

SHALLOW UNDERGROUND TUNNEL/CHAMBER EXPLOSION TEST

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INTRODUCTION

A considerable amount of research has been performed in the last two decades to develop a technical data base and methods to predict the airblast and ejecta/debris hazards from accidental explosions in underground magazines. Much of the work was concerned with detonations in magazines so deep that venting of the detonation through the magazine cover rock does not occur. The effect of cover venting on the reduction of external airblast from the entrance portal has been demonstrated in small-scale tests performed in the United Kingdom (Millington, 1985). The Shallow Underground Tunnel/Chamber Test Program was designed to provide large-scale airblast and ejecta/debris effects from a detonation of 20,000-kg (net explosive weight) in a shallow underground magazine.

The test program was primarily funded on an equal share basis by three organizations: the U.S. Department of Defense Explosives Safety Board; the Safety Services Organisation of the Ministry of Defence, United Kingdom; and the Norwegian Defence Construction Service. Additional funds were provided by the Pyrotechnie Saint Nicolas, France; the Royal Swedish Fortifications Administration, Sweden; and the Amt fur Bundesbauten, Switzerland, to expand the scope of blast instrumentation and debris measurements.

This paper summarizes the hazard analyses (Joachim, 1990) based on the technical data acquired during the test.

OBJECTIVE

The overall objective of the test program was to determine the hazardous effects (debris, airblast, and ground shock) produced by a simulated accidental detonation of explosive stores which ruptures the overhead cover of the underground chamber. The results will be used to evaluate and validate quantity-distance (Q-D) safety standards for underground storage of munitions.

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DESCRIPTION OF TEST

The Shallow Underground Tunnel/Chamber Explosion Test Program involved the detonation of a 20,000-kg charge of Composition B explosive, simulating the accidental explosion of ammunition stored inside an underground magazine in granitic rock. A large-scale storage chamber and access tunnel were constructed for this test at a selected site on the Naval Weapons Center test range at China Lake, CA (Halsey, et al, 1989). For the TNT-equivalent (1.1 equivalence factor) 20,000-kg net explosive weight (NEW), the chamber loading density was 66.4 kg/m³. The storage chamber (with the 20,000-kg explosive charge) and access tunnel are shown in plan and profile in Figure 1. Active measurements included (1) internal chamber and access tunnel airblast pressures, (2) free-field overpressure along the 0, 30, 45, 60, 90, and 180-degree azimuths, measured from the tunnel portal, (3) beta densitometer/general purpose blast stations at the 75-m range along the 15, 30, and 60-degree azimuths, and (4) ground motion measurements along the 0, 90, and 180-degree azimuths (note: the 0-degree azimuth is the extension of the tunnel axis beyond the portal). Passive airblast and ejecta/debris measurement devices consisted of blast cubes, wire drag gages, smoke puffs, and artificial missiles. In addition, an ejecta collection study was performed and motion picture film analyzed to quantify the ejecta missile ranges.

AIRBLAST INHABITED BUILDING DISTANCE

The distances required for protection of inhabited areas from airblast and debris depends, to a large degree, on the depth of overburden over the storage chamber. The chamber cover depth for the Shallow Underground Tunnel/Chamber Explosion Test ranged from 9.4 to 13.7 m (scaled cover depth from 0.34 to 0.49 m/kg^{1/3}). The minimum scaled cover depth required to ensure containment of the explosion (except for gas venting through the access tunnel), and to ensure that no significant surface disruption occurs, is 1.4 m/kg^{1/3} in the current DOD Explosives Safety Standards (DOD 6055.9-STD) and 0.2 m/kg^{1/3} in the Manual on NATO Safety Principles (NATO AC/258). For overburden depths less than this, the Standards require consideration of both airblast and debris effects. When the actual scaled overburden depth is less than 0.2 m/kg^{1/3}, the Standards state that the airblast at large distances may

not be appreciably reduced from that of a surface burst. Thus, the scaled cover depth for this test fell between these limits, and the Standards (DOD 6055.9-STD) require that airblast and debris projection must be considered in the Q-D hazard analysis. However, the scaled cover depth exceeded the NATO AC/258 minimum scaled cover depth. Therefore, the NATO criteria require consideration of debris and ground shock hazards for the Tunnel/Chamber test.

The present DOD Standards use two different airblast pressure criteria to define Inhabited Building Distances--5 kPa (0.73 psi) for underground storage, and 6.2 kPa (0.9 psi) for open or other above-ground storage. For the 22,000-kg NEW detonated in the Shallow Underground Tunnel/Chamber Explosion Test, the distances to these two pressure contours as given in the present Standards (DOD 6055.9-STD) are shown in Figure 2. For comparison, Figure 2 also shows the actual distances to the 5 and 6.2 kPa pressure contours that were defined by measured pressures on the Tunnel/Chamber Test. Since overpressures were not measured along the 120-degree radial on the test, the distance to the 5 and 6.2 kPa contours along the 120-degree azimuth were assumed to be the same as on the 180-degree azimuth.

As also shown in Figure 2, the distance along the extended tunnel axis to the 6.2-kPa overpressure level indicated by the test data is close to the airblast Inhabited Building Distance specified by the present Standards for above-ground storage ($20 Q^{1/3}$). The off-axis distance to the measured 6.2-kPa level is approximately two-thirds the distance specified by the Standards for above-ground storage at 30 degrees, 61 percent at 60 degrees, 50 percent at 90 degrees, and 20 percent at 180 degrees.

Figure 3 compares the Inhabited Building Distances, derived from the Standards and from test data, as a function of azimuth. The measured distance to the 5-kPa peak pressure on the Tunnel/Chamber tests falls well within the airblast Inhabited Building Distance specified in the Standards. The measured distance to the 5-kPa pressure level was 75 percent of the distance the Standards call for along the 0-degree azimuth, 58 percent at 30 degrees, 71 percent at 60 degrees, 88 percent at 90 degrees, and 68 percent at 180 degrees. Thus, except over the arc that extends from 120 degrees to approximately 150 degrees, the present airblast Inhabited Building Distance can be seen to be generally conservative for underground magazines with

geometries and loading densities similar to the Shallow Underground Tunnel/Chamber Explosion Test.

In 1987, a 4,540-kg ANFO charge (3,815-kg TNT-equivalent NEW) was detonated in a KLOTZ Club test in an underground tunnel/chamber test facility at Alvdalen, Sweden (Vretblad, 1988). Figure 4 shows the measured distances to the 5 and 6.2-kPa overpressure contours for this test. Also shown are the 5-kPa contour specified by the present Standards (DOD 6055.9-STD) for underground storage of the 3,815-kg NEW tested at Alvdalen, and the 6.2-kPa contour specified by the Standards for above-ground storage of the same NEW.

Along the extended tunnel axis (0-degree azimuth), the measured distance to the 5-kPa pressure was 85 percent of the distance specified by the Standards. Off-axis (Figure 5), the measured distance was 80 percent of the current Standard at 45 degrees from the tunnel axis, 41 percent at 75 degrees, 13 percent at 110 degrees, and 11 percent at 180 degrees. The comparison in Figure 4 also shows that the measured distance to the 6.2-kPa overpressure for the Alvdalen test is far less than that specified by the current Standards for Inhabited Building Distance from above-ground explosions.

In Figure 6, the Inhabited Building Distance (distance to the 5-kPa overpressure level) derived from the Shallow Underground Tunnel/Chamber test data is plotted versus loading density, where loading density is the NEW in the chamber divided by the total volume (chamber plus access tunnel). The Alvdalen test in Sweden was conducted in an underground complex containing two chambers, as depicted in Figure 4. The overburden depths were sufficient to prevent rupture of the detonation chamber. Total volume for this tunnel/chamber system was taken as the volume of the loaded chamber, plus the volume of the access tunnel through which the airblast exited to the portal (disregarding the volume of the second empty, chamber).

