be noted that this statistics includes the Oklahoma City bombing in 1995.
- Lightning (U.S.) –  $2.52E-07$ . According to the National Center for Health Statistics, from 1992-1994, an average of 65 people died each year from lightning strikes. The average annual population was 257,733,843.
- Hornets, Wasps, Bees (U.S.) –  $1.75E-07$ . According to the National Center for

Health Statistics, from 1992-1994, an average of 45 people died each year from hornet, wasp or bee stings. The average annual population was 257,733,843.

- Snake, Lizard, Spider Bites (U.S.)  $2.72E-08$ . According to the National Center for Health Statistics, from 1992-1994, an average of 7 people died each year from snake, lizard or spider bites. The average annual population was 257,733,843.

#### 4.3 Risk to All Workers (Collective Risk)

The scale supporting the protection criterion for all workers is shown in Figure 7. The intent of these criteria is to provide aggregate protection for workers at a specific post, camp, or station or other explosives site. This scale is labeled voluntary  $E_f$  because the risk associated with the action is accepted as a voluntary action taken by an individual. For example, when a person accepts a job with known risks it is "voluntary." Figure 7 plots the data on a URS and the following paragraphs describe each data point.

Note that included on the scale, in blue (italics), are statistics that have been normalized to a population of 1000 people to better illustrate their relevance to the regulatory standards. The implication of this normalization is that a typical post, camp, or station may have 1000 workers in the exposed population.

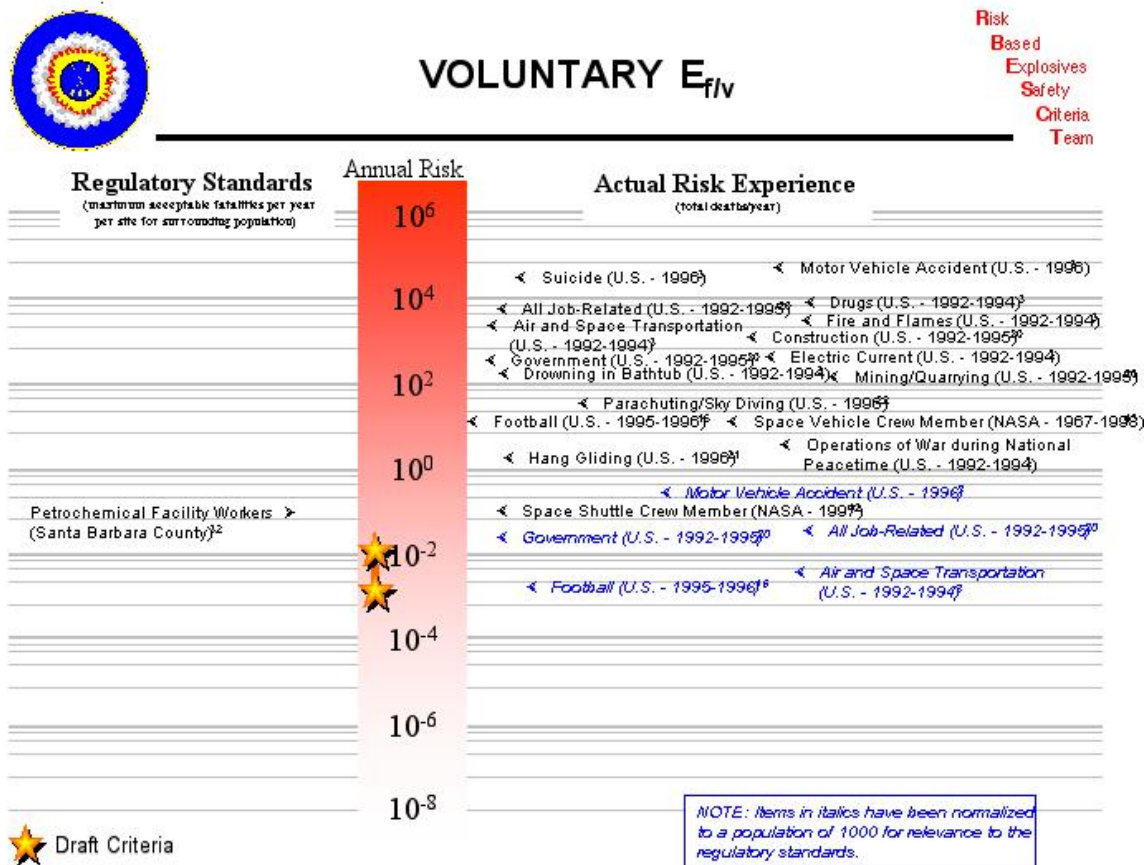


Figure 7: Voluntary Expected Fatalities



### Regulatory Standards

- Petrochemical Facility Workers (Santa Barbara County) –  $1.10E-01$ . From the *RCC Standard 321-97 Supplement, Common Risk Criteria for National Ranges: Inert Debris*, this is the maximum annual societal fatality risk to workers at a petrochemical facility under guidelines imposed by the county of Santa Barbara in California.

### Actual Risk Experience

- Space Vehicle Crew Member (NASA) –  $2.76E-02$ . Obtained from a 1998 Knight Ridder, Associated Press report, this statistic is based on NASA deaths from 1967-1998. The average number of space vehicle crew member deaths per year has been 0.47 with an average annual population size of 17. 15 space vehicle crew members died during this period; 11 from accidents that occurred during space travel and 4 during preparations.
- Hang Gliding (U.S.) –  $8.48E-04$ . Based on statistics emailed to the author from the United States Hang Gliding Association, 7 of 8,250 reported hang gliders died in hang glider-related accidents in 1996.
- Mining/Quarrying (U.S.) –  $2.72E-04$ . From 1992-1995, the Bureau of Labor Statistics reported that each year, an average of 169 out of an average annual population of 621,100 miners and quarry workers died from job-related incidents.
- Motor Vehicle Accidents (U.S.) –  $1.63E-04$ . According to the National Center for Health Statistics, in 1996, 43,300 people died in motor vehicle accidents, out of a reported population of 265,283,783.
- Construction (U.S.) –  $1.55E-04$ . From 1992-1995, the Bureau of Labor Statistics reported that each year, an average of 957 out of an average annual population of 6,172,581 construction workers died from job-related incidents.
- Parachuting/Sky Diving (U.S.) –  $1.26E-04$ . Based on statistics emailed to the author from the United States Parachute Association, 39 of 310,000 reported participants died in parachuting or sky diving accidents in 1996.
- Suicide (U.S.) –  $1.18E-04$ . According to the National Center for Health Statistics, during the years 1994 and 1996, an average of 31,022 people committed suicide out of an average population of 262,812,386.
- All Job-Related (U.S.) –  $4.00E-05$ . From 1992-1995, the Bureau of Labor Statistics reported that each year, an average of 5,076 out of an average annual population of 126,906,250 workers died from job-related incidents.
- Government (U.S.) -  $3.00E-05$ . From 1992-1995, the Bureau of Labor Statistics reported that each year, an average of 543 out of an average annual population of 18,100,000 government workers died from job-related incidents.
- Drugs (U.S.) –  $2.74E-05$ . According to the National Center for Health Statistics, from 1992-1994, an average of 7,054 people died each year from drug-related accidents out of an average annual population of 257,733,843.
- Fire and Flames (U.S.) –  $1.53E-05$ . According to the National Center for Health Statistics, from 1992-1994, an average of 3,948 people died each year from fire and flame related incidents. The average annual population was 257,733,843.
- Air and Space Transportation (U.S.) –  $3.91E-06$ . According to the National Center for Health Statistics, from 1992-1994, an average of 1,009 people died each year in



air and space transportation accidents. The average annual population was 257,733,843.

- Electric Current (U.S.) –  $2.11E-06$ . According to the National Center for Health Statistics, from 1992-1994, an average of 545 people died each year from incidents involving electrocution. The average annual population was 257,733,843.
- Football Players (U.S.) –  $1.71E-06$ . Based on statistics from the Annual Survey of Football Injury Research, 1931 – 1996 by F. O. Mueller and R.D. Schindler, an annual average of 14 football players die from directly-related football injuries out of an estimated 8,200,000 average annual participants. All of the deaths were high school students.
- Drowning in the Bathtub (U.S.) –  $1.23E-06$ . According to the National Center for Health Statistics, from 1992-1994, an average of 317 people drowned each year while in the bathtub. The average annual population was 257,733,843.
- Operations of War during National Peacetime (U.S.) –  $4.66E-08$ . According to the National Center for Health Statistics, from 1992-1994, an average of 12 people were killed in operations of war even though the nation was at peace. The average annual population was 257,733,843.

#### 4.4 Risk to all People (Public Collective Risk)

The scale supporting the protection criterion for all people is shown in Figure 8. This scale is labeled involuntary  $E_f$  because the risk associated with the action is not accepted as a voluntary action taken by the individuals. For example, death from cancer, homicide or lightning is generally not the result of a voluntary decision by an individual to accept risk. Figure 8 plots the data on a URS and the following paragraphs describe each data point.

Note that included on the scale, in blue (*italics*), are statistics that have been normalized to a population of 1000 people to better illustrate their relevance to the regulatory standards. The implication of this normalization is that the number of persons surrounding a typical post, camp, or station may be 1000.

##### Regulatory Standards

- Chemical Plants (Denmark) –  $1.10E-02$ . From the ACTA Report to the Air Force, Acceptable Risk Criteria for Launches from National Ranges: Rationale, reproduced from a report on quantitative and qualitative risk criteria for risk acceptance produced for Miljøstyrelsen, this is the upper limit of a defined region at which risks of annual fatality expectations become unacceptable, as recommended by a Danish national task force of engineers.
- Hazardous Material Storage (Hong Kong) –  $7.00E-03$ . From the *RCC Standard 321-97 Supplement, Common Risk Criteria for National Ranges: Inert Debris*, this is the *de manifestis* annual collective risk standard adopted by Hong Kong as an acceptable public fatality risk profile standard for facilities storing hazardous material.
- Nuclear Power Plants and Chemical Industries (Dutch) –  $1.10E-03$ . From the *RCC Standard 321-97 Supplement, Common Risk Criteria for National Ranges: Inert*

*Debris*, this is listed as the acceptable risk standard used by Dutch industries for the collective public annual fatality risk.

- Petrochemical Facility – General Public (Santa Barbara County) –  $1.00E-03$ . From the *RCC Standard 321-97 Supplement, Common Risk Criteria for National Ranges: Inert Debris*, this is the maximum annual societal fatality risk to the general public surrounding a petrochemical facility under guidelines imposed by the county of Santa Barbara in California.

