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PROJECTILE AND FRAGMENT PENETRATION IN SNOW AND FROZEN SOIL

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INTRODUCTION: The work ~~described herein~~ was accomplished as part of an investigation of terminal ballistics in snow, ice and frozen soil. conducted for the ~~Field Engineering Division, Directorate of Facilities Engineering, OCE.~~ The objectives ~~of this investigation~~ are to develop design criteria for effective utilization of indigenous cold regions materials in field fortifications, to develop methods for estimating the terminal effectiveness of remotely emplaced munitions and sensor systems, and to evaluate foreign expertise in these areas. To accomplish these objectives, a number of laboratory and field investigations ~~have been~~ were conducted to quantify the effectiveness of various projectiles fired into snow, ice and frozen soil targets. The performance of fragment-simulating projectiles (FSP's) that simulate typical fragments from mortar and rocket rounds have also been studied. Penetration data from these tests were analyzed using a theory developed for use with unfrozen soil targets and were found to be in reasonable agreement with predicted penetrations in both snow and frozen soil.

BALLISTIC TEST LABORATORY: The laboratory penetration tests were conducted in the CRREL ballistics laboratory in Hanover, N.H. The laboratory was constructed to permit investigation of terminal ballistics in snow, ice and frozen soil. It consists of a 16 x 28-ft wood frame building containing a controlled temperature target room, a weapons room, and instrumentation and projectile preparation areas (Fig. 1). A detailed description of this facility was presented by Farrell (1975).

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TEST SOIL DESCRIPTION: Four different soils were used in the laboratory tests: a sand, a sandy clay, a marine clay and a silt. The first three matched, as closely as practicable, unfrozen soils tested by the U. S. Army Engineer Waterways Experiment Station (USAEWES). Because the strengths of these frozen soils were estimated, only an approximate correlation between measured and predicted penetrations was obtained. The silt soil was added to the program because a relatively large quantity of soil was needed to develop the comprehensive data package necessary to correlate measured with predicted penetrations and this soil was available locally in sufficient amounts.

TARGET PREPARATION: The soil samples were molded in 12-in.-square, 12-in.-high boxes constructed of 3/4-in.-thick plywood. The boxes were lined with polyethylene to minimize loss of moisture. The samples were compacted in 1-in.-thick layers using approximately 40 blows from a 10-lb hammer with an 18-in. drop height. The soil was tempered overnight at 40°F prior to molding. After each layer was molded, the sample was placed in a coldroom at -5°F for freezing. This one-layer-at-a-time preparation method minimized moisture migration during freezing of the test specimens.

The snow targets were prepared by sifting snow through a no. 4 sieve into 20-in.-square, 12-in.-high plywood boxes. The snow sintered in these boxes quite quickly, allowing the ends of the boxes to be removed and a sufficient number of boxes aligned to assure projectile retention in the snow.

PROJECTILES: Two different projectiles were used to obtain laboratory data: 5.56-mm cubes and 7.62-mm NATO ball ammunition (Fig. 2). The cubes were designed as fragment-simulating projectiles, as described by Kakel (1971), while the 7.62-mm round represents approximately the mid-energy level for small arms projectiles.

PENETRATION TEST RESULTS: Impact velocity vs penetration data for the 5.56-mm steel FSP's fired into Hanover silt are given in Figure 3. These data show that penetration into the frozen silt was roughly half that into the unfrozen soil. Small temperature changes of the frozen soil had a relatively small influence on penetration; but reducing the temperature from -3 to -25°C noticeably reduced penetration.

At velocities above about 700 m/sec deformation of the FSP's was noted in both the frozen and unfrozen silt (Fig. 4). The decrease in penetration obtained in the frozen soil at the higher velocities is attributed to the increase in frontal area of the projectile that resulted from this deformation. The magnitude of this area change is shown by the data in Figure 5 where a coefficient of deformation, C_D

