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The Stability of Strategic Earth Penetrators–The DSP-300 Field Test Series (U)

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The Stability of Strategic Earth Penetrators—The DSP-300 Field Test Series (U)

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Abstract (U)

During the 1960s and 1970s, hundreds of earth penetrator field tests were conducted into soil. In general, this database applies to penetrators with relatively high length-to-diameter ratios (L/Ds), and it indicates that high L/D penetrators follow stable trajectories in soil targets. Strategic earth penetrators packaged in reentry vehicles can result in penetrator designs with low L/Ds. Therefore, in order to extend the previous technology database, the DSP-300 field test series was initiated to investigate the stability of low L/D penetrator designs. One-half scale model penetrators were fired into a soil target using Sandia's Davis gun. Test results indicated that strategic earth penetrators of recent interest to SNLL and LLNL were stable for anticipated worst-case impact conditions. In addition, a minimum taper angle of 1° was established as a design criterion for tapered afterbody penetrators.

Acknowledgements

Special thanks to D. B. Sparger and J. E. Collins who assisted in all aspects of the test series. The author also acknowledges J. M. Hachman for his design contributions. Lastly, the author wishes to thank M. L. Chiesa for many useful discussions related to earth penetrator stability.

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Nomenclature

CG — Center-of-gravity (% of overall length referenced from nose tip)

CRH — Caliber radius head, tangent ogive nose shape. For a 3 CRH tangent ogive nose shape, the radius of the circular arc defining the nose contour is equal to 3 times the outer diameter at the tangent point, i.e., the intersection point between the nose and afterbody.

DSP — Davis gun Strategic earth Penetrator

L/D — Length-to-diameter ratio. For penetrators with tapered afterbodies, the diameter at the midpoint of the afterbody was used.

W/A — Weight-to-cross sectional area ratio. For penetrators with tapered afterbodies, the area is based on the diameter at the midpoint of the afterbody.

1 Introduction

During the 1960s and 1970s, hundreds of earth penetrator field tests were conducted into soil [1]. In general, this database applies to penetrator designs with cylindrical afterbodies and relatively high length-to-diameter ratios (L/Ds). For example, the W86/PII tactical earth penetrator had a L/D of approximately 10. These tests indicate that high L/D cylindrical afterbody penetrators follow stable trajectories in soil targets.

Driven by reentry vehicle packaging constraints in conjunction with strategic yield requirements, low L/D penetrators were first studied during the mid to late 1970s. Laboratory-scale test results [2,3,4] were encouraging and suggested it may be possible to design a stable low L/D earth penetrator. Furthermore, small-scale low L/D penetrators having tapered afterbodies were shown to be more stable than cylindrical afterbody penetrators. It was speculated that a tapered afterbody design provided greater stability over a cylindrical shape due to reduced flow separation between the penetrator afterbody and target. Similarly, it is this effect which causes high L/D penetrators to be more stable than low L/D designs. Soil contact with the penetrator afterbody constrains lateral movement of the penetrator aft end thereby providing a stabilizing moment. Insufficient contact between penetrator and target reduces this stabilizing moment, thus facilitating deviation from a straight-line trajectory. Therefore, although stability is diminished with a low L/D design compared to a high L/D shape, stability is enhanced with a tapered, rather than cylindrical, afterbody.

In 1982, a joint Sandia National Laboratories, Livermore (SNLL) and Lawrence Livermore National Laboratories (LLNL) low L/D tapered afterbody penetrator was conceptualized. [redacted] by these results, the DSP-300 field test series was initiated to extend the previous penetrator technology. Specifically, the purpose of this 1/2-scale model test program was to investigate the stability of low L/D strategic earth penetrators as a function of impact conditions (i.e., velocity, angle of attack and impact angle) and design features (e.g., CG and penetrator afterbody shape).

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2 Experimental Procedure

The DSP-300 field test series utilized Sandia's Davis gun to evaluate stability of low L/D earth penetrators. This 12 inch inner diameter, smooth-bore recoilless cannon (Figure 1) accelerated 1/2-scale model uninstrumented penetrators to steady impact velocities. Due to the fact that the penetrator had a smaller diameter than the gun bore, the penetrator afterbody was supported with a polyurethane foam sabot (density=15 lb/ft^3) and a 4340 steel pusher plate that fit the inner diameter of the gun barrel (Figure 2). Projectile velocity and attitude (pitch plane only) were recorded with 2 image motion or streaking cameras, one focused near the barrel muzzle and the other aimed several feet from the impact point. (See Figure 3 for typical photographic results.) Following impact and penetration of the target, the trajectory was reconstructed and penetrator recovered by drilling several vertical shafts.

