

Calculation of Hazardous Soil Debris Throw Distances Around Earth Covered Magazines

by

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1.0 Introduction

Earth-covered magazines must be sited so that personnel in nearby inhabited areas are protected from hazardous blast pressures, fragments, and thermal loads. DoD 6055.9-STD "Ammunitions and Explosives Safety Standards"⁽¹⁾ gives criteria for determining the distance required to provide such protection. For charge weights less than 45,000 lbs of Class/Division 1.1 explosive, the default distance required in DoD 6055.9 to provide protection from hazardous fragments controls the required siting distance between an earth-covered magazine and an inhabited building. For lower explosive weights (charge weights less than 6000 lbs), the default fragment protection distance controls over the required blast and thermal protection distance by a factor of two or more.

The default fragment protection distances are not intended to directly account for the many variables that affect fragment and structural debris throw from earth covered magazines. Rather, they are intended to be very easy to apply and to provide an acceptable amount of protection for a wide range of explosive weights. As a result the default distances can be very conservative, especially for lower explosive amounts. DoD 6055.9 does allow for a reduced fragment protection distance, and therefore a lesser siting distance, if it can be shown by analysis that the hazardous fragments and debris from structural elements of the facility do not present a hazard (no more than one fragment per 600 ft²) beyond the reduced distance and if the required blast and thermal protection are provided. Calculated fragment protection distances are typically less than the default distance for low explosive weights and for these cases, usually result in a reduced siting distance. Therefore, there has been considerable interest in calculating the fragment protection distance around storage and testing sites containing relatively low explosive weights. An example of this is a recent program

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at Southwest Research Institute (SwRI) where a detailed test program was conducted to investigate the fragmentation of building walls under explosive loading and wall debris throw so that a model could be developed, based largely on the test data, that predicts the maximum hazardous structural debris throw distance from a building.⁽²⁾ This program, which was funded by the U.S. Department of Energy, addressed only conventionally constructed buildings (without earth cover) containing a maximum of 250 lbs of TNT.

For the case of earth covered magazines, the distance soil debris from the earth cover is thrown must be considered in any analysis of the required fragment protection distance. All fragments and debris with 58 ft-lbs of kinetic energy, or more, are considered hazardous by DoD 6055.9. Since a cubic soil fragment weighing just 0.28 lbs will have 58 ft-lbs of energy upon impact with its free-fall velocity, an explosion in an earth covered magazine will produce many hazardous soil debris, or dirt clods. In a recent project for the LTV Missiles and Electronics Group, a method was developed and used by SwRI to calculate the maximum distance soil debris are throw by an explosion in an earth covered magazine. In this paper this method is discussed and compared against limited full scale data. The required fragment protection distances calculated around two earth covered magazines at the LTV testing site with this method are also presented.

2.0 General Discussion of the Problem

The method presented in this paper for calculating soil debris dispersion is based on the same three steps that are used to predict building debris dispersion in Reference 2. These three steps are; 1) calculate the total impulse (shock plus quasistatic) applied to the building walls and roof, 2) using the impulse and the building material type as inputs, calculate the initial launch conditions of the building debris (that is, the debris initial velocities, launch angles, masses, and drag characteristics), and 3) using the initial launch conditions as inputs, calculate the distances traveled by the debris with a computer code that models the drag and gravity forces acting on the debris during flight.

These steps are used as a guide to develop the method for calculating soil debris dispersion because they make up a general theoretical approach that has been used successfully, along with test data, to predict building debris dispersion.⁽²⁾ These steps are also similar in concept to a previous method which was developed to predict the response of the roof of earth covered magazines to an internal explosion and was verified in a scaled experimental test program.⁽³⁾ The application of these general steps to the case of calculating soil debris throw from a typical earth covered magazine is more complex in some respects than the case of calculating building debris throw in Reference 2. The additional complexities which must be considered for the case of soil debris throw are discussed below.