Table 1 compares the Inhabited Building Distances for airblast specified by the current Standards with those indicated by the Tunnel/Chamber test and Alvdalen tests. Note that, as a maximum, the hazard area indicated by the test data is less than half that required by the Standards.

A series of model tests were conducted at WES on small-scale munition storage magazines. The WES model (Smith, et al, 1989) consisted of a small-

scale (1:75 scale) tunnel and magazine cast into a large concrete block. Since there was no rupture of the concrete block (simulating the magazine overburden) over the range of loading densities tested (Figure 6), no venting through the chamber cover occurred. This resulted in higher free-field airblast overpressures from the tunnel entrance, which gave significantly greater Inhabited Building Distances than implied by either the Norwegian model or the full-scale Tunnel/Chamber Test, both of which vented through the cover.

GROUND MOTION HAZARD RANGE

For the Shallow Underground Tunnel/Chamber Test, the measured compressional wave velocity of the rock mass in the region of the explosive storage chamber ranged from 944 to 1,526 m/s, with an average value of 1,309 m/s (Halsey, 1989). These values are more typical of compressional wave velocities in soil, rather than in solid rock, and indicated that the rock at the Tunnel/Chamber site was heavily jointed and weathered. The plot of the ground motion arrival time recorded on the test (Figure 7) indicates a higher compressional wave velocity (2,166 m/s), implying the existence of less weathered, more competent rock at depth. This value is within the compressional wave velocity range for material described in the Standards as soft rock.

Data points for maximum particle velocity vectors measured on the Tunnel/Chamber Test are plotted in Figure 8 as a function of slant distance from the center of the chamber. The velocity curve given by Vretblad (1988) falls slightly below the measured data along the 0-degree azimuth (i.e., the extended tunnel axis), but closely matches the far-field data in other directions.

The gages beyond the 100-m range along the 0-degree azimuth in the Tunnel/Chamber Test were emplaced in desert alluvium soil in the valley floor in front of the tunnel, while the gages in other directions were emplaced on the rock surface. Using the criterion of 6.1 cm/s and the equation given in the Standards (Section G.4.d.(1)) for soft rock, the calculated Inhabited Building Distance for ground shock should be 160 m. Based on an interpolation of the data, the Tunnel/Chamber test results indicate that the 6.1 cm/s level

occurred at a distance of 580 m. For the 90 and 180-degree azimuths, the test measurements indicate a range of 155 m.

The NATO (AC/258) Inhabited Building Distances for ground shock are also displayed in Figure 8. The NATO criteria specifies levels of damage that occur at certain peak particle velocity thresholds--5 cm/s (threshold of no damage), 14 cm/s (minor damage), and 19 cm/s (major damage). These values are independent of velocity direction or earth media. The NATO Inhabited Building Distances for major damage from a detonation corresponding to the Shallow Underground Tunnel/Chamber Explosion Test are 300 m in soil (0-degree azimuth) and 120 m in rock.

There are two dominant factors associated with the Tunnel/Chamber Test that may explain the discrepancies between the predicted and the measured ranges to the 6.1-cm/s level of ground shock along the 0-degree azimuth. The first is the fact that the gages along the 0-degree azimuth were emplaced in soil, rather than rock. Since the detonation chamber was surrounded by rock, the use of the relation for soil in the Standards is obviously inappropriate. On the other hand, the use of the relation for soft rock does not take into account the effect of the soil layer overlying the bed rock along the 0-degree radial, in front of the tunnel opening.

The second factor is the apparent fact that the ground motions recorded by the gages on the 0-degree azimuth were predominately induced by airblast issuing from the tunnel portal. This is indicated by the arrival times of the ground motions at the gage locations, which match the arrival times recorded by the airblast gages along the 0-degree azimuth. Thus, it is obvious that the direct-induced motions transmitted to the gages in front of the tunnel, through the bedrock initially and then through the overlying soil, were completely obscured by the strong airblast-induced motions.

Figure 8 also shows a prediction curve from NATO AC/258 that does account for airblast-induced motions. This curve is based on the equation

$$v_v = P / \rho c_p \quad (1)$$

where v_v is the vertical velocity of motion, m/s

P is the airblast overpressure at the location of interest, Pa

ρ is the density of the material, kg/m³

and c_p is the wave velocity of the material, m/s

In NATO AC/258, c_p is defined as the seismic velocity of the material.

However, Hadala (1973) found that the stress wave velocity is actually the controlling parameter in regions where the airblast-induced motions outrun the direct-induced ground shock. Using a typical stress wave velocity for desert alluvium and the overpressures measured on the Tunnel/Chamber Test, a prediction curve for airblast-induced ground motion velocity based on Equation 1 is shown in Figure 8. While the curve obviously overpredicts the close-in motions directly in front of the tunnel portal, it comes within 50 percent or so of matching the measured velocities on the 0-degree azimuth at the distances of interest for ground shock hazard definition.

A final comparison made in Figure 8 is with the curve established for ground shock velocity by Vretblad (1988), based on the results of the Alvdalen tests in Sweden. Vretblad's equation provides a better fit to the off-axis ground shock data at the ranges of interest for the Tunnel/Chamber Test, but still underpredicts the motions measured at the most distant gages.

In summary, the NATO AC/258 equation for airblast-induced motions provides the best fit to the data along the 0-degree azimuth for the Tunnel/Chamber Test, at the ranges of interest for defining the Inhabited Building Distance. For other off-axis directions, the NATO AC/258 equation for direct-induced motions and Vretblad's equation both closely predict the motions measured on the Tunnel/Chamber Test at ranges of interest. In all cases, however, the values predicted by these methods should be increased by a factor of two to provide a safe upper bound of the motions measured on the test.

EJECTA/DEBRIS HAZARDS

The DOD Explosives Safety Standards and the NATO AC/258 debris hazard criteria consider two sources of hazardous debris--material blown through the access tunnel portal and rock thrown by the overburden rupture. The Explosives Safety Standards require an Inhabited Building Distance for debris of 610 m along and 15 degrees either side of the extended access tunnel

centerline. The NATO AC/258 debris Inhabited Building Distance is 600 m over the same 30-degree arc.

The current Explosives Safety Standards (DOD 6055.9-STD) criterion for debris hazard range is the distance to a fragment or debris density of one hazardous particle per 56 m². Analysis of the debris on the motion picture records of the Tunnel/Chamber Test indicates that almost all debris seen on the film is potentially lethal (kinetic energy greater than 79 J), and thus considered hazardous. As shown in Figure 9, a debris density of one missile impact per 56 m² occurred at a distance of 656 m. For debris originating from rupture of the cover, the Standards give a hazard range of 236 m. Similarly the NATO AC/258 criteria predict a hazard range of 246 m from cover rupture.

The debris and ejecta collection on the Tunnel/Chamber Test was concentrated within a sector extending 45 degrees each side of the extended tunnel axis; therefore the effect of azimuth on debris range can only be based on data within this sector. These data are shown in Figure 9, where curves are drawn to approximate the debris limits at 0, 20, and 40 degrees. As shown here, the distance to a debris density of one strike per 56 m² is 656 m, 447 m, and 287 m along the 0, 20, and 40-degree azimuths, respectively. For the Tunnel/Chamber Test configuration, Figure 10 compares debris hazard range, as a function of azimuth, based on criteria given in the Explosives Safety Standards and NATO AC/258, with ranges derived from the actual debris data collected on the test. As shown in the comparison, both sources slightly underpredict the hazard ranges in front of this tunnel/chamber geometry and loading density.