All DSP-300 series tests were conducted into Antelope Lake, a dry hard clay lake bed, located at Sandia's Tonopah Test Range (TTR), Nevada. Although Antelope Lake is relatively homogeneous for a natural geology, a soil testing program was initiated to characterize the target site concentrating on the near surface soil layers (<50 feet). The target was cored and mechanical property tests were performed by the U. S. Army Waterways Experiment Station [8]. Appendix A contains the TTR coordinates of the coring site as well as the impact points of all tests performed.

Worst-case impact conditions anticipated for the SNLL/LLNL strategic earth penetrator program were: an impact velocity of 2500 ft/sec, an impact angle of 45° and an angle of attack equal to 2° (nose up). (Refer to Figure 4.) Impact conditions for the DSP-300 test series were parameterized as follows: impact velocities from 1940 to 2560 ft/sec, impact angles from 20° to 45°, and angles of attack from 0° to 4° (nose up). Every penetrator evaluated in this study was tested at impact conditions equal to or more severe than worst-case conditions.

Beginning with the 1982 preliminary design, the external shape and mass properties of penetrators jointly agreed upon between SNLL and LLNL changed significantly over a period of several years. This was primarily due to packaging of various nuclear physics package envelopes and internal components. The stability of these penetrators was investigated in this test series as they evolved.

Figures 5–11 contain drawings of all the 1/2-scale model penetrator designs tested in this study.[1] These penetrators had 3 CRH tangent ogive noses, which was a compromise between a more blunt shape (better for packaging and stability) and a more pointed configuration (better for loads and penetrability). Although the external dimensions of each penetrator reflected a 1/2-scale replica, the wall thickness was

[1]The pertinent scaling laws are summarized in Appendix B.

chosen to (1) be sufficient to withstand in-barrel Davis gun loads, and (2) achieve the appropriately scaled weight and CG. Selected design features of the DSP-300 series penetrators are summarized in Table 1.

In order to assess the stability of various designs tested at different impact conditions, it was important to have a quantitative stability criterion. A simple method to evaluate stability performance could depend on the observed lateral displacement from a straight-line trajectory. In this study, the degree of stability assigned to a trajectory was based on the ratio (expressed in percent) of the total lateral deviation to the overall path length. (The total lateral deviation is equal to the vector sum of the lateral deviations in the pitch and yaw planes.) Trajectories were judged to be stable, marginally stable and unstable for <20%, 20–30% and >30% path length deviation, respectively. To make this subjective criterion more palatable, all designs having marginally stable trajectories were retested at less severe impact conditions until a stable path was achieved.