- 1) The shock impulse on the magazine walls includes impulse from repeated shock wave reflections off each reflecting surface in the magazine. Because of the typically high loading densities within magazines, and the resulting very high temperature and

pressure environment in the magazine immediately after the explosion, the shock wave reflections will travel much more quickly, and decay more slowly, than they would in a room with a low loading density. Therefore, the methods in TM5-1300⁽⁴⁾ and in Reference 2 for calculating shock impulse, which are based on only one shock wave reflection off each reflecting surface, may significantly underestimate the shock impulse affecting debris throw from an earth covered magazine.

- 2) There is no known available method for predicting the duration of the shock impulse in the magazine taking into account the early time failure of the magazine door and front wall, and subsequent leakage of the shock wave outside the magazine. This issue is important for a typical magazine because of the high loading density discussed above and the resulting long duration shock pressure history.
- 3) There is no known available method for time-stepping through the venting process that considers simultaneous nonuniform shock impulse and quasistatic impulse acting on the vent panel. The FRANG code,⁽⁵⁾ which is an available tool for calculating quasistatic impulse in a room with a vent panel, assumes that all shock impulse is applied prior to the buildup of quasistatic impulse. This is the typical case for rooms with lower loading densities. However, in a typical magazine, it is expected that the shock impulse duration can extend throughout most or all of the quasistatic duration because of the factors discussed in No. 1 above.
- 4) There is no known computer code for time-stepping through the venting process which considers venting through multiple vent areas which have significantly different mass per unit area. In the magazine venting occurs very quickly through the door, which fails first, and then begins at a slightly later time through the front wall, which fails second, and finally occurs through the roof, which fails before any of the earth covered sides because it has less soil cover. The mass per unit area and the time to initial venting of each of these three vent areas are significantly different from each other. The FRANG code only considers venting through one covered vent area with a given mass per unit area.
- 5) The manner in which the soil cover breaks up into debris is not well known because the size, initial velocity, and the initial launch angles of soil debris from earth covered magazines subjected to internal explosions have not been measured in experimental programs.

The method described below for calculating soil debris dispersion addresses these problems based on the use of available predictive tools for calculating impulse in the magazine which are modified by engineering judgement to take into account the above-mentioned shortcomings in these methods. It is expected that as more data and improved predictive tools become available, these data and predictive tools can replace some of the current need for engineering judgement.

3.0 Description of the Method Used to Calculate Soil Debris Dispersion

The first step in the procedure for calculating the soil debris dispersion is to calculate the total impulse on the magazine roof and walls that contributes to the initial velocity of the soil debris. The assumption is made that, while spall of the soil can occur, the maximum soil debris velocity is caused by the acceleration of the overall soil mass from the full duration of the blast load, or from the impulse. The calculation of the impulse is subject to the difficulties listed in numbers 1 through 4 above. The shock impulse, which is subject to the difficulties in numbers 1 and 2 above, is calculated on the roof and the frontwall of the magazine in this method with the BLASTINW code.⁽⁶⁾ This code is considered the most appropriate available shock impulse prediction tool for the high loading densities typical of storage magazines because it considers repeated shock reflections off each reflecting surface throughout the input time of interest and it predicts the time at which quasistatic pressure begins to load each building surface. A second major assumption in this method is that the duration of the shock impulse is assumed equal to the time up until critical venting of the quasistatic impulse out the frontwall. Critical venting is defined as the condition where the vent panel has moved out a distance such that the vent area around the vent panel is equal to the area of the originally covered vent opening. The assumption here is that the opening created by the movement of the vent panel (front wall of the magazine) up until critical venting provides a sufficient area for the shock waves to vent out, or leak from the magazine and thus cease to reflect within the magazine. Very high shock impulses are calculated (as high as 35 psi-sec) up until the time of critical venting (about 5 to 7 milliseconds after detonation) in magazines with 1000 to 5000 lbs of explosive and loading densities of 0.5 to 1.3 lb/ft³. As a means of comparison, these impulses are considerably higher than those calculated for the same buildings with the SHOCK computer code,⁽⁷⁾ which only considers one reflection off each reflecting surface, that is called out in References 2 and 4 for calculating the shock impulse inside of buildings which typically have loading densities at least an order of magnitude smaller than earth covered magazines. The currently available version of the BLASTINW code only considers rectangular structures. Comparisons performed at Southwest Research Institute⁽⁸⁾ between measured shock pressures in cylindrical structures and those calculated by BLASTINW using a circumscribed square cross section showed relatively good agreement. Therefore, the shock impulse in a typical semicircular arch magazine can be approximated using a rectangular structures constructed in this manner. New versions of BLASTINW will consider cylindrical structures.⁽⁹⁾ The shock pressure history calculated by the BLASTINW code has not been validated at the high loading densities typical for earth covered magazines.