CONCLUSIONS

The Inhabited Building Distances for airblast given in the current DOD Explosives Safety Standards are very conservative for the area in front of the access tunnel portal (azimuths from 0 to 90 degrees and 270 to 0 degrees), as shown in Figure 2. Over an arc from 90 degrees to 270 degrees (Figure 3), the distance specified by the manual provides a reasonable upper bound of the data measured on the Shallow Underground Tunnel/Chamber Test.

The manual sets damage criterion for airblast pressure against inhabited

buildings as 5 kPa (50 mb). As shown in Figure 2, the 5-kPa overpressure level measured during the Shallow Underground Tunnel/Chamber Explosion Test occurred at approximately the same distance that the Standards specify as the airblast Inhabited Building Distance for open storage of a 20,000-kg Composition B charge. The airblast Inhabited Building Distances specified in the Standards for underground storage are even more conservative when compared to the results of tests at Alvdalen, Sweden, as shown in Figure 4. The airblast Inhabited Building Distance is strongly dependent on the explosive loading density (charge weight divided by the volume of the access tunnel plus storage chamber) of the magazine, as shown in Figure 6.

Using a peak pressure criterion of 5 kPa (0.73 psi) for airblast Inhabited Building Distance, the test data indicate that the actual Quantity-Distance ($Q-D_{ib}$) is 25 percent less, and the $Q-D_{ib}$ area some 50 percent less than the values specified by the current Standards for underground storage. If the same damage criterion for inhabited buildings (6.2 kPa or 0.9 psi) used for above-ground storage is applied to underground storage, the test results indicate that the actual $Q-D_{ib}$ for underground storage is approximately equal to the $Q-D_{ib}$ specified in the Standards for above-ground storage, but the $Q-D_{ib}$ area is only one-third that specified for above-ground storage.

The Inhabited Building Distances for ground shock given by the Explosives Safety Standards and the NATO AC/258 yield reasonable results for shock transmitted through rock. For the case of a soil layer over bedrock, however, such as existed at the Tunnel/Chamber Test site, the Standards and NATO AC/258 both severely underestimate distances to the particle velocity levels used as criteria for Inhabited Building Distance to protect against ground shock.

The results of the Shallow Underground Tunnel/Chamber Explosion Test indicate that Inhabited Building Distance for ejecta/debris along the extended tunnel axis (0-degree azimuth) is underestimated by the NATO AC/258 guidance. The data indicate (Figure 9) that the Inhabited Building Distance for debris decreases with angle from the 0-degree azimuth, and approaches the distance specified by the standards and NATO AC/258 at an azimuth of 45 degrees.

RECOMMENDATIONS

Additional data are needed to evaluate the effect of storage loading density and cover depth on the Inhabited Building Distance for airblast. Previous data from WES model tests, shown in Figure 6, indicate that a non-linear relation exists. These data, from fully-contained storage magazine models, provide an upper bound for airblast Inhabited Building Distance as a function of loading density. Additional tests, where the extent of venting is varied over a range of cover depths (and other factors held constant), are needed to isolate this effect.

Computer model studies can also help define the effect of venting on external blast hazards, after a reliable material is established that simulates the response of the rock surrounding the magazine chamber.

The Shallow Underground Tunnel/Chamber Test demonstrated that current Inhabited Building Distance criteria for ground shock in a layered geology (with soil over rock) is inadequate. Improved methods must be developed to better predict these distances in complex geologies.

The Inhabited Building Distance that is currently specified in the Standards for debris expelled from the access tunnel should be reevaluated and corrected. Recent work in Sweden indicates that the large distances to which debris was thrown out the access tunnel on the Tunnel/Chamber Test could be reduced by a barrier outside the tunnel portal. Additional study is needed to evaluate such methods, and their most effective design, to reduce the external debris hazard.

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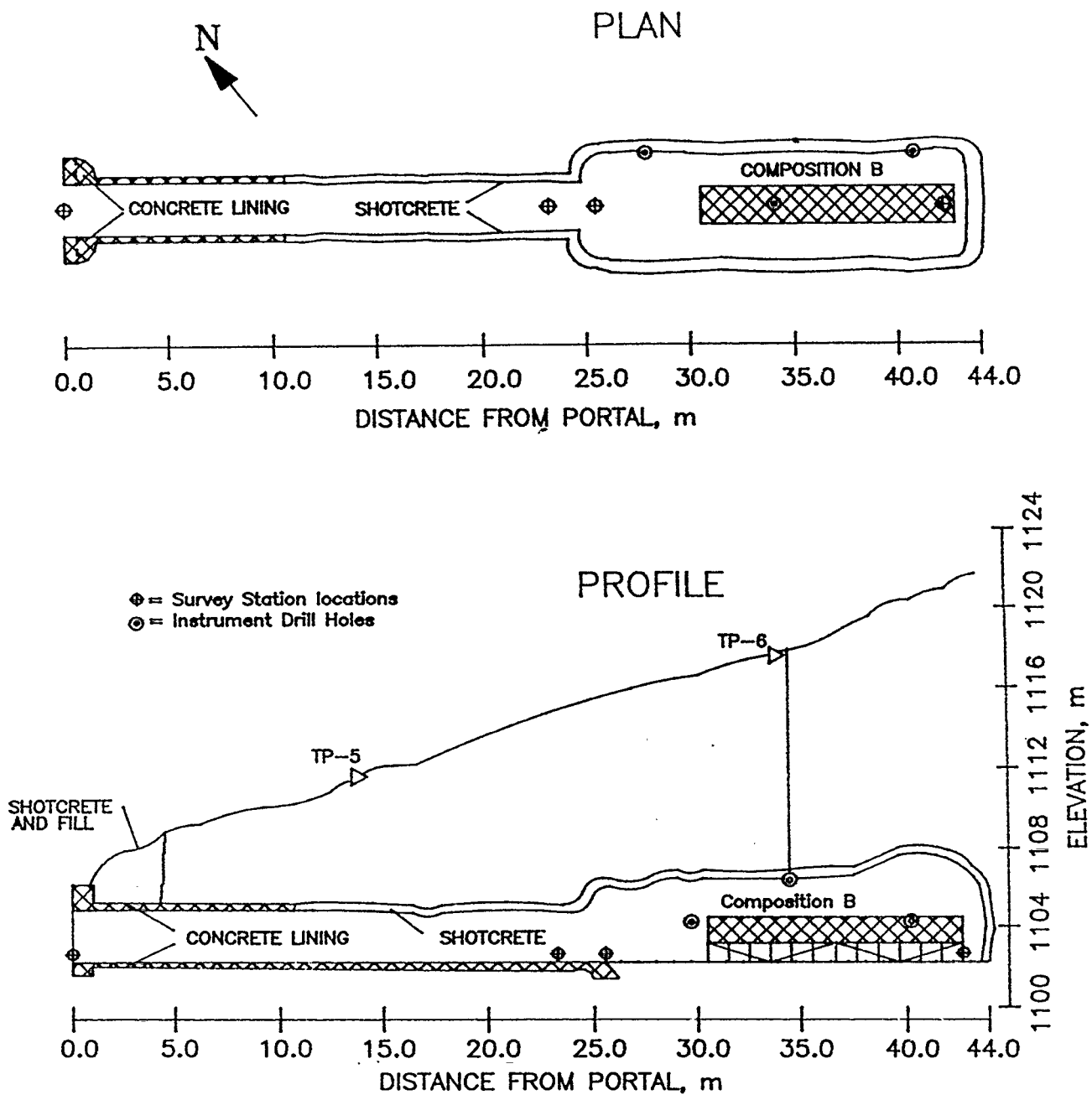


Figure 1. Location of 20,000-kg Composition B explosive charge for Shallow Underground Tunnel/Chamber Explosion Test Program (plan and profile).