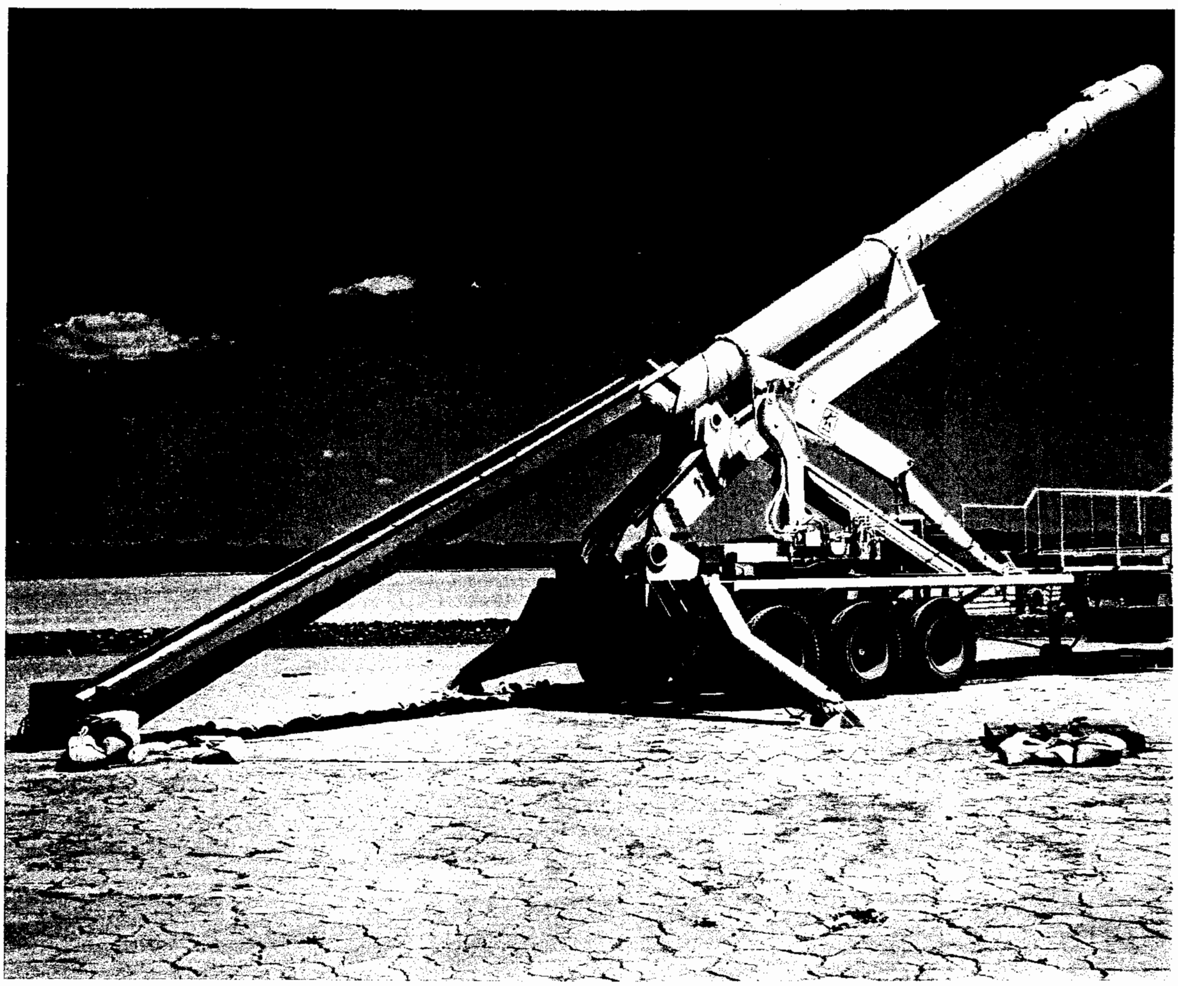

Figure 1: Davis gun test set-up

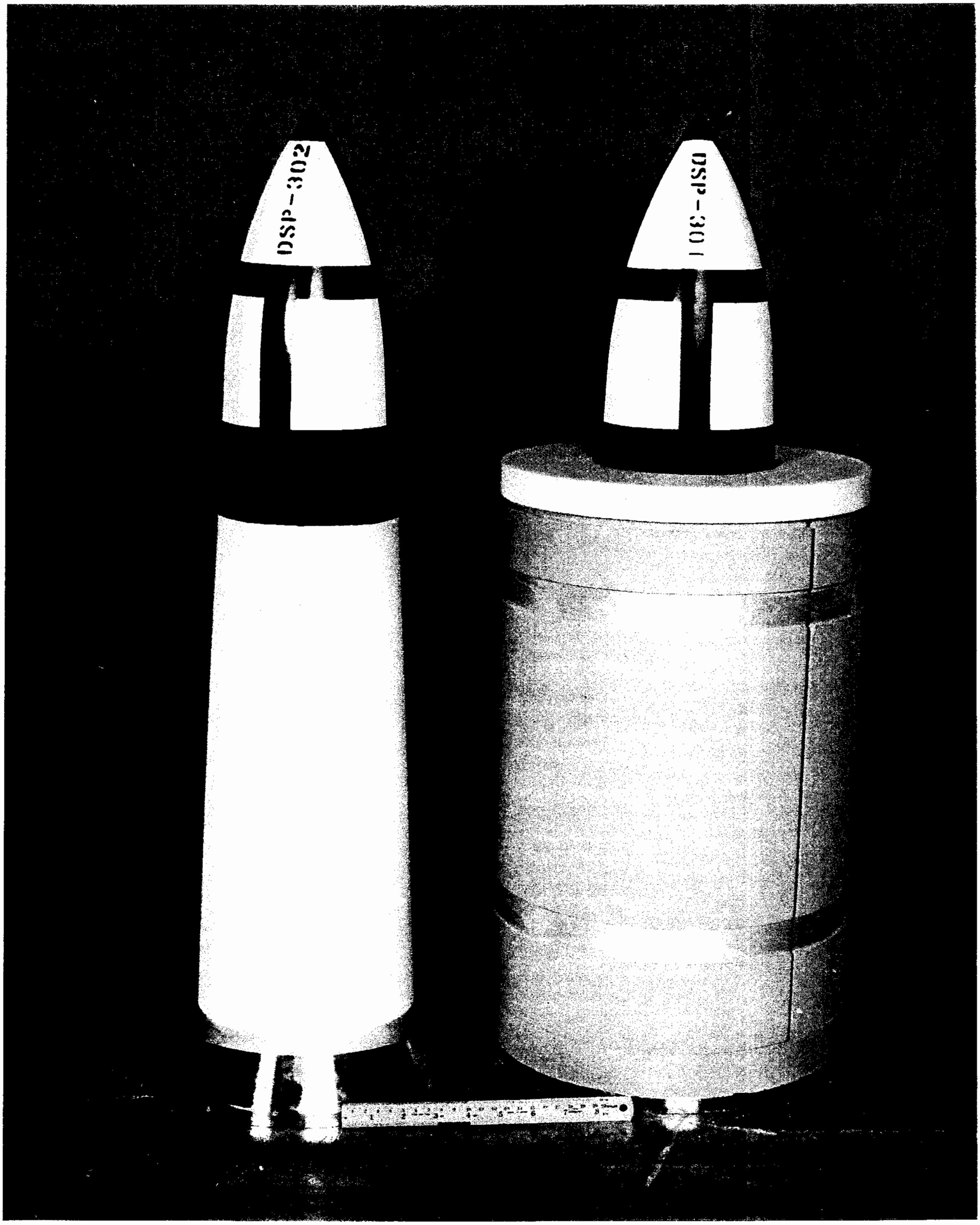

Figure 2: Penetrator, sabot and pusher plate assembly

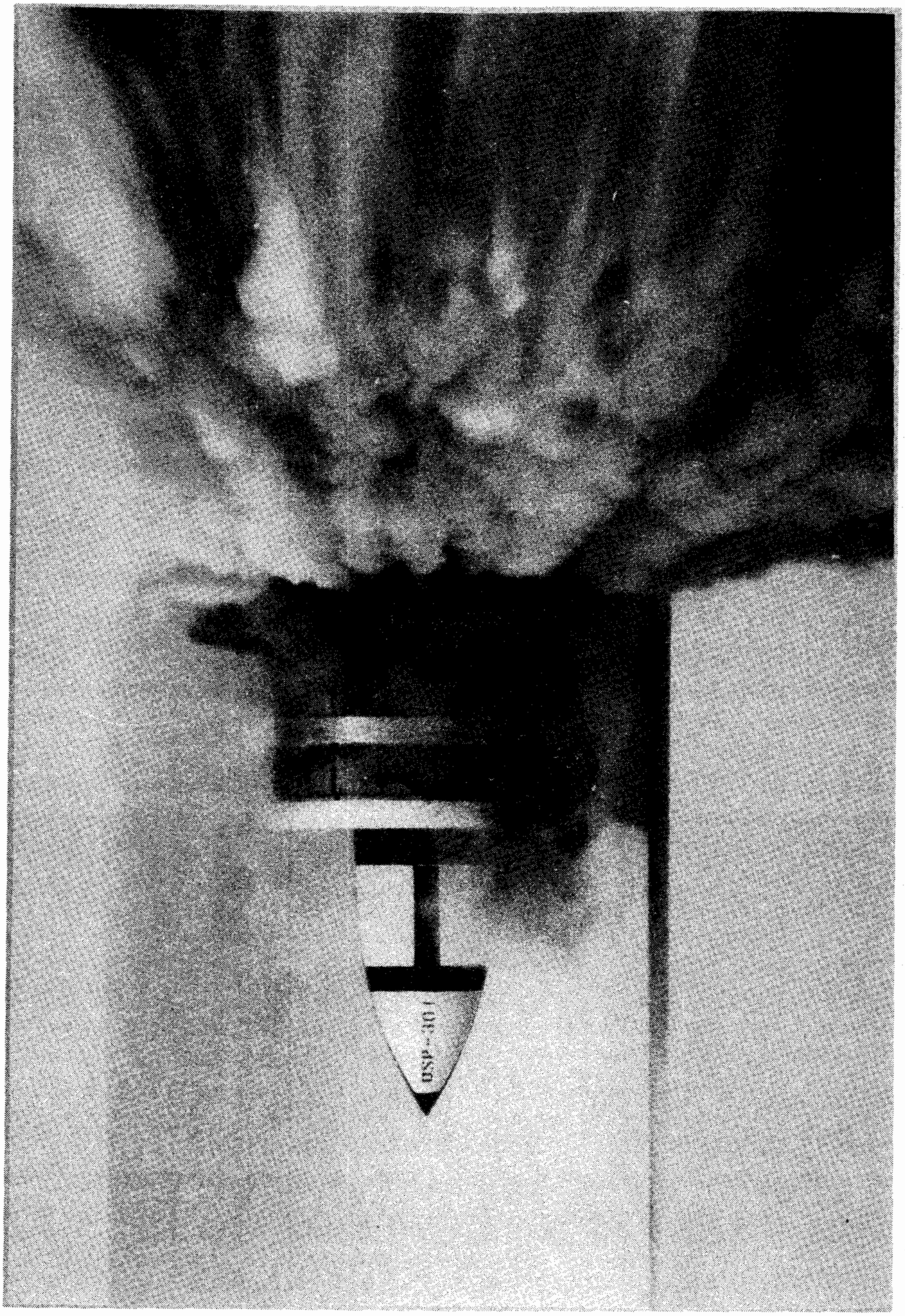

Figure 3: Typical streaking camera record of penetrator in free flight

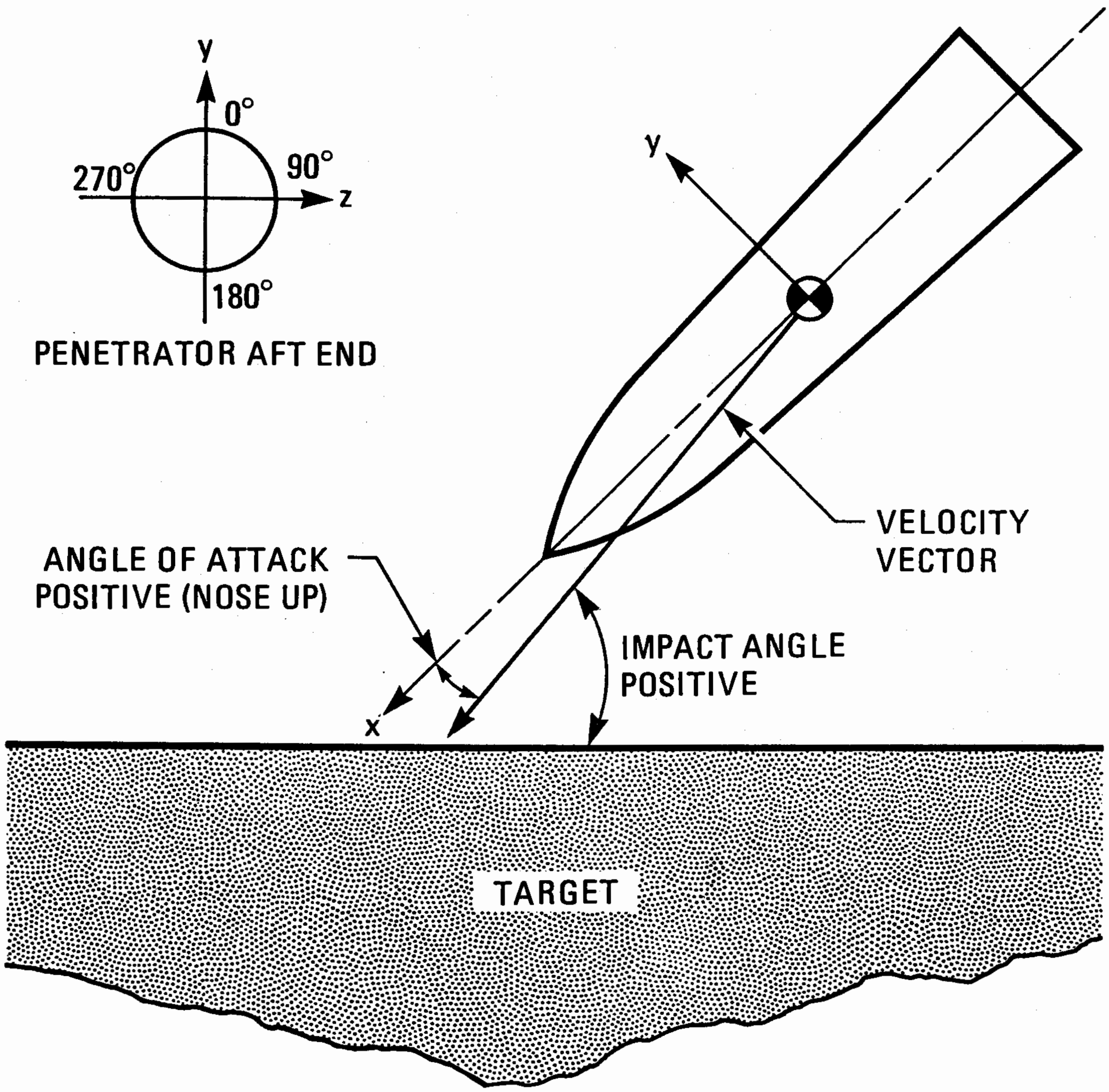

Figure 4: Definition of penetrator impact conditions. The x-y and x-z planes are the pitch and yaw planes, respectively.

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3 Test Results

General observations concerning the post-test penetrator condition will be addressed first. This will be followed by the results from the individual tests grouped according to design.

