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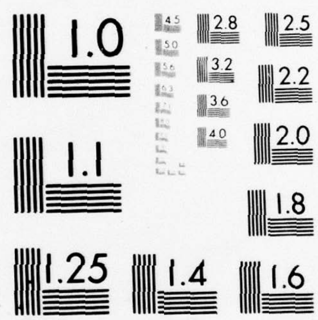

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TUNNEL DESTRUCTION STATE-OF-THE-ART

JUN 1978 11p.

CHARLES E. JOACHIM
U. S. ARMY ENGINEER WATERWAYS EXPERIMENT STATION
VICKSBURG, MISSISSIPPI 39180

Current Army tunnel destruction criteria (1) are based on limited nuclear-explosive (NE) and high-explosive (HE) test data. The PILE DRIVER (2) and HARDHAT (3) events investigated tunnel and support system response where yields were relatively large and tunnel diameter small compared to typical underground openings and localized stress fields of low yield weapons. Some limited tunnel destruction information was obtained from underground events of the PLUMBBOB and HARDTACK II Series (4). These events used access drifts which were designed to be self closing at the weapon point.

The limited NE data are augmented by HE results from the Underground Explosion Test (UET) Program, a series of model and prototype-scale experiments in granite and sandstone (5). Weapon standoff distances (charge c.g. to tunnel wall) were at or near the maximum for major damage. Limited tunnel destruction was produced by a series of hasty and deliberate tests (6) on abandoned railroad tunnels in basalt. Additional HE data were obtained from model tests at the Waterways Experiment Station (WES) (7) using 2-pound TNT charges and tunnel diameters varying from 1.2 to 6.6 inches. Recent laboratory scale HE experiments (8) conducted at the WES under the ESSEX program investigated the effects of tunnel diameter, standoff distance, charge confinement, material strength and to a limited extent, tunnel spacing and liner strength variations on tunnel damage.

This paper summarizes the analysis conducted to develop predictions for the effects of low-yield nuclear weapons against tunnels and underground openings in rock.

DISCUSSION

During the data analysis phase, Hopkinson's (cube root) yield scaling and NE-HE equivalence (for fully contained detonations) were assumed. This analysis showed good correlation between the UET (HE) and HARDHAT (NE) tunnel damage data. These detonations were at or near the maximum standoff distance for major damage. The remaining NE damage data exhibit considerable scatter. These NE events were conducted at the Nevada Test Site (NTS) in tuff, a weakly cemented highly variable material. The data scatter is probably due to local variations in material properties or water contents. HE damage data from detonations inside tunnels (basalt) and vertical shafts (sandstone) demonstrate that this weapon placement option produces only superficial tunnel damage unless very large yields are employed.

The current Army tunnel damage classification system (1) and typical damage profile are depicted in Figure 1. The four damage zones (1, 2, 3, and 4) in this system are the zone of complete damage, the zone of rock breakage, the zone of continuous slabbing and the zone of discontinuous damage, respectively. Damage to the outer limit of Zone 2 is classified as severe and constitutes closure in this system.

Tunnel closure data from medium strength models (8) (tunnel diameter 50 feet*) are plotted versus standoff distance in Figure 2. Symbols denote charge depth of burst (DOB) groupings. Lines are shown which connect maximum closure data for each group, forming envelopes of maximum closure length. These data indicate a general trend of increased length of tunnel closure with increased DOB. Charge tangent to (and above) the model surface (negative DOB) did not produce closure. Shallow charge DOB's (14 to 15 feet) resulted in significant tunnel closure. Comparison between the shallow and intermediate DOB (38 to 130 feet) data shows that the intermediate detonations resulted in a 25 percent increase in the length of tunnel closed. Comparison between the intermediate and deeper DOB (160 to 180 feet) data indicates that the deep detonations produced no significant increase in tunnel closure lengths within the data scatter.

Figure 2 also shows that for medium strength material, very little damage occurred at standoff distances greater than 130 feet and that the optimum standoff distance for producing tunnel closure in this material is in the range of approximately 40 to 100 feet. At smaller standoff distances there was not enough material blown into the tunnel to produce closure or an appreciable obstacle.

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*All dimensions given in this discussion are scaled to 1 kiloton.