Quasistatic impulse is calculated with the FRANG⁽⁶⁾ computer code. The magazine door is considered as uncovered vent area (since the very high impulses involved overwhelm the door mass and cause the door to be thrown out very quickly) and the front wall is input into the FRANG code as the covered wall area. The calculation of quasistatic impulse is subject to difficulties number 3 and 4 described in the previous section. As an approximate method of dealing with the third difficulty using the FRANG code, a portion of the shock impulse acting on the vent wall up until the time of the critical venting is input into FRANG. This portion of the impulse, which is assumed

by the code to be immediately applied, is chosen so as to cause the vent panel to move out approximately the same distance in the FRANG code as it is actually moved by the gradually applied shock impulse during the time up until critical venting. The BLASTINW output shows the shock impulse on the front wall increases nearly linearly with time. This implies that the average shock impulse (one-half the shock impulse at critical venting) input into the FRANG code, and therefore applied immediately to the covered vent area, will cause approximately the same vent panel movement prior to critical venting as the actual (linearly increasing) shock impulse. The approximate nature of this method is caused primarily by the fact that venting of quasistatic pressure is sensitive to the time history of the vent wall movement prior to critical venting, not just to the overall distance the vent wall moves prior to critical venting. This approximate method requires an iterative approach where, 1) the critical venting time is first assumed, 2) based on this assumed time, the average shock impulse on the headwall calculated with the BLASTINW code up until the assumed critical vent time is input into FRANG, 3) the FRANG code is then run, and 4) the calculated time until critical venting is compared to the assumed value. If the assumed and calculated critical vent times match closely, then the critical vent time, and thus the assumed duration of the relevant shock impulse, is known.

The FRANG output using the above approach predicts that a significant amount of additional quasistatic impulse occurs in the structure after critical venting since it takes some time for venting through the front wall to cause the pressure in the structure to drop to zero. However, the two foot of fill over the roof of the magazine also begins to vent at about the same time critical venting occurs through the front wall. The approximate time required for venting to begin through the roof is determined by calculating the time required for the roof to move through the roof and overlying soil thickness. This time is calculated assuming the roof velocity is equal to the impulse divided by the roof and soil mass, and that impulse builds up linearly prior to critical venting and is constant thereafter. Only the quasistatic impulse from the FRANG code occurring prior to venting through the roof is considered because it is assumed that the quasistatic pressure will drop to zero very quickly after venting through the large roof area begins.

In summary methods have been presented to calculate the shock impulse (with BLASTINW), the shock impulse duration (equal to the time up until critical venting as calculated with FRANG), the quasistatic impulse (with FRANG using a iterative method to apply the correct shock impulse to the vent panel), and quasistatic impulse duration (the time up until venting begins through the roof). This concludes the first, and most complicated, step in the method which is to calculate the total shock and quasistatic impulse affecting soil debris dispersion. The complexity is primarily due to the fact that existing tools for predicting impulse are based on assumptions that are applicable for typical testing and assembly bays but are not thought applicable to magazines with high loading densities and multiple covered vent areas.

