

DEVELOPMENT OF PRIMARY FRAGMENTATION SEPARATION DISTANCES FOR CASED CYLINDRICAL MUNITIONS

by

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Abstract

The U. S. Army Engineering and Support Center, Huntsville (USAESCH) is currently engaged in projects which require the detection, removal, and destruction of buried ordnance. During removal and destruction operations, the public and the personnel performing the work must be provided protection from both accidental and intentional explosive detonations.

DOD 6055.9-STD, "DoD Ammunition and Explosives Safety Standards," establishes permissible exposures to explosive effects including fragmentation, blast overpressure, thermal effects, ground shock, and noise. For fragmentation from an accidental detonation, the safety standard allows a maximum exposure of one hazardous fragment per 600 square feet where a hazardous fragment is defined as a fragment having an impact energy of 58 foot-pounds or greater. For an intentional detonation, DOD 6055.9-STD requires protection from all fragmentation.

The USAESCH, Structural Branch, has developed analytical procedures to calculate minimum fragmentation separation distances from both accidental and intentional detonations. Both procedures satisfy the safety standard and are applicable to cased, cylindrical munitions.

In this paper, these analytical procedures are reviewed and discussed. Software is presented by which minimum fragmentation separation distances from accidental detonations can be calculated. Finally, the method validation is reviewed and conclusions are provided.

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1.0 CALCULATION OF MINIMUM FRAGMENTATION SEPARATION DISTANCES FROM ACCIDENTAL DETONATIONS

1.1 Analytical Method

The high order detonation of a cased munition produces primary fragments that may be characterized by their weight and initial velocity. For a munition with a cylindrical casing, these fragmentation characteristics are calculated using the methods described in Army Technical Manual 5-1300 (TM 5-1300), Section 2-17.2. [1]

DoD 6055.9-STD [2] defines a hazardous fragment as one having an impact energy of 58 ft-lbs or greater. For an accidental explosive detonation, the public may not be exposed to a debris density greater than one hazardous fragment per 600 square feet. The range to this debris density is calculated using the probabilistic, primary fragment distribution model described in NATO AASTP 1, AC/258-D/258, "NATO Safety Principles for the Storage and Transportation of Ammunition and Explosives" [3] and detailed in CEHNC-ED-CS-S-98-2, "Method for Calculating Fragment Range to No More Than One Hazardous Fragment per 600 Square Feet." [4] The steps involved are as follows:

1. Model the cased munition. In most instances, the casing diameter and thickness will not be constant. Consequently, the munition is typically modeled as a series of cylinders. The techniques used to develop an accurate model are provided in HNC-ED-CS-S-98-1, "Methods for Predicting Primary Fragmentation Characteristics of Cased Munitions." [5]
2. Calculate the characteristics of the fragments produced by the cased munition in accordance with Army TM 5-1300 [1] as described in HNC-ED-CS-S-98-1. [5] For each region of the model, calculate:
 - a. V_o = initial fragment velocity (ft/sec)
 - b. $W_{f \max}$ = maximum fragment weight (lb)
 - c. $W_{f \text{ avg,}}$ = average fragment weight (lb)
 - d. Q_o = total number of fragments produced by the cylindrical casing
3. Apply the probabilistic, primary fragmentation distribution model described in NATO AASTP 1 [3] to determine the range to one hazardous fragment per 600 square feet. For each region of the model:
 - a. Let E_{cr} be the critical level of kinetic energy at impact which defines a hazardous fragment (i.e., 58 ft-lbs). For an assumed distance R (in feet), calculate the lightest fragment having an impact energy of 58 ft-lbs. Use the lighter mass resulting from the solution of the following two equations:

$$E_{cr} = \frac{1}{2} \cdot m \cdot V_o^2 \cdot e^{-\left(\frac{2R}{L_f \cdot m^{1/3}}\right)} \quad (\text{NATO Eq. 5-11})$$

$$E_{cr} = \frac{1}{2} \cdot g \cdot L_1 \cdot m^{4/3} \quad (\text{NATO Eq. 5-12})$$

where

$$L_1 = \frac{2 \cdot k^{2/3}}{C_D \cdot \rho} \quad (\text{NATO Eqs. 5-5, 5-6})$$

k = shape factor = 162.9 lb/ft³

ρ = atmospheric density = 0.076 lb/ft³

C_D = drag coefficient = 0.80

m = fragment mass (lb - sec² / ft)

NATO equation 5-11 [3] calculates the impact energy of a fragment traveling through air under the action of drag. NATO equation 5-12 [3] calculates the impact energy of a fragment in free fall without the effect of drag. For most cases the first equation (5-11) will control.