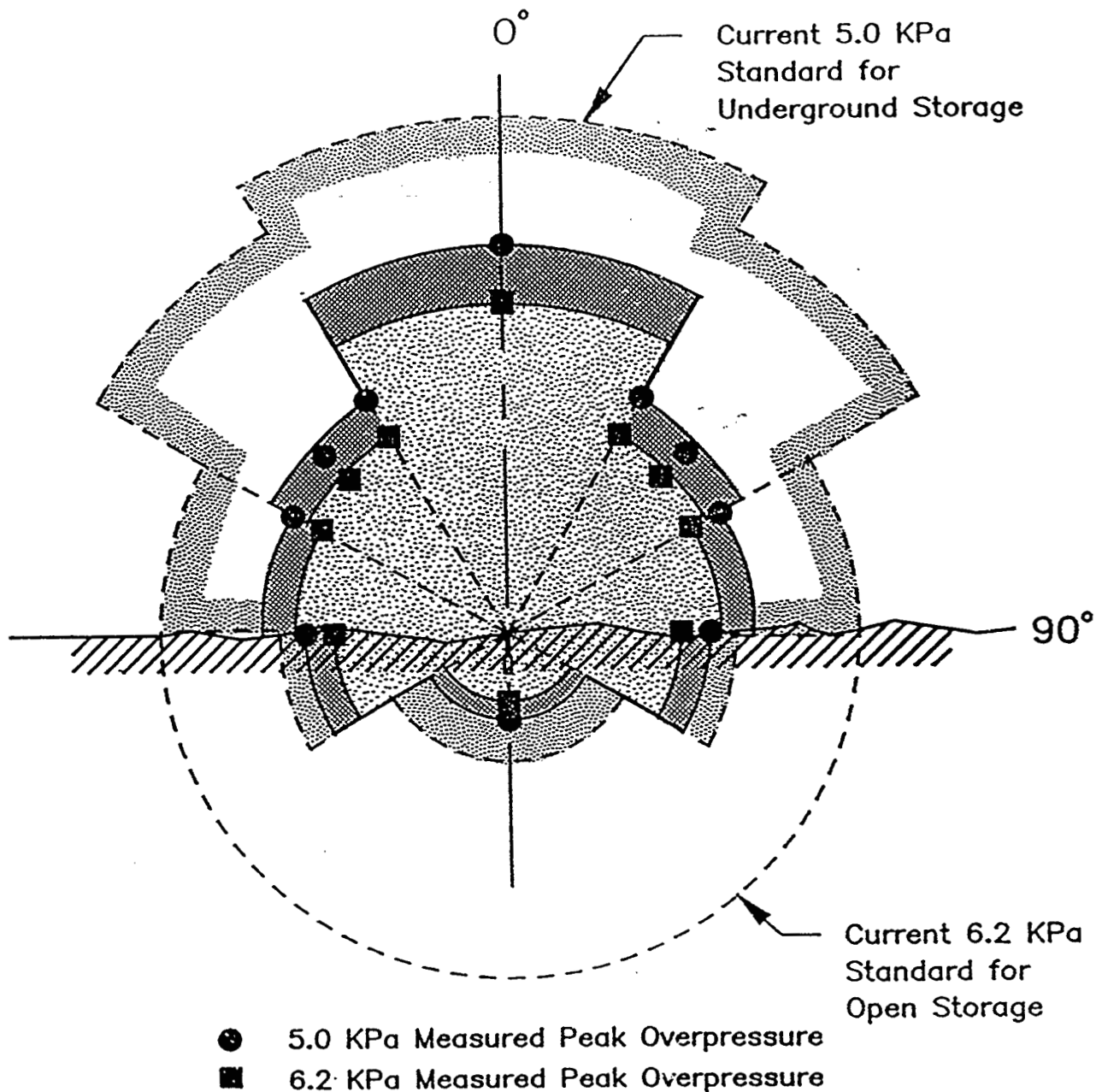


Figure 2. Airblast Inhabited Building Distances specified by Explosive Safety Standards (DOD 6055.9 STD) for open and underground munitions storage, compared to 5.0 and 6.2 kPa distances measured on Shallow Underground Tunnel Chamber Explosion Test (20,000 kg, Composition B, 66.4 kg/m³ (TNT equivalent) loading density).

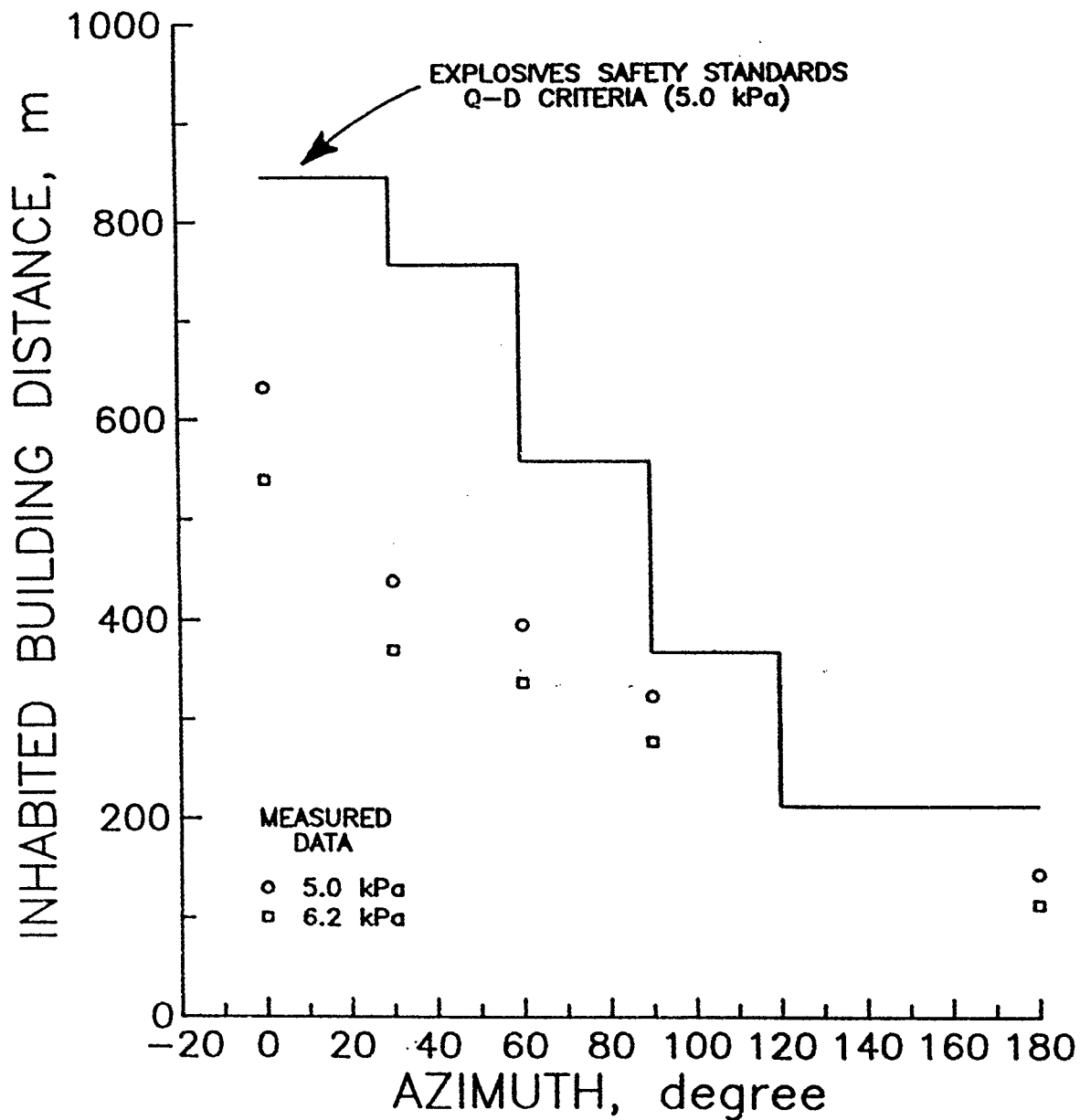


Figure 3. Airblast Inhabited Building Distances specified by Standards (DOD 6055.9-STD) compared to measured distances to 5.0 and 6.2 kPa pressure levels for the Shallow Underground Tunnel/Chamber Explosion Test (20,000 kg, Composition B, 66.4 kg/m³ (TNT equivalent) loading density).