The next step is to determine the initial launch conditions of the soil debris which are the debris initial velocity, vertical launch angle, mass, and the drag characteristics. Because of the numerous difficulties involved in assuming even worst case initial launch condition, no attempt is made to define the range of each of the debris initial launch condition values. Therefore only the worst case, or furthest throw distance of the soil debris is considered in this method rather than the distance where a critical density (more than 1 per 600 ft²) of soil debris occurs. However, since the soil cover is assumed to break into many small clods, it is thought that critical debris densities will probably occur at, or very near, the maximum soil debris throw distance.

The two launch characteristics which affect the calculated debris throw distance most are velocity and launch angle. The total shock plus quasistatic impulse, as calculated using the procedures discussed above, is used to determine the maximum soil debris velocities. All the force in the applied impulse is assumed to accelerate the soil debris and, therefore, the soil debris velocity is equal to the total impulse divided by the mass of the overlying soil and structure. This assumption is considered valid because any strain energy absorbed by the earth magazine, which is designed to support only the surrounding soil loads and not any of the very large internal blast pressures, is negligible compared to the energy applied during an explosion. The worst case launch angles are considered to be a function of the magazine geometry. In arch magazines (such as that shown in Figure 1) soil debris across the cross section is assumed to be launched at the angle normal to the cross section. This assumption is based on an assumed radial expansion of the magazine cross section under the largely uniform internal blast pressures. In rectangular magazines (such as that shown in Figure 2), and out the back of arch magazines, where the backwall and roof meet at right angles, the prevalent launch angles are straight up vertically and straight out horizontally. However, these two cases do not represent worst case launch angles because the vertical throw, which will have high velocity, will not translate a large distance horizontally, while the horizontal soil throw will have a relatively low velocity because of the large mass of soil backing the walls. Soil thrown at a forty-five degree launch angle, but subject to a reduced impulse (less than the total calculated impulse acting on the roof and walls), is considered the worst case launch angle for this case. These two magazine cross sections, a semicircular cross section and a rectangular cross section, are discussed separately in more detail below.

For the case of the semicircular cross section, the mass of the surrounding soil, and thus its initial velocity, varies around the radius of the cross section as Figure 1 shows. Assuming that soil debris launch angles are equal to the direction of the unit normal off the cross section, the soil near the crown with the least depth, and therefore the largest initial launch velocity, will have a very high launch angle (near 90 degrees). This launch angle precludes a large debris throw distance. At the other extreme is soil over the 45 degree radial, which lies on the optimum launch angle but has more overlying soil and therefore, a relatively low launch velocity. In order to simplify the method, two launch angles are assumed (based on trial and error calculations with a number of possible angles) to represent possible worst case conditions for soil debris throw; 1) a 70 degree launch angle where a very high velocity will be combined with a steeper launch angle, and 2) a 45 degree launch angle where more soil mass, and thus a much lower launch velocity, is combined

