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CRITERIA FOR BLAST DAMAGE FROM DISTANT GUN FIRE AND EXPLOSIONS

by

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Introduction

Activities on many Army installations involve the firing of guns and the detonation of explosives. These activities generate blast waves that propagate to neighboring communities and cause complaints of damage. This paper describes the procedure for processing claims, reviews the types of residential damage claimed, and describes the blast damage threshold criteria.

The energy releases that disturb communities emanate from a variety of sources: muzzle blast from artillerv and tank guns, blast from high explosive (HE) rounds fired by these weapons, and charges fired above, on and below the surface (see Figure 1). As one might expect, the large number of military reservations in the US with a potential for causing damage, resulted in the Army establishing a "regulation" to deal with complaints of damage. Army Regulation 27-20 was established and requires that claims of damage that cannot be settled by the offending government agency must be forwarded through the Staff Judge Advocate Office at Fort Meade, Maryland, to the Ballistic Research Laboratory at Aberdeen Proving Ground, Maryland, where they are to be evaluated and then returned to Fort Meade (see Figure 2) for final disposition and/or settlement. If the claim is denied the claimant has the right of appeal.

The claim file should contain statements by the claimant and reports by the offending agency. The claimant's report describes the nature of the damage incurred and the date of the occurrence. The spectrum of damage complaints is wide, ranging from cracked concrete to nail popping (see Figure 3). The agency alleged to have caused the damage prepares a report (with photos) that describes the condition of the structure and highlights any condition of the property that may have a bearing on the claim. In addition, the agency report includes a map which shows the position of the structure with respect to the explosion or gun firing point and a statement of details on the explosions or firing activities at the time of the alleged damage. If meteorological conditions at the time of the alleged damage are available, they are also included in the report.

Determining the blast pressure that a structure experiences as a result of these kinds of energy releases is often not a straightforward procedure. There are unknowns in the forcing function and unknowns regarding the response of the structure to a forcing function. In order to resolve the claim, assumptions have to be made that put the problem in a framework which allows drawing from an established database. Some of the assumptions are minor when considered in the light of the strong influence played by the atmosphere and the characteristic lack of information on the atmospheric conditions prevailing at the time of the blast. Figure 4 shows typical missing parameters.

Airblast, not ground shock, is the most important factor to consider in the claim evaluation process. Weak overpressures travel at near sound velocity and hence their propagation velocity with respect to the ground is significantly altered by temperatures and winds. For the charge weights and distances of interest, the travel time is relatively long and one can expect the atmosphere to have a strong influence on the pressure level. The missing elements in Figure 4 may well become unimportant because of the strong influence of the winds and temperature.

Static Charge and HE Shell

There are data relating pressure and distance for charges detonated on the surface and in free air, but no data in the very low pressure region (<1034 Pa or .05 psi), that can be used directly because of the strong influence of the changing atmosphere. A free air, pressure vs. distance relationship was established however, by a committee of the Acoustical Society of America [1]. It used a hydrocode to extend selected higher pressure data to the very low pressure region. The equation and curve, Figure 5, are taken from reference 1. This curve is used in claim evaluations to determine a baseline pressure which will be altered in some manner by the atmosphere. If the charge were detonated on the ground, the curve indicated by 2 kg would provide a better estimate of pressure in a standard atmosphere.

Chapter 5 of reference 1 contains a detailed description of the influence of real atmospheres in the low overpressure region and the author of the reference infers that pressure could be amplified by a factor of five under unusual meteorological conditions. If the claim file does not include pertinent meteorological data, the pressure obtained from Figure 5 is increased by a factor of five to ensure a fair evaluation. It is felt that the claimant should not be penalized because of a lack of specific information.

A claim which involves a structure that is close to a bare static charge allows the most accurate prediction of pressure. The atmosphere has had little time to influence the wave and there has been only a mild extrapolation of a rather extensive database. However, this case is rarely encountered because Army proving grounds normally fire static charges in remote areas. Accidental explosions could of course occur close to residential areas. The detonation of an in-flight HE shell is a frequent scenario for provoking claims of damage. For shell detonating in an impact area, one will not know the height of burst or have accurate positioning of the round. The lack of data on these variables is deemed not important for most cases because the distance between impact areas and residential structures is, by design, substantial. The procedure is to assume a free-air detonation on the near boundary of the impact area.

Muzzle Blast

Many claims stem from the muzzle blast of tank guns and artillery weapons. These produce a non-symmetrical blast pattern that extends from the near field to the far field. There is a directivity effect, an enhancement of the pressure in front of the weapon and attenuation toward the rear. The theoretical treatment of muzzle blast in the far field is shallow, but there are experimental databases. Schomer et al. [2] used pressure measurements from gun firings to relate pressure to available propellant energy, gun tube elevation and azimuth, and length of gun tube. Unfortunately, these parameters are not usually included in the claim file. Pater [3] conducted a study of blast from naval guns that was similar to the Schomer study. Both concluded that directivity can add as much as 14 db (a factor of five increase in pressure). Luz [4] used the Schomer pressure vs. distance data to determine the frequency of occurrence of disturbing pressures in communities that border tank gun and artillery firing ranges taking into account the range of meteorological conditions experienced in practice. Luz's work can be plotted to establish pressure vs. distance curves if a fixed frequency of occurrence is maintained. Figure 6 shows the pressures that could be expected to be exceeded by 1% and 50% of the firings in the direction of fire of a 120 mm tank gun. The difference in pressure between the 1% and 50% curves is attributed to changes in meteorological conditions. The plotting parameter db is related to Pascals, Pa, by the equation $db = 20 \log \frac{Pa}{20 \times 10^{-6}}$. The data from the 120 mm sabot (KE) round was selected as a baseline for scaling because it would minimize the chance of having a significant bow shock signature, and the cartridge contains a significant propellant load. It should produce a maximum muzzle blast for its caliber. Figure 7 is a plot of pressures expected for 1% exceedance of the firings in the front, side and rear of the gun. The pressure differences are not as great as those attributed to meteorology and shown in Figure 6, but angle of fire can be important.

Figure 8 is an estimate of pressure for 1% exceedance from 155 mm howitzer firings. The projection was obtained by increasing the distance for selected pressures by the ratio of diameters of the 120 mm and 155 mm guns. The graph shows exceedance toward the front, side and rear of the weapon. The rate of pressure decay for all orientations is the same. Figure 9 is a similar plot for the 8" howitzer. The projections may overpredict toward the front of the weapons and underpredict toward the rear because of the presence of muzzle brakes on many artillery weapons. Artillery firing positions are often near the military reservation boundary, allowing the weapon to fire to a rather centrally positioned impact area. The figures show that rather high pressures can be experienced within 5 km of large caliber guns when meteorological conditions are unfavorable.

Criteria based on 1% exceedance do not account for the "unusual" day. In other words, what actual maximum pressure could be expected when the value at 1% is exceeded. Recent firings at Aberdeen Proving Ground afforded an opportunity to obtain a rather unusual set of data that included what is considered to be a maximum pressure. A 155 mm howitzer fired 100 inert rounds on a day when no other guns were firing. This allowed one to associate the pressure measured at a recording station with a specific gun at a specific location. The propelling charge and angle of elevation of the howitzer were such that the projectiles traveled supersonically from the muzzle to apogee. They did not exceed the speed of sound on their downward trajectory. The scenario indicates that the pressure measured was from muzzle blast and not the ballistic wave. Unusually high readings were obtained at one monitoring station which was down range of the weapon and 39 degrees off of the line of fire. A plot of sound velocity as a function of altitude in the direction of the station within a few minutes of the high reading is shown in Figure 10a. The plot includes the added velocity due to the component of wind in the direction of the station. Figure 10b shows the relative position of the station and firing point. The sound profile plot suggests that strong pressure amplification could be expected in the direction toward the recording station.