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Document should remain for unlimited distribution. Per: (Mrs.) Anne G. Taylor, ARO.

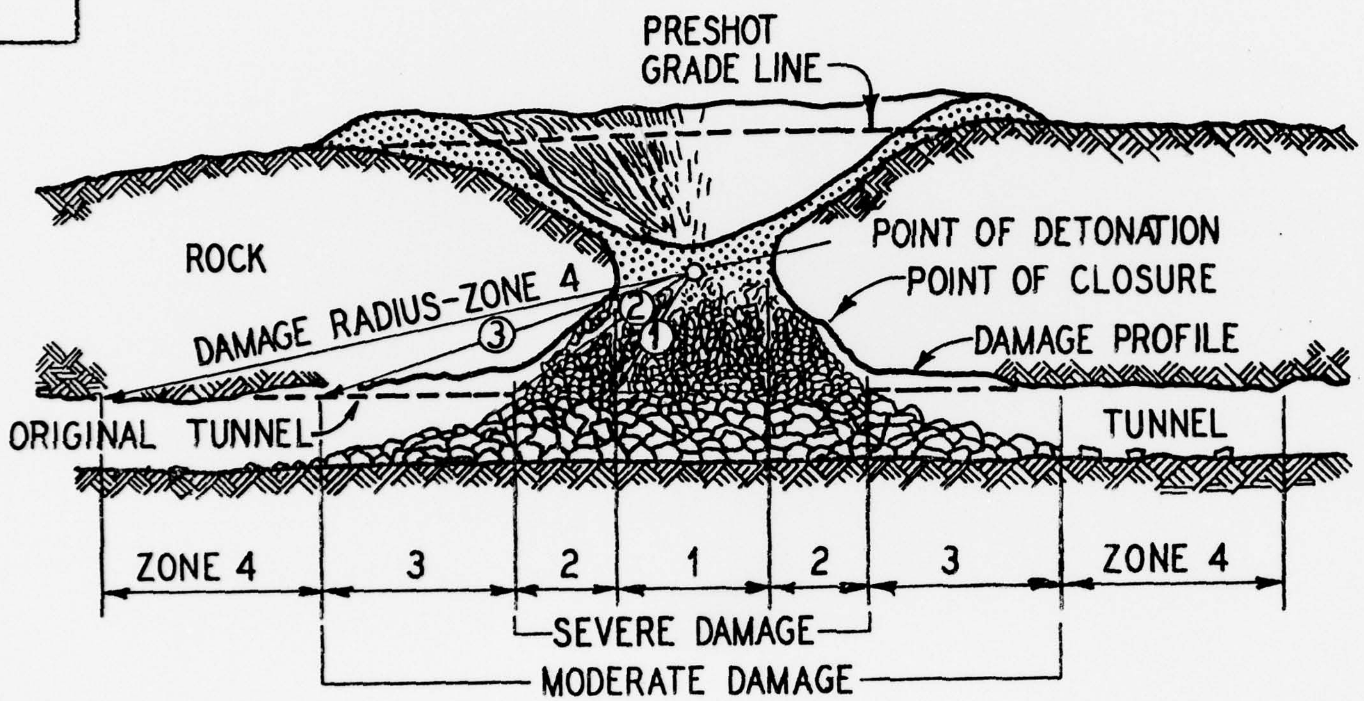


Figure 1. Typical tunnel damage profile and damage zones (1)