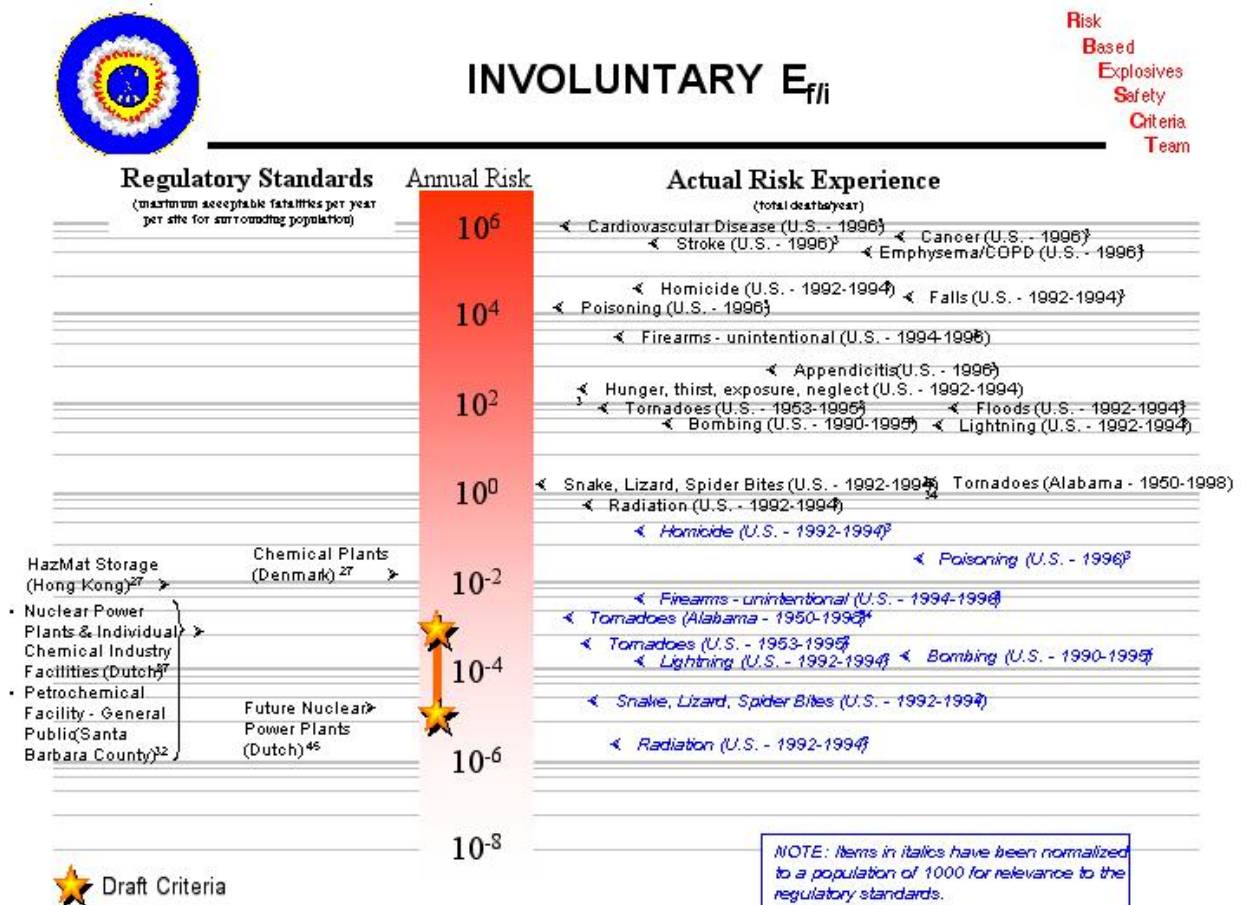


**Figure 8: Involuntary Expected Fatalities**

- Chemical Plants (Denmark – *de minimis*) Not Shown –  $1.10E-04$ . From the ACTA Report to the Air Force, *Acceptable Risk Criteria for Launches from National Ranges: Rationale*, reproduced from a report on quantitative and qualitative risk criteria for risk acceptance produced for Miljøstyrelsen, this is the lower limit of a defined region at which risks of annual fatality expectations become acceptable, as recommended by a Danish national task force of engineers.
- Hazardous Material Storage (Hong Kong – *de minimis*) Not Shown –  $7.00E-05$ . From the *RCC Standard 321-97 Supplement, Common Risk Criteria for National Ranges: Inert Debris*, this is the *de minimis* annual collective risk standard adopted by Hong Kong as an acceptable public fatality risk profile standard for facilities storing hazardous material.

- Future Nuclear Power Plants (Dutch) –  $1.10E-05$ . From the *RCC Standard 321-97 Supplement, Common Risk Criteria for National Ranges: Inert Debris*, this is listed as the acceptable risk standard used by Dutch industries for the collective public annual fatality risk; applicable to future nuclear power plants.

#### Actual Risk Experience

- Cardiovascular Disease (U.S.) –  $3.58E-03$ . According to the National Center for Health Statistics, in 1996, 950,164 people out of a population of 265,283,783 died from cardiovascular disease.
- Cancer (U.S.) –  $2.04E-03$ . According to the National Center for Health Statistics, in 1994 and 1996, an average of 536,922 Americans died each year from cancer. This is out of an average annual population of 262,812,386.
- Stroke (U.S.) –  $5.96E-04$ . According to the National Center for Health Statistics, in 1994 and 1996, an average of 156,624 Americans died each year from cancer. This is out of an average annual population of 262,812,386.
- Emphysema/COPD (U.S.) –  $3.83E-04$ . According to the National Center for Health Statistics, in 1996, 101,628 Americans died from complications of emphysema (chronic obstructive pulmonary disease). This is out of a population of 265,283,783.
- Homicide (U.S.) –  $9.74E-05$ . According to the National Center for Health Statistics, from 1992-1994, an average of 25,115 Americans were the victims of homicide. This is out of an average population of 257,733,843.
- Falls (U.S.) –  $5.32E-05$ . According to the National Center for Health Statistics, in 1996, 14,100 people died from falls. This is out of a population of 265,283,783.
- Poisoning (U.S.) –  $3.92E-05$ . According to the National Center for Health Statistics, in 1996, 10,400 people died from poisoning. This is out of a population of 265,283,783.
- Firearms – unintentional (U.S.) –  $5.44E-06$ . In the National Safety Council's *Accident Facts – 1997 Edition*, the average number of people who died each year from firearm accidents, from 1994-1996, was 1,429. This was out of an average annual population of 262,793,348 as reported by the US Census Bureau.
- Tornadoes (Alabama) –  $1.81E-06$ . According to statistics published by the National Weather Services Forecast Office, the average number of people who died in Alabama each year from tornadoes, from 1950-1998, was 7. This was out of an average annual population of 3,863,155 as reported by the US Census Bureau.
- Appendicitis (U.S.) –  $1.60E-06$ . According to the National Center for Health Statistics, in 1996, 424 people died from appendicitis. This is out of a population of 265,283,783.
- Hunger, thirst, exposure, neglect (U.S.) –  $8.15E-07$ . According to the National Center for Health Statistics, from 1992-1994, an average of 210 people died each year from hunger, thirst, exposure or neglect. This is out of an average annual population of 257,733,843.
- Floods (U.S.) –  $3.69E-07$ . According to the National Center for Health Statistics, from 1992-1994, an average of 95 people died each year flooding. This is out of

an average annual population of 257,733,843.

- Tornadoes (U.S.) –  $4.08E-07$ . In the National Safety Council's *Accident Facts – 1997 Edition*, the average number of people who died each year from tornadoes, from 1953-1995, was 88. This was out of an average annual population of 215,686,274 as reported by the US Census Bureau.
- Bombing (U.S.) –  $2.77E-07$ . According to statistics published by the FBI Explosives Unit Bomb Data Center, from 1990-1995, an average of 71 Americans were killed each year by bombings. The average annual population was 256,140,612 as reported by the National Center for Health Statistics. It should be noted that this statistics includes the Oklahoma City bombing in 1995.
- Lightning (U.S.) –  $2.52E-07$ . According to the National Center for Health Statistics, from 1992-1994, an average of 65 people died each year from lightning strikes. This is out of an average annual population of 257,733,843.
- Snake, Lizard, Spider Bites (U.S.)  $2.72E-08$ . According to the National Center for Health Statistics, from 1992-1994, an average of 7 people died each year from snake, lizard or spider bites. This is out of an average annual population of 257,733,843.
- Radiation (U.S.) –  $2.33E-09$ . In *A Brief Chronology of Radiation and Protection* by J.E. Ellsworth III, it is noted that, from 1991-1995, an average of 0.6 people died each year due to radiation. The average annual population was 257,626,760.

## 5.0 Conclusions

The RBESCT has been conducting research for data on which to base the criteria chosen for personnel protection. Accident data, regulations, and legal precedents have been reviewed to identify data relevant to the level of personnel protection. These data have been plotted on the Universal Risk Scales. A foundation has been laid which can benefit the international explosives safety community, as well as other safety communities, who are using risk-based analyses and numerical risk criteria. We invite the international explosives safety community to review the universal risk scales and offer additional data for incorporation into the scales. Such comments can be forwarded to [mhardwick@apt-research.com](mailto:mhardwick@apt-research.com).

The Appendix contains the sources referenced in the Universal Risk Scales.

## Appendix – Documents and Organizations Referenced in Figures 5 - 8

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- <sup>20</sup> Bureau of Labor Statistics. "Census of Fatal Occupational Injuries Summary" <http://stats.bls.gov> August 1997 (25 January 1999)
- <sup>21</sup> United States Hang Gliding Association. E-mail to author. 27 January 1999.
- <sup>22</sup> United States Parachute Association. E-mail to author. 27 January 1999.

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- <sup>43</sup> Knight Ridder. "1 out of 36 people who launch into space die in a space-related

accident.” *Tribune Information Services*, October 25, 1998.

<sup>44</sup> Norwegian Department of Defence. 1996. *Storage of Ammunition - Quantitative Risk Assessment - Evaluation and Further Approach*. NO (ST) IWP 3-96.

<sup>46</sup> *Swiss Technical Requirements for Storage of Ammunition*. TLM 75, Part 2, Appendix 8-2 (Rev. 90).

<sup>47</sup> Air Quality Management District of the South Coast Basin. *New Source Review of Carcinogenic Air Contaminants for a New Facility*. California: Rule 1401.

<sup>48</sup> Air Quality Management District of the South Coast Basin. *New Source Review of Carcinogenic Air Contaminants for a Single Facility*. California: Rule 1402.

<sup>49</sup> *Industrial Union Department v. American Petroleum Institute*. Item 448 U.S. 607. Washington, D.C., 1980.

<sup>50</sup> United Kingdom Health and Safety Executive. 1988. *The Tolerability of Risk from Nuclear Power Stations*. London: Her Majesty’s Stationery Office.



# UNIVERSAL RISK SCALES – A TOOL FOR DEVELOPING RISK CRITERIA BY CONSENSUS

*Bill Pfitzer*  
APT Research, Inc.  
4950 Research Drive  
Huntsville, Alabama 35805  
phone: 256-327-3395, fax: 256-837-7786  
email: [bpfitzer@apt-research.com](mailto:bpfitzer@apt-research.com)

*Meredith Hardwick*  
APT Research, Inc.  
4950 Research Drive  
Huntsville, Alabama 35805  
phone: 256-327-3380, fax: 256-837-7786  
email: [mhardwick@apt-research.com](mailto:mhardwick@apt-research.com)

*Tom Pfitzer*  
APT Research, Inc.  
4950 Research Drive  
Huntsville, Alabama 35805  
phone: 256-327-3388, fax: 256-837-7786  
email: [tpfitzer@apt-research.com](mailto:tpfitzer@apt-research.com)

## Abstract

In 1999, the Risk-Based Explosives Safety Criteria Team (RBESCT) developed the Universal Risk Scales (URS) to assist in the job of selecting appropriate criteria for defining “How safe is safe enough?” The URS summarizes legal precedents and standards that contain criteria for risk acceptance. These data are plotted as points alongside a logarithmic scale quantifying risk. Also plotted on the scale are numerous points representing actual risk statistics derived from historical accident data. The URS was the foundation for selection of the risk criteria currently used to perform risk-based explosives safety siting assessments with the U.S. Department of Defense. This paper provides an update to the previously published URS.