The recording station which is 8.3 km distant, showed a peak value of 126.7 db (44.5 Pa) which is higher than the pressure expected from the 1% exceedance at that distance (see Figure 8). This value is plotted in Figure 11 and a line was drawn through the point with the same slope as the 1% value. It represents the maximum expected value for muzzle blast from the 155 mm howitzer. It is used as the upper limit, or rare event. An upper limit curve for the 8" howitzer was scaled from the 155 mm data point. Measurements at 0 degrees from the angle of fire may show a somewhat higher reading but that geometry is not considered to be a typical proving ground configuration. Residential structures in the line of fire would not be close enough to sustain damage.

Ballistic Waves From Projectiles

The ballistic wave or "bow" shock developed when projectiles exceed the speed of sound account for pressures that are at times believed to be from HE shell or muzzle blast. At angles close to the line of fire the pressure from the ballistic wave can be higher than that from muzzle blast, but the character of the wave is different. Bow shock has a sharp but short pressure signal. Muzzle blast, having traveled a longer time has undergone more distortion by the atmosphere. In most scenarios bow shock can be disturbing, but not a damaging mechanism. An artillery shell, between launch and near apogee will be supersonic and the bow shock will be directed upward. Some projectiles will exceed the speed of sound as they fall toward their impact zone, directing the blast downward. The distance between impact zone and residential housing is most often sufficient to attenuate the bow shock to a non-damaging level.

Buried Munitions

A large percentage of claims received involve damage from the detonation of buried explosives. Explosives that are buried to the extent that no venting occurs (completely contained) will produce a very low grade "earth pressure pulse" which is caused by the upward motion of the ground over the charge. It is unlikely that this pressure pulse will cause a problem. The likely scenario occurs with charges that vent to the atmosphere and the degree of venting will be unknown. Demolition activity most often involves several hundred pounds of explosives placed in pits and covered with an unspecified amount of earth. Detonation of the explosives causes the earth cover to lift, degrading the blast to some degree, but releasing substantial blast with the potential to cause problems.

In 1982 the White Engineering Associates made airblast and ground shock measurements from a series of typical DEMIL events at the MacAlester Army Ammunition Plant in Oklahoma. Measurements were made close in and out to a distance of 17 km in all four compass quadrants. They derived an equation from the data and established a maximum probable pressure-distance relationship. Figure 12 is a plot of that relationship for 1 kg and for 227 kg (500 lbs.), the amount of explosives frequently detonated in a DEMIL event. There are indications that all DEMIL operations are not conducted with the same degree of care. The most unfavorable condition would be no burial at all and no pit. If that were the case the charge weight would effectively be doubled and the relationship in Figure 5 would apply.

Blast/Structure Interaction

The blast/structure interaction is very difficult to define in the low pressure region. The blast from distant explosions is likely to be refracted downward by the atmosphere to strike the roof and walls of the structure at undefined angles, and the original sharp shock front has more than likely been degraded to some form of a compressional wave. One must deal with a structure in a pressure "environment" rather than attempt to determine loading on the different surfaces of a structure. Damage will have to be inferred from the pressure environment.

A structure responding to the blast environment deforms in a complex manner that depends on many factors that will not be available to the claim reviewer. Experiments by Siskind et al. [5], showed that the measured frequencies of residential structures and their midwalls were between 4 and 11, and 11 and 26 Hz respectively. Small explosive yields will have greater effect on midwalls than on the more massive structural sections. The midwall response is responsible for pictures being knocked from walls and knickknacks toppling from shelves. Siskind relates peak overpressure to midwall velocity and shows that at very weak pressures, <69 Pa (.01 psi), midwall velocities can exceed 51 mm/s (2 in/s). This can produce an acceleration of .5 g's which is sufficient to cause noticeable rattling. Precariously placed items could be knocked from shelves at this "g" level.

Airblast Damage Criteria

The low pressure region in which residential homes may experience light damage has not been of interest to the military, hence there is virtually no military data base from which to draw. However, in the early 1960's, the FAA was interested in the effects of a "sonic boom," which would be generated by the proposed flying of a supersonic transport (SST) across the country. The sonic boom pressure pulse is a low magnitude pulse with a duration of tens of milliseconds and, in that respect, it is not unlike the blast problems of interest here. In those experiments, residential homes were instrumented with transducers for the measurement of structural response to the pressure field imposed by a number of aircraft flying at supersonic speeds. The FAA-sponsored experiments concluded that it was improbable that a 144.7 Pa (.021 psi, or 137 db) pressure pulse would cause even slight damage to a residential type structure [6]. The reference, authored by Wiggins, summarizes much of the FAA-sponsored work and contains a chart showing minor and major damage that could be expected at various pressure levels. Table 1 is a reproduction of that chart with the pressure values converted from psf to Pa. While the FAA experiments included aircraft of various weights flown at different Mach numbers to vary the duration of the pressure pulse, the conclusion by Wiggins does not associate the damage level with the duration of the pressure wave.

In 1980, Siskind et al. [7] conducted experiments to determine the response of structure to ground vibration and airblast from surface mining. They link damage to residential homes to the type of home and the frequency content of the blast wave. With due consideration given to structural response and frequency content of the blast wave, he suggests that at a scaled distance equal to .32 $km/kg^{1/3}$, there should be no damage, if no consideration is given to amplification by atmospheric conditions. This equates to 187 Pa (.027 psi) which is consistent with the results of the "sonic boom" study.

The damage threshold criteria currently used in claim evaluations is 138 Pa (.02 psi). This value is 20 Pa less than the minimum value shown in Table 1. The lower value is an adjustment to account for structures that are subjected to repeated blasts and for those with sub-standard design or construction.

Typical Damage Claims

Most claim files will state that explosions caused some type of light damage such as broken windows, cracked plaster or knickknacks broken when knocked from shelves. This type of damage is what one would expect from low pressure blast. Many claims, however, will seek payment for concrete slabs and masonry basement walls. Often the claimant hears the blast, hears a picture or knickknack fall and then looks for further damage. He then finds cracks in masonry and thinks the blast caused that as well.

Claims of damage are frequently received from owners of mobile homes. Often these homes are made semi-permanent by supporting them with concrete or cinder blocks. These are inadequate supports in many cases because too few are used, placing excessive or uneven loads on them. In time, uneven settlement causes stresses to build to the point that paint may flick or even a window may crack. A low level blast may well trigger damage if the structure is already in a high state of stress.

This prestressing of a structure is not unique to mobile homes. Files will show that homes of high value often have cracked foundations which will cause misalignment of the structure to the extent that doors will not properly close or windows become stuck. Photographs, often furnished with a claim file, will at times show downspouts that empty directly to the soil in close proximity to the area of a cracked foundation. More than likely the localized high moisture content of the soil, coupled with freeze and thaw cycles caused the foundation to crack. It would be most unusual for one to evaluate a claim where airblast or ground motion would be high enough to damage a foundation. Such a claim would also show substantial above ground damage. It is not uncommon to review a claim where the government is blamed for causing below grade foundation damage, but no window breakage or damage to objects being knocked from shelves. This would be an obvious case of foundation damage that is not related to explosive activity.

Ground Shock

The claim file will often state that damage was caused by ground shock, but rarely will one encounter a legitimate ground shock claim. Wiggins [6] describes results of sonic boom experiments showing the ground shock developed by the sonic boom pulse striking the earth and concludes that airblast induced ground shock is negligible. An extrapolation of the referenced data shows that 137 Pa (.02 psi) blast would cause only .46 mm (.018 in/s) particle velocity in the earth. Humans can detect movement at velocities as low as .25 mm/s (.01 in/s) so they may sense the motion but it is not the damage mechanism. The Bureau of Mines [8] reports that earth particle velocities less than 50.8 mm/s (2 in/s) will not cause damage. For the types of explosions of interest here, those not completely confined, airblast effect will override the ground shock effects unless the charge is heavily confined and close to the structure.