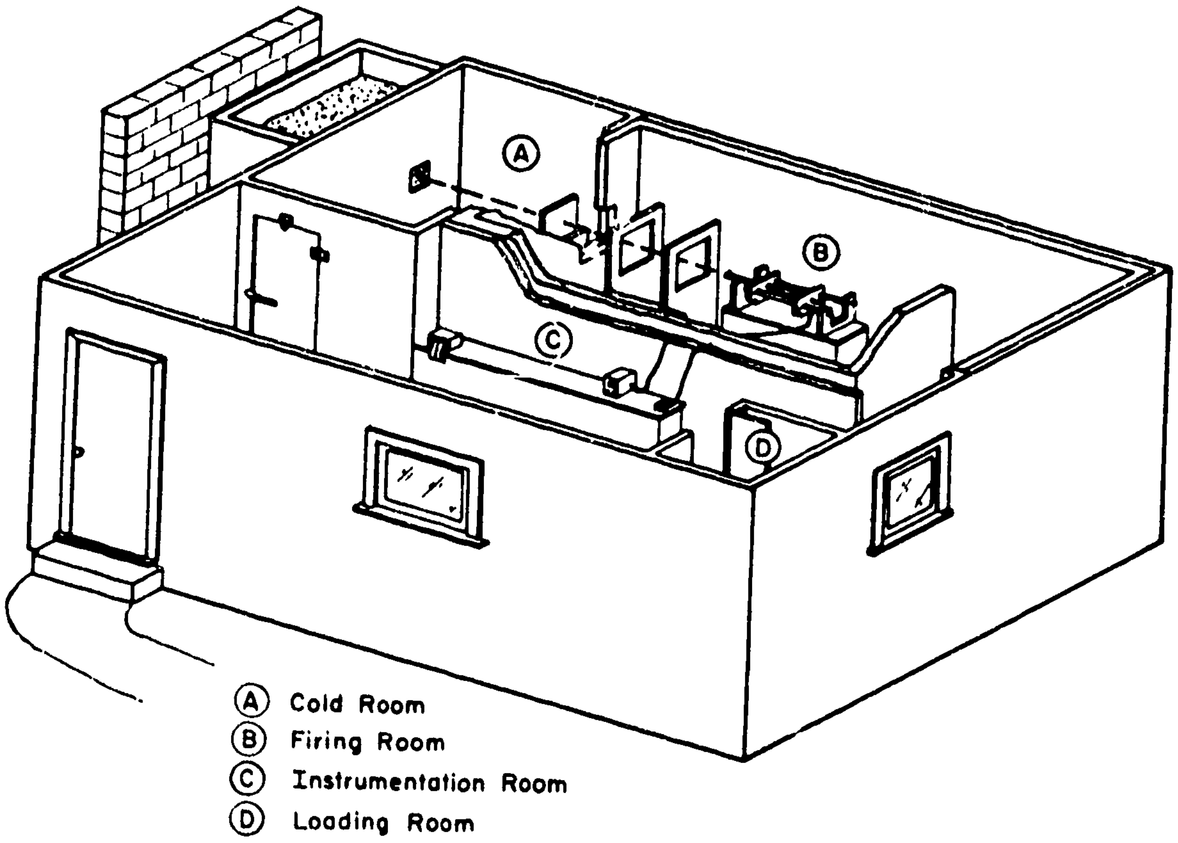


Figure 1. CRREL terminal ballistics facility (TBF).

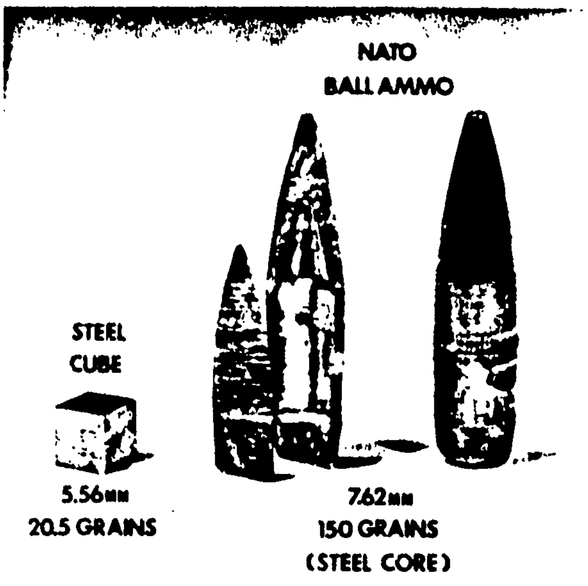


Figure 2. Projectiles used in ballistic test program.

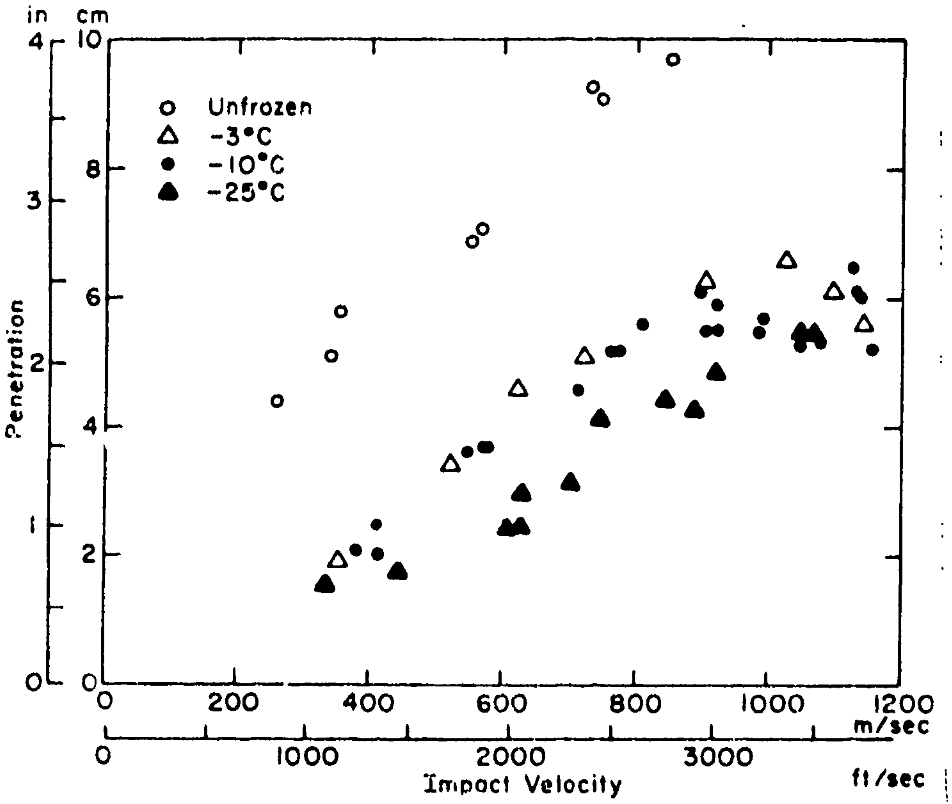


Figure 3. Impact velocity vs penetration for 5.56-mm steel cubes in Hanover silt.

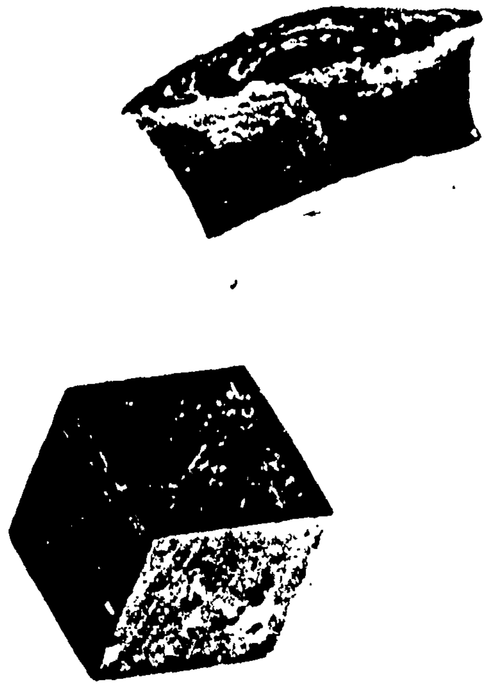


Figure 4. Deformed 5.56-mm steel cube.