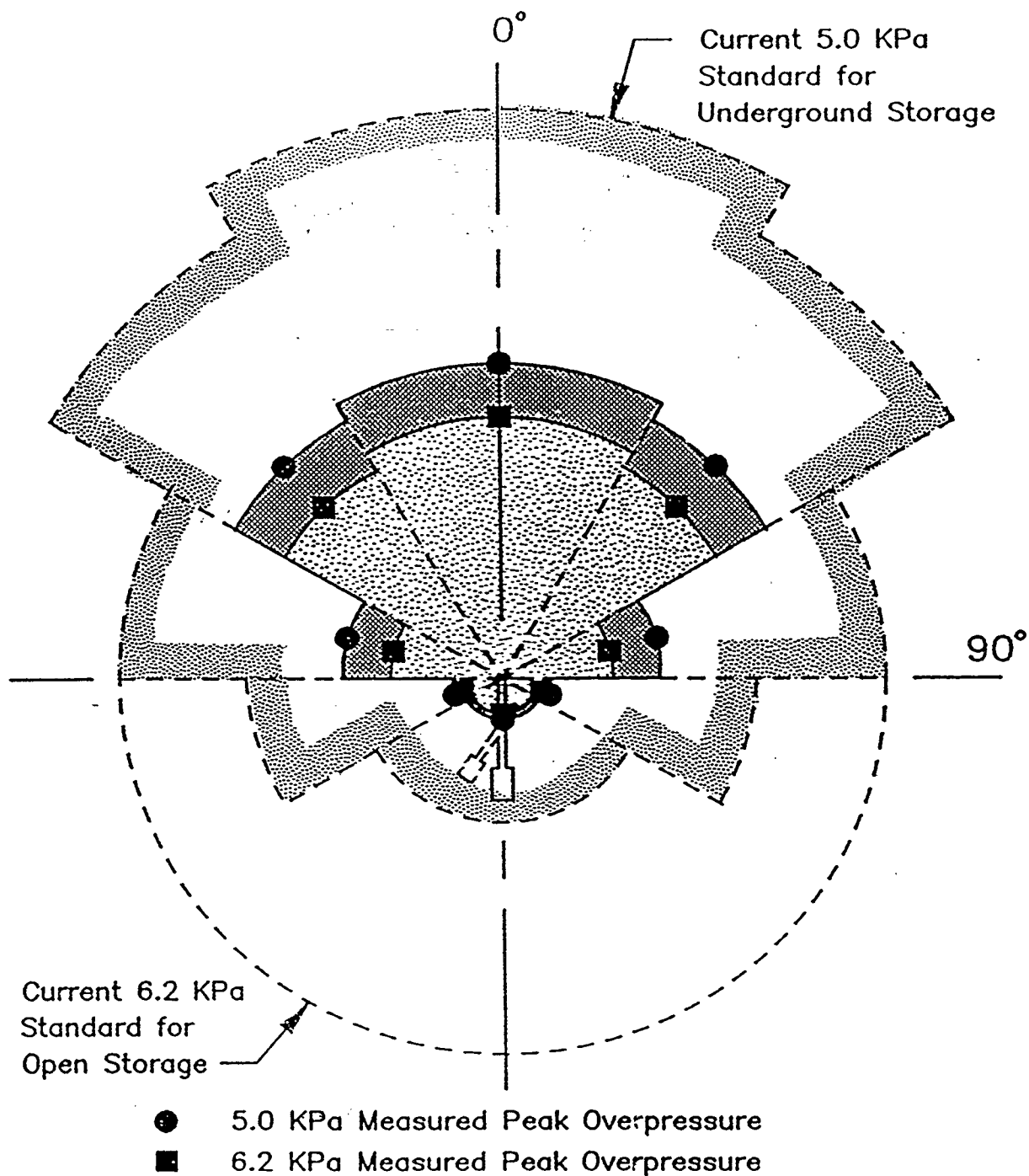


Figure 4. Airblast Inhabited Building Distances specified by Standards (DOD 6055.9-STD) for open and underground munitions storage, compared to 5.0 and 6.2 kPa distances measured in 1987 KLOTZ Club Test 8 at Alydalen, Sweden (4540 kg ANFO, 12.7 kg/m³ TNT equivalent) loading density.