Summary

Figure 13 is a plot showing the distance at which damage could be expected from typical ordnance activities on a day when meteorological effects would provide a maximum increase in pressure. Such days are rare, but possible. The plot for the 155 mm muzzle blast is the maximum muzzle blast plot shown on Figure 11. The 8" muzzle blast plot is scaled from that. Muzzle blast from the 8" howitzer could shake items from shelves in houses that are 7 km distant. The blast from a 155 mm HE round could do the same at the same distance. Structures more distant than 5 km from gun firings, impact areas, or properly executed DEMIL events would not expect structural damage. It should be noted that normal testing events, following established procedures will rarely cause structural damage to distant structures and that firings can continue without incidence on days when meteorological conditions do not enhance pressure.

Cont'd

This paper recommends "safe from damage" distances for typical military blast-producing events. Your criticism of these distances and your recommendations for improved damage criteria is invited. The Army wants to be fair to its neighbors and it wants just and defensible criteria.

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4. G.A. Luz "A Statistical Model for Predicting the Probability of Complaints of Noise," JASA Supplement 1, Vol. 78, Fall 1985.

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7. D.E. Siskind, M.S. Stagg, J.W. Kopp and C.H. Dowding, "Structure Response and Damage Produced by Ground Vibration from Surface Mine Blasting," Bureau of Mines Report of Investigation/1980, RI 8507.

8. H.R. Nicholls, C.F. Johnson and W.I. Duvall, "Blasting Vibrations and their Effect on Structure," Bulletin 656, Bureau of Mines, 1973.

Table 1. Maximum Safe Predicted Peak Overpressures for Representative Building Materials and Bric-a-Brac Other than Glass

MATERIAL	WHITE SANDS MINOR	WHITE SANDS MAJOR
INTERIOR WALLS AND CEILINGS	pa	pa
PLASTER ON WOOD LATH	158	620
PLASTER ON GYPLATH	358	765
PLASTER ON EXPANDED METAL LATH	765	765
PLASTER ON CONCRETE BLOCK	765	765
GYPSUM BOARD (NEW)	765	765
GYPSUM BOARD (OLD)	213	765
NAIL POPPING (NEW)	255	765
BATHROOM TILE (OLD)	213	406
DAMAGED SUSPENDED CEILING (NEW)	186	765
STUCCO (NEW)	234	765
BRIC-A-BRAC		
EXTREMELY PRECARIOUSLY PLACED OR UNSTABLE ITEMS	N/A	144
NORMALLY STABLE OR PLACED ITEMS	N/A	261
MISCELLANEOUS		
BRICK CRACKED	896	N/A
GLASS DOOR LOOSENED	896	N/A
TWISTED MULLIONS	427	N/A
POPPED MOLDING	896	N/A

STATIC CHARGE FIRINGS - ABOVE GROUND FOR RESEARCH AND DEMONSTRATION

DEMIL - OLD EXPLOSIVES IN A PIT AND COVERED WITH EARTH

DEMOLITION - DESTRUCTION OF TOWERS, BRIDGE SUPPORTS, ETC. (OFF RESERVATION)

TANK GUNS - 105 MM AND 120 MM GUNS (MUZZLE BLAST, HE AND BALLISTIC SHOCK)

ARTILLERY - 105 MM, 155 MM AND 8 IN. HOWITZERS (MUZZLE BLAST, HE AND BALLISTIC SHOCK WITH SELECTED SCENARIOS)