## Introduction

In 1999, the Department of Defense (DoD) sponsored the initial development of risk criteria for use in risk-based management of explosive materials. Initially, these criteria were to be used on a trial basis for decisions associated with siting of explosives facilities. To support the development of these criteria, various data relating to risk-acceptability were gathered from a variety of sources. To be compared, these data needed to be accumulated in a common format. This need led to the development of the URS.

The URS proved to be a valuable tool in reaching consensus within the RBESCT on the risk criteria used for siting explosives facilities. The scales have also been used to compare relevant data to assist policy makers in selecting appropriate risk related criteria in other areas. As the use of risk-based techniques expands within the area of explosives safety, and into other areas where hazards to the public reside, further research is needed to support the development of risk criteria applicable to these areas. This paper provides an update on the RBESCT’s continuing research into the fundamental question - “How safe is safe enough?”



## The URS Format

The answer to this question, “How safe is safe enough?” is an essential ingredient in establishing any risk criterion. Though the question is fundamental to achieving the practical goal of establishing risk criteria, it is also a somewhat philosophical question, in that it requires individuals to make subjective interpretations of legal precedents, societal values and past risk experiences. Opinions vary widely as to what types of information should be considered when making these judgments, and these differences of opinion become all the more pronounced when the relative importance of individual data points is considered. For this reason, consensus decisions regarding risk criteria are particularly difficult to achieve. To facilitate decisions of this type, the URS was developed to display on a single scale a wide variety of information for the purpose of comparison. The intent is to display as much information as practical, with the hope that the individual participants in the decision will find among the data, information they consider relevant. There are two primary types of information shown on the URS. The first, is various risk-related legal precedents and governmental standards which may be considered relevant to the case at hand, the second is real-world statistical data derived from documented accident experience.



**Figure 1: URS Format**

Figure 1 shows the format of the URS. The logarithmic scale was chosen because it can display a wide variety of disparate data and allows the aggregate weight of the individual data points to be viewed at once. This scale also enables large differences in the amount of actual risk to be displayed in a small numerical space. For instance, the difference between the values of zero and one on a linear scale is small; in fact, most people think of this numerical space in linear terms of percent. The linear paradigm, however, does not provide the necessary perspective for a useful understanding of the concept of risk. Measured risk is better viewed logarithmically; as orders of magnitude, to allow comparisons of relative risk. The URS format attempts to achieve this perspective so that the concept of relative risk can be more properly understood.

## The DDESB Risk criteria

In the course of their research and deliberations the RBESCT developed a set of four risk criteria for managing explosives risk at DoD facilities. These four risk criteria were approved by the DDESB in December 1999. The criteria are shown in Figure 2.

| Risk to:                        | Criteria                                                                                                                                                                                               |
|---------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Any 1 worker<br>(Annual $P_i$ ) | <ul style="list-style-type: none"> <li>Limit maximum risk to <math>1 \times 10^{-4}</math></li> </ul>                                                                                                  |
| All workers<br>(Annual $E_i$ )  | <ul style="list-style-type: none"> <li>Attempt to lower risk to <math>1 \times 10^{-3}</math></li> <li>Accept above <math>1 \times 10^{-2}</math> with significant national need only</li> </ul>       |
| Any 1 person<br>(Annual $P_i$ ) | <ul style="list-style-type: none"> <li>Limit maximum risk to <math>1 \times 10^{-6}</math></li> </ul>                                                                                                  |
| All public<br>(Annual $E_i$ )   | <ul style="list-style-type: none"> <li>Attempt to lower risk if above <math>1 \times 10^{-5}</math></li> <li>Accept above <math>1 \times 10^{-3}</math> with significant national need only</li> </ul> |

**Figure 2: Risk Criteria Developed by RBESCT**

As a by-product of their work, the team also developed a set of four generalized URS scales to fit the four more specific criteria for explosives risk. When considering the types of protection the criteria should provide, the team decided the criteria should address the protection of individuals, and of groups of individuals, and that also the criteria should address the protection of persons who have voluntarily accepted some level known risk, and of persons who have not voluntarily accepted the risk.

### The Four Urs Scales

In the figures that follow, all data are shown in terms of annual risk. Each figure contains a star indicating the level of risk associated with the DDESB criteria. The surrounding data points are the product of research for relevant supporting data. Many data points are shown because individuals may ascribe more or less relevance to each data point.

#### Risk To Any One Worker

The scale supporting the criterion for protection of any one worker is shown in Figure 3. This scale is labeled “individual voluntary” because the risk to the individual is accepted voluntarily as a condition of employment. Figure 3 plots the data on a URS and the following paragraphs describe each data point.



**Figure 3: Individual Voluntary**

### Regulatory Standards

- Nuclear Power Plant Workers (UK HSE) –  $1.00\text{E-}03$ . In the *UK Health and Safety Executive – The Tolerability of Risk from Nuclear Power Stations*, this is stated as the “suggested maximum tolerable risk to workers in any industry...about the most risk that is ordinarily accepted under modern conditions for workers in the UK and it seems reasonable to adopt it as the dividing line between what is just tolerable and what is intolerable.”
- Israeli MOD Launch Operations (Mission Essential) –  $1.00\text{E-}03$ . From the *RCC Standard 321-97 Supplement, Common Risk Criteria for National Ranges: Inert Debris*, this is the number used by the Israeli Ministry of Defense as an annual individual risk criterion for mission essential workers.
- Swiss Ammunition Storage –  $1.00\text{E-}04$ . From the *Swiss Technical Requirements for Storage of Ammunition (TLM 75), Part 2, Appendix 8-2*, this is the maximum allowable individual fatality risk per year for directly involved persons.
- Swiss Ammunition Storage (Handling by Army Personnel) –  $3.00\text{E-}05$ . From the *Swiss Technical Requirements for Storage of Ammunition (TLM 75), Part 2, Appendix 8-2*, this is the maximum allowable individual fatality risk per year for Army personnel handling ammunition and explosives.
- RCC Standard 321-97 (Mission Essential) –  $3.00\text{E-}05$ . From the *RCC Standard 321-97, Common Risk Criteria for National Ranges: Inert Debris*, this is the individual annual risk for mission essential personnel from the commonality criteria for national ranges, expressed in terms of expected fatalities.
- Chemical Risks to Workers (Court Case) –  $2.20\text{E-}05$ . The Occupational Safety and Health Administration regulates chemical risks when it can be shown that they pose a “significant risk.” In the Supreme Court decision from the case of *Industrial Union Department v. American Petroleum Institute*, 448 U.S. 607 (1980), Justice Stevens stated that “. . .if the odds are one in a thousand. . . a reasonable person might well consider the risk significant and take appropriate steps to decrease or eliminate it.” Based on a working lifetime of forty-five years, this translates into an annual individual risk of  $2.2 \times 10^{-5}$ . (Reproduced from the ACTA report to the Air Force, *Acceptable Risk Criteria for Launches from National Ranges: Rationale*.)
- UK Ammunition Storage (UK HSE) –  $1.00\text{E-}03$ . From the *AASTP-4, Part I*, this is the maximum allowable individual fatality risk per year for a worker; applicable to storage of ammunition.
- Norway Ammunition Storage –  $4.00\text{E-}05$ . From the *AASTP-4, Part I*, this is the maximum allowable individual fatality risk per year for a worker; applicable to storage of ammunition.
- Australia Ammunition Storage –  $5.00\text{E-}04$ . From the *AASTP-4, Part I*, this is the maximum allowable (upper limit) individual fatality risk per year for a worker; applicable to storage of ammunition.

### **Actual Risk Experience**

- Climbing Annapurna 1 –  $4.23E-01$  - Between 1950 and 2003 there were ~130 attempts to ascend Annapurna 1 (a Himalayan peak of  $\geq 8000\text{m}$ ). Of these attempts, 55 (42.3%) ended in the death of the climber.
- Going Over Niagara Falls in a Barrel –  $2.00E-01$  - Since 1901 there have been 15 daredevil attempts to negotiate Niagara/American Falls in a barrel-type floatation device. Of these attempts, three (20%) resulted in the death of the daredevil. (*Stunting at the falls now carries a maximum fine of \$10,000.*)
- Russian roulette -  $1.67E-01$ . Playing one round only, using a six-shot revolver. Chance of fatality -- one-in-six.
- Mountain Climbing (all peaks  $\geq 8000\text{m}$ , world-wide) –  $9.2E-02$  - Between 1950 and 2003 there were ~6332 attempted ascents of mountain peaks  $\geq 8000$  meters. Of these attempts, 582 (9.2%) resulted in the death of the climber.
- Commercial Fishing (Alaska - vessel length  $>79\text{ft}$ ) –  $7.14E-03$  - According to a 1991 study by the National Academy of Sciences, between 1982 -1987 there was an average of ~20 fatalities/year among an average population of ~2800 workers aboard large commercial fishing vessels in Alaskan waters.
- Commercial Fishing (US – 1993) –  $1.55E-03$  - According to the Bureau of Labor Statistics “commercial fisher” was at the top of the list of high risk occupations.
- Timber Cutters (US – 1993) –  $1.33E-03$  - According to the Bureau of Labor Statistics “timber cutter” was second on the list of high risk occupations.
- Space Vehicle Crew Member (NASA) –  $2.76E-02$ . Obtained from a 1998 Knight Ridder, Associated Press report, this statistic is based on NASA deaths from 1967-1998. The average number of space vehicle crew member deaths per year has been 0.47 with an average annual population size of 17. 15 space vehicle crew members died during this period: 11 from accidents that occurred during space travel and 4 during preparations.
- Hang Gliding (U.S.) –  $8.48E-04$ . Based on statistics emailed to the author from the United States Hang Gliding Association, 7 of 8,250 reported hang gliders died in hang glider-related accidents in 1996.
- Mining/Quarrying (U.S.) –  $2.94E-04$ . For three year period 2000-2002. From National Safety Counsel publication *Injury Facts*.
- Agriculture (U.S.) –  $2.10E-04$ . For three year period 2000-2002. From National Safety Counsel publication *Injury Facts*.
- Motor Vehicle Accidents (U.S.) –  $1.57E-04$ . For three year period 2000-2002. From National Safety Counsel publication *Injury Facts*.
- Construction (U.S.) –  $1.28E-04$ . For three year period 2000-2002. From National Safety Counsel publication *Injury Facts*.
- Parachuting/Sky Diving (U.S.) –  $1.26E-04$ . Based on statistics emailed to the author from the United States Parachute Association, 39 of 310,000 reported participants died in parachuting or sky diving accidents in 1996.
- Suicide (U.S.) –  $1.06E-04$ . For three year period 2000-2002. From National Safety Counsel publication *Injury Facts*.
- Hostile Actions (U.S. Marines) –  $7.65E-05$ . Based on data from the DoD Washington Headquarters Services – Directorate for Information Operations and Reports, from 1980-1998 an average of 14 out of an annual average of 188,251 active duty Marines died each year as a result of hostile actions.
- Motor Vehicle Accidents (New York City) –  $7.47E-05$ . According to the New York State Department of Health, from 1993-1996 an annual average of 560 people died from MVA-related accidents out of an average population of 7,493,400 commuters.
- All Job-Related (U.S.) –  $3.70E-05$ . For three year period 2000-2002. From National Safety Counsel publication *Injury Facts*.
- Manufacturing (U.S.) -  $3.00E-05$ . For three year period 2000-2002. From National Safety Counsel publication *Injury Facts*.
- Government (U.S.) –  $2.40E-05$ . For three year period 2000-2002. From National Safety Counsel publication *Injury Facts*.
- Drugs (U.S.) –  $2.74E-05$ . According to the National Center for Health Statistics, from 1992-1994, an average of 7,054 people died each year from drug-related accidents out of an average annual population of 257,733,843.
- Hostile Actions (U.S. Military) –  $1.55E-05$ . Based on data from the DoD Washington Headquarters Services – Directorate for Information Operations and Reports, from 1980-1998, an average of 30 out of an annual average of 1,908,078 active duty members of the armed forces died each year as a result of hostile actions.
- Hostile Actions (U.S. Army) –  $1.29E-05$ . Based on data from the DoD Washington Headquarters Services – Directorate for Information Operations and Reports, from 1980-1998, an average of 9 out of an annual average