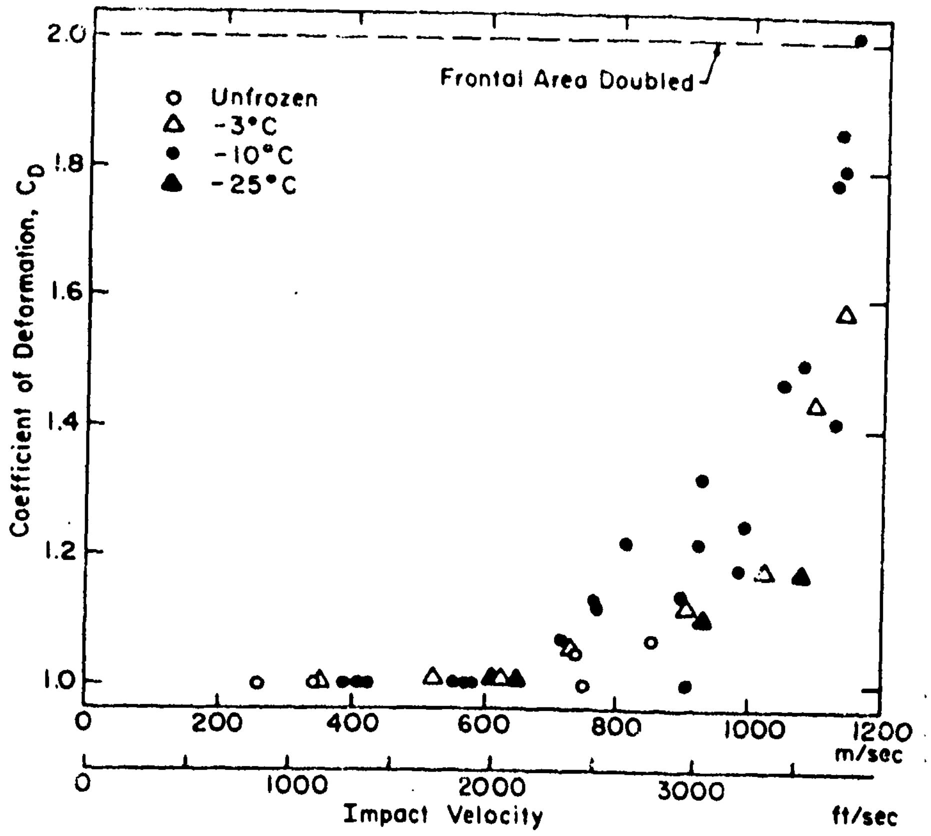


Figure 5. Deformation coefficient vs impact velocity for 5.56-mm steel cube fragment simulating projectiles in Hanover silt.

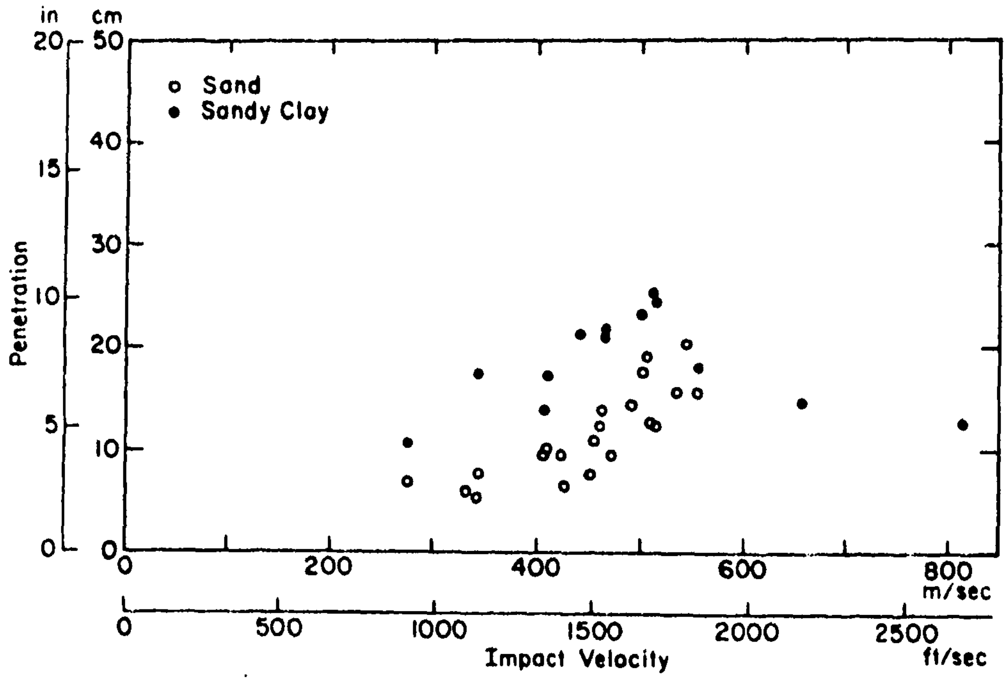


Figure 6. Impact velocity vs penetration for 7.62-mm NATO ball ammunition fired into frozen soil targets at -10°C.

(deformed FSP frontal area divided by original area), is plotted versus impact velocity. For a given impact velocity, the temperature of the frozen soil appears to have a strong influence on the magnitude of projectile deformation.