FIGURE 1. MILITARY ACTIVITIES PRODUCING BLAST WAVES

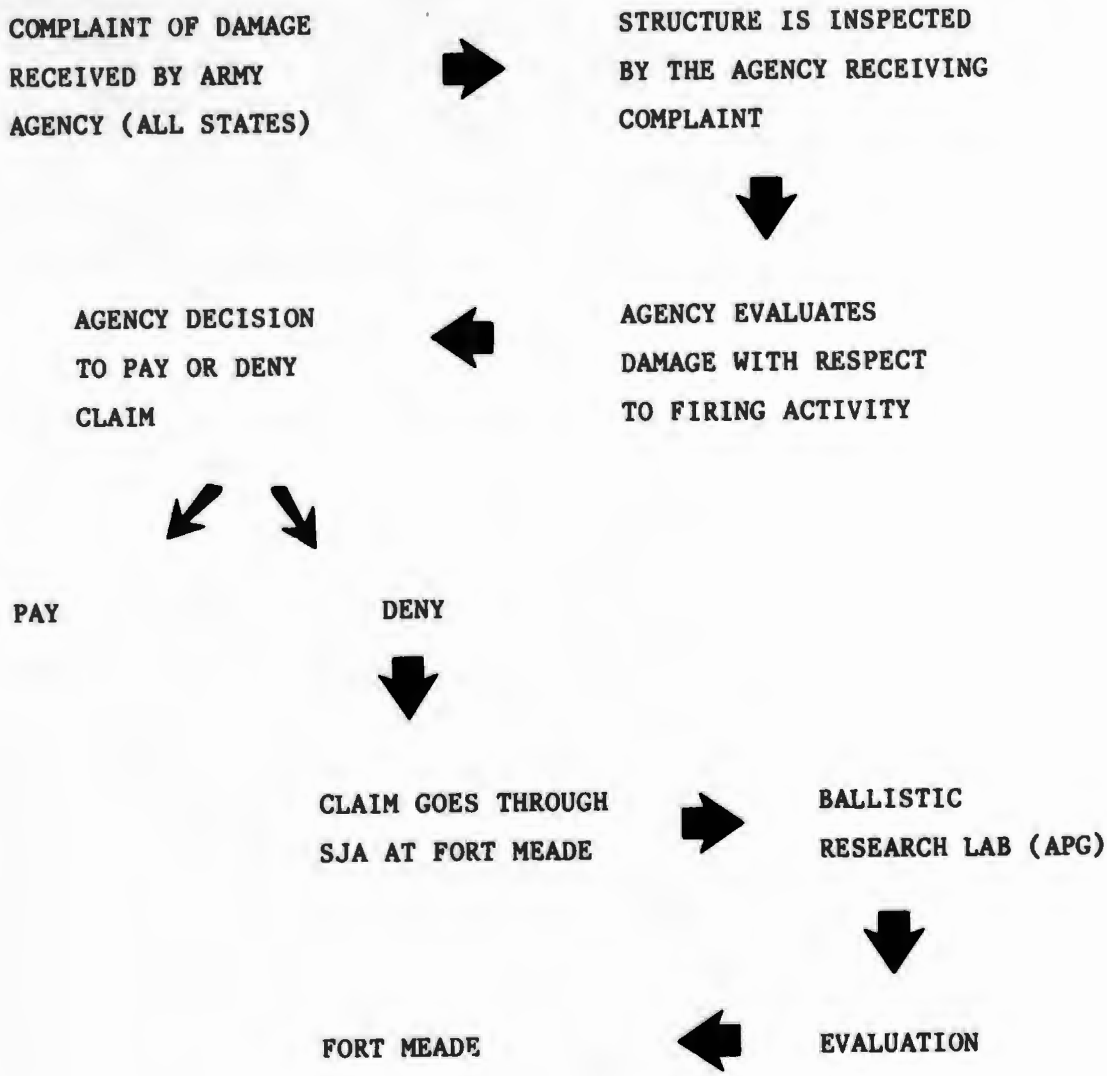


FIGURE 2. COMPLAINT PROCEDURE

OBJECTS FALLING FROM SHELVES

MIRRORS AND PICTURES FALLING FROM WALLS

PAINT FLAKING

NAIL POPPING

DAMAGED SEALS IN THERMOPANE DOORS/WINDOWS

BATHROOM TILE