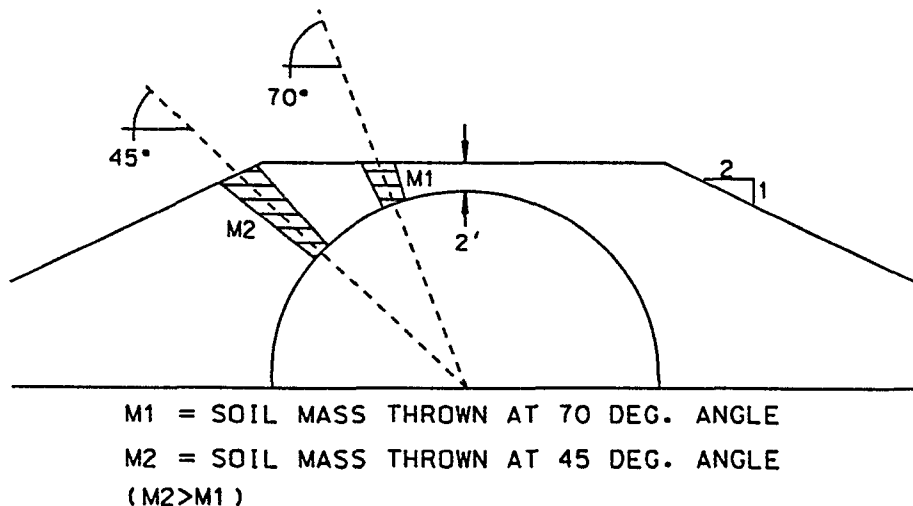


Figure 1. Assumed Soil Masses Thrown at Critical launch Angles (45° and 70°) in Plane of a Circular Area Magazine Cross Section

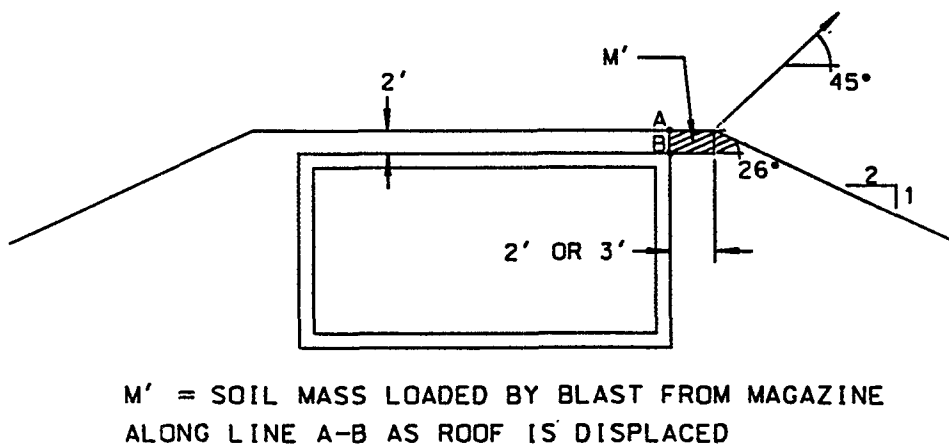


Figure 2. Assumed Soil Mass Thrown at 45° Launch Angle in Plane of a Rectangular Box Magazine

with a near optimal launch angle. The furthest throw distance calculated for these two discrete soil masses, which are illustrated in Figure 1, is assumed to be the hazardous soil debris throw distance. For typical arch magazines, the magazine backwall and roof usually meet at a right angle. Therefore soil debris out the back is analyzed in a similar manner as soil debris throw from a rectangular magazine discussed below.

In a rectangular structure, where the roof and wall meet at a right angle, most of the soil debris will be thrown straight upwards because the roof, which has much less earth cover than the walls, will fail first and be thrown primarily upward. However, the launch angle considered worst case for soil debris throw distance in this method is a 45 degree angle out the top corners of the magazine as mentioned previously. The area of the assumed soil block which is thrown the maximum distance is shown in Figure 2. However, this soil mass is not directly loaded by the impulse in the structure. It is loaded only as the roof moves upward and exposes it to internal blast pressures. Since the shock impulse increases approximately linearly with time, the shock pressure in the magazine (which causes the major part of the total calculated impulse) acting on the structure and surrounding soil can be assumed to be largely constant neglecting the very short duration transients that occur. For the assumption of a largely constant internal pressure, the impulse acting on the soil mass assumed to be thrown the furthest distance, which is surface A-B in Figure 2, can be calculated as one third of the total impulse in the structure.⁽¹⁰⁾ Therefore, soil debris velocity of this critical soil mass is calculated as one third the impulse on the roof divided by the soil mass (the shaded area in Figure 2) and the launch angle is assumed to be forty-five degrees.