Figure 6 contains velocity vs penetration data for 7.62-mm NATO ball ammunition fired into frozen sand and sandy clay soils. These tests, conducted at a temperature of -10°C and for a given impact velocity, show significantly higher penetrations for this projectile than were previously observed for the FSP's into frozen silt. It is suggested that this increased penetration results from the higher energy of the 7.62-mm projectile due to its increased mass, rather than a difference in soil target properties. At velocities higher than about 600 m/sec the jackets of many 7.62-mm projectiles failed. Several of these rounds were also observed to tumble at impact velocities between 570 and 730 m/sec. This tumbling resulted in significantly reduced penetrations as shown in Figure 7.

Typical impact velocity vs penetration data for FSP's into snow are given in Figure 8. Compared to similar data in frozen silt (Fig. 3) penetration of these FSP's in snow appears to be relatively insensitive to impact velocity. The data also indicate that snow temperature does not affect projectile penetration. As with soil, projectile deformation is suggested as a factor influencing penetration into snow at velocities above about 600 m/sec.

PENETRATION PREDICTION TECHNIQUES: There are two methods frequently used to analyze projectile penetration data. One of the most widely accepted, described by Young (1972), utilizes penetration test results to prepare empirical equations relating impact velocity to penetration depth. Young's equations contain a projectile nose-shape factor and represent target properties with a soil constant ranging from 0.2 to 50. These equations have been verified for projectile weights from 0.9 to 2613 kg and impact velocities from 33 to 843 m/sec. Equation 1 was proposed by Young for impact velocities greater than 66 m/sec and produces a linear relationship between penetration and impact velocity:

$$D = 0.0117\ KSN\ \sqrt{W/A}\ (V-30.5) \qquad (1)$$

where

D = depth of penetration, m

K = mass scaling factor, dimensionless

S = soil constant, dimensionless (1 to 2 for frozen silt or clay)

N = nose performance coefficient, dimensionless (0.56 for flat nose)

W = projectile weight, kg

A = projectile area, cm^2

V = velocity, m/sec

This approach has the advantages of relative mathematical simplicity together with the inclusion of a projectile nose-shape factor. It has also been adapted for predicting penetrations through layered materials. Its primary disadvantages are that penetration tests must be conducted on all target materials of interest to develop appropriate material constants and that a mass scaling factor must be determined for projectiles weighing less than 27 kg.

Another common approach to penetration analysis is to develop a mathematical model for predicting penetration that considers pertinent projectile characteristics and target strength properties.

One such model, based on dynamic cavity expansion theory, was developed by Ross and Hanagud (1969). It was used by Rohani (1973) to analyze penetration data from unfrozen soils. This model, equation 2, describes a spherical nose projectile penetrating a homogeneous isotropic material. The projectile is further characterized by its weight and radius. The target material is idealized as a locked-elastic, locked-plastic medium (Fig. 9) and described in terms of its mass density, yield strength, plastic and elastic moduli and compressibility.

$$P = \frac{3W}{4Ag\ \rho_P\ B_2} + \frac{B_1 R}{2\ B_2} \quad \ln \left(1 + \frac{2B_2\ \rho_P\ V^2}{3B_3}\right) \qquad (2)$$