WINDOWS

BRICKWORK

FOUNDATIONS AND FOOTINGS

STRUCTURE MISALIGNMENT

PATIO/WALKS/SLABS

SWIMMING POOLS

WELLS

FIGURE 3. SPECTRUM OF DAMAGE CLAIMS

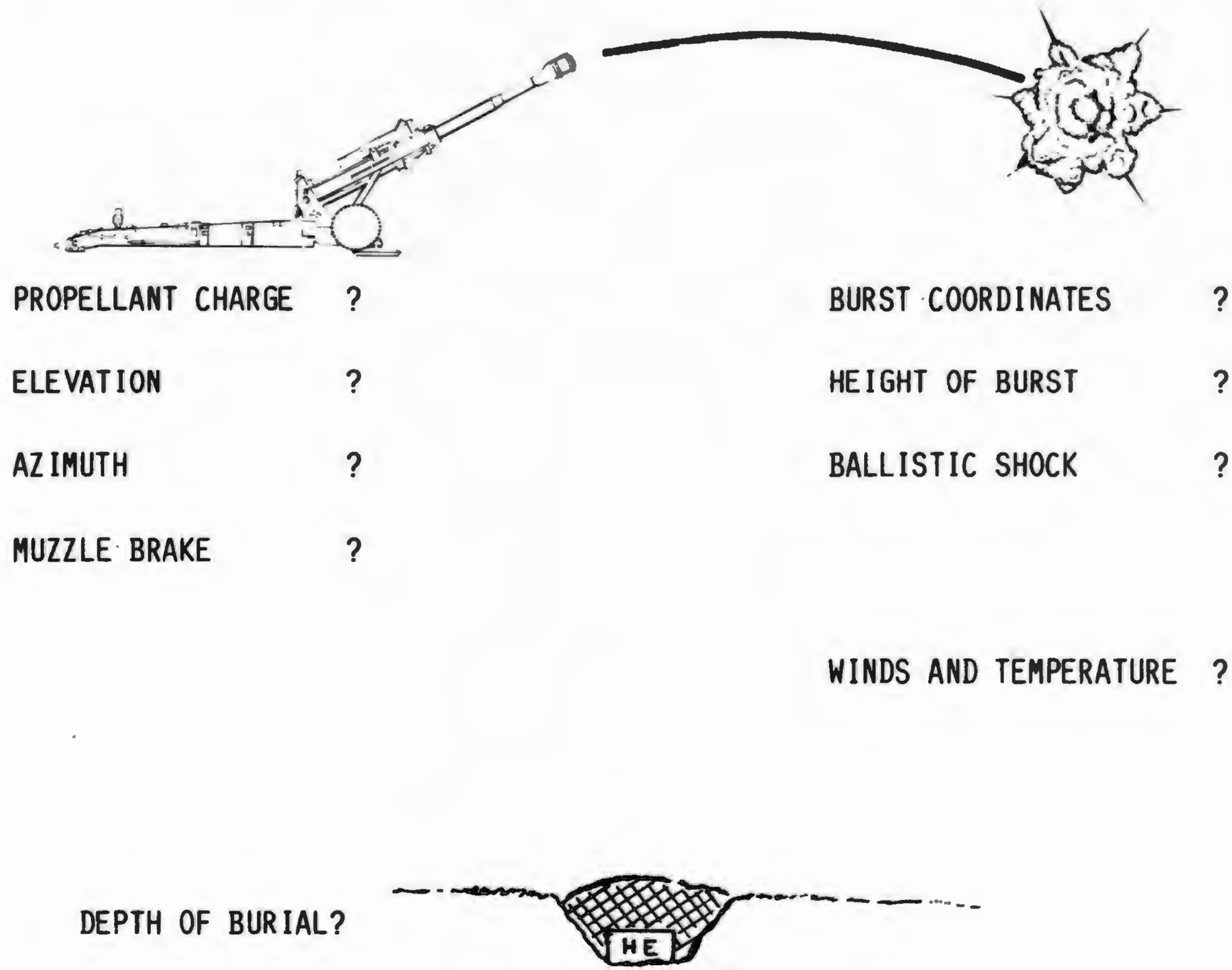


FIGURE 4. FREQUENT UNKNOWNS IN BLAST SCENARIOS

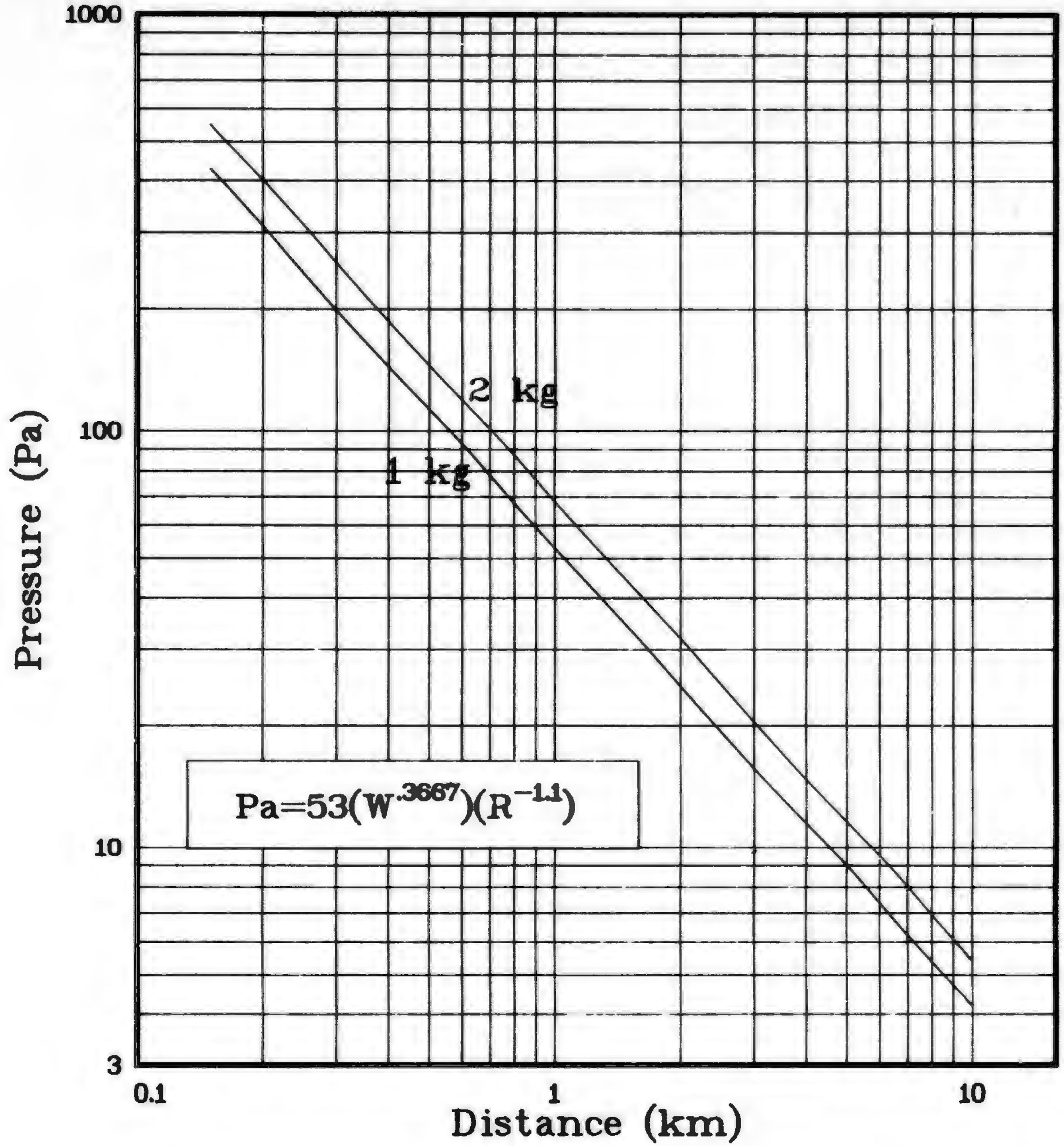