of 680,291 active duty Army personnel died each year as a result of hostile actions.

- Surgical/Medical Care Complications (U.S.) –  $1.04E-05$ . According to the National Center for Health Statistics, from 1992-1994, an average of 2,670 people died each year from surgical or medical care-related incidents out of an average annual population of 257,733,843.
- Hostile Actions (U.S. Navy) –  $7.72E-06$ . Based on data from the DoD Washington Headquarters Services – Directorate for Information Operations and Reports, from 1980-1998, an average of 4 out of an annual average of 524,521 active duty naval personnel died each year as a result of hostile actions.
- Hostile Actions (U.S. Air Force) –  $4.47E-06$ . Based on data from the DoD Washington Headquarters Services – Directorate for Information Operations and Reports, from 1980-1998, an average of 2 out of an annual average of 515,015 active duty Air Force personnel died each year as a result of hostile actions.
- Football Players (U.S.) –  $1.71E-06$ . Based on statistics from the *Annual Survey of Football Injury Research, 1931 – 1996* by F. O. Mueller and R.D. Schindler, an annual average of 14 football players die from directly-related football injuries out of an estimated 8,200,000 average annual participants. All of the deaths were high school students.
- Drowning in the Bathtub (U.S.) –  $1.23E-06$ . According to the National Center for Health Statistics, from 1992-1994, an average of 317 people drowned each year while in the bathtub, out of an average annual population of 257,733,843.

## Risk To Any One Person

The scale supporting the protection criterion for any one person is shown in Figure 4. This scale is labeled “individual involuntary” because the risk is not accepted as a voluntary action taken by an individual. For example, victims of homicide, stroke or tornado generally do not die as the result of a voluntary decision to accept risk. Figure 4 plots the data on a URS and the following paragraphs describe each data point.

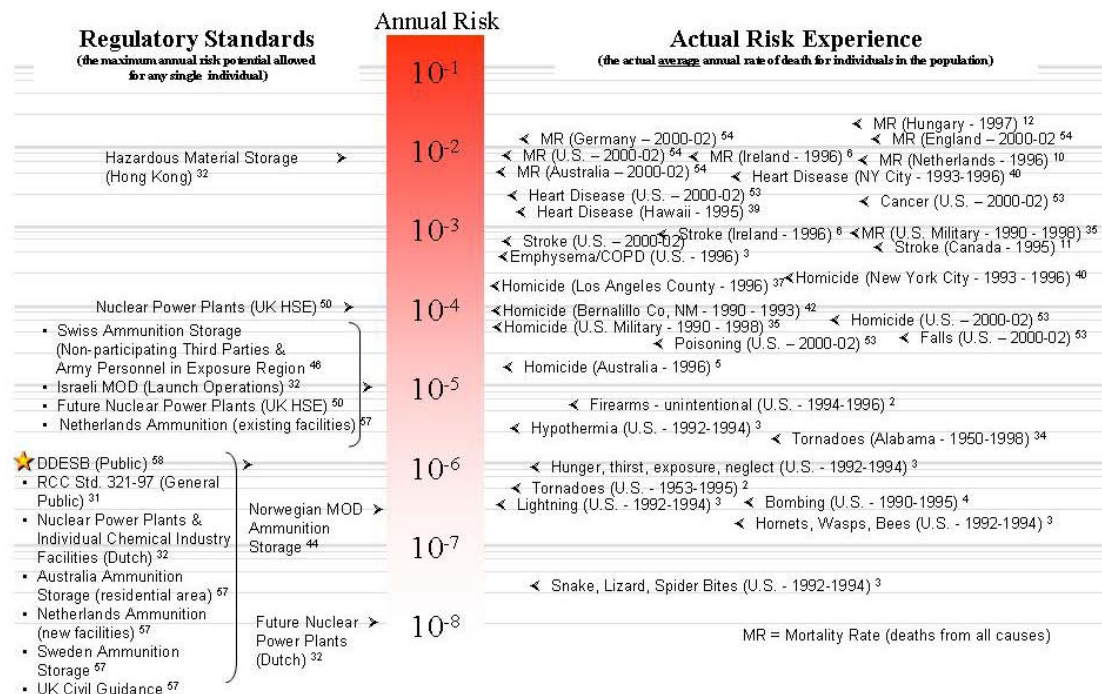


**Figure 4: Individual Involuntary**

## Regulatory Standards

- Nuclear Power Plants (UK HSE) –  $1.00E-04$ . In the *UK Health and Safety Executive – The Tolerability of Risk from Nuclear Power Stations*, it is stated that this is the “suggested maximum tolerable risk to any member of the public from any large-scale industrial hazard.” It is further explained that, “if the maximum tolerable risk for any worker is set at around 1 in 1000 per annum, it seems right to suggest that the maximum level that we [UK HSE] should be prepared to tolerate for any individual member of the public from any large-scale

industrial hazard should be not less than ten times lower, i.e., 1 in 10,000 (1 in 10<sup>4</sup>)."

- Swiss Ammunition Storage (Non-Participating Third Parties and Army Personnel in Exposure Region) – 1.00E-05. From the *Swiss Technical Requirements for Storage of Ammunition (TLM 75), Part 2, Appendix 8-2*, this is the maximum allowable individual fatality risk per year for both non-participating third persons and for Army personnel in the exposure region of the facility dealing with ammunition and explosives.
- Israeli MOD Launch Operations (Uninformed General Public) – 1.00E-05. From the *RCC Standard 321-97 Supplement, Common Risk Criteria for National Ranges: Inert Debris*, this is listed as the number established by the Israeli Ministry of Defense for the maximum annual individual fatality risk from launch operations for the non-participating, uninformed general public. Higher risk levels are tolerated for non-participating, uninformed workers in industrial facilities.
- Future Nuclear Power Plants (UK HSE) – 1.00E-05. In the *UK Health and Safety Executive – The Tolerability of Risk from Nuclear Power Stations*, this is listed as the upper bound of the "range of risk to members of the public living near nuclear installation from normal operations." It is also listed as "the risk of death in an accident at work in the very safest parts of industry." In explanation, under the section, Safety in Operation, it is stated that "the annual risk of plant failure leading to an uncontrolled release at a modern station is of the order of 1 in a million. When we [UK HSE] reckon in the 'unquantifiable' sources of risk, we [UK HSE] must judge the chance overall to be in the region between 1 in 100,000 and 1 in 1 million per annum."
- RCC Standard 321-97 (General Public) – 1.00E-06. From the *RCC Standard 321-97, Common Risk Criteria for National Ranges: Inert Debris*, this is the individual annual risk for the general public from the commonality criteria for national ranges, expressed in terms of expected fatalities.
- Nuclear Power Plants (UK HSE – *de minimis*) Not Shown – 1.00E-06. Although not specifically stated as *de minimis* in the *UK Health and Safety Executive – The Tolerability of Risk from Nuclear Power Stations*, this is stated as, "the level of risk below which, so long as precautions are maintained, it would not be reasonable to insist on expensive further improvements to standards." It is otherwise stated as "a broadly acceptable risk to an individual of dying from some particular cause." For determining *de minimis*, the question to ask is whether the risk level is high enough to warrant regulation. As such, this clearly qualifies as *de minimis*.
- Nuclear Power Plants & Individual Chemical Industry Facilities (Dutch) – 1.00E-06. From the *RCC Standard 321-97 Supplement, Common Risk Criteria for National Ranges: Inert Debris*, this is listed as the acceptable risk standard used by Dutch industries for public individual fatality; applicable to established nuclear power plants and chemical industries.
- Norwegian MOD Ammunition Storage – 2.00E-07. From *NO (ST) IWP 3-96, Storage of Ammunition – Quantitative Risk Assessment – Evaluation and Further Approach*, the Norwegian government has specified that this is the maximum permitted risk of death per year for a member of the public due to an accident in an ammunition storage area.
- Future Nuclear Power Plants (Dutch) – 1.00E-08. From the *RCC Standard 321-97 Supplement, Common Risk Criteria for National Ranges: Inert Debris*, this is listed as the acceptable risk standard used by Dutch industries for public individual fatality; applicable to future nuclear power plants.
- Australia Ammunition Storage – 1.00E-06. From the *AASTP-4, Part I*, this is the maximum allowable individual fatality risk per year for public individual fatality at a residence; applicable to storage of ammunition.
- The Netherlands Ammunition Storage (new facilities) – 1.00E-06. From the *AASTP-4, Part I*, this is the maximum allowable individual fatality risk per year for public individual fatality; applicable to storage of ammunition.
- Sweden Ammunition Storage – 1.00E-06. From the *AASTP-4, Part I*, this is the maximum allowable individual fatality risk per year for public individual fatality; applicable to storage of ammunition.
- UK Civil Guidance – 1.00E-06. From the *AASTP-4, Part I*, this is the maximum allowable individual fatality risk per year for public individual fatality; applicable to storage of ammunition.
- The Netherlands Ammunition Storage (existing facilities) – 1.00E-05. From the *AASTP-4, Part I*, this is the maximum allowable individual fatality risk per year for public individual fatality; applicable to storage of ammunition.

### Actual Risk Experience

- Mortality Rate (Hungary) – 1.38E-02. The Hungarian Central Statistical Office reported that in 1997, 139,434 people died out of a population of 10,135,000. This includes all modes of fatality.
- Mortality Rate (England) – 1.06E-02. For three year period 2000-2002. From National Safety Counsel publication *International Injury Facts*.