where

V = velocity, ft/sec

P = penetration, ft

W = projectile weight, lb

A = projectile area, ft^2

g = acceleration of gravity, ft/sec^2

R = projectile radius, ft

ρ_P = locked plastic density of target material, $slugs/ft^3$

and

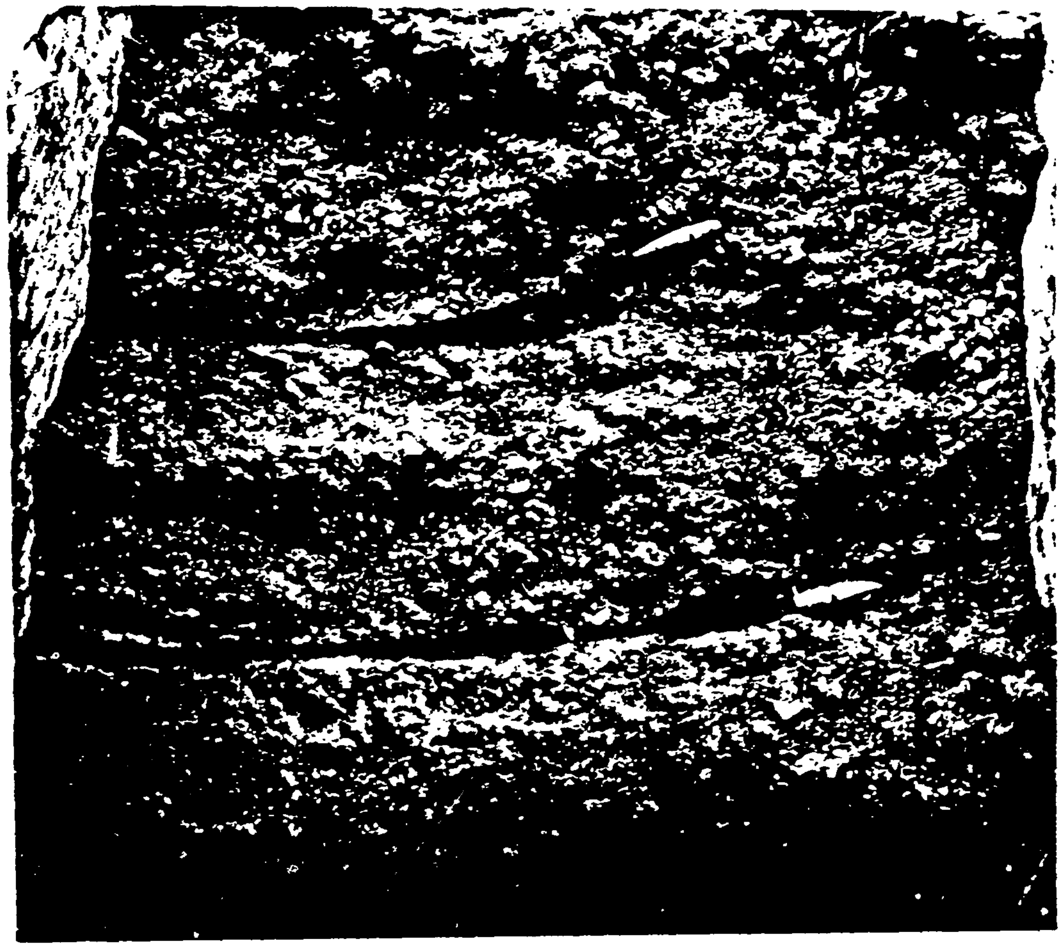


Figure 7. 7.62-mm projectile penetration into sandy clay at -8°C and 16% water content. Impact velocity of top projectile that tumbled was 621 m/sec, penetration was 21.5 cm. Velocity of bottom projectile was 380 m/sec, penetration was 27.5 cm.

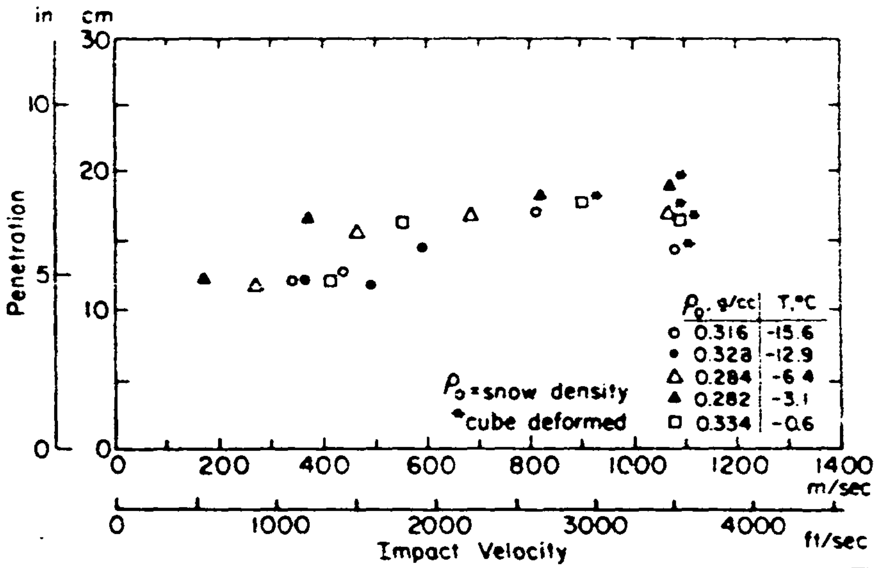


Figure 8. Impact velocity vs penetration for 5.56-mm aluminum cubes fired into snow.

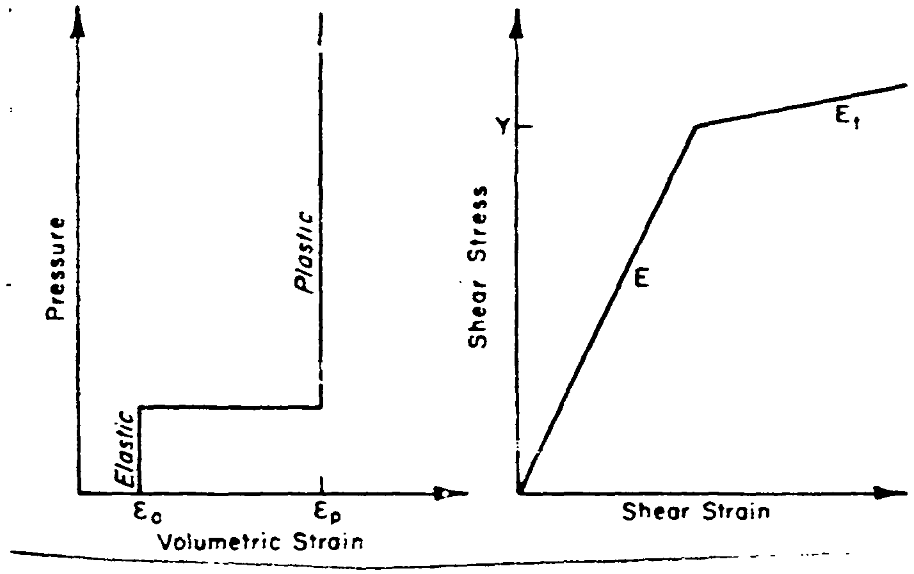


Figure 9. Idealized stress strain curves.

$$\rho_P = \rho_o \exp (\Sigma_p) \qquad (3)$$

where

ρ_o = initial density of target material, slugs/ft^3

Σ_p = plastic volumetric strain, %

and

$$B = \frac{y}{2E} - \frac{\Sigma_i}{3} \qquad (4)$$

where

y = yield strength of target material, psf
E = Young's modulus of target material, psf
Σ_i = elastic volumetric strain, %

$$\alpha_p = 1 - \frac{\rho_o}{\rho_P} \qquad (5)$$

$$\delta = \alpha_p \exp (-3B) \qquad (6)$$

$$B_1 = 1 - \delta^{1/3} \qquad (7)$$

$$B_2 = 3/2 - 1+\alpha_p) \delta^{1/3} + 1/2 \delta^{4/3} \qquad (8)$$

$$B_3 = 4/9E (1- \exp(-3B) - 2/3 y \ln \delta + 2/27 \pi^2 E_t - 4/9 E_t \eta \qquad (9)$$

where

E_t = plastic modulus of deformation, psf

and

$$\eta = \sum_{n=1}^{\infty} \frac{\delta^n}{n^2} \qquad (10)$$

The advantage of this method is that it does not require any empirical constants. Its disadvantages are: that the target yield strength is assumed to be independent of projectile velocity and penetration depth; projectile mass and/or caliber area change during penetration are not accounted for; and it is strictly applicable only to projectiles with a spherical nose-shape. Rigorous use of this approach also requires that the constitutive properties of the target material be obtained at strain rates equal to those occurring under actual projectile penetration.