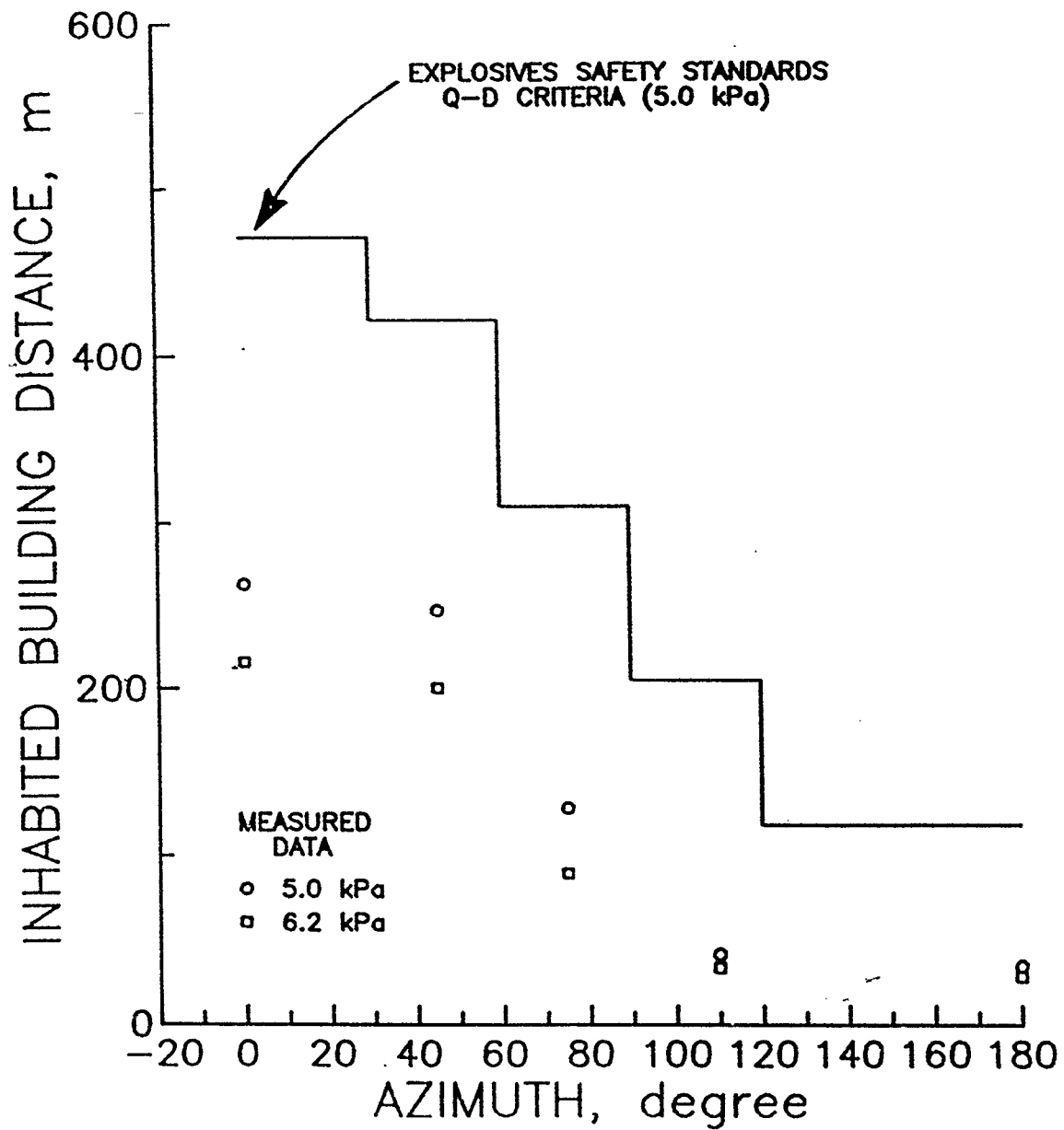


Figure 5. Airblast Inhabited Building Distances specified by Explosives Safety Standards for underground munitions storage, compared to measured distances to 5.0 and 6.2 kPa pressure levels, for 1987 KLOTZ Club Test 8 at Alydalen, Sweden (4540 kg ANFO, 12.7 kg/m³ (TNT equivalent) loading density).

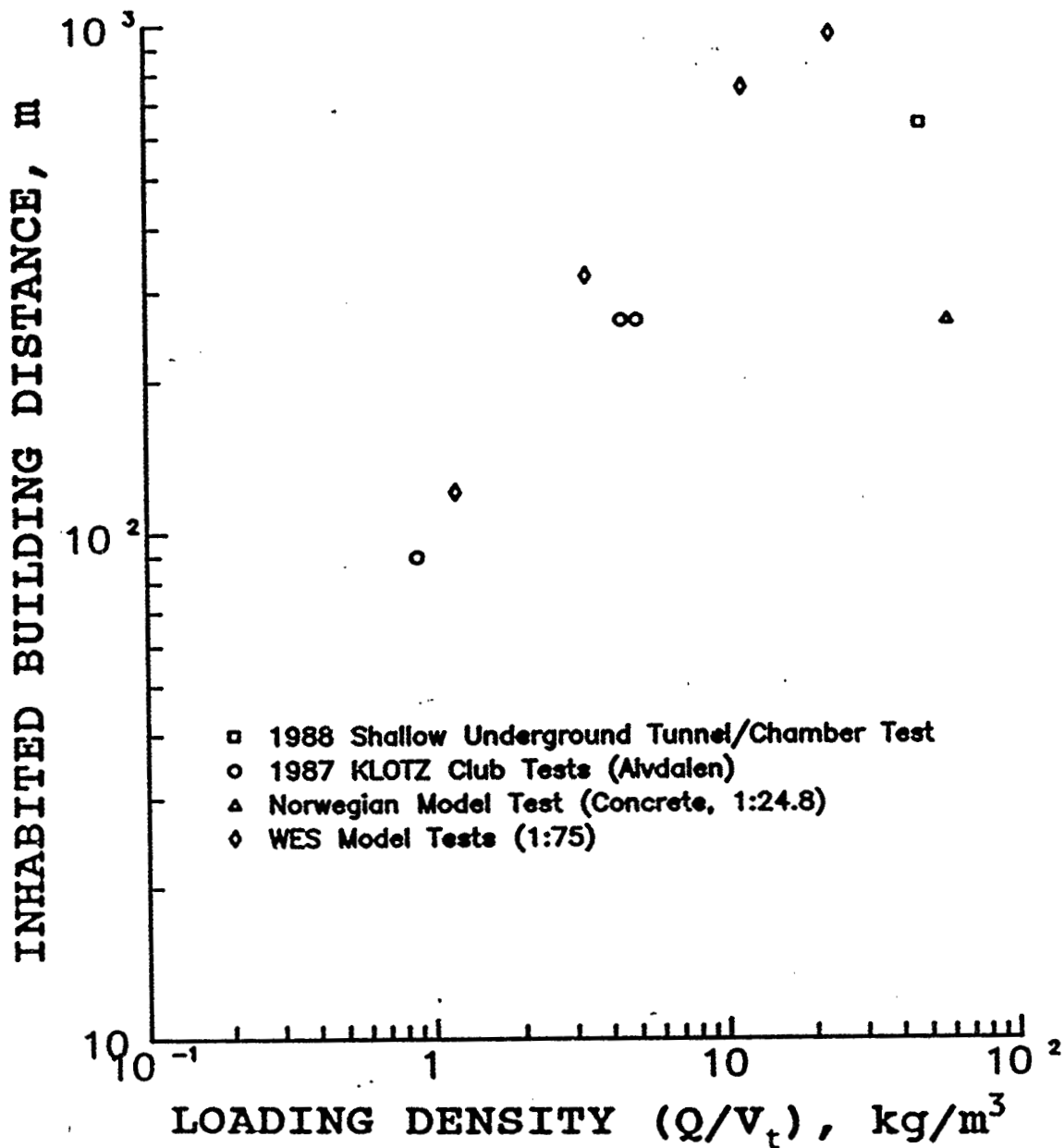


Figure 6. Airblast Inhabited Building Distance along the 0-degree azimuth (extended tunnel axis) as a function of loading density, as indicated by full-scale and model test data. (Note: Loading density is defined as charge weight, Q , divided by total volume, V_t , which is volume of the chamber plus the tunnel portion between the chamber and the portal).