- Mortality Rate (Germany) –  $1.05E-02$ . For three year period 2000-2002. From National Safety Council publication *International Injury Facts*.
- Mortality Rate (Italy) –  $9.59E-03$ . The Italian Istituto Nazionale in Statistics reported that in 1997, 564,679 people died out of a population of 58,882,065. This includes all modes of fatality.
- Mortality Rate (U.S.) –  $8.73E-03$ . For three year period 2000-2002. From National Safety Council publication *International Injury Facts*.
- Mortality Rate (Netherlands) –  $8.70E-03$ . The Centraal Bureau voor de Statistiek reported that in 1996, 135,434 people died out of a population of 15,567,107. This includes all modes of fatality.
- Mortality Rate (Ireland) –  $8.69E-03$ . The Central Statistics Office of Ireland reported that in 1996, 31,514 people died out of a population of 3,626,050. This includes all modes of fatality.
- Mortality Rate (Australia) –  $6.92E-03$ . For three year period 2000-2002. From National Safety Council publication *International Injury Facts*.
- Heart Disease (U.S.) –  $2.58E-03$ . For three year period 2000-2002. From National Safety Council publication *International Injury Facts*.
- Cancer (U.S.) –  $2.01E-03$ . For three year period 2000-2002. From National Safety Council publication *International Injury Facts*.
- Heart Disease (Hawaii) –  $1.93E-03$ . The Hawaiian State Department of Health, Office of Health Status Monitoring reported that in 1995, 2,286 Hawaiians died from heart disease. The US Census Bureau reported that the Hawaiian population that same year was 1,183,066. This probability of fatality was significantly lower than the national average.
- Mortality Rate (U.S. Military) –  $8.87E-04$ . Based on data from the DoD Washington Headquarters Services – Directorate for Information Operations and Reports, from 1980-1998, an average of 1,692 out of an annual average of 1,183,066 active duty military personnel died each year. This includes all modes of fatality.
- Stroke (Ireland) –  $8.04E-04$ . The Central Statistics Office of Ireland reported that in 1996, 2,917 people out of a population of 3,626,050, died from stroke.
- Homicide (Washington D.C.) –  $5.98E-04$ . The District of Columbia Department of Health State Center for Health Statistics reported that in 1995, 325 people out of a population of 543,213 were the victims of homicide.
- Stroke (U.S.) –  $6.09E-04$ . For three year period 2000-2002. From National Safety Council publication *Injury Facts*.
- Stroke (Canada) –  $4.81E-04$ . According to Statistics Canada, in 1995 15,537 people died from stroke. This is out of a reported population of 32,301,455.
- Emphysema/COPD (U.S.) –  $3.83E-04$ . According to the National Center for Health Statistics, in 1996, 101,628 Americans died from complications of emphysema (chronic obstructive pulmonary disease). This is out of a population of 265,283,783.
- Homicide (New York City) –  $1.86E-04$ . The New York State Department of Health reported that, from 1993-1996, an average of 1,397 people out of an annual average population of 7,493,400 were victims of homicide.
- Homicide (Los Angeles County) –  $1.49E-04$ . For 1980-1998, the California Department of Justice, Criminal Justice Statistics Center reported that an annual average of 1,398 people out of 9,382,550 were victims of homicide.
- Homicide (U.S.) –  $7.94E-05$ . For three year period 2000-2002. From National Safety Council publication *Injury Facts*.
- Falls (U.S.) –  $4.80E-05$ . For three year period 2000-2002. From National Safety Council publication *Injury Facts*.
- Poisoning (U.S.) –  $4.62E-05$ . For three year period 2000-2002. From National Safety Council publication *Injury Facts*.
- Homicide (Australia) –  $1.80E-05$ . The Australian Bureau of Statistics reported that, in 1996, 330 people out of a population of 18,311,000 were the victims of homicide.
- Suffocation by Ingested Object (U.S.) –  $1.6E-05$ . For three year period 2000-2002. From National Safety Council publication *Injury Facts*.
- Firearms – unintentional (U.S.) –  $5.44E-06$ . In the National Safety Council's *Accident Facts – 1997 Edition*, the average number of people who died each year from unintentional firearm accidents, from 1994-1996, was 1,429. This was out of an average annual population of 262,793,348 as reported by the US Census Bureau.
- Hypothermia (U.S.) –  $2.37E-06$ . According to the National Center for Health Statistics, from 1992-1994, an average of 611 people died each year from hypothermia. This is out of an average annual population of

257,733,843.

- Tornadoes (Alabama) –  $1.81E-06$ . According to statistics published by the National Weather Services Forecast Office, the average number of people who died in Alabama each year from tornadoes, from 1950-1998, was 7. This was out of an average annual population of 3,863,155 as reported by the US Census Bureau.
- Hunger, thirst, exposure, neglect (U.S.) –  $8.15E-07$ . According to the National Center for Health Statistics, from 1992-1994, an average of 210 people died each year from hunger, thirst, exposure or neglect. This is out of an average annual population of 257,733,843.
- Tornadoes (U.S.) –  $4.08E-07$ . In the National Safety Council's *Accident Facts – 1997 Edition*, the average number of people who died each year from tornadoes, from 1953-1995, was 88. This was out of an average annual population of 215,686,274 as reported by the US Census Bureau.
- Bombing (U.S.) –  $2.77E-07$ . According to statistics published by the FBI Explosives Unit Bomb Data Center, from 1990-1995, an average of 71 Americans were killed each year by bombings. The average annual population was 256,140,612 as reported by the National Center for Health Statistics. It should be noted that this statistics includes the Oklahoma City bombing in 1995.
- Lightning (U.S.) –  $2.52E-07$ . According to the National Center for Health Statistics, from 1992-1994, an average of 65 people died each year from lightning strikes. The average annual population was 257,733,843.
- Hornets, Wasps, Bees (U.S.) –  $1.75E-07$ . According to the National Center for Health Statistics, from 1992-1994, an average of 45 people died each year from hornet, wasp or bee stings. The average annual population was 257,733,843.
- Snake, Lizard, Spider Bites (U.S.)  $2.72E-08$ . According to the National Center for Health Statistics, from 1992-1994, an average of 7 people died each year from snake, lizard or spider bites. The average annual population was 257,733,843.

### Risk To All Workers (Collective Risk)

The scale supporting the protection criterion for all workers is shown in Figure 5. The intent of these criteria is to provide aggregate protection for workers at a specific post, camp, or station or other explosives site. This scale is labeled “group voluntary” because the risk is accepted as a voluntary action taken by the individuals in the group. For example, when a person accepts a job with known risks it is voluntary. Figure 5 plots the data on a URS and the following paragraphs describe each data point.

Note that included on the scale, in blue (*italics*), are statistics that have been normalized to a population of 1000 people to better illustrate their relevance to the regulatory standards. The implication of this normalization is that a typical post, camp, or station may have 1000 workers in the exposed population.



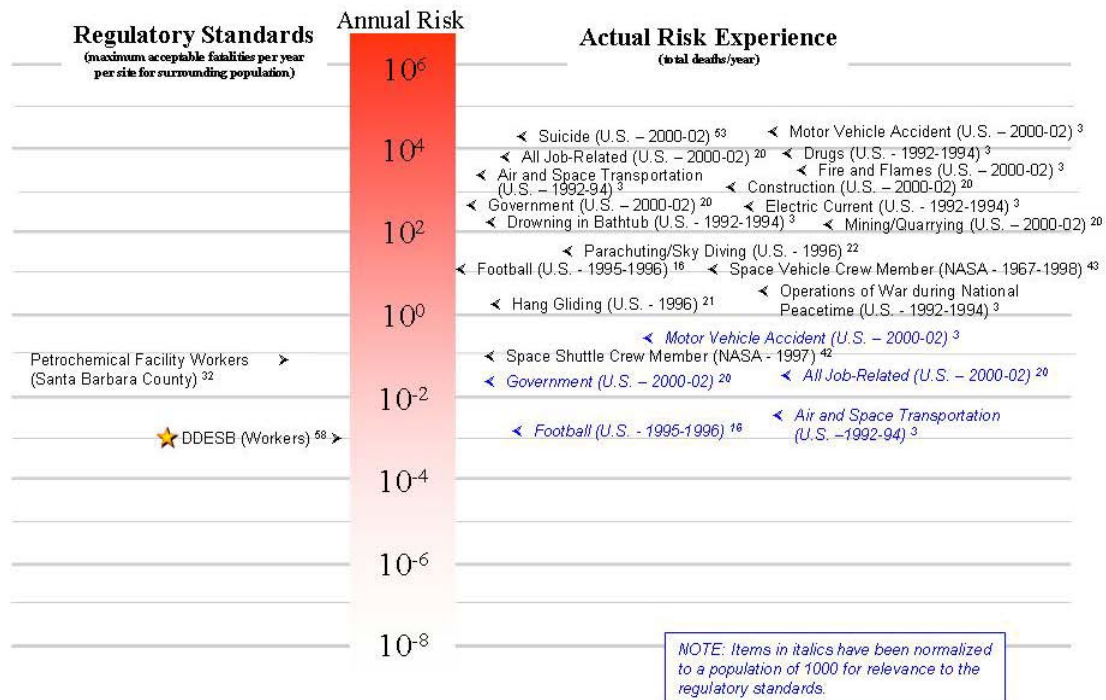


**Figure 5: Group Voluntary**

### Regulatory Standards

- Petrochemical Facility Workers (Santa Barbara County) –  $1.10E-01$ . From the *RCC Standard 321-97 Supplement, Common Risk Criteria for National Ranges: Inert Debris*, this is the maximum annual societal fatality risk to workers at a petrochemical facility under guidelines imposed by the county of Santa Barbara in California.