TARGET STRENGTH DATA: Frozen soil strength data were obtained from unconfined compression tests. These tests were conducted at a strain rate of 4444%/min on 1.4-in.-diam, 4.5-in.-high cylindrical samples. The samples were compacted in 1-in. layers using 60 blows of a Harvard miniature compactor per layer (40-lb spring with 1/2-in.-diam compaction head). After compaction the specimens were tempered at 33°F for one week to assure uniform moisture distribution and then placed in a 5°F cold chamber for freezing. Ends of the samples were squared by lapping prior to testing.

Typical stress/strain curves from these tests are shown in Figure 10. The yield strength, elastic and plastic moduli were obtained by fitting idealized curves (dashed lines on Fig. 10) of the form shown in Figure 9 to these stress/strain curves. The compressibility was estimated by assuming that the volumetric strain Σ_p is equivalent to the volume of air in the soil sample. Data obtained from the compression tests on Hanover silt are summarized below.

Temp, °C	ρ_o, slugs/ft^3	E, psf	Y, psf
-3	3.7	17.6×10^6	29.8×10^4
-10	3.7	30.9×10^6	46.3×10^4
-25	3.7	57.6×10^6	86.4×10^4

Snow strength properties were obtained by relating the snow targets' density to yield strength, compressibility and elastic modulus using information presented by Mellor (1964). Typical values are tabulated below.

ρ_o, slugs/ft^3	(g/cc)	E, psf	Y, psf
0.58	(0.3)	4.3×10^6	0.14×10^4
0.78	(0.[illegible])	13.2×10^6	0.22×10^4
0.97	(0.5)	20.7×10^6	2.16×10^4

COMPARISON OF MEASURED WITH PREDICTED PENETRATION: Predicted penetration of the 5.56-mm FSP's into frozen silt, computed using Equation 2, is compared with test results in Figure 11. There appears to be a tendency to underpredict penetration at velocities between 600 and 1000 m/sec. This could have resulted, in part, from differences in soil properties between the ballistic targets and the unconfined compression test specimens. The average dry unit weight of the soil

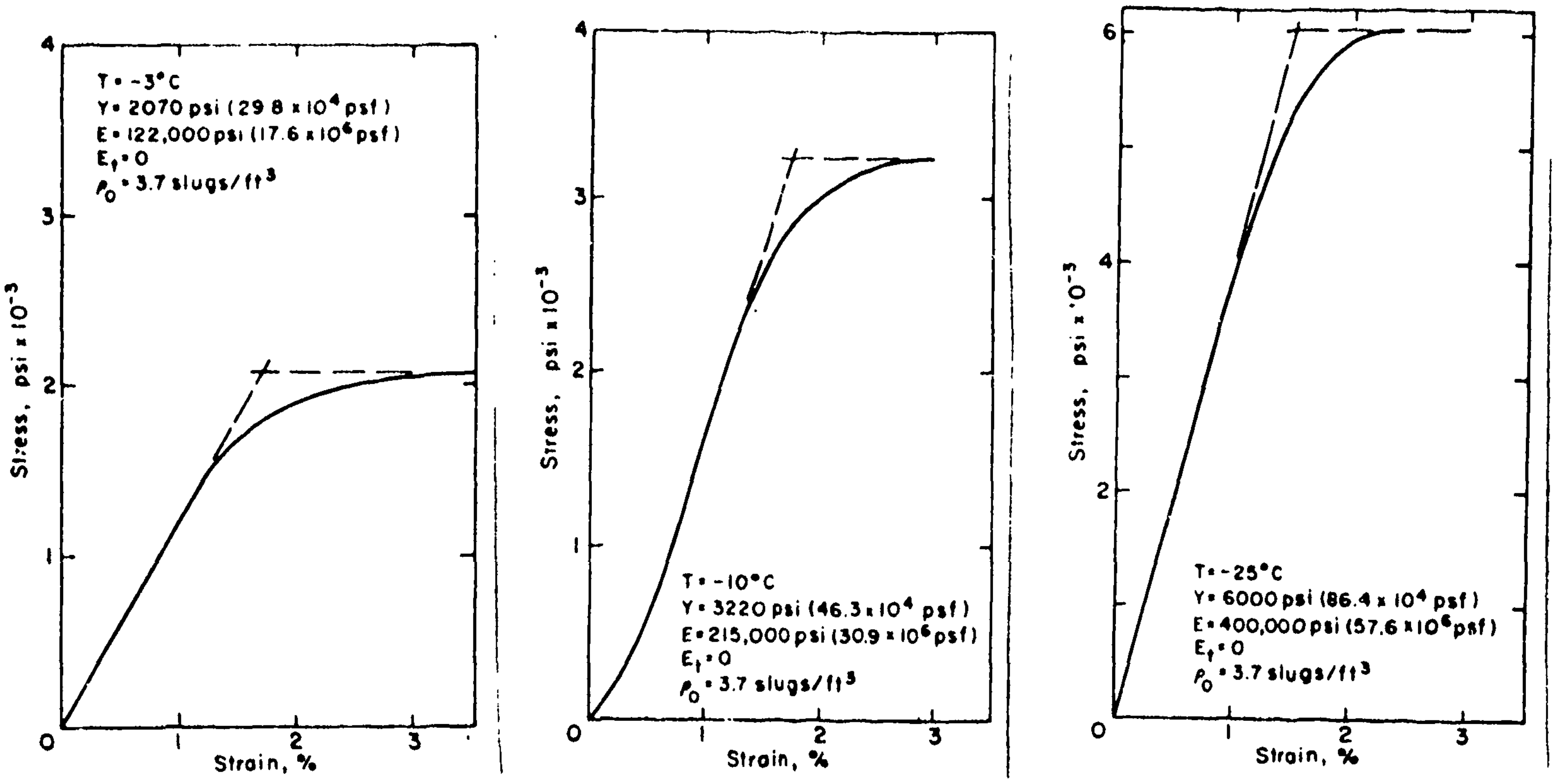


Figure 10. Stress vs strain curves from unconfined uniaxial compression tests on frozen Hanover silt.