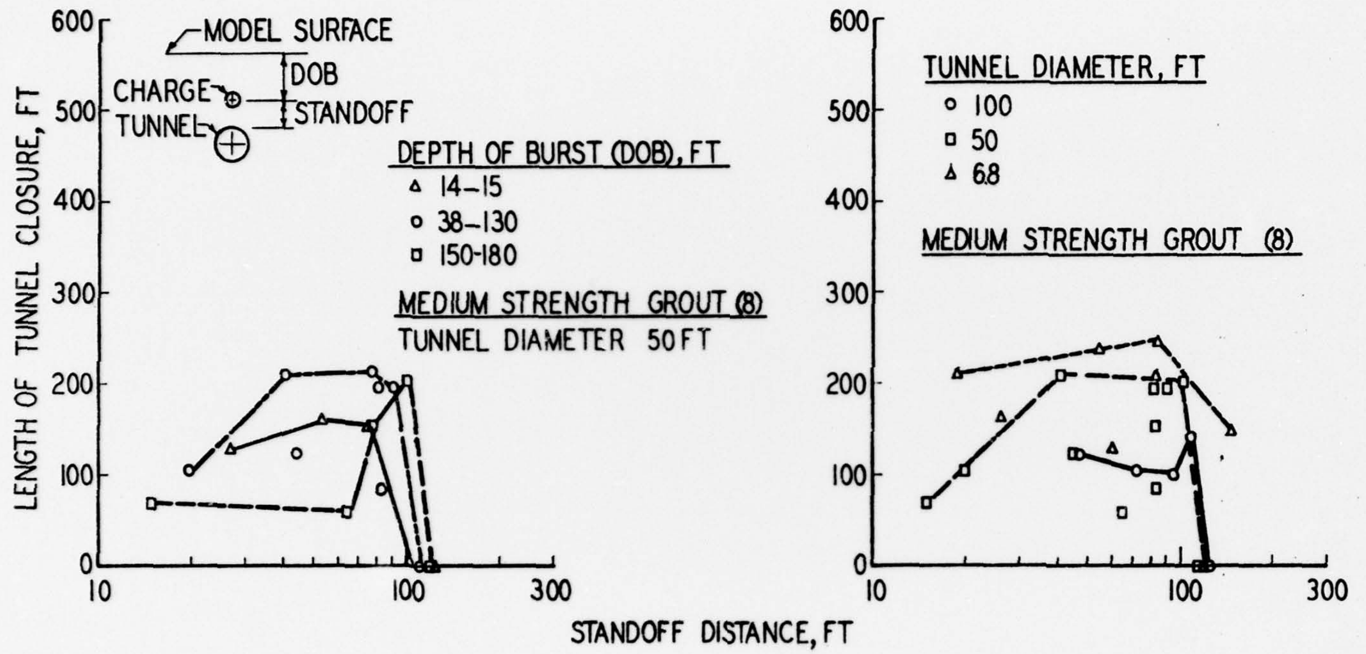


Figure 2. Effect of depth of burst on tunnel closure scaled to 1 KT

Figure 3. Effects of tunnel size on damage scaled to 1 KT

The effect of tunnel size on length of tunnel closure is presented in Figure 3. Data for three tunnel diameters (100, 59, and 6.8 feet are shown. The maximum standoff distance at which closure occurred was essentially independent of tunnel diameter. As standoff distance decreased a minimum was reached for the larger tunnels where the debris volume was insufficient to fill the tunnel. (Although there was considerable data scatter, the tunnel closure remained relatively constant over a range of standoff distances from approximately 40 to 100 feet.) There was a distinct trend for more damage, as indicated by closure length, as tunnel size decreased.

Tunnel closure data for low, medium and high strength models for tunnel diameters in the range of 50 feet are plotted versus standoff distance in Figure 4. Also shown for comparison are the UET (granite and sandstone), HARDHAT (granite) and NTS (tuff) data. As shown here, these data are in good agreement with the low strength model results, although there is considerable scatter in the NTS (tuff) results.

The maximum standoff distance at which closure occurred increased with decreasing material strength. As shown in Figure 4, six times the length of tunnel was closed in the low strength as in the high strength material for similar test geometries.

A comparison between lined and unlined tunnels is presented in Figure 5. These tests were conducted with the medium strength material and one tunnel diameter (50 feet). Aluminum tubing cast into the model served as tunnel liners for these experiments. Three thicknesses of tubing were used giving thickness to inside diameter (t/d) ratios of 0.0090, 0.029, 0.033, and 0.060. As shown here, tunnel liners reduced the maximum standoff distance at which closure occurred and the length of tunnel closed. These meager data also indicate a tendency for decreased damage with increased liner thickness. The thinnest liner (t/d of 0.0090) failed by buckling over an appreciable portion of its length but did not close completely.