- b. Assuming the Mott distribution for number of fragments with respect to mass, the areal density q of fragments of individual mass greater than m , on a surface normal to the ray at distance R , is given by:

$$q = \frac{Q_o}{4R^2} \cdot e^{-\sqrt{\frac{2m}{m_o}}} \quad (\text{NATO Eq. 5-7 - modified})$$

where

m_o = average fragment mass = $W_{f \text{ avg}}/g$

g = gravitational constant = 32.2 ft/sec²

In the foregoing equation, the total number of fragments was divided by 4 to yield a conservative estimate of the number of fragments projected toward the target. A more detailed discussion is provided in section 1.2.

- c. Determine the probability, p , of hazardous fragment impact on a target at distance R from the cased explosive:

$$p = 1 - e^{-q \cdot A_T} \quad (\text{NATO Eq. 5-10})$$

where A_T = area of the target

For a standing man facing the explosion and taking no evasive action, a conservatively large value of 0.58 m^2 (6.24 ft^2) is recommended for the area A_T .

4. Calculate the probability, P , for hazardous fragment impact on the target from the entire munition as the sum of the probabilities, p , for each region times 100%. A percentage equal to 1.00 corresponds to a debris density of one hazardous fragment per 600 square feet. If P is not equal to 1.00, choose a new distance R and repeat from step 3. If P is less than 1.00, try a smaller R ; if P is greater than 1.00, try a larger R . Iterate until $P = 1.00$.

1.2 Software

The USAESCH, Structural Branch has also developed software to calculate the range to a debris density of no more than one hazardous fragment per 600 square feet. The software, HAZFRG, is written in FORTRAN. HAZFRG is written as an expert system to include all decision making processes indicated in the method above. The primary use of this software is for calculating the withdrawal distance for an accidental detonation during an unexploded ordnance (UXO) removal action.

As previously noted, for each model region, only one-quarter of the total number of fragments is used. A cross-section of a cased munition is shown in Figure 1. The case has been divided into three regions. During a UXO removal action, the munition is usually at or below ground level. Fragments from Region A will be directed into the ground. For any target, only the fragments from Region B or Region C (one-quarter of the case) need be considered to have the potential to strike the target. This is a conservative number of fragments since some of these fragments will be high angle fragments and will travel only a short range from the source.

It is the policy of the Ordnance and Explosives Center of Expertise (OE-CX) that the minimum withdrawal distance for any UXO removal action be 200 ft. For this reason, the minimum range reported by HAZFRG is 200 ft. When the range reported is 200 ft the actual range to a debris density of no more than one hazardous fragment per 600 square feet may be somewhat less than 200 ft.

1.2.1 Input Data

Data may input into HAZFRG either interactively or using a data file, HAZIN. At the beginning of execution, HAZFRG prompts the user to indicate which method of data entry is desired.

The data required includes the following items:

1. A title for the problem
2. The number of regions in the model
3. The type of explosive
4. The Gurney velocity of the explosive (ft/sec)
5. The Mott scaling constant, B , for the explosive ($\text{oz}^{1/2} \cdot \text{in}^{-7/6}$)

6. For each model region
 - a. The length of the region (in)
 - b. The thickness of the case (in)
 - c. The inner diameter of the case (in)
 - d. The weight of the explosive (lb)

If the interactive data entry option is chosen, the user is prompted for each of these data items. If the data file option is to be used then the user must create a data file named HAZIN prior to execution of HAZFRG. This data file will contain the number of model regions + 2 lines of data. The problem title will be on the first line (maximum length = 72 characters). The second line will contain data items 2 – 5 separated by commas. Data item 3 must be enclosed by single quotation marks (‘). The following lines (one for each model region) will contain items 6a – 6d separated by commas. A sample data file is shown in section 1.2.3.

1.2.2 Output

An output file, HAZOUT, is created by HAZFRG. This output file contains all of the input data plus some intermediate results for each model region as well as the range to a debris density of no more than one hazardous fragment per 600 square feet.