3.1 Post-test Penetrator Condition

All penetrators tested resulted in negligible steel removed from the nose and very little wear on the afterbody. In addition, a patch of paint just aft of the nose was still evident following tests of cylindrical afterbody penetrators. Due to this excellent post-test condition, most penetrators tested were reused in subsequent Davis gun shots.

During penetration, the 12 inch diameter steel pusher plate (initially attached with 2 each #10–32 screws at 90° and 270°) is stripped from the smaller diameter penetrator. For oblique impacts, the pusher plate rotates and may slap the penetrator aft end causing localized plastic deformation. Post-test observations indicated this occurred in all 0° angle of attack tests, but in only 50% of the non-zero angle of attack tests. This deformation varied circumferentially between 0° and 360°. In only one test was there a strong possibility that the trajectory was significantly influenced by this phenomenon. (See DSP-309 test results.)

3.2 DSP-301, 302, 305 and 306 Results

The penetrator design associated with the above 4 tests is shown in Figure 5. This joint SNLL/LLNL strategic earth penetrator, known as the 500SI design, evolved from the preliminary 1982 concept [9]. Packaging the primary and secondary envelope resulted in a 55% CG and an afterbody taper angle of approximately 2.5°.

Figures 12–15 contain the impact conditions and trajectories for DSP-301, 302, 305 and 306.

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A 3/4-scale model of the 500SI design (DSP-202) was tested into Antelope Lake, TTR at almost identical impact conditions as DSP-301. The objective of comparing DSP-202 with DSP-301 was to investigate the affect of scaling on stability. As anticipated, good agreement was obtained between the two tests, i.e., both trajectories were similar [10].

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Figure 13: DSP-302 impact conditions and trajectory

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Figure 14: DSP-305 impact conditions and trajectory