Five tests were conducted in the medium strength material to study the effects of parallel tunnel spacing on damage. Tunnel diameter (50 feet) and charge standoff distance (63 feet) were held constant for these experiments. Tunnel closure length from these experiments is plotted versus the ratio of tunnel spacing (center to center distance) to tunnel diameter (s/d) in Figure 6. A significant increase (approximately 50 percent) in the length of tunnel closed occurred for s/d ratios slightly greater than unity. As the s/d ratio approached 2, the length of tunnel closed fell within the data

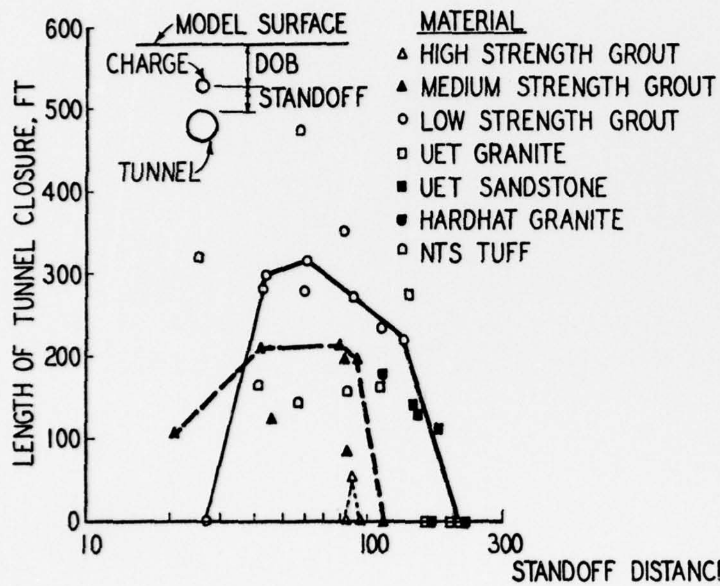


Figure 4. Effect of material strength on damage scaled to 1 KT

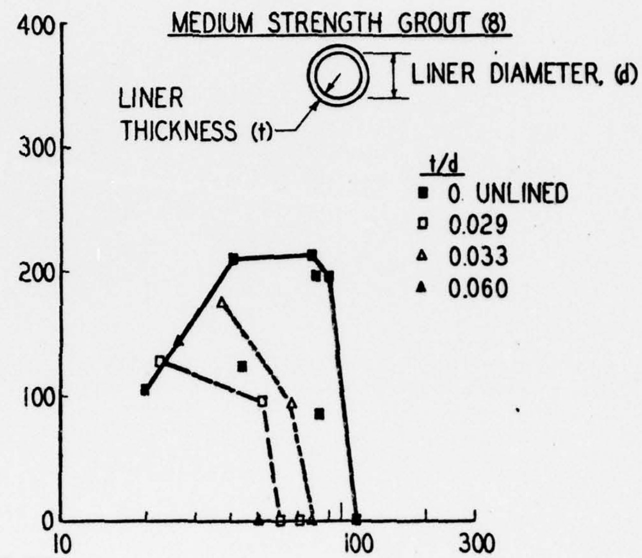


Figure 5. Influence of liner thickness on damage scaled to 1 KT

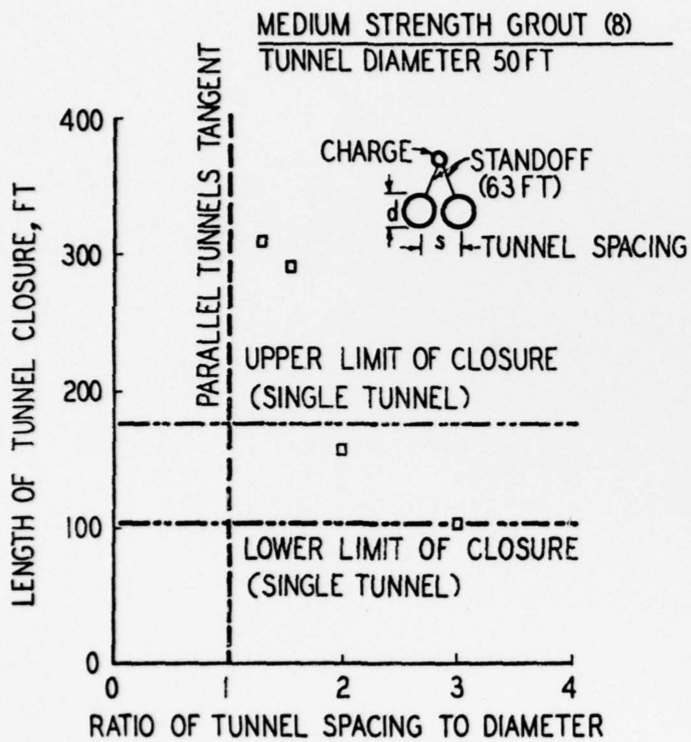


Figure 6. Effect of tunnel spacing on damage scaled to 1 KT

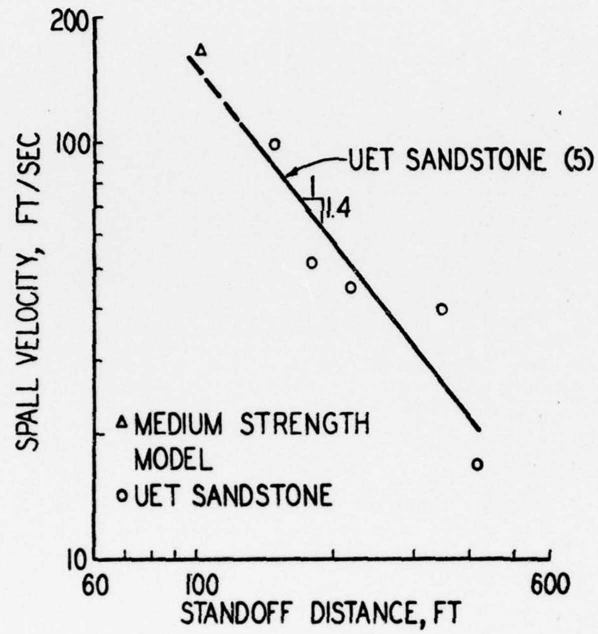


Figure 7. Spall velocity versus standoff distance scaled to 1 KT

scatter experienced from single tunnel at this standoff. The largest s/d ratio possible with this tunnel diameter-standoff distance combination is 3.5.