For each region, the output file lists:

1. The length of the region, L (in)
2. The average case thickness of the region, t_c (in)
3. The average inner diameter of the case in the region, d_i (in)
4. The weight of the case over the region, W_c (lb)
5. The weight of the explosive contained in the region, W (lb)
6. The fragment distribution factor, M_A
7. The initial fragment velocity, V_o (ft/sec)
8. The total number of fragments from the region, N_T .

The case is assumed to be constructed of mild steel; the case weight is based on this assumption. The fragment distribution factor, the initial fragment velocity and the total number of fragments are calculated based on methods described in Army TM 5-1300 [1] and discussed in HNC-ED-CS-S-98-1. [5] The number of fragments used in the calculation of the debris density is one-quarter of the total number of fragments. This and other conservative assumptions are discussed in section 1.3.

The range to a debris density of no more than one hazardous fragment per 600 square feet is listed in the output file. Also, the probability of impact on a person approximately 6 ft tall by one or more hazardous fragments at this range is listed. A sample output file is shown in section 1.2.3.

1.2.3 Example

The range to a debris density of no more than one hazardous fragment per 600 square feet is calculated for a 105 mm M1 projectile. This munition is modeled as shown in HNC-ED-CS-S-98-1. [5] The model has four regions with the geometric properties shown in Table 1.

TABLE 1 - 105 mm M1 Fragmentation Model Geometry							
Region	Length (in)	Thickness (in)	Outer Diameter (in)	Inner Diameter (in)	Inner Volume (in ³)	Explosive Weight (lbs)	Case Weight (lbs)
A	3.21	0.67	4.13	2.79	19.62	1.22	6.64
B	4.76	0.52	4.13	3.09	35.70	2.22	7.97
C	2.82	0.41	3.62	2.80	17.36	1.08	3.31
D	2.82	0.49	2.98	2.00	8.86	0.55	3.07

The data file used to determine the range to a debris density of no more than one hazardous fragment per 600 square feet for a 105 mm M1 projectile is shown in Table 2. Note that the explosive type (Comp B) is enclosed in single quotation marks. If the explosive type is not enclosed in single quotes the program will “crash”.

Table 2 - Input File (HAZIN) for 105 mm M1 Projectile
105 mm M1
4,'COMP B',9100.,0.222
3.21,0.67,2.79,1.22
4.76,0.52,3.09,2.22
2.82,0.41,2.8,1.08
2.82,0.49,2.0,0.55

The output file for the 105 mm M1 projectile is shown in Table 3. As shown, the debris density to no more than one hazardous fragment per 600 square feet is 341 feet. The probability of a person approximately 6 feet tall being impacted by one or more hazardous fragments is 0.99 percent.

Table 3 - Output File (HAZOUT) for 105 mm M1 Projectile

RANGE TO 1 HAZARDOUS FRAGMENT PER 600 SQUARE FEET
105 mm M1

NUMBER OF REGIONS IN MODEL = 4
EXPLOSIVE TYPE = COMP B
GURNEY ENERGY = 9100.
MOTT CONSTANT = .222
NUMBER OF REGIONS IN MODEL = 4
EXPLOSIVE TYPE = COMP B
GURNEY ENERGY = 9100.
MOTT CONSTANT = .222
REGION 1
LENGTH (in) = 3.21
AVG. CASE THICKNESS (in) = .670
AVG. INNER DIAMETER (in) = 2.790
CASE WEIGHT (lb) = 6.64
EXPLOSIVE WEIGHT (lb) = 1.22
FRAGMENT DISTRIBUTION FACTOR = .278
AVG. FRAGMENT WEIGHT (lb) = .00963283
INITIAL FRAGMENT VELOCITY (fps) = 4055.45
NUMBER OF FRAGMENTS = 689.24
REGION 2
LENGTH (in) = 4.76
AVG. CASE THICKNESS (in) = .520
AVG. INNER DIAMETER (in) = 3.090
CASE WEIGHT (lb) = 7.97
EXPLOSIVE WEIGHT (lb) = 2.22
FRAGMENT DISTRIBUTION FACTOR = .219
AVG. FRAGMENT WEIGHT (lb) = .00599825
INITIAL FRAGMENT VELOCITY (fps) = 4869.29
NUMBER OF FRAGMENTS = 1329.11
REGION 3
LENGTH (in) = 2.82
AVG. CASE THICKNESS (in) = .414
AVG. INNER DIAMETER (in) = 2.800
CASE WEIGHT (lb) = 3.35
EXPLOSIVE WEIGHT (lb) = 1.08
FRAGMENT DISTRIBUTION FACTOR = .172
AVG. FRAGMENT WEIGHT (lb) = .00370821
INITIAL FRAGMENT VELOCITY (fps) = 5182.51
NUMBER OF FRAGMENTS = 902.82