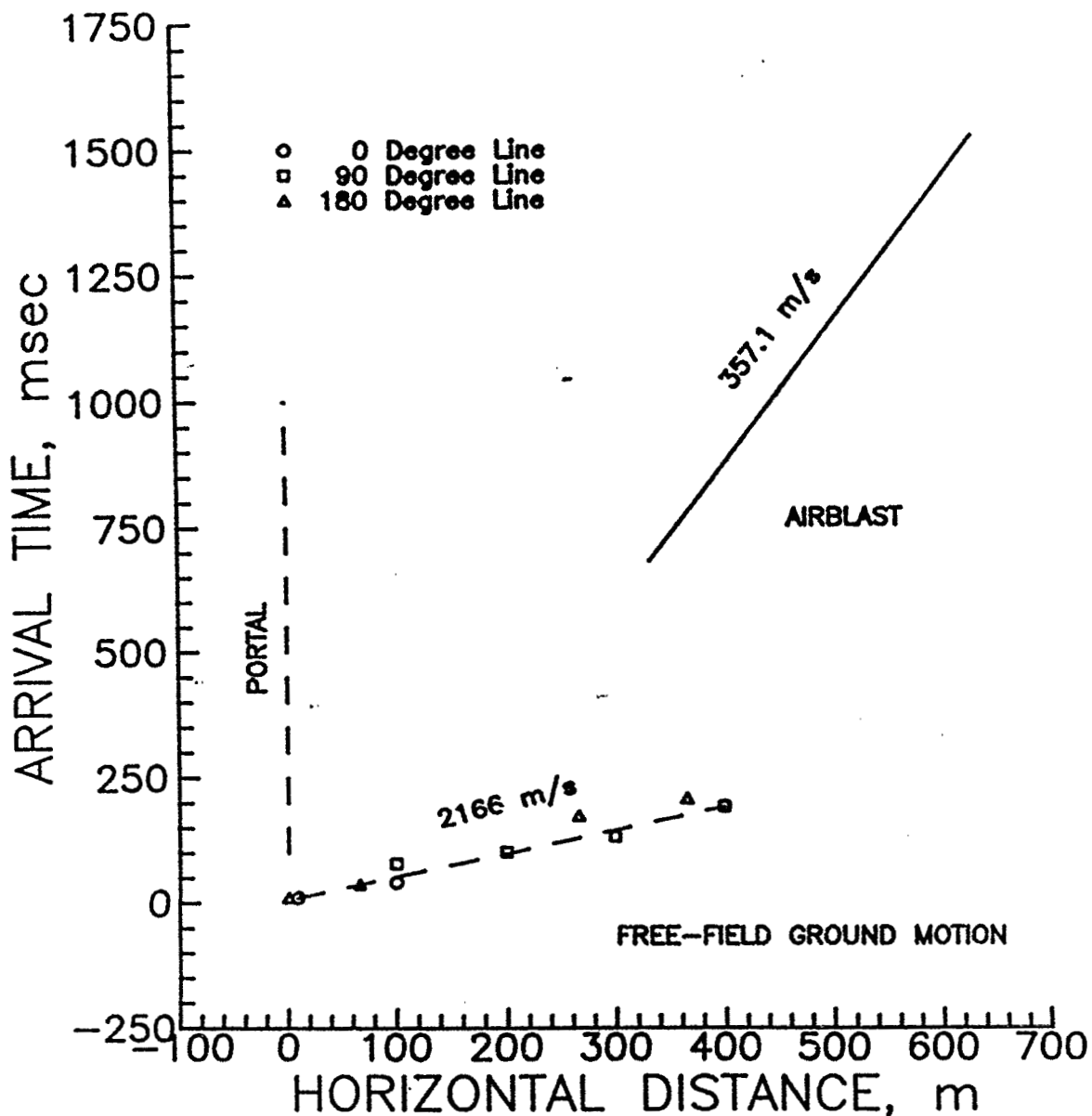


Figure 7. Free-field ground shock arrival time versus distance from center of chamber, Shallow Underground Tunnel/ Chamber Explosion Test. Long-range free-field airblast arrival along 0-degree line, is shown for comparison.

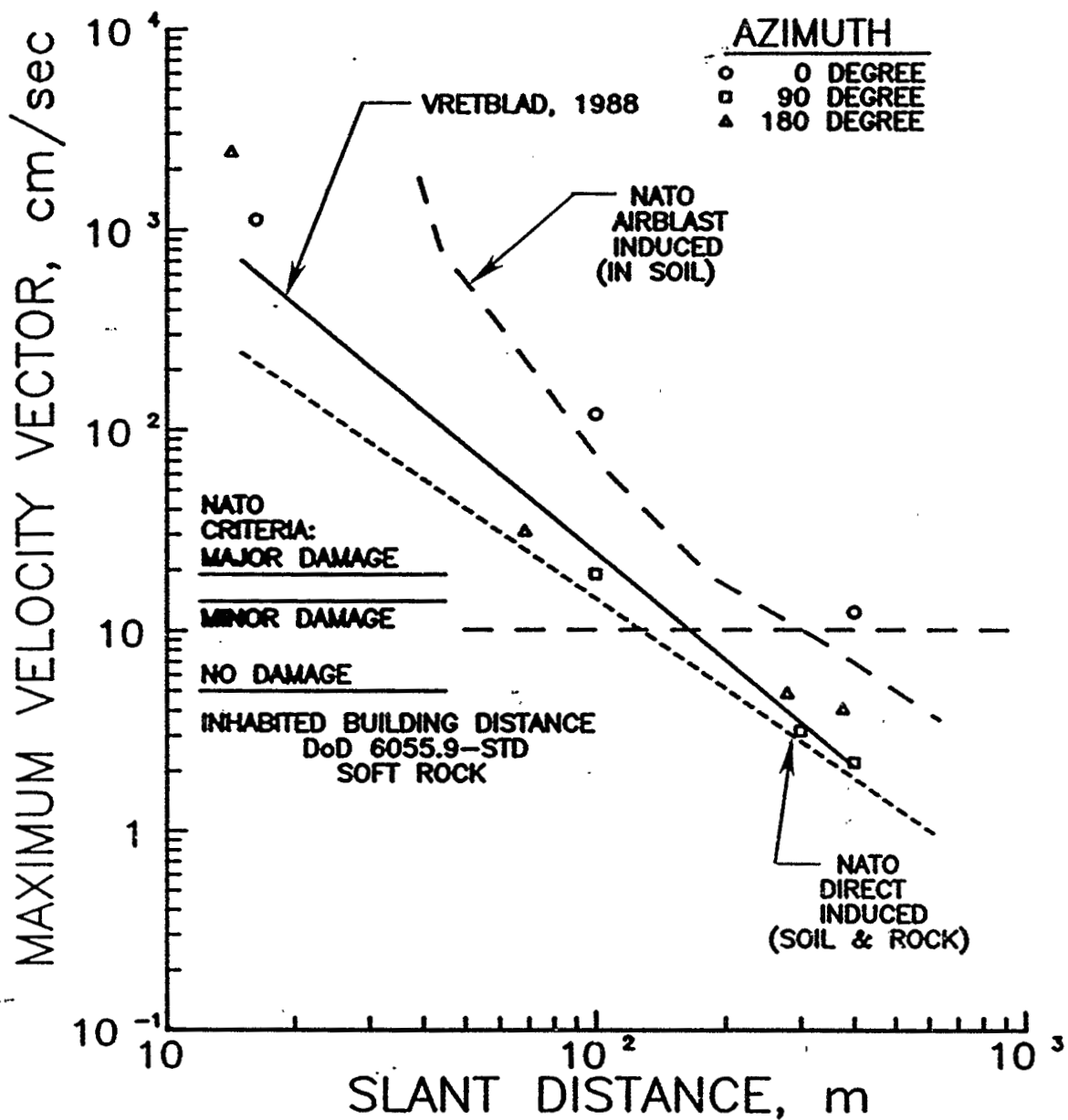


Figure 8. Maximum velocity vector versus slant distance from center of the charge; comparison of prediction curves with data from 0, 90, and 180-degree azimuths on Tunnel/Chamber Test.