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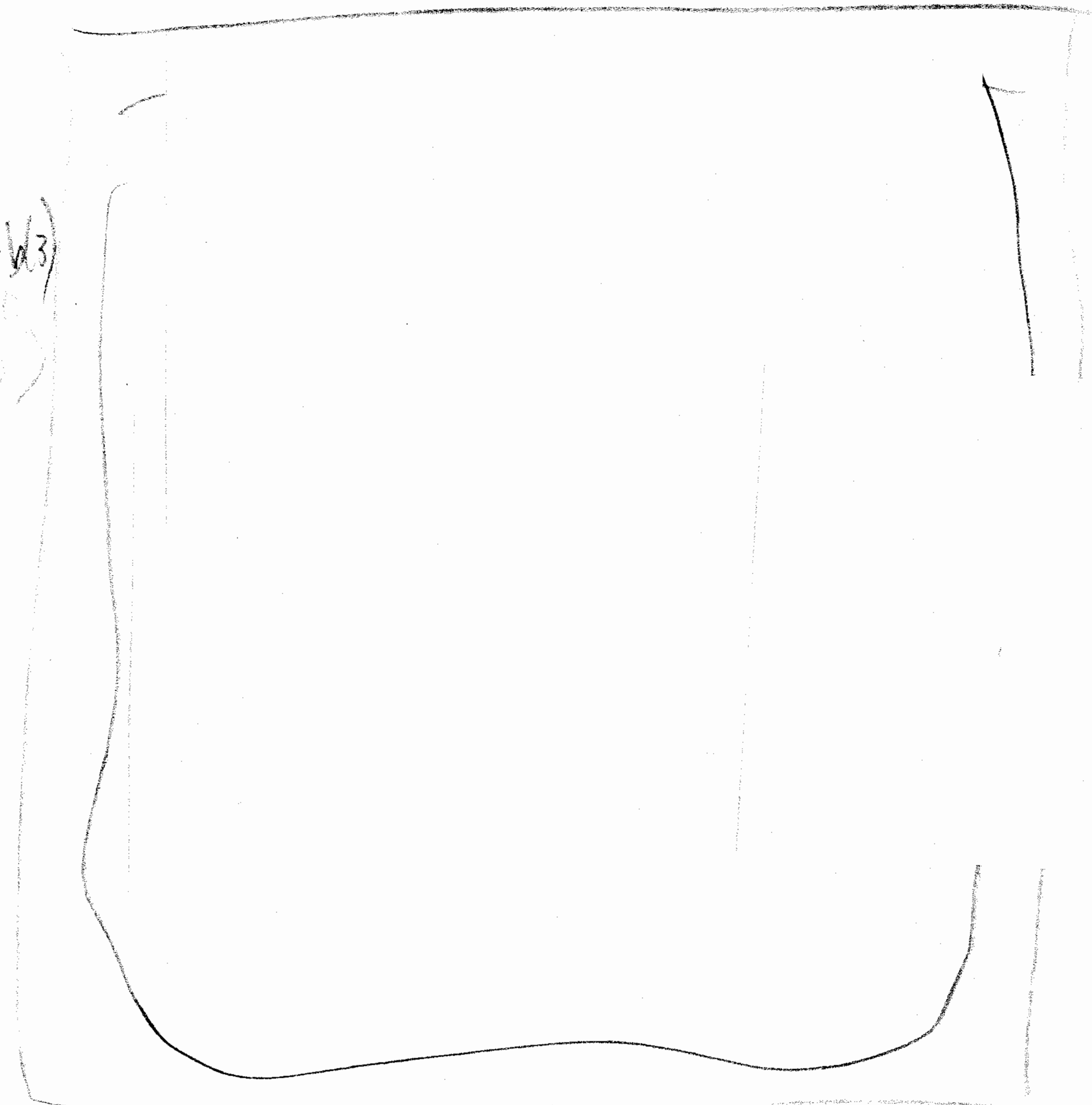

Figure 15: DSP-306 impact conditions and trajectory

3.3 DSP-303, 304, 307, 308 and 310 Results

Efficient packaging of the 500SI physics package resulted in a CG aft of 55%. Therefore, to study the affect on stability of moving the CG aft of 55%, a series of tests were conducted with a penetrator having the same external shape and weight as the 500SI design, but with the CG at 60% (Figure 6).

Trajectories for DSP-303, 304, 307 and 310 are presented in Figures 16–19. [redacted]

Due to the concern of the pusher plate impacting the penetrator aft end, a Davis gun pusher plate separation or stripper system (designed by B. G. Prentice) was utilized in DSP-307 and DSP-308. These tests successfully demonstrated that a sufficient velocity differential existed between the penetrator and pusher plate to allow penetrator burial prior to pusher plate impact with the target. However, in DSP-307 the holding fixture (initially bolted to the muzzle of the gun) was totally destroyed. This may have caused the penetrator to rotate, perhaps explaining why the test model turned laterally (in the yaw plane) during penetration (Figure 18). DSP-308, a horizontal Davis gun shot, tested a redesigned pusher plate stripper system. This also proved unsuccessful since the penetrator angle of attack changed from a preset value of 0° to about 2° after exiting the stripper. Further details can be found in Reference [11].