Table 3 (Cont.) - Output File (HAZOUT) for 105 mm M1 Projectile

REGION	4
LENGTH (in)	= 2.82
AVG. CASE THICKNESS (in)	= .487
AVG. INNER DIAMETER (in)	= 2.000
CASE WEIGHT (lb)	= 3.05
EXPLOSIVE WEIGHT (lb)	= .55
FRAGMENT DISTRIBUTION FACTOR	= .191
AVG. FRAGMENT WEIGHT (lb)	= .00455837
INITIAL FRAGMENT VELOCITY (fps)	= 4022.77
NUMBER OF FRAGMENTS	= 668.52
RANGE TO NO MORE THAN ONE HAZARDOUS FRAGMENT PER 600 SQUARE FEET	= 341.41
PROBABILITY OF IMPACT BY ONE OR MORE HAZARDOUS FRAGMENT	= .99

1.3 Validation

This method and the software have been validated by comparing the results to the distances listed in Table 9-2 of DoD 6055.9-STD [2] for several munitions. The munitions used for validation are the 105 mm M1 projectile, the 155 mm M107 projectile, and the 500 lb bomb. The range to a debris density of no more than one hazardous fragment per 600 square feet for each of these munitions is shown in Table 4. All of the calculated values are larger than the distances listed in DoD 6055.9-STD, Table 9-2. [2] Some of the conservative estimates made in the calculations which contribute to this difference are:

- 1) 1/4 of the total number of fragments are considered.
- 2) A drag coefficient of 0.80 (cube, edge-on) is used. In comparison, the drag coefficient for a long rectangular member, edge-on is 1.55.
- 3) All fragments are assumed to have the same initial velocity.
- 4) As recommended in NATO AASTP 1 [3], a 0.58 m² (6.24 ft²) target (person) is assumed. Explosive safety requirements are based upon a 6 ft² target.
- 5) The charge weight is increased by 20% before calculating the fragmentation characteristics and initial fragment velocity.
- 6) The values in DoD 6055.9-STD [2] are based on fragmentation characteristics from small scale arena tests whereas the calculated values are based on theoretical fragmentation characteristics.

It should also be noted that the range is calculated for the M64A1 500 lb bomb whereas the range for the Mk 82 500 lb bomb is listed in DoD 6055.9-STD, Table 9-2. [2] Since the geometries of these bombs are slightly different one would expect the ranges to a debris density of no more than one hazardous fragment per 600 square feet to be different.

Table 4 - Range to Debris Density of No More Than One Hazardous Fragment per 600 Square Feet		
Munition	Calculated Range (ft)	Range (ft) from Table 9-2, DoD 6055.9-STD
105 mm M1	341	270
155 mm M107	447	400
500 lb Bomb	680	670

2.0 CALCULATION OF MINIMUM FRAGMENTATION SEPARATION DISTANCES FROM INTENTIONAL DETONATIONS

For intentional detonations, DOD 6055.9-STD [2] provides default separation distances for protection of non-essential personnel and the public from munition fragmentation. These separation distances are: 1250 feet for non-fragmenting explosive materials; 2500 feet for fragmenting explosive materials with a diameter less than 5 inches; and 4000 feet for bombs and projectiles with a diameter of 5 inches or greater. In lieu of these default values, the standard also allows the application of the maximum debris throw range, with an applicable safety factor.

The Structural Branch has developed a conservative method to calculate the maximum distance that the primary fragments from a munition will travel. In order to provide the required safety factor, this distance is calculated using the maximum weight fragment, from Army TM 5-1300 [1], and the worst case trajectory, from “TRAJ” computer code.