Figure 5. Explosion Pressure vs. Distance

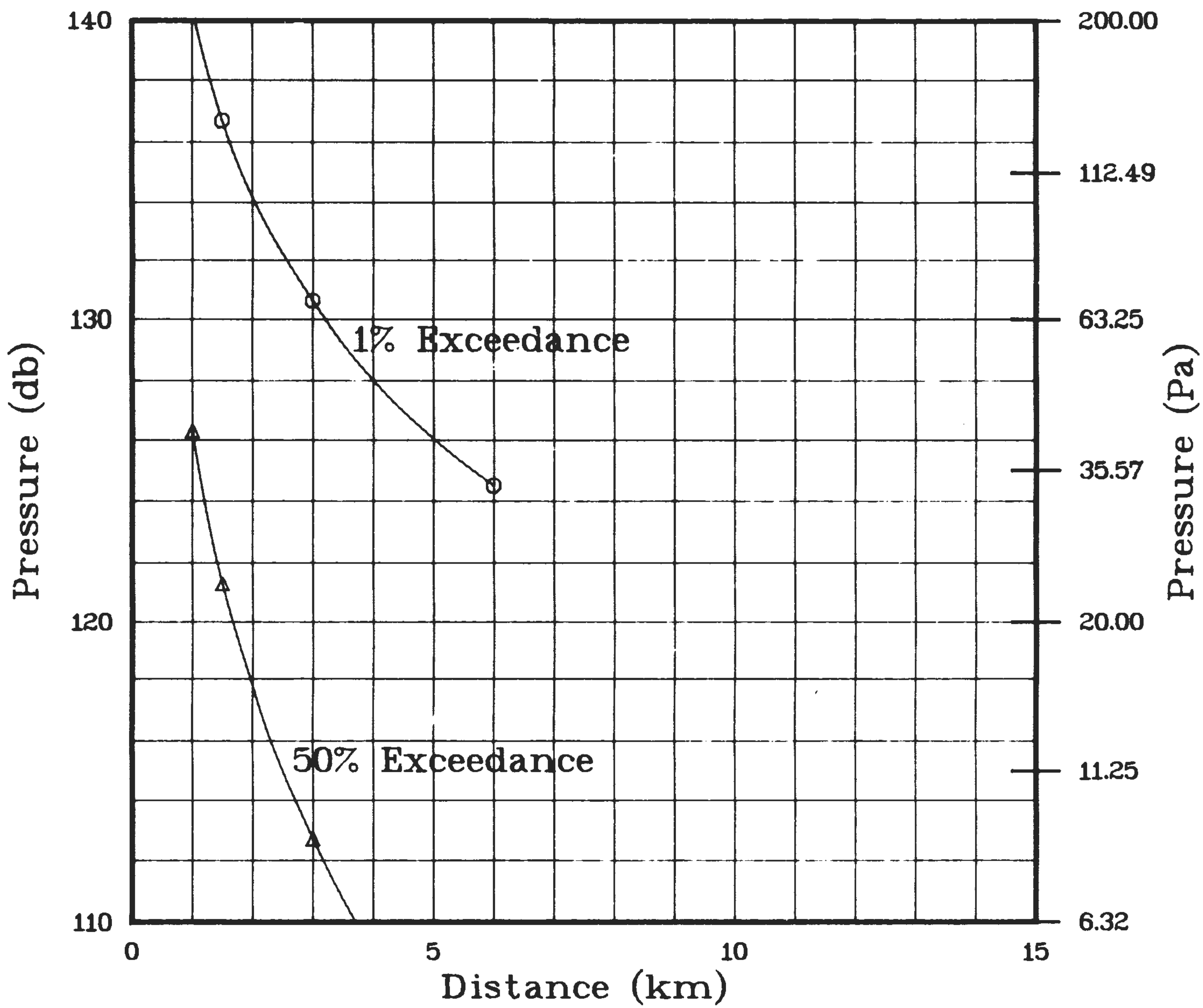


Figure 6. 120 mm Tank Gun Muzzle Blast. Pressure vs. Distance in Front of Gun

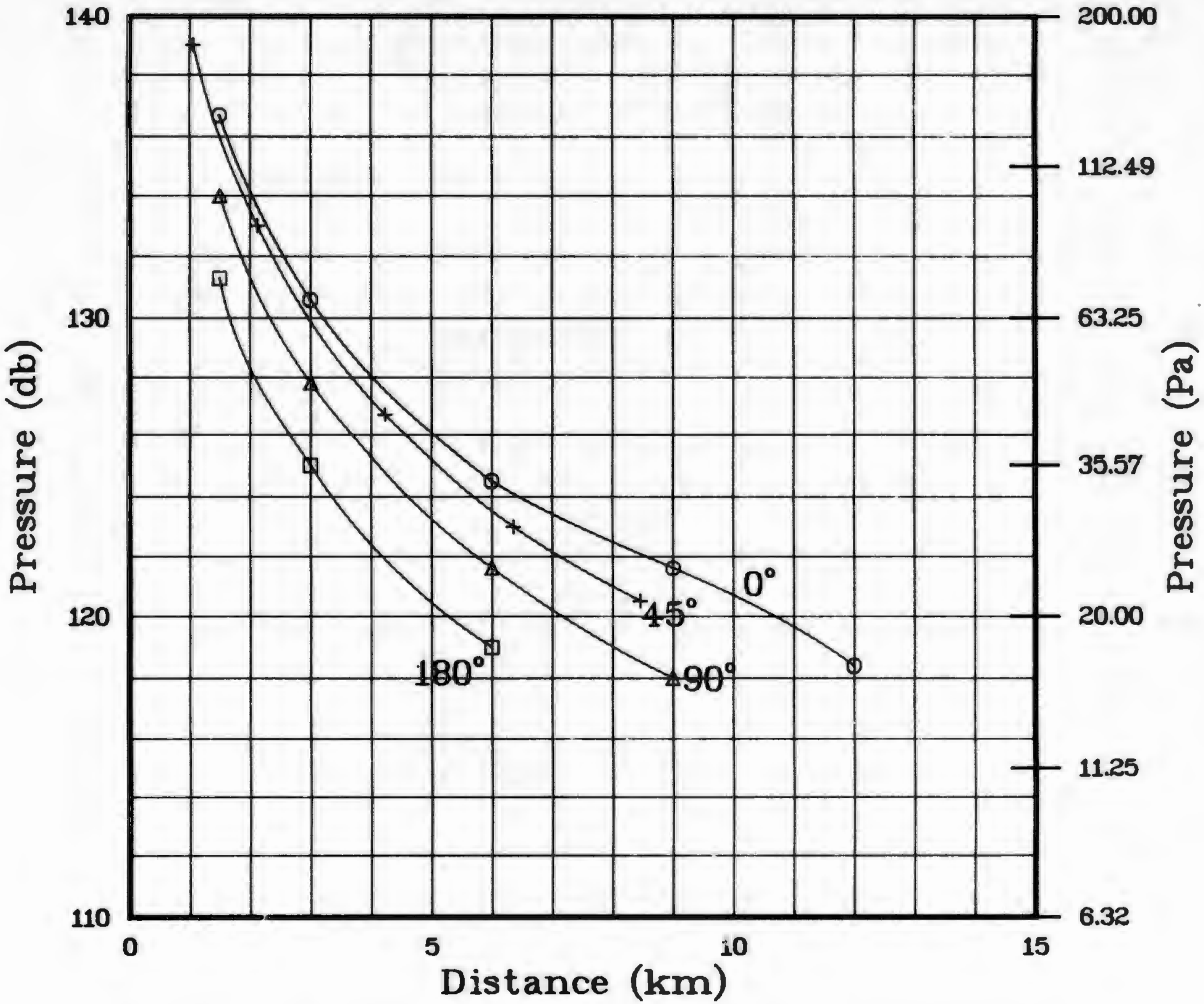


Figure 7. 120 mm Tank Gun, Pressure vs. Distance. 1% Exceedance at 0°, 45°, 90°, and 180°