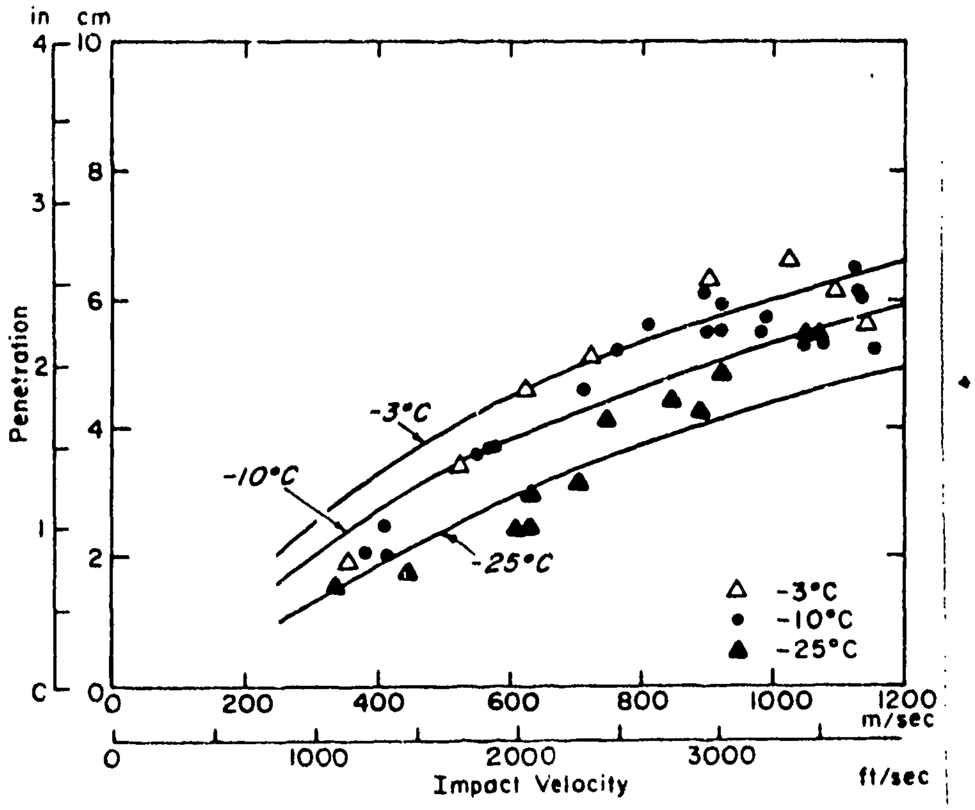


Figure 11. Comparison of test data with predicted penetration curves for 5.56-mm steel cubes into Hanover silt.

targets was about 10 lb/ft^3 (0.31 slug/ft^3) less than that of the unconfined test samples. This lower soil target density resulted because the size and shape of available soil compaction equipment was not compatible with the size and shape of the target samples. The penetration computations were thus made using parameters biased on the high strength/low penetration side which should result in measured penetrations being somewhat larger than predicted.

A similar comparison between measured and predicted penetration in snow is presented in Figure 12. These computed penetrations are in excellent agreement with the test data. These data are of particular importance because they show the effect of projectile mass and verify that mass is correctly represented in Equation 2.

FIELD TEST PROGRAM: A field test program was conducted in Alaska to expand the scope of the laboratory experiments. A complete description of this program was presented by Johnson (1975). The program included extensive tests to evaluate the ability of snow structures to resist penetration by 5.56-mm, 7.62-mm and 50-cal ammunition. Projectile penetration vs snow density data obtained during these tests are given in Figure 13. As expected, the smallest and lightest projectile (5.56-mm) had the least penetration. The small increase in penetration of the 50-cal round relative to the 7.62-mm was not expected. It had been estimated, using the Ross Hanagud equation, that the 50-cal round would penetrate about twice as deep as the 7.62-mm. The relatively low observed penetration of the 50-cal round is attributed to increased resistance generated by case rupture and deformation (Fig. 14).

Data from these tests and the laboratory experiments, which emphasized the influence of snow density on penetration, suggested the concept of a hardened snow trench for hasty expedient protection of troops against small arms fire. A trench in the snow can be excavated very rapidly. Even when the snow is so light that it appears it would offer little or no resistance to small arms fire, tests have shown that such a trench (Fig. 15a) offers a surprising amount of protection. An important reason for the effectiveness of this trench is that fire against it normally strikes the snow at a shallow angle, resulting in ricocheting and broaching of the rounds. Increasing the density of the snow ahead of the trench by rodding and packing (Fig. 15b) greatly increases the probability for ricocheting as well as reducing penetration of bullets that do not ricochet or broach. In tests where approximately one hundred 5.56- and 7.62-mm rounds were fired at these trenches from close range, only two 5.56-mm and three 7.62-mm bullets came through the snow into the simple trench and no penetrations were observed into the hardened trench. Forty rounds of