3.0 CONCLUSIONS

The USAESCH, Structural Branch has developed a method for calculating the range to a debris density of no more than one hazardous fragment per 600 square. This method is based upon NATO AASTP 1 [3] and uses fragmentation characteristics developed in accordance with Army TM 5-1300. [1] To ensure safety, the method incorporates conservative fragment and target assumptions. The method and associated software have been validated against the values in DoD 6055.9-STD, Table 9-2 [2] and have been approved by the Department of Defense Explosives Safety Board.

In addition, a method has been developed to calculate the minimum fragmentation separation distance from intentional explosive detonations. To ensure safety and satisfaction of DoD requirements, this method is based upon conservative fragment and trajectory assumptions.

4.0 REFERENCES

1. Technical Manual 5-1300, “Structures to Resist the Effects of Accidental Explosions,” Revision 1, Department of the Army, November 1990.

2. DoD 6055.9-STD, "DoD Ammunition and Explosives Safety Standards," Department of Defense, July 1997.
3. NATO AASTP 1, AC/258-D/258, "NATO Safety Principles for the Storage and Transportation of Ammunition and Explosives," North Atlantic Treaty Organization, October 1991.
4. CEHNC-ED-CS-S-98-2, "Method for Calculating Fragment Range to No More Than One Hazardous Fragment per 600 Square Feet," U. S. Army Corps of Engineers Engineering and Support Center, Huntsville, AL, January 1998.
5. CEHNC-ED-CS-S-98-1, "Methods for Predicting Primary Fragmentation Characteristics of Cased Explosives," U. S. Army Corps of Engineers Engineering and Support Center, Huntsville, AL, January 1998.

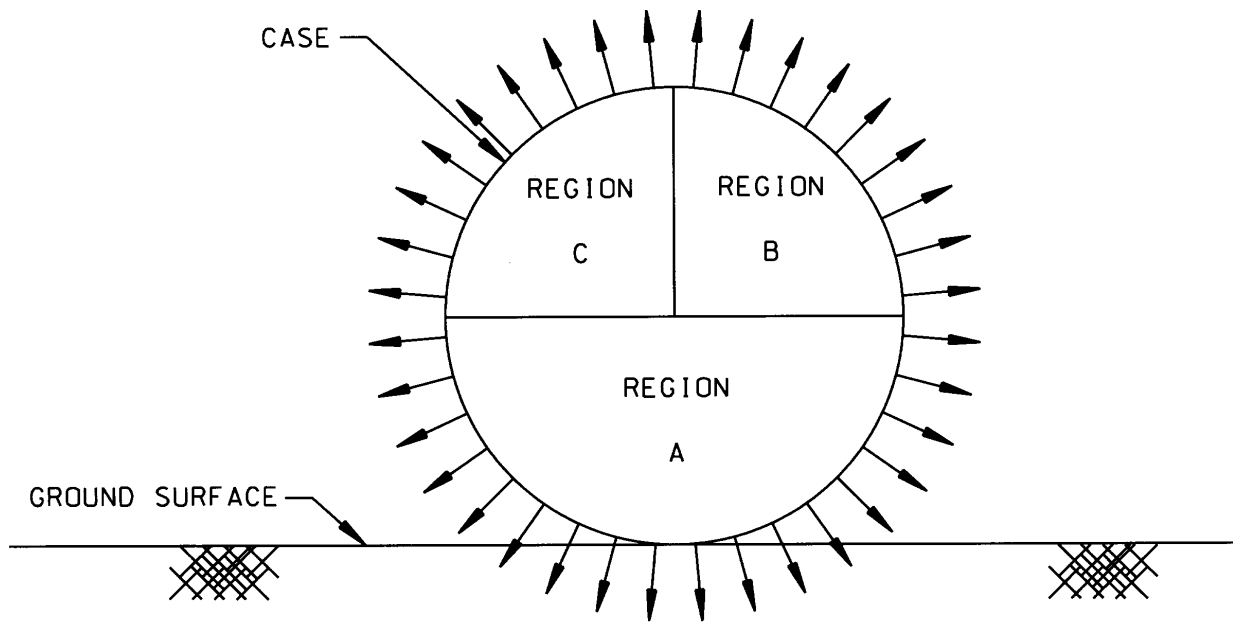


Figure 1 – Fragmentation Regions for Cylindrical Munitions