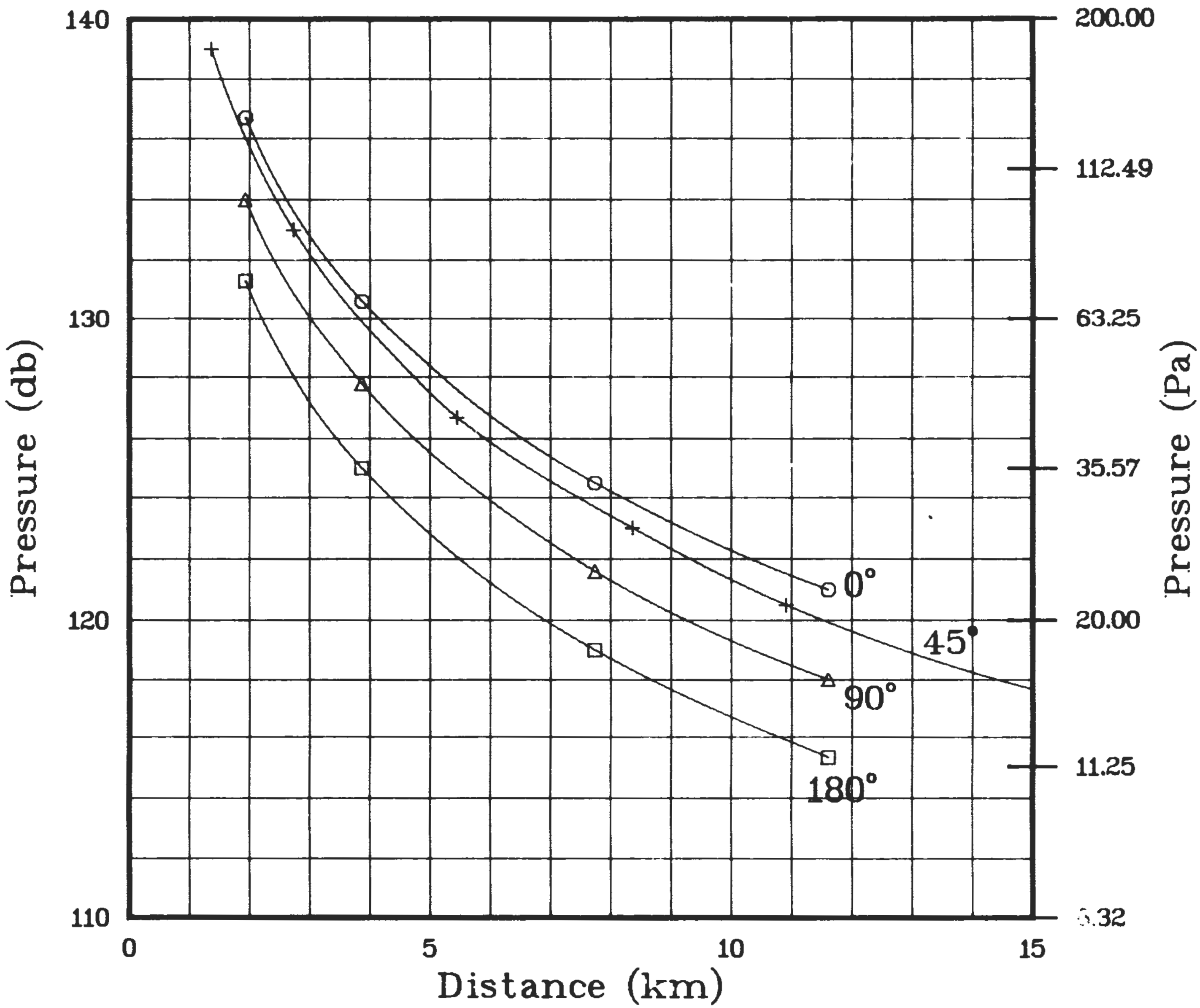


Figure 8. 155 mm Tank Gun, Pressure vs. Distance. 1% Exceedance at 0^o, 45^o, 90^o, and 180^o

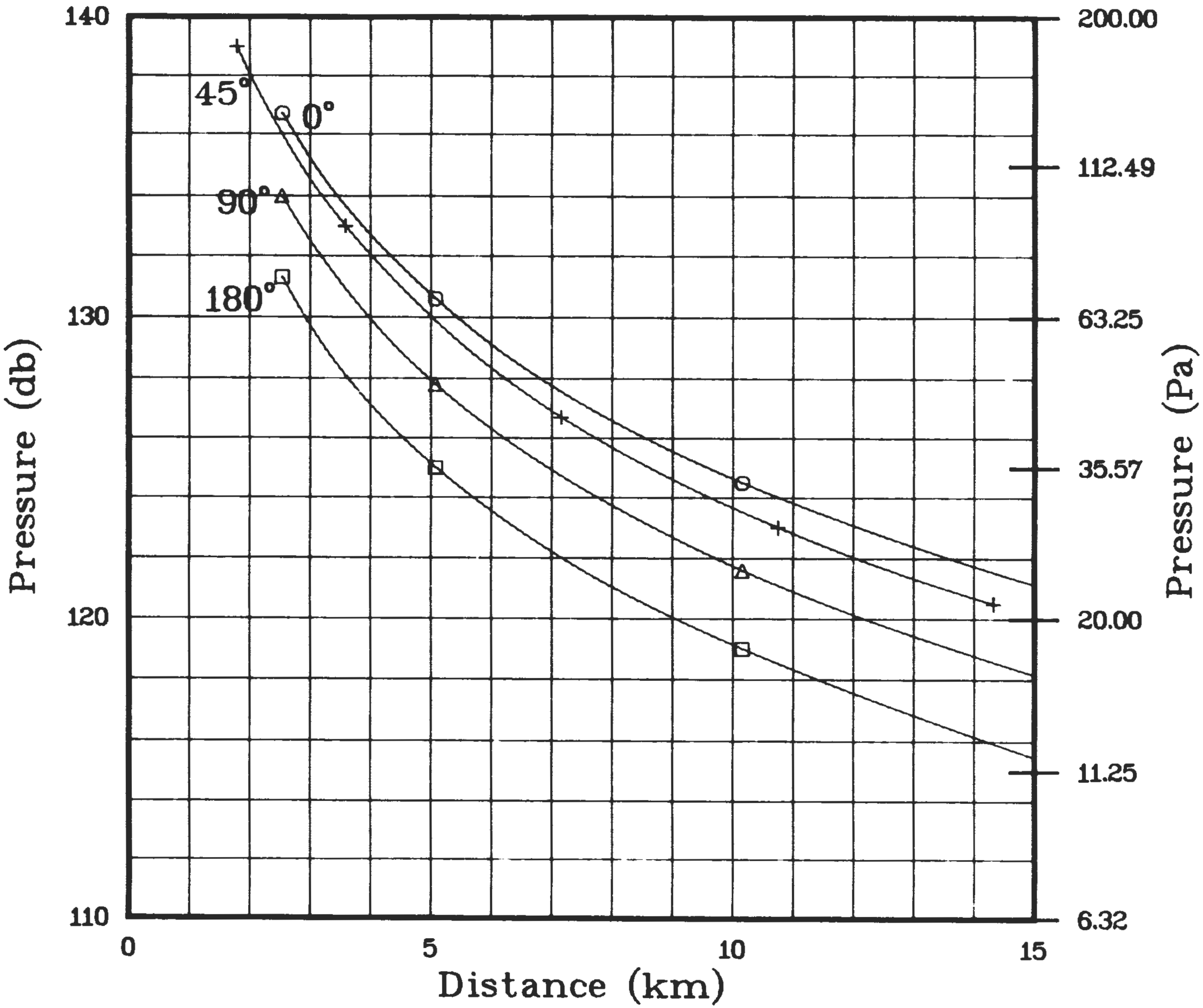
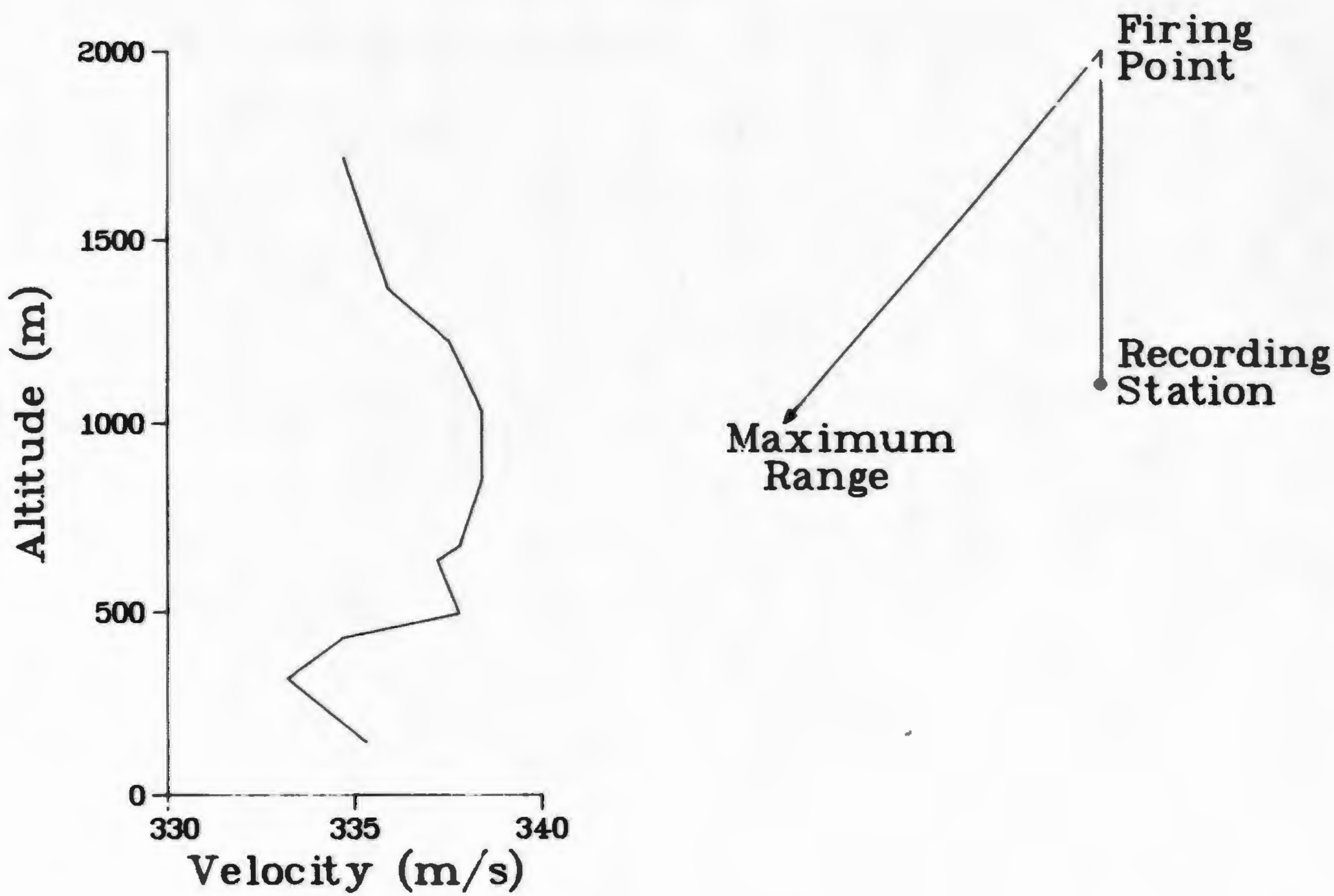