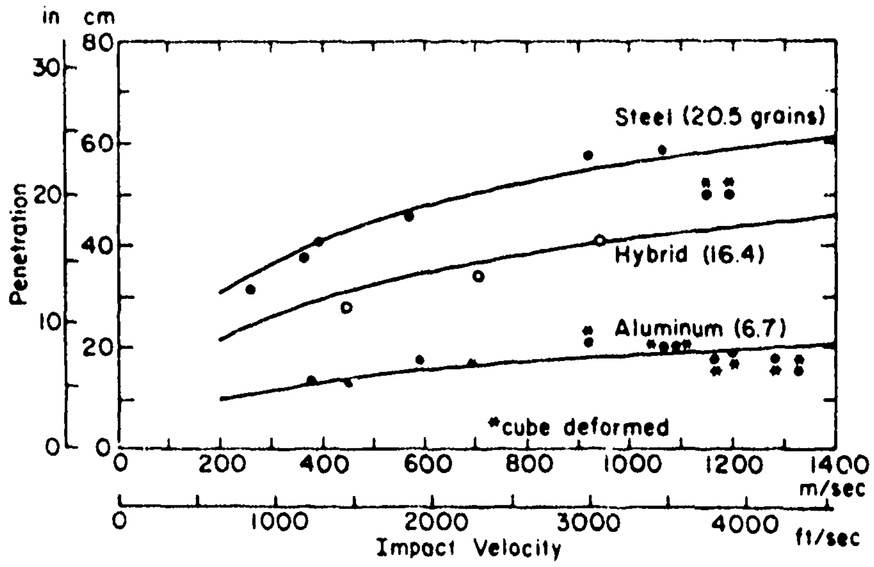


Figure 12. Comparison of test data with predicted penetration curves for 5.56-mm cubes in snow. Snow temperature -13°C, density 0.8 slug/ft^3 (0.41 g/cc).

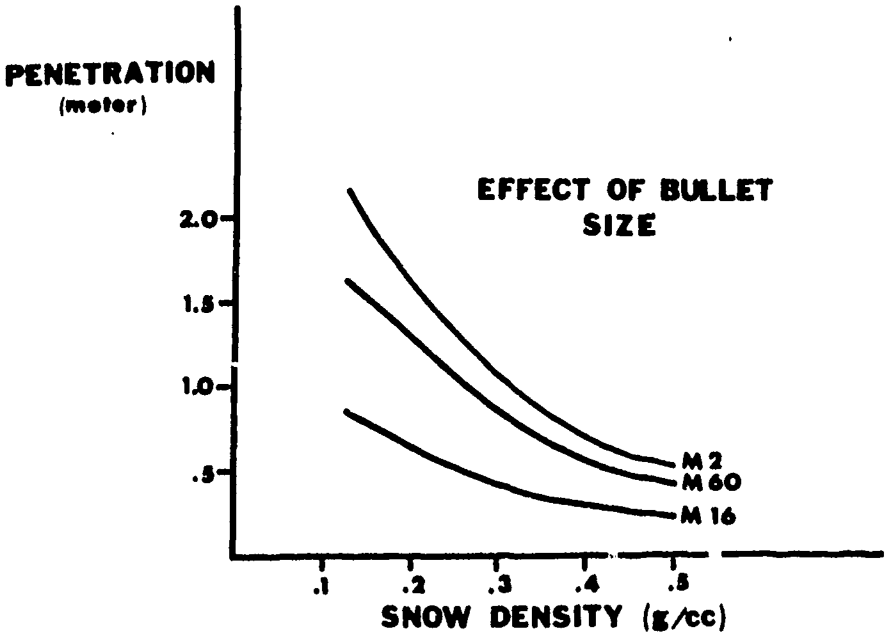
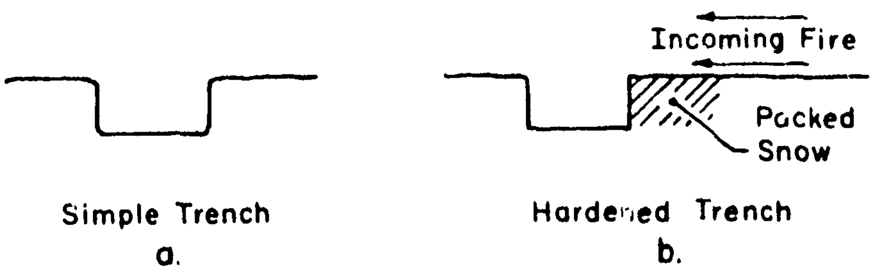


Figure 13. Bullet penetration vs snow density for 5.56-mm, 7.62-mm and 50-cal ammunition.

Figure 14. 50-cal projectile after impact into snow, illustrating magnitude of case damage.



Simple Trench
a.

Hardened Trench
b.

Figure 15. Snow trenches for personnel protection.

50-cal ammunition were also fired against the hardened trench and, again, no penetrations were observed.

CONCLUSIONS: Based on these test data, projectile penetrations into frozen soil are significantly lower than in unfrozen soil. For the 5.56-mm steel FSP's, penetration was reduced by about a factor of 2 in frozen Hanover silt. Temperature of the frozen soil influenced projectile penetration, with penetration decreasing at lower temperatures. But for Hanover silt, temperature changes in excess of 10°C were required to obtain significant changes in penetration.

For a projectile at a given impact velocity, penetration is a function of target properties with yield strength, density and compressibility probably being the most important. A theoretical technique based on dynamic cavity expansion in a locked-elastic, locked-plastic medium can be used to calculate projectile penetration in both frozen soil and snow with reasonable accuracy.

There are some critical impact velocities above which damage to projectiles occurred not only in frozen soil, but also in snow. In frozen soil the 5.56-mm steel FSP's deformed at velocities above about 800 m/sec and 7.62-mm NATO rounds started to tumble and/or strip their jackets above a velocity of about 600 m/sec. In snow, the aluminum FSP's started to deform at impact velocities above 900 m/sec and steel cubes above 1000 m/sec.

Snow can be used as a construction material for expedient defensive positions and affords protection against small arms fire up to 50 cal. In part this protection was achieved by designing the position to cause ricocheting and broaching of the rounds fired at it.

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