A spall velocity measurement made in a model test is compared to the UET sandstone results in Figure 7. The sandstone curve is extended (dashed line) into the region of the model. The spall velocity data point is the peak value of an integrated acceleration time history. Good correlation is seen between the model and the UET spall velocity data.

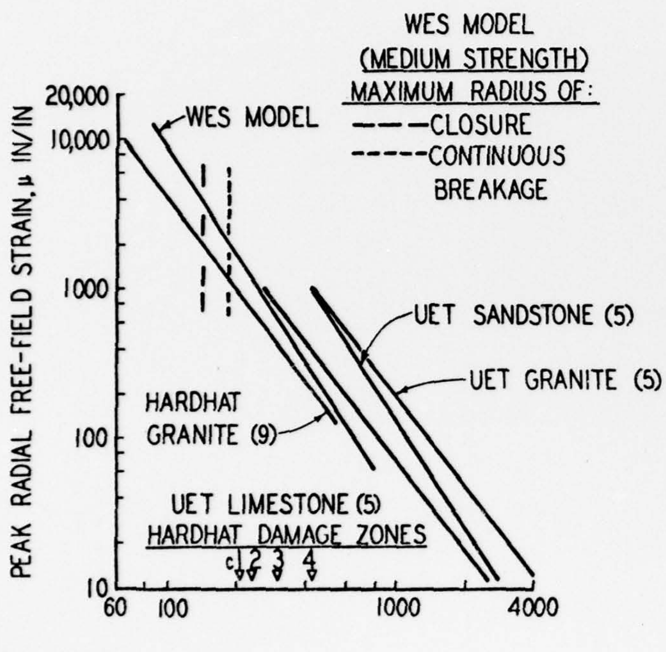
A comparison of least square fits to the WES model (medium strength material), UET (limestone, granite and sandstone), and HARDHAT (granite) radial free-field strain data is shown in Figure 8. These strain curves are indicative of the tunnel input loading (times the appropriate concentration factor) which produced the varying degrees of tunnel damage. Damage zone limits are also shown for the WES model (dashed vertical lines) and HARDHAT (triangles). Calculated (from data fit) peak free-field radial strains in the WES model were 3850 and 2050 micro-inches/inch for the maximum radius for closure and continuous breakage, respectively.