### Actual Risk Experience

- Space Vehicle Crew Member (NASA) –  $2.76E-02$ . Obtained from a 1998 Knight Ridder, Associated Press report, this statistic is based on NASA deaths from 1967-1998. The average number of space vehicle crew member deaths per year has been 0.47 with an average annual population size of 17. 15 space vehicle crew members died during this period; 11 from accidents that occurred during space travel and 4 during preparations.
- Hang Gliding (U.S.) –  $8.48E-04$ . Based on statistics emailed to the author from the United States Hang Gliding Association, 7 of 8,250 reported hang gliders died in hang glider-related accidents in 1996.
- Mining/Quarrying (U.S.) –  $2.94E-04$ . For three year period 2000-2002. From National Safety Counsel publication *Injury Facts*.
- Motor Vehicle Accidents (U.S.) –  $1.57E-04$ . For three year period 2000-2002. From National Safety Counsel publication *Injury Facts*.
- Construction (U.S.) –  $1.28E-04$ . For three year period 2000-2002. From National Safety Counsel publication *Injury Facts*.
- Parachuting/Sky Diving (U.S.) –  $1.26E-04$ . Based on statistics emailed to the author from the United States Parachute Association, 39 of 310,000 reported participants died in parachuting or sky diving accidents in 1996.
- Suicide (U.S.) –  $1.06E-04$ . For three year period 2000-2002. From National Safety Counsel publication *Injury Facts*.
- All Job-Related (U.S.) –  $3.70E-05$ . For three year period 2000-2002. From National Safety Counsel publication *Injury Facts*.
- Government (U.S.) –  $2.40E-05$ . For three year period 2000-2002. From National Safety Counsel publication *Injury Facts*.
- Drugs (U.S.) –  $2.74E-05$ . According to the National Center for Health Statistics, from 1992-1994, an average of 7,054 people died each year from drug-related accidents out of an average annual population of 257,733,843.
- Fire and Flames (U.S.) –  $1.2E-05$ . For three year period 2000-2002. From National Safety Counsel publication

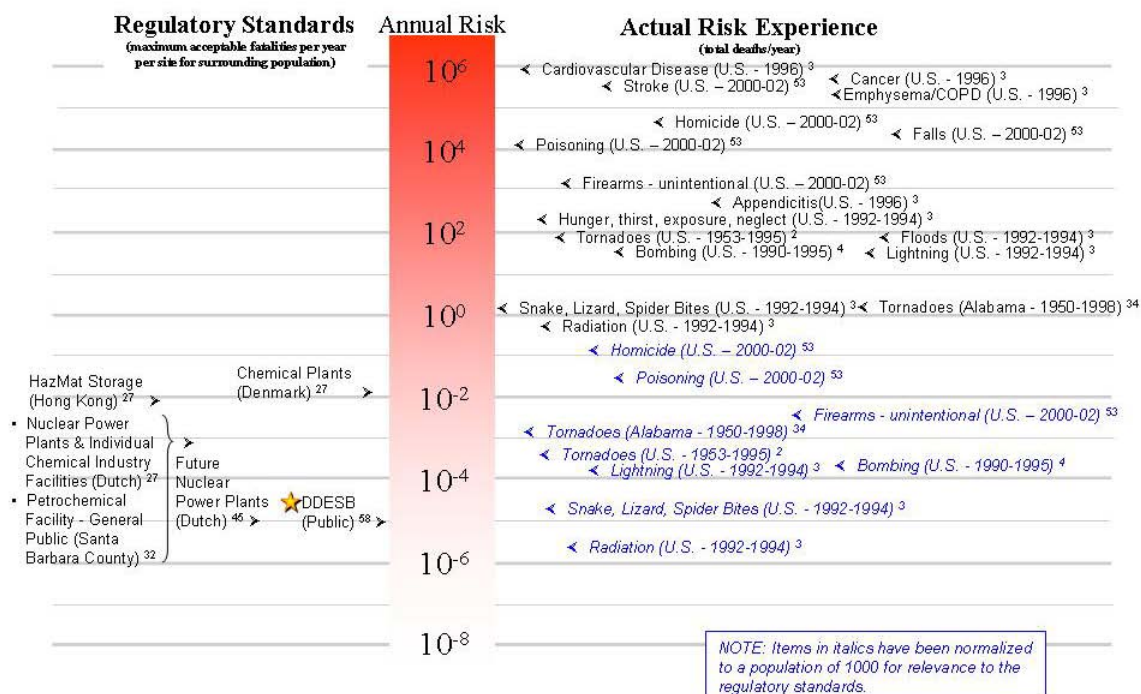
### Injury Facts.

- Air and Space Transportation (U.S.) –  $3.91E-06$ . According to the National Center for Health Statistics, from 1992-1994, an average of 1,009 people died each year in air and space transportation accidents. The average annual population was 257,733,843.  
The risk associated with various modes of transportation is often expressed in terms of fatalities per passenger/mile. According to National Safety Counsel publication *Injury Facts*, when averaged over the 10 year period from 1991 to 2000, the risk of passenger fatality due to air travel was  $\sim 3.0E-02$  per  $10.0E+08$  miles traveled.
- Electrocution (U.S.) –  $2.11E-06$ . According to the National Center for Health Statistics, from 1992-1994, an average of 545 people died each year from incidents involving electric current. The average annual population was 257,733,843.
- Football Players (U.S.) –  $1.71E-06$ . Based on statistics from the *Annual Survey of Football Injury Research, 1931 – 1996* by F. O. Mueller and R.D. Schindler, an annual average of 14 football players die from directly-related football injuries out of an estimated 8,200,000 average annual participants. All of the deaths were high school students.
- Drowning in the Bathtub (U.S.) –  $1.23E-06$ . According to the National Center for Health Statistics, from 1992-1994, an average of 317 people drowned each year while in the bathtub. The average annual population was 257,733,843.
- Operations of War during National Peacetime (U.S.) –  $4.66E-08$ . According to the National Center for Health Statistics, from 1992-1994, an average of 12 people were killed in operations of war even though the nation was at peace. The average annual population was 257,733,843.

### Risk To All People (Public Collective Risk)

The scale supporting the protection criterion for all people is shown in Figure 6. This scale is labeled “group involuntary” because the risk is not accepted as a voluntary action taken by the individuals in the group. For example, death from cancer, homicide or lightning is generally not the result of a voluntary decision by an individual to accept risk. Figure 6 plots the data on a URS and the following paragraphs describe each data point.

Note that included on the scale, in blue (italics), are statistics that have been normalized to a population of 1000 people to better illustrate their relevance to the regulatory standards. The implication of this normalization is that the number of persons surrounding a typical post, camp, or station may be 1000.



## Figure 6: Group Involuntary

### Regulatory Standards

- Chemical Plants (Denmark) –  $1.10E-02$ . From the ACTA Report to the Air Force, *Acceptable Risk Criteria for Launches from National Ranges: Rationale*, reproduced from a report on quantitative and qualitative risk criteria for risk acceptance produced for Miljøstyrelsen, this is the upper limit of a defined region at which risks of annual fatality expectations become unacceptable, as recommended by a Danish national task force of engineers.
- Hazardous Material Storage (Hong Kong) –  $7.00E-03$ . From the *RCC Standard 321-97 Supplement, Common Risk Criteria for National Ranges: Inert Debris*, this is the *de manifestis* annual collective risk standard adopted by Hong Kong as an acceptable public fatality risk profile standard for facilities storing hazardous material.
- Nuclear Power Plants and Chemical Industries (Dutch) –  $1.10E-03$ . From the *RCC Standard 321-97 Supplement, Common Risk Criteria for National Ranges: Inert Debris*, this is listed as the acceptable risk standard used by Dutch industries for the collective public annual fatality risk.
- Petrochemical Facility – General Public (Santa Barbara County) –  $1.00E-03$ . From the *RCC Standard 321-97 Supplement, Common Risk Criteria for National Ranges: Inert Debris*, this is the maximum annual societal fatality risk to the general public surrounding a petrochemical facility under guidelines imposed by the county of Santa Barbara in California.
- Chemical Plants (Denmark – *de minimis*) Not Shown –  $1.10E-04$ . From the ACTA Report to the Air Force, *Acceptable Risk Criteria for Launches from National Ranges: Rationale*, reproduced from a report on quantitative and qualitative risk criteria for risk acceptance produced for Miljøstyrelsen, this is the lower limit of a defined region at which risks of annual fatality expectations become acceptable, as recommended by a Danish national task force of engineers.
- Hazardous Material Storage (Hong Kong – *de minimis*) Not Shown –  $7.00E-05$ . From the *RCC Standard 321-97 Supplement, Common Risk Criteria for National Ranges: Inert Debris*, this is the *de minimis* annual collective risk standard adopted by Hong Kong as an acceptable public fatality risk profile standard for facilities storing hazardous material.
- Future Nuclear Power Plants (Dutch) –  $1.10E-05$ . From the *RCC Standard 321-97 Supplement, Common Risk Criteria for National Ranges: Inert Debris*, this is listed as the acceptable risk standard used by Dutch industries for the collective public annual fatality risk; applicable to future nuclear power plants.

### Actual Risk Experience

- Cardiovascular Disease (U.S.) –  $3.58E-03$ . According to the National Center for Health Statistics, in 1996, 950,164 people out of a population of 265,283,783 died from cardiovascular disease.
- Cancer (U.S.) –  $2.04E-03$ . According to the National Center for Health Statistics, in 1994 and 1996, an average of 536,922 Americans died each year from cancer. This is out of an average annual population of 262,812,386.
- Stroke (U.S.) –  $6.09E-04$ . 159,791 fatalities annually for three year period 2000-2002. From National Safety Counsel publication *Injury Facts*.
- Emphysema/COPD (U.S.) –  $3.83E-04$ . According to the National Center for Health Statistics, in 1996, 101,628 Americans died from complications of emphysema (chronic obstructive pulmonary disease). This is out of a population of 265,283,783.
- Homicide (U.S.) –  $7.94E-05$ . 19,252 fatalities annually for three year period 2000-2002. From National Safety Counsel *Injury Facts* publication.
- Falls (U.S.) –  $4.80E-05$ . 13,462 fatalities annually for three year period 2000-2002. From National Safety Counsel *Injury Facts* publication.
- Poisoning (U.S.) –  $4.62E-05$ . 13,125 fatalities annually for three year period 2000-2002. From National Safety Counsel publication *Injury Facts*.
- According to the National Center for Health Statistics, in 1996, 10,400 people died from poisoning. This is out of a population of 265,283,783.
- Firearms – unintentional (U.S.) –  $3.4E-06$ . 810 fatalities annually for three year period 2000-2002. From National Safety Counsel publication *Injury Facts*.
- Tornadoes (Alabama) –  $1.81E-06$ . According to statistics published by the National Weather Services Forecast Office, the average number of people who died in Alabama each year from tornadoes, from 1950-1998, was 7. This was out of an average annual population of 3,863,155 as reported by the US Census Bureau.
- Appendicitis (U.S.) –  $1.60E-06$ . According to the National Center for Health Statistics, in 1996, 424 people died

from appendicitis. This is out of a population of 265,283,783.

- Hunger, thirst, exposure, neglect (U.S.) –  $8.15E-07$ . According to the National Center for Health Statistics, from 1992-1994, an average of 210 people died each year from hunger, thirst, exposure or neglect. This is out of an average annual population of 257,733,843.
- Floods (U.S.) –  $3.69E-07$ . According to the National Center for Health Statistics, from 1992-1994, an average of 95 people died each year flooding. This is out of an average annual population of 257,733,843.
- Tornadoes (U.S.) –  $4.08E-07$ . In the National Safety Council's *Accident Facts – 1997 Edition*, the average number of people who died each year from tornadoes, from 1953-1995, was 88. This was out of an average annual population of 215,686,274 as reported by the US Census Bureau.
- Bombing (U.S.) –  $2.77E-07$ . According to statistics published by the FBI Explosives Unit Bomb Data Center, from 1990-1995, an average of 71 Americans were killed each year by bombings. The average annual population was 256,140,612 as reported by the National Center for Health Statistics. It should be noted that this statistics includes the Oklahoma City bombing in 1995.
- Lightning (U.S.) –  $2.52E-07$ . According to the National Center for Health Statistics, from 1992-1994, an average of 65 people died each year from lightning strikes. This is out of an average annual population of 257,733,843.
- Snake, Lizard, Spider Bites (U.S.)  $2.72E-08$ . According to the National Center for Health Statistics, from 1992-1994, an average of 7 people died each year from snake, lizard or spider bites. This is out of an average annual population of 257,733,843.
- Radiation (U.S.) –  $2.33E-09$ . In *A Brief Chronology of Radiation and Protection* by J.E. Ellsworth III, it is noted that, from 1991-1995, an average of 0.6 people died each year due to radiation. The average annual population was 257,626,760.