Figure 9. 8" Howitzer, Pressure vs. Distance. 1% Exceedance at 0^{o}, 45^{o}, 90^{o}, and 180^{o}



(A) (B)

Figure 10. Sound Velocity Profile and Range Geometry

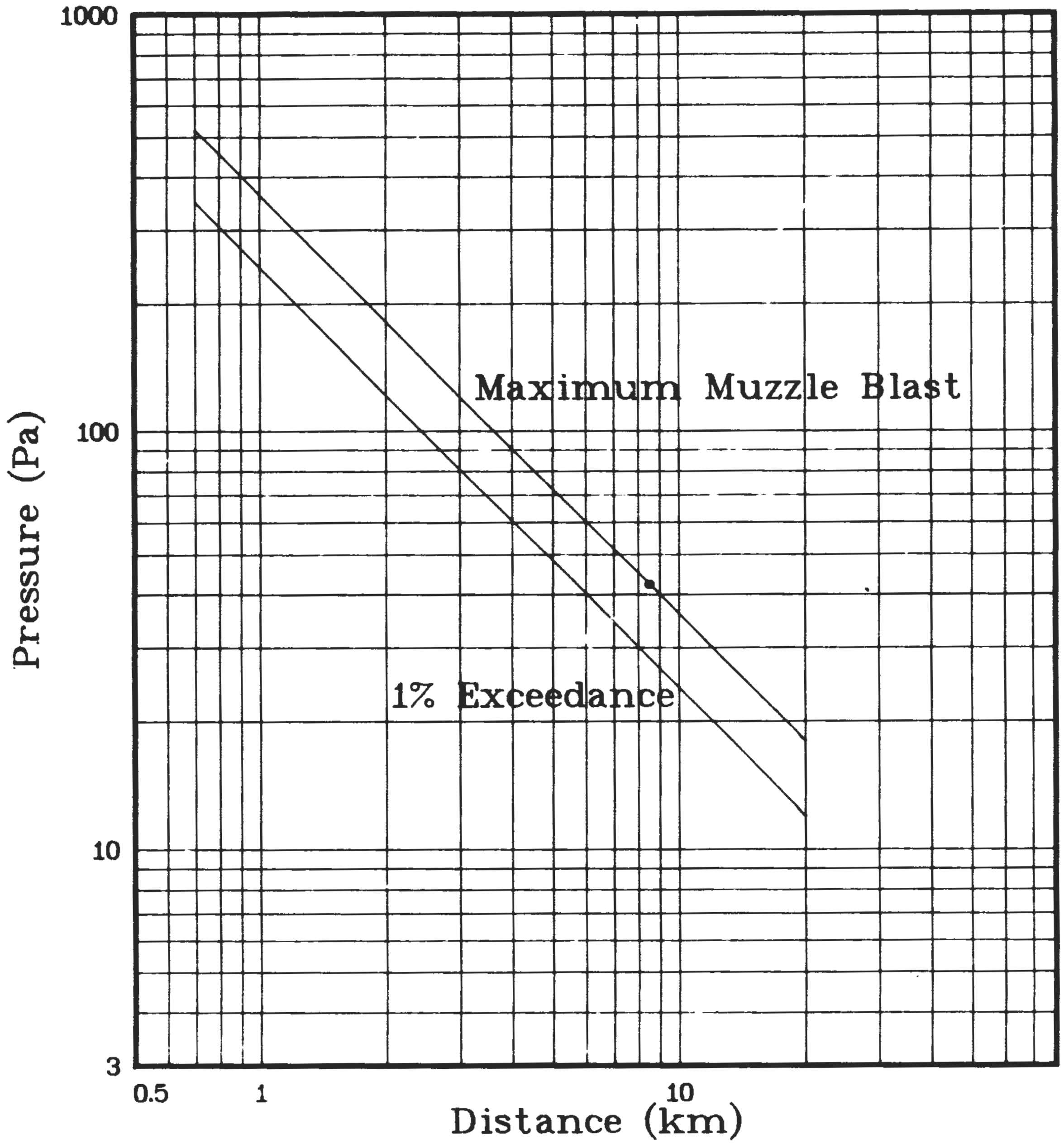


Figure 11. 1% Exceedance and Maximum Muzzle Blast from 155 mm Howitzer at 39^{o}

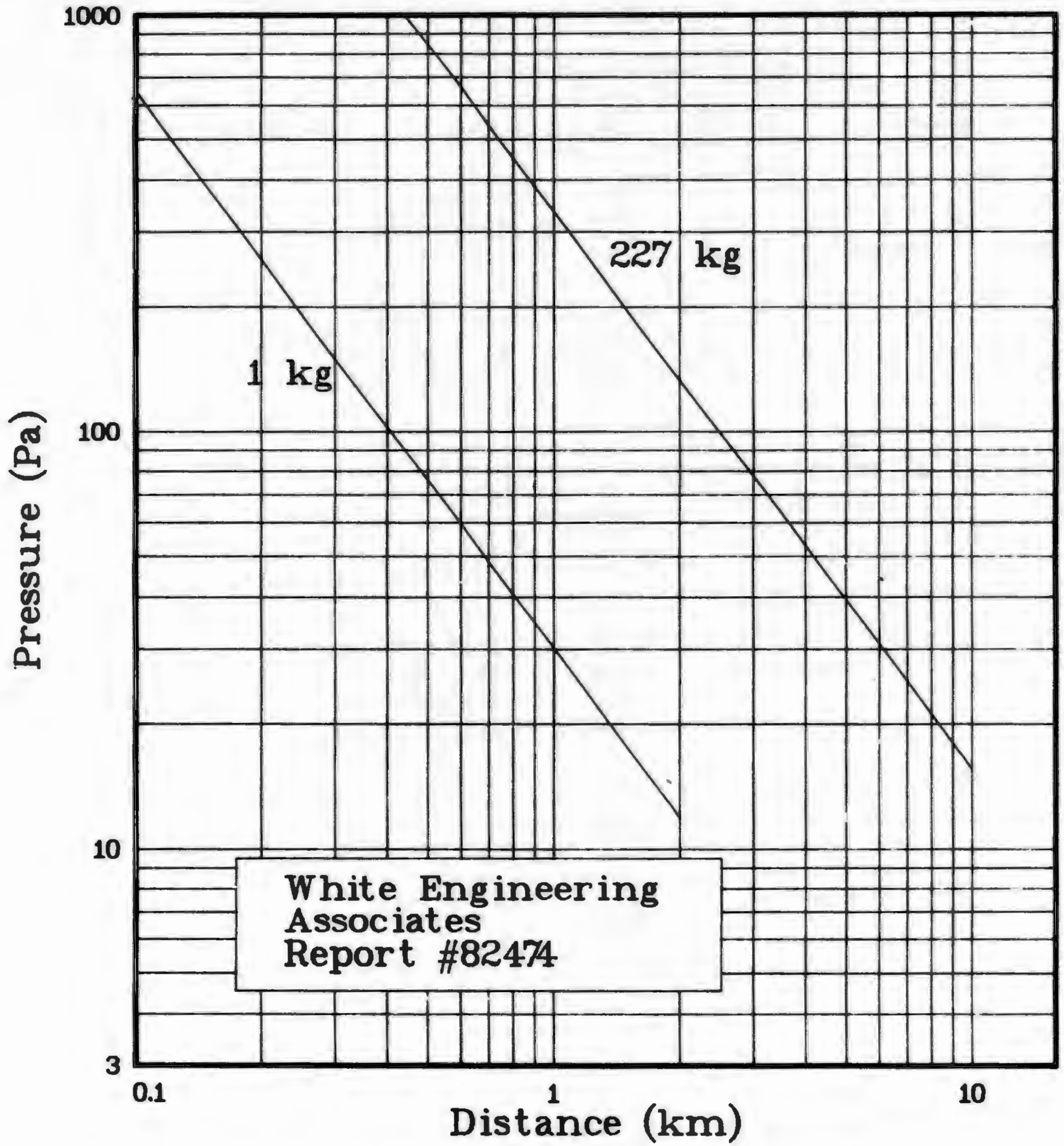


Figure 12. Maximum Probable Pressure from DEMIL Event

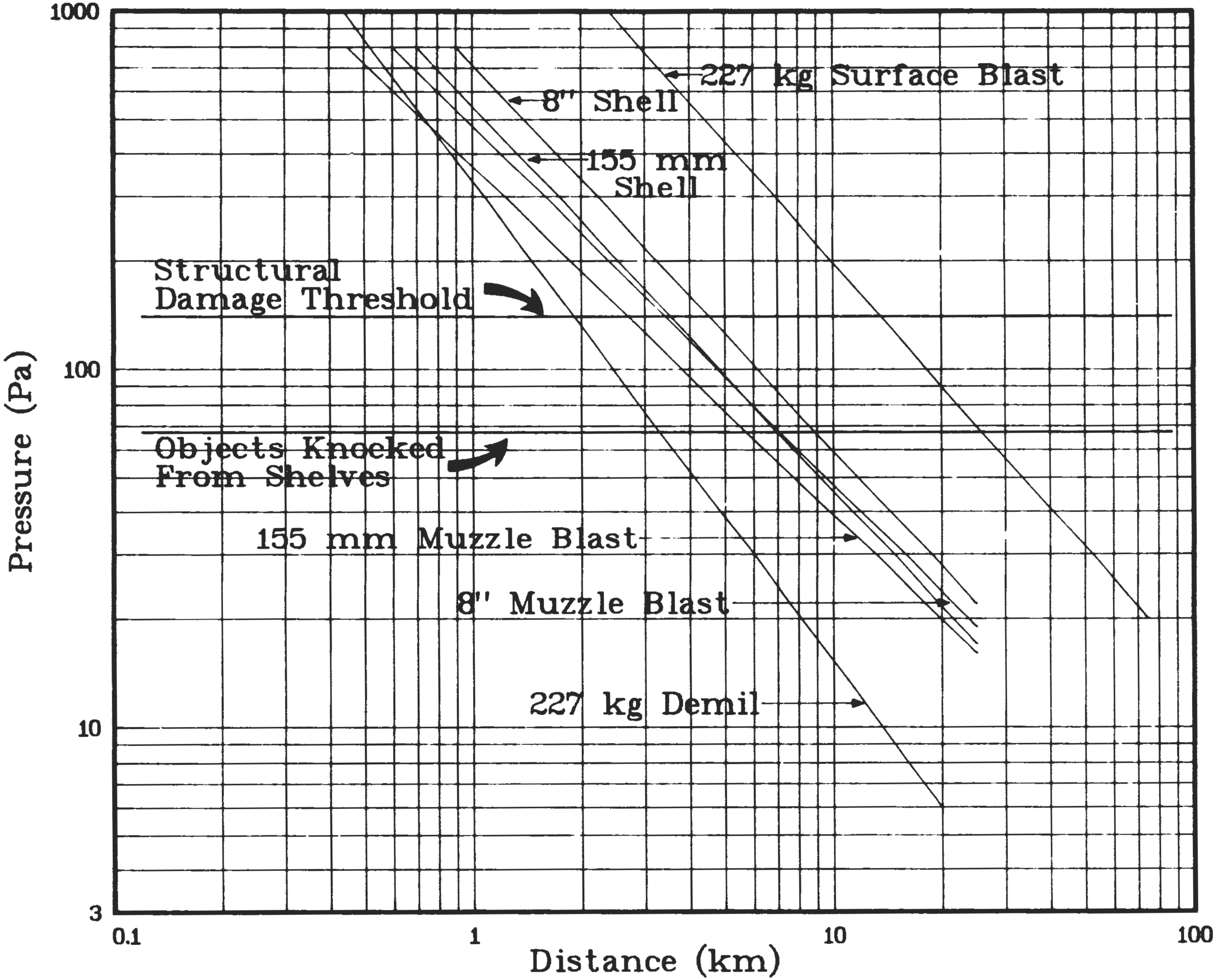


Figure 13. Critical Distance for Typical Ordnance Activities--Worst Case Meteorology