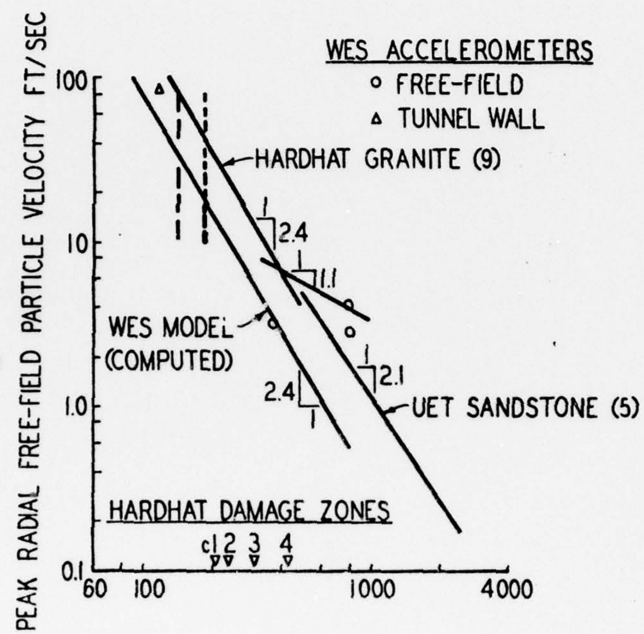
Peak radial particle velocity data from the free-field test block are presented in Figure 9. The model tunnel peak particle velocity data point shown here was calculated assuming a free-field velocity of one-half the spall velocity. Assuming the one-dimensional relation $v = \varepsilon c$ where c is 9330 ft/sec, the WES model peak free-field radial strain curve from Figure 8 was used to calculate the velocity curve shown in Figure 9. Also included in this figure are data fits from the larger UET events (rounds 814, 815, 816, and 817) in sandstone and the HARDHAT experiment. Although a factor of two difference exists between the WES model calculated velocity and the HARDHAT curve, closure for both experiments occurred at a peak free-field particle velocity of approximately 40 ft/sec.

CONCLUSIONS

Tunnel damage, as indicated by the degree of closure, is highly dependent on the strength of the rock; significantly greater damage is associated with the weaker materials (Figure 4).

Within the bounds of the test conditions, the smaller tunnels underwent the greatest damage for a given weapon standoff distance (Figure 3).





RADIAL DISTANCE, FT

Figure 8. Peak radial free-field strain versus distance scaled to 1 KT

Figure 9. Peak radial free-field particle velocity versus distance scaled to 1 KT

For a 1 KT weapon and a tunnel diameter of 50 feet the optimum standoff distance for tunnel closure is in the region between 40 and 100 feet in medium and low strength materials (Figure 5).

Tunnel closure at the optimum standoff distance (40 to 100 feet) was approximately 50 percent greater in the low strength grout than in the medium strength material; tunnels in the high strength material were virtually undamaged at these standoff distances.

Virtually no closure would be expected in the weaker geologic materials at standoff distances exceeding 250 feet.

A comparison of the model test results with data in real geologic materials (UET granite and sandstone, HARDHAT granite, and NTS tuff) showed that the low strength rock simulant did the best job of modeling tunnel damage (Figure 4); it is believed that the low-strength material best compensates for the joints, cracks, and faults present in natural rock masses.

Limited data from experiments using aluminum tubing to simulate tunnel liners indicates a reduction in damage with increased liner thickness (Figure 5).

A significant increase (approximately 50 percent) in damage to parallel tunnels, as indicated by closure length, occurred when the tunnel centerlines were spaced slightly greater than one tunnel diameter apart (Figure 6).

Closure occurs at a peak free-field radial velocity in excess of approximately 40 ft/sec (Figure 9).

To achieve maximum damage to tunnels 50 feet in diameter and smaller from a 1 KT weapon, the device should be detonated at or above the spring line at a DOB of 40 feet or greater and at a standoff distance between 40 and 100 feet.

Damage decreases with decreased DOB. Tunnel damage is 80 percent of maximum at DOB of 15 feet. No significant tunnel damage occurs from weapons detonated 15 feet above the surface.

When stemmed or unstemmed devices are detonated inside the tunnel the yield required for closure is a function of tunnel diameter. A weapon yield (KT) $(D/20)^3$ is required for closure with weapons placed inside the tunnel where D is the tunnel diameter.

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