The final required soil debris launch characteristics are the debris mass and drag characteristics. The primarily cohesive soil fill over the magazine is assumed to break into many clods with widely varying mass. Therefore the size and drag characteristics of the soil debris are very difficult to predict theoretically. Fortunately, the throw distance is not very sensitive to these two launch characteristics. It is known from testing of buried explosive charges in clay that typically chunky soil debris is produced rather than "pancake" shaped debris. It is also known that the maximum size debris near the outer limits of soil dispersion from large cratering experiments weigh approximately one-thousandth the charge weight.⁽¹¹⁾ The charge weights stored in earth covered magazines vary considerably but, assuming that they vary between 1000 and 10000 lbs, the largest soil debris weights would be between one and ten pounds. Based on these limited guidelines a "typical" debris weight of one pound is assumed for the single fragment throw distance, or trajectory calculations, and it is assumed that the fragments are cubic.

Finally, in the last step in the soil debris dispersion calculation procedure, the MUDEMIMP code⁽¹²⁾ (or a similar trajectory code) is used to calculate the throw distance for each worst case (or possible worst case) soil fragment under consideration. The maximum debris velocity, calculated from the total impulse and soil mass as discussed above, the assumed launch angle, the soil fragment mass (1 pound), and the drag coefficient for the assumed cubic shape are input into the trajectory code and a distance to first impact is calculated. No roll of the soil debris after first impact is assumed since the soil is assumed to deform substantially upon impact. It is assumed that

no structural debris, which is buried under at least two feet of soil and will have similar or less severe initial launch angle and velocity, will be thrown further out the soil covered sides of the magazine than the calculated maximum soil debris throw distance. Limited test data shows this to be generally true for standard corrugated arch magazines.⁽¹³⁾

No procedure is developed for calculating soil debris throw out the front of the magazine since structural debris throw from the headwall and door is assumed to control the hazardous fragment distance in this direction.

The best way to gain confidence in this procedure is to compare it to data. This is discussed next.

4.0 Comparison of Analysis Procedure for Soil Debris Dispersion Around Earth Covered Magazines to Data

Data from the test report in Reference 13 (tests on standard earth covered igloos conducted at Naval Ordnance Test Station in the early 1960's) was used to judge the adequacy of the procedure discussed above. Seven full scale tests are described in this report in which several thousand pounds of explosive (equivalent TNT weights ranging from 1275 pounds to 100,000 pounds) were detonated in standard steel arch earth covered magazines. Table 1 shows the charge weights, loading densities, and reported soil debris throw (for the tests where this was reported) for the seven tests. The tests were conducted to verify interline distances between earth covered magazines necessary to prevent sympathetic detonation. Therefore very little soil and structure debris information was recorded. Structural debris throw distances out the front of the magazines were typically very large (up to 3000 ft. for test 2 in Table 1).

Table 1. Summary of Earth-Covered Magazine Test Series Results in Reference 13

Test No.	Charge Weight (Equiv. TNT)	<u>Charge wt</u> Vol (lb/ft ³)	Soil Throw (where reported)		
			Front	Side	Rear
1	2200	1.3		500 ft	
2	2200	1.3	100 ft	500 ft	300 ft
3 & 4	1290	0.78			
5	1275	1.04			
6	100,000	6.0		3300 ft	2500 ft

Since soil debris dispersion is reported for Test 2 in Table 1, and this method was developed so that it could be applied for magazines with charge weights near 2000 lbs, Test 2 was used to compare the method described in the previous section to data. Since the arch magazines used in the tests have a semicircular cross section influencing debris throw out the sides and a perpendicular cross section influencing debris throw out the back, where the roof and back wall met at right angles, the procedures for both of the typical cross sections considered by this method can be compared to the data. Table 2 shows the calculated soil debris throw distances out the sides of the arch magazine and out the back of the magazine compared to the measured values. The safety factor of 1.3 implied by this comparison is the same as that called out in Reference 2 for calculating the maximum hazardous debris distance around buildings. Therefore, the procedure for calculating soil debris throw described in the previous section, which is based in large part on a first principles approach and, in several key areas, engineering judgement, predicts debris throw with an acceptable amount of conservatism as compared to the measured values.