## Catastrophic Risk Scale

The RBESCT has also been developing a URS for Catastrophes as shown in figure 7. On the right-hand side of the figure are data gathered by the team in compiling a survey of past catastrophic events. These catastrophic events are grouped into three categories: 1) pre-historic natural catastrophes, 2) historic natural disasters, and 3) human-caused disasters (which include some human-induced natural disasters).

The scale across the bottom right of Figure 7 indicates approximately when the event occurred in years before present (ybp). The scale in the center of the figure indicates the approximate number of fatalities associated with the event (NA for prehistoric events). On the left side of Figure 7 a few of the more notable historic governance milestones in management of catastrophic risk are listed.

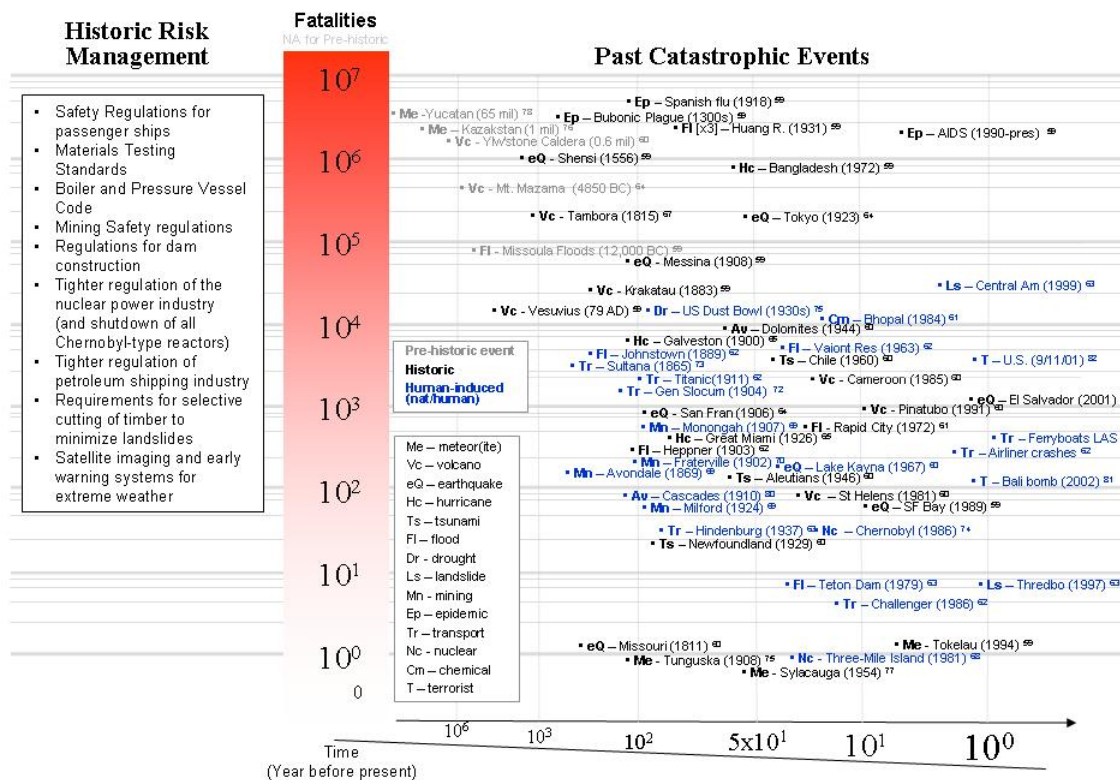


**Figure 7: URS for Catastrophes**

The RBESCT has not found a catastrophic criterion in use by other U.S. agencies or nations. At this time the RBESCT is not recommending a criterion for a catastrophic event.

## CONCLUSIONS

The RBESCT has been conducting research for data to support the criteria chosen for personnel protection. Accident data, regulations, and legal precedents have been reviewed to identify data relevant to the level of personnel protection. These data have been plotted on the Universal Risk Scales. A foundation has been laid that can benefit the international explosives safety community, as well as other safety communities who are using risk-based analyses and numerical risk criteria. We invite the international explosives safety community to review the universal risk scales and offer additional data for incorporation into the scales. Such comments can be forwarded to [mhardwick@apt-research.com](mailto:mhardwick@apt-research.com).

The Appendix contains the sources referenced in the Universal Risk Scales.

## Appendix – Documents and Organizations Referenced in Figures 3 - 7

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## Attachment 13 – PTR Methodology

## PURPOSE

This memorandum describes the methodology used in SAFER Version 3.1 for addressing risk to public traffic routes. Specific questions addressed are:

1. Why are all traffic routes considered public?
2. Why does SAFER calculate the risk within a 2IBD arc?
3. How does SAFER determine 2IBD?
4. How is the P(e) calculated?
5. How are the physical effects and consequences calculated?
6. How is the personnel exposure calculated?
7. What are the inputs to the uncertainty model?
8. How are the consequences calculated (i.e., number of fatalities, major injuries, and minor injuries)?

## DISCUSSIONS

1. Why are all traffic routes considered public?

In accordance with DoD 6055.09-STD, all exposures on sited traffic routes are considered public exposures.

2. Why does SAFER calculate the risk within a 2IBD arc?

Since traffic routes are areas that have short intervals of exposure, a 2IBD arc was selected in order to increase the exposure interval.

3. How does SAFER determine 2IBD?

SAFER determines 2IBD by the following equation for both the Sited and Expected NEWQD.

$$2IBD = 2*IBD \quad (1)$$

where the IBD is taken from Table 1, *IBD Determination*.

**Table 1. IBD Determination**

| HD    | NEWQD                                         | IBD                                                      |
|-------|-----------------------------------------------|----------------------------------------------------------|
| 1.1,  | less than or = 30,000                         | 1250                                                     |
| 1.5,  | greater than 30,000 & less than or = 100,000  | $40*NEWQD^{1/3}$                                         |
|       | greater than 100,000 & less than or = 250,000 | $2.42*NEWQD^{0.577}$                                     |
|       | greater than 250,000                          | $50*NEWQD^{1/3}$                                         |
| 1.2.1 | less than or = 70                             | 200                                                      |
|       | greater than 70                               | $-735.186+(237.559*(\ln(NEWQD)))-(4.274*(\ln(NEWQD)^2))$ |
| 1.2.2 | less than or = 20                             | 100                                                      |
|       | greater than 20                               | $101.649-(15.934*(\ln(NEWQD)))+(5.173*(\ln(NEWQD)^2))$   |
| 1.2.3 | any                                           | 396                                                      |
| 1.3   | less than 1,000                               | 75                                                       |
|       | greater than or = 1,000                       | $8*NEWQD^{1/3}$                                          |
| 1.4   | NA                                            | NA                                                       |
| 1.6   | any                                           | 1250                                                     |

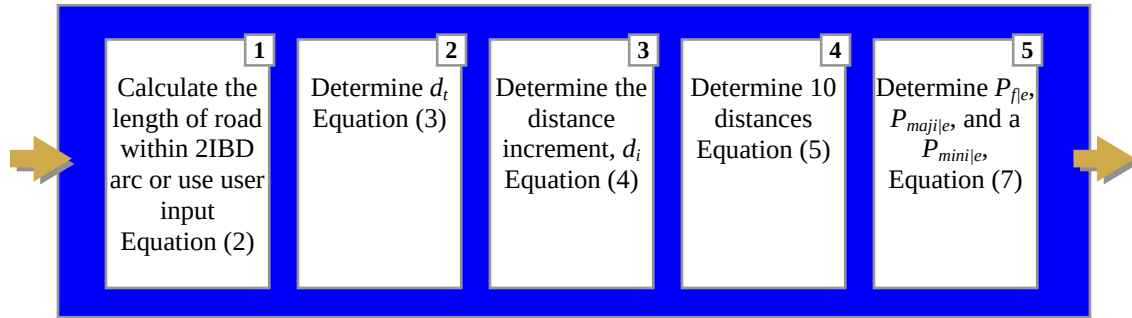
#### 4. How is the P(e) calculated?

The P(e) is determined using the same methodology that is used for non-PTR cases. See Section 4.1.2 of Technical Paper #14 for more details on the P(e) determination.

#### 5. How are the physical effects and consequences calculated?

In non-PTR cases SAFER calculates the values for  $P_{fle}$ ,  $P_{maji|e}$ , and a  $P_{mini|e}$ , at a single distance. For a PTR case SAFER calculates  $P_{fle}$ ,  $P_{maji|e}$ , and a  $P_{mini|e}$  at 10 distances and averages the results together to determine a final  $P_{fle}$ ,  $P_{maji|e}$ , and a  $P_{mini|e}$ . A building model that represents a passenger vehicle is included in SAFER in order to calculate structural response.

The final  $P_{fle}$ ,  $P_{maji|e}$ , and a  $P_{mini|e}$  values are calculated using 5 substeps.



Inputs:

- 2IBD, calculated by SAFER
- Length of Road Within 2IBD Arc (ft),  $L$ , calculated by SAFER or user input
- Distance between then PES and closest point to the road,  $d_{close}$ , user input

##### Substep 1

If needed SAFER will calculate the Length of Road Within 2IBD Arc (ft),  $L$ , by:

$$L = 2 * \left( \sqrt{(2IBD)^2 - (d_{close})^2} \right) \quad (2)$$

where the distance between the PES and closest point to the road is entered by the user and 2IBD is calculated by SAFER.

##### Substep 2

SAFER calculates half of the distance traveled,  $d_t$ , by:

$$d_t = L/2 \quad (3)$$

where  $L$  is calculated in equation (2) or entered by the user.

##### Substep 3

SAFER calculates a distance increment,  $d_i$  by:

$$d_i = d_t/9 \quad (4)$$

where  $d_t$  is calculated in equation (3).

##### Substep 4

Using the distance increment,  $d_i$  calculated in Substep 3, 10 distance points are calculated using equation (5).

$d_1$  = distance between PES and the closest point to the road  $d_{close}$ , user input

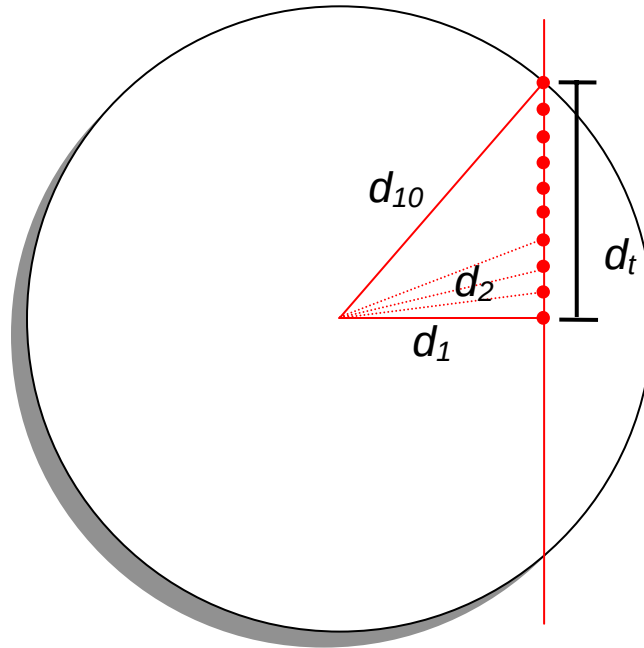
$$d_2 = \sqrt{(d_1)^2 + [d_i * (2 - 1)]^2}$$

$$d_3 = \sqrt{(d_1)^2 + [d_i * (3 - 1)]^2}$$

$$d_n = \sqrt{(d_1)^2 + [d_i * (n - 1)]^2}$$

$$d_{10} = \sqrt{(d_1)^2 + (d_i)^2} = 2IBD$$

(5)



Using the 10 distances calculated in above, SAFER will calculate the physical effects and consequences for each distance.