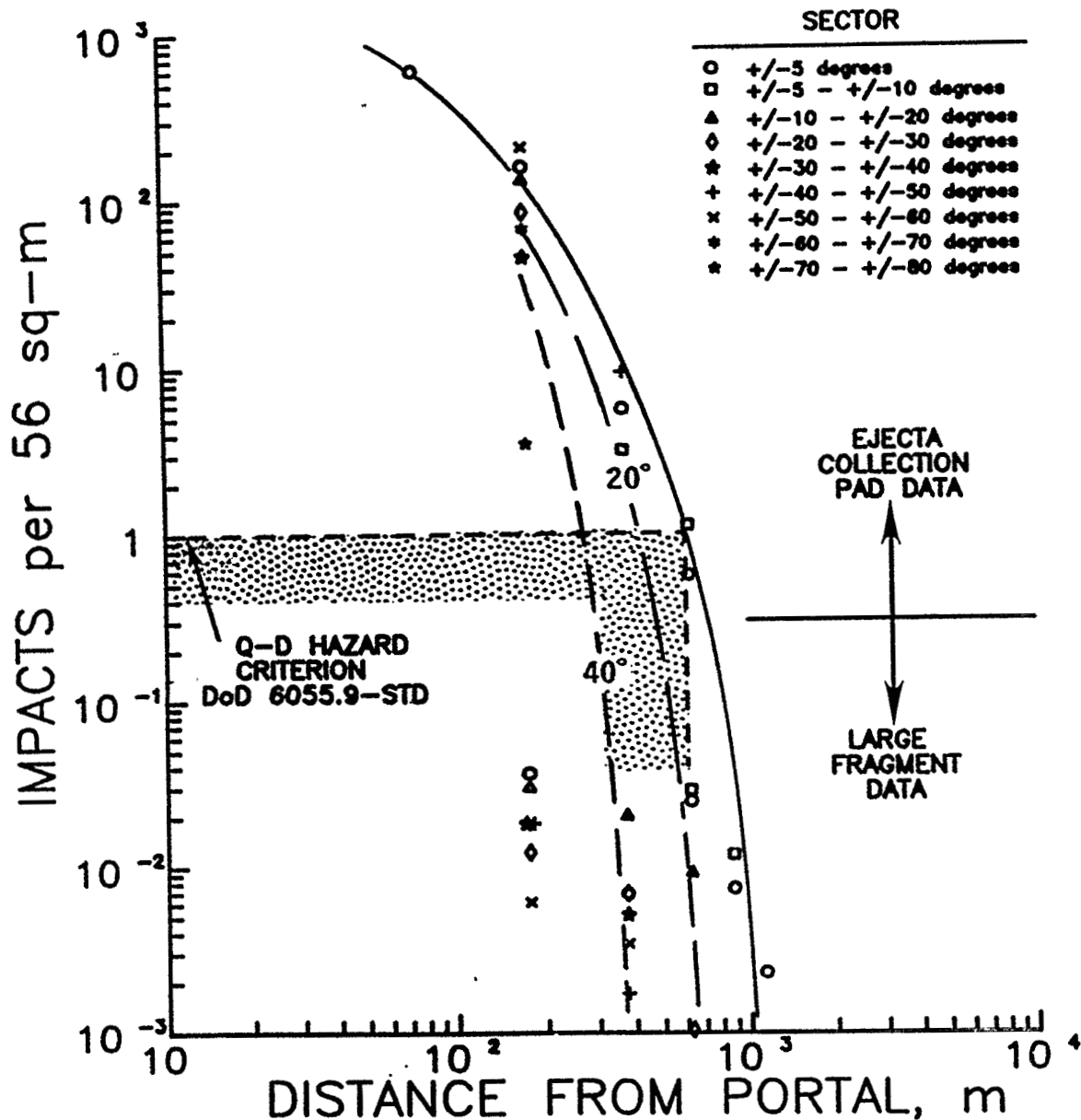


Figure 9. Ejecta/debris missile impact density versus distance from the portal, Shallow Underground Tunnel/Chamber Explosion Test. Curves show general limits of missile density ranges along extended tunnel axis (0-degree azimuth) and with ± 20 degree and ± 40 degree sectors.

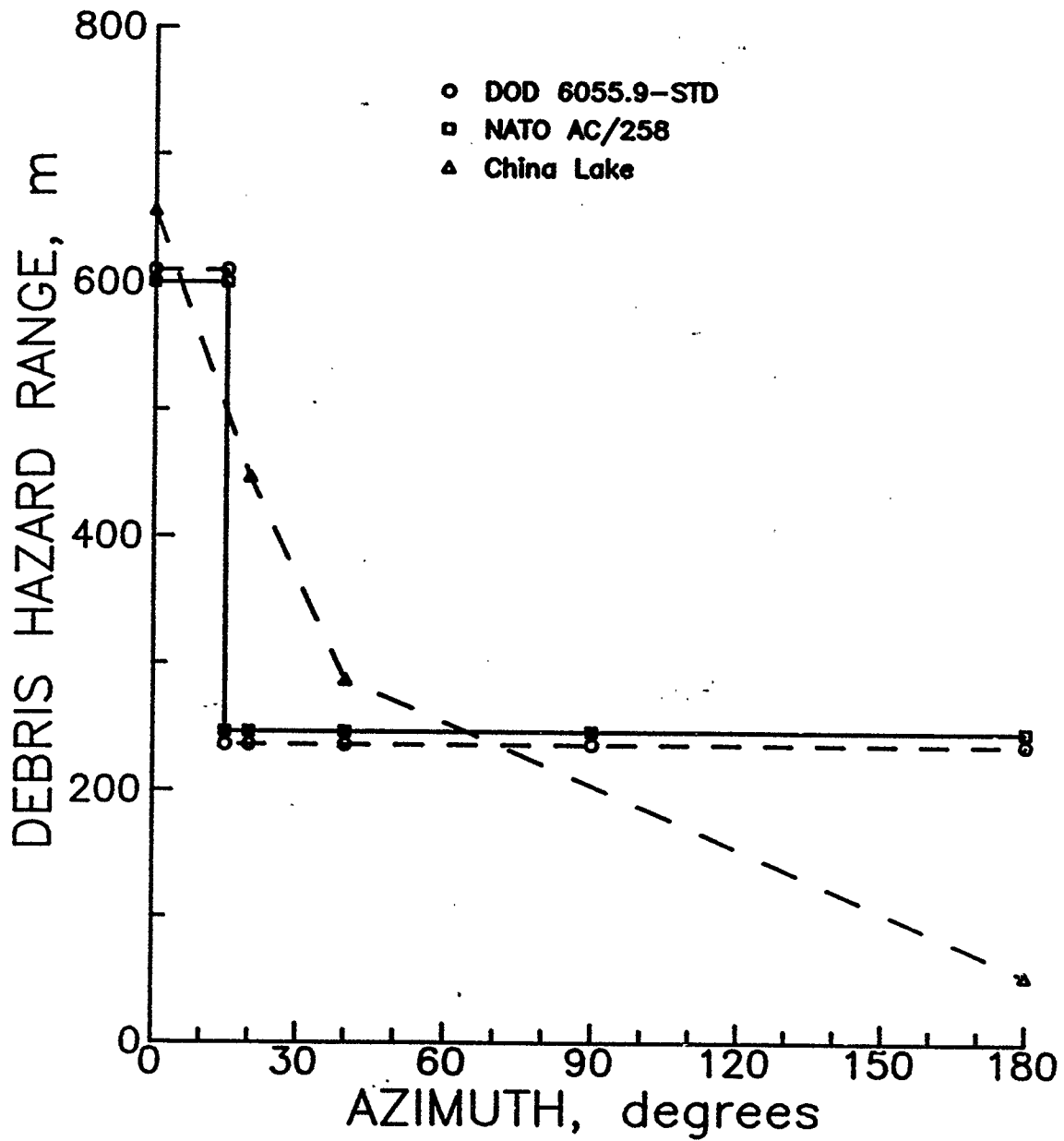


Figure 10. Inhabited Building Distances from debris hazards specified in the Explosives Safety Standards and NATO AC/258 for a 20,000-kg detonation, compared to ranges indicated by data collection on the Shallow Underground Tunnel/Chamber Explosion Test.

Table 1. Comparison of Airblast Inhabited Building Distances for 22,000 kg NEW; Current Standards versus Measured Distances (in metres).

Source	Hazard Zone ¹							Percent of Current Standard
	D ₅ 0°-30°	Percent of Current Standard	D ₄ 30°-60°	D ₃ 60°-90°	D ₂ 90°-120°	D ₁ 120°-180°	Hazard Area (m ²)	
<u>FOR 5.0 kPa (0.73 psi)</u>								
Current Standards (DOD 6055.9-STD) for UNDERGROUND storage	845	100	756	557	366	211	952,000	100
Measured Distances, Shallow Underground Tunnel/Chamber Test	632	75	438	394	322	143	467,000	49
Measured Distances, Alvdalen Test (Vretblad, 1988) Scaled to 22,000 kg NEW	471	56	444	229	73.0	61.5	254,000	27
<u>FOR 6.2 kPa (0.9 psi)</u>								
Current Standards (DOD 6055.9-STD) for ABOVE-GROUND storage	540	100	540	540	540	540	916,000	100
Measured Distances, Shallow Underground Tunnel/Chamber Test	539	100	369	336	276	112	336,000	37
Measured Distances, Alvdalen Test (Vretblad, 1988) Scaled to 22,000 kg NEW	388	72	358	159	59.7	50.4	145,000	16

Note: ¹ See Figure 98.