Table 2. Comparison of Soil Debris Dispersion Procedure with Data from Test 2 in Reference 11

Direction from Magazine	Calculated Maximum Debris Throw Distance (ft)	Reported Maximum Debris Throw Distance (ft)	Ratio of Calculated Values to Measured Values (Safety Factor)
Out sides	645	500	1.29
Out back	400	300	1.33

5.0 Application of the Method to a Missile Storage Facility

Based on the good comparison to the data shown in Table 2, this method was used to predict the maximum soil debris throw distance, and thus maximum debris throw distance, out the back and sides of several earth covered magazines at the LTV Missiles and Electronics Group test site in Grand Prairie, Texas.⁽¹⁰⁾ The magazines had similar explosive weights and lower loading densities than the magazine in the test used to judge this procedure. Therefore, the very limited "validation" described above was considered applicable. The magazines in question were spaced at less than the required siting distance away from nearby inhabited building out the side and back of the magazines. For the planned explosive storage limits, the required siting distance (per Reference 1) was controlled by the default fragment protection distance of 1250 ft. As permitted in Reference 1, a fragment analysis was performed to calculate the necessary fragment protection distance more accurately. One magazine was a standard earth covered magazine with 12'x 25' plan area and a corrugated metal arch cross section covered with a minimum 2 ft of soil fill. The other magazine was a rectangular concrete box with 2 ft of soil cover over the roof. Table 3 shows the loading densities and explosive weights which were analyzed.

Table 3. Calculated Hazardous Blast Overpressure and Fragment Distances Around Magazines with Class 1.1 Explosive

Explosive Weight (lbs)	Type of Building	Loading Density (lb/ft ³)	Back		Side		Default Fragment Distance
			Blast (ft)	Fragment (ft)	Blast (ft)	Fragment (ft)	
5000	Corrugated Metal Arch Earth-covered Magazine	0.75	427	390	598	570	1250
1000	Rectangular Box Earth-covered Magazine	0.5	250	372	350	372	1250

Table 3 also shows the calculated hazardous distances out the side and back of the two magazines. Both the hazardous blast and soil debris distances were calculated because the greater of these two distances controls the required siting distance from a Class/Division 1.1 explosive storage area. It was assumed that no hazardous structural debris would be thrown further out the side and back of the magazines than the soil debris based on the data from the test series mentioned above. The hazardous blast overpressure distances were calculated with the formulas in the footnotes of Table 9-1 in Reference 1. The planned explosive material in the magazines was contained in missiles which were constructed largely of plastic, but also had a few components made of metal. The dispersion of the metal components, based on initial velocities supplied by LTV and the residual velocities calculated after the missile fragments had penetrated the surrounding soil and structure, were also considered in this analysis. The number of components was sufficiently small so that no hazardous densities (more than 1 fragment per 600 square feet) were calculated.

In summary, Table 3 shows that a significantly reduced hazardous distance was calculated out the side and back of these two magazines because the fragment analysis allowed in Reference 1, which included calculation of the maximum soil debris throw distance, was used instead of the default hazardous fragment distances.

6.0 Recommendations and Conclusions

A method for predicting the maximum distance soil debris throw from earth covered magazines has been presented and compared to limited data. The predicted maximum soil debris throw distances were 1.3 times that reported values which implies that the method predicts soil debris throw with an adequate amount of conservatism. It is recommended that this method (or any similar method) should be compared against data measured at a comparable loading density in

a comparable structure if possible before being used to predict soil debris throw from an earth covered magazine because it is thought the phenomena which affect debris throw are structure dependent and loading density dependent. Finally, the many assumptions that are necessary, and the lack of data to verify these assumptions in anything but a limited overall sense, point out a need for research in this area.

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