#### Substep 5

SAFER calculates the final  $P_{fle}$ ,  $P_{maji|e}$ , and  $P_{mini|e}$ , by averaging the results from the 10 distances calculated in Substep 4.

$$P_{fle} = \frac{\sum_{distance1}^{distance10} (P_{fle})}{10}$$

$$P_{maji|e} = \frac{\sum_{distance1}^{distance10} (P_{maji|e})}{10}$$

$$P_{mini|e} = \frac{\sum_{distance1}^{distance10} (P_{mini|e})}{10}$$

(6)

Outputs:

- Probability of fatality given an event,  $P_{fle}$
- Probability of major injury given an event,  $P_{maji|e}$
- Probability of minor injury given an event,  $P_{mini|e}$

#### 6. How is the personnel exposure calculated?

The personnel exposure is calculated for both the group and an individual. In addition to the exposure determination, a standard deviation for both is calculated.

Inputs:

- Length of Road Within 2 IBD Arc (ft),  $L$ , user input or calculated by SAFER
- Number of vehicles per day, user input
- Maximum number of vehicles per hour, user input
- Maximum number of people per vehicle, user input
- Average number of people per vehicle, user input
- Average vehicle speed (mph), user input
- Minimum vehicle speed (mph), user input
- Maximum number of trips an individual makes per day, user input
- Average number of trips an individual makes per day, user input

##### Substep 1

Calculate the group exposure by:

$$\text{group exposure} = \frac{(L/5280) * \text{number of vehicles per hour} * \text{number of people per vehicle}}{\text{average vehiclespeed}} \quad (7)$$

where the distance traveled,  $L$ , is determined by SAFER or entered by the user, expected vehicles per hour is calculated by dividing the number of vehicles per day by 24 hours, the number of people per vehicle is entered by the user, and the average speed is entered by the user.

##### Substep 2

Next, the upper bound group exposure is determined:

$$\text{upper bound group exposure} = \frac{(L/5280) * \text{maximum vehicles per hour} * \text{maximum number of people per vehicle}}{\text{minimum vehiclespeed}} \quad (8)$$

where the distance traveled,  $L$ , is determined by SAFER or entered by the user, maximum vehicles per hour is entered by the user, the maximum number of people per vehicle is entered by the user, and the minimum speed is entered by the user.

The standard deviation in the group exposure is calculated by:

$$\text{standard deviation (group exposure)} = \frac{\ln(\text{upper bound exposure}/\text{group exposure})}{3} \quad (9)$$

##### Substep 3

Calculate the individual exposure by:

$$\text{individual exposure} = \frac{(L/5280) * (\text{average number of trips an individual makes per day}/24)}{\text{average vehiclespeed}} \quad (10)$$

where the distance traveled, L, is determined by SAFER or entered by the user, trips per hour is calculated by SAFER using the user input of average number of trips an individual makes per day, and the average speed is entered by the user.

#### Substep 4

The upper bound individual exposure is determined by:

$$\text{upper bound individual exposure} = \frac{(L/5280) * (\text{maximum number of trips an individual makes per day} / 24)}{\text{minimum vehicle speed}} \quad (11)$$

where the distance traveled, L, is determined by SAFER or entered by the user, maximum number of trips an individual makes per day is entered by the user, and the minimum vehicle speed is entered by the user.

The standard deviation in the group exposure is calculated by:

$$\text{standard deviation (individual exposure)} = \frac{\ln(\text{upper bound individual exposure} / \text{individual exposure})}{3} \quad (12)$$

Outputs:

- Group exposure
- Standard deviation in group exposure
- Individual exposure
- Standard deviation in individual exposure

#### 7. What are the inputs to the uncertainty model?

The standard deviation inputs related to personnel exposure were described in Question #5 above. All other uncertainty inputs are determined in the same manner as in non-PTR cases. The complete listing of uncertainty inputs is shown in the table below.

| Symbol               | Short Title                                  | Methodology                                  |
|----------------------|----------------------------------------------|----------------------------------------------|
| $\Delta t_o$         | median value of $\Delta t$                   | assume delta t is equal to one for PTR cases |
| $\sigma_{\Delta t}$  | standard deviation of $\Delta t$             | see Technical Paper #14                      |
| $S_o$                | median value of environmental factor         | see Technical Paper #14                      |
| $\sigma_S$           | standard deviation of environmental factor   | see Technical Paper #14                      |
| $\lambda_{oo}$       | median value of lambda                       | see Technical Paper #14                      |
| $\sigma_{\lambda o}$ | standard deviation of lambda                 | see Technical Paper #14                      |
| $E_{oo}$             | epistemic median daily exposure              | see Technical Paper #14                      |
| $\sigma_e$           | random variation standard deviation exposure | see Technical Paper #14                      |
| $\sigma_{e1}$        | random variation in lambda due to exposure   | NA                                           |
| $\sigma_{Eo}$        | epistemic standard deviation of exposure     | NA                                           |
| $P_{f100}$           | epistemic median $P_{f e}$ blast             | based on average of 10 distance runs         |
| $P_{f200}$           | epistemic median $P_{f e}$ building damage   | based on average of 10 distance runs         |
| $P_{f300}$           | epistemic median $P_{f e}$ debris            | based on average of 10 distance runs         |
| $P_{f400}$           | epistemic median $P_{f e}$ glass             | based on average of 10 distance runs         |
| $\sigma_y$           | standard deviation yield                     | see Technical Paper #14                      |

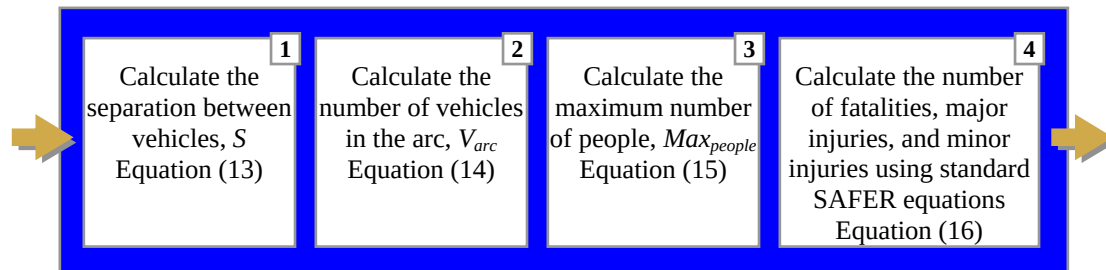
| Symbol          | Short Title                                   | Methodology             |
|-----------------|-----------------------------------------------|-------------------------|
| $\sigma_{y0}$   | epistemic standard deviation yield            | see Technical Paper #14 |
| $\rho_{Ne}$     | correlation between NEW and exposure          | NA                      |
| $\rho_{Ae}$     | correlation between PES activity and exposure | NA                      |
| $\sigma_{NEW1}$ | standard deviation NEW                        | Set to 1.0.             |
| $\sigma_{NEW2}$ | standard deviation NEW                        | NA                      |
| $\sigma_1$      | standard deviation for variation in o/p       | see Technical Paper #14 |
| $\sigma_2$      | standard deviation for variation in b/c       | see Technical Paper #14 |
| $\sigma_3$      | standard deviation for variation in debris    | see Technical Paper #14 |
| $\sigma_4$      | standard deviation for variation in glass     | see Technical Paper #14 |
| $\sigma_{10}$   | epistemic standard deviation for overpressure | see Technical Paper #14 |
| $\sigma_{20}$   | epistemic standard deviation for bldg damage  | see Technical Paper #14 |
| $\sigma_{30}$   | epistemic standard deviation for debris       | see Technical Paper #14 |
| $\sigma_{40}$   | epistemic standard deviation for glass        | see Technical Paper #14 |

#### 8. How are the consequences calculated (i.e., number of fatalities, major injuries, and minor injuries)?

Consequences for PTR cases (i.e. when the ES is a moving vehicle) are computed using the same SAFER algorithms used for other ES types. There is however one input to those algorithms that must be calculated in a unique way for the PTR case.

In a non-PTR case the maximum number of people exposed is defined as the upper limit entered by the user in Step 3. For PTR case, SAFER must calculate the maximum number of people exposed,  $Max_{people}$ .

SAFER does this in 4 substeps:



Inputs:

- Length of Road Within 2 IBD Arc (ft),  $L$ , calculated by SAFER or user input
- Maximum number of vehicles per hour,  $Max_{vehiclesperhour}$ , user input
- Minimum vehicle speed (mph),  $Min_{speed}$ , user input
- Maximum number of people per vehicle,  $Max_{people per vehicle}$ , user input
- Probability of fatality given an event,  $P_{fle}$ , calculated by SAFER
- Probability of major injury given an event,  $P_{majile}$ , calculated by SAFER
- Probability of minor injury given an event,  $P_{minii|e}$ , calculated by SAFER

Substep 1

SAFER calculates the separation between vehicles,  $S$ , by:

$$S = \text{Min}_{\text{speed}} / \text{Max}_{\text{vehiclesperhour}} * 5280 \text{ ft/mile} \quad (13)$$

where  $\text{Min}_{\text{speed}}$  and  $\text{Max}_{\text{vehiclesperhour}}$  is entered by the user.

*Substep 2*

SAFER calculates the number of vehicles in the arc,  $V_{\text{arc}}$  by:

$$V_{\text{arc}} = L / S \quad (14)$$

where  $L$  is the Length of Road Within 2 IBD Arc and  $S$  is calculated in *Substep 1* above.

*Substep 3*

SAFER calculates the maximum number of people,  $\text{Max}_{\text{people}}$ , by:

$$\text{Max}_{\text{people}} = V_{\text{arc}} * \text{Max}_{\text{people per vehicle}} \quad (15)$$

where  $V_{\text{arc}}$  is calculated in Substep 2 above and the maximum number of people per vehicle,  $\text{Max}_{\text{people per vehicle}}$ , is entered by the user.

*Substep 4*

Calculate the consequences (i.e., number of fatalities, major injuries, and minor injuries) using standard SAFER equations:

$$\begin{aligned} \text{Number of fatalities} &= P_{\text{fle}} * \text{Max}_{\text{people}} \\ \text{Number of major injuries} &= P_{\text{maji|e}} * (1 - P_{\text{fle}}) * \text{Max}_{\text{people}} \\ \text{Number of minor injuries} &= P_{\text{mini|e}} * (1 - P_{\text{fle}} - P_{\text{maji|e}}) * \text{Max}_{\text{people}} \end{aligned} \quad (16)$$

Outputs:

- Number of fatalities
- Number of major injuries
- Number of minor injuries



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