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b(3)

Figure 16: DSP-303 impact conditions and trajectory

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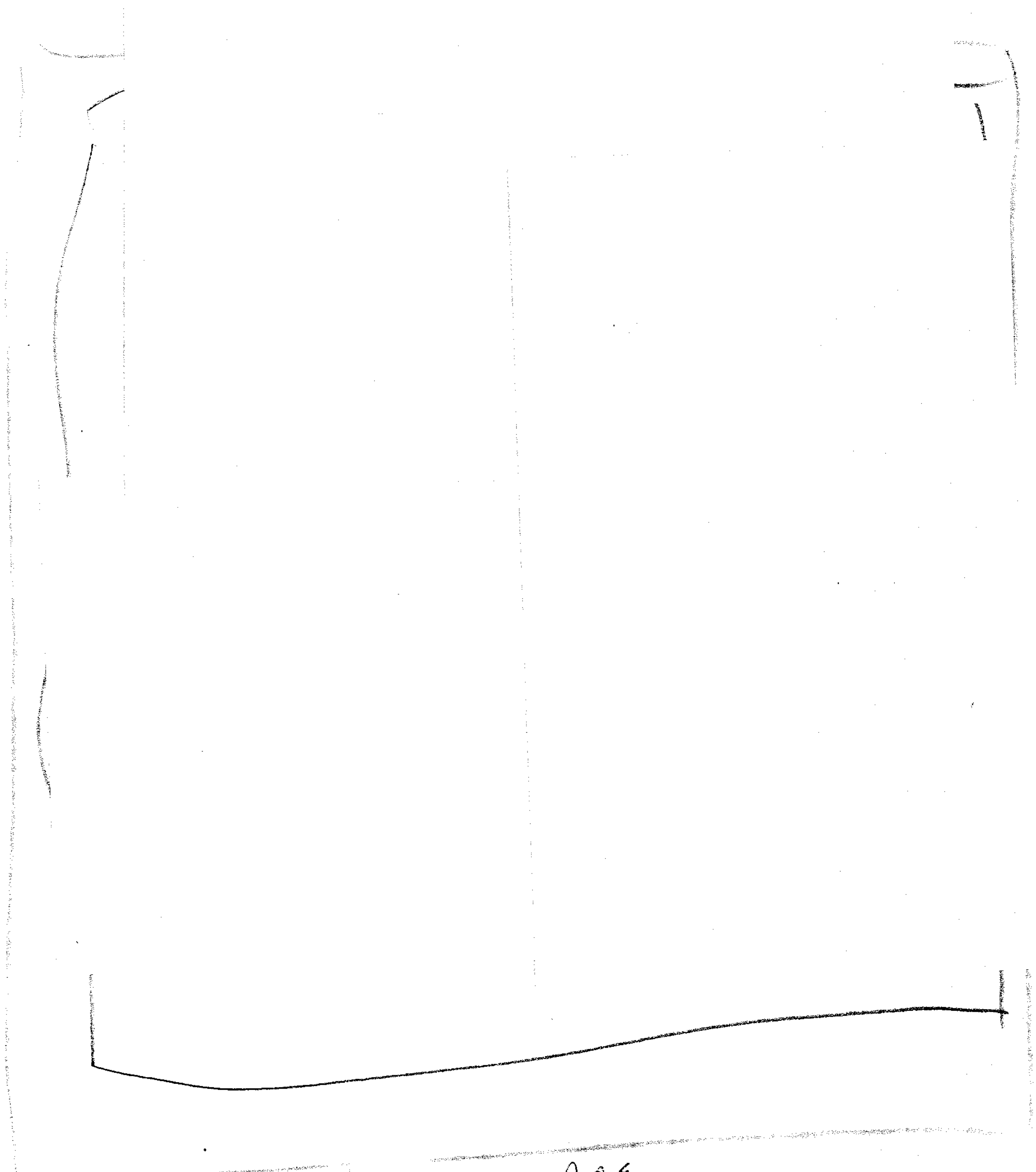
DOD b(3)

Figure 17: DSP-304 impact conditions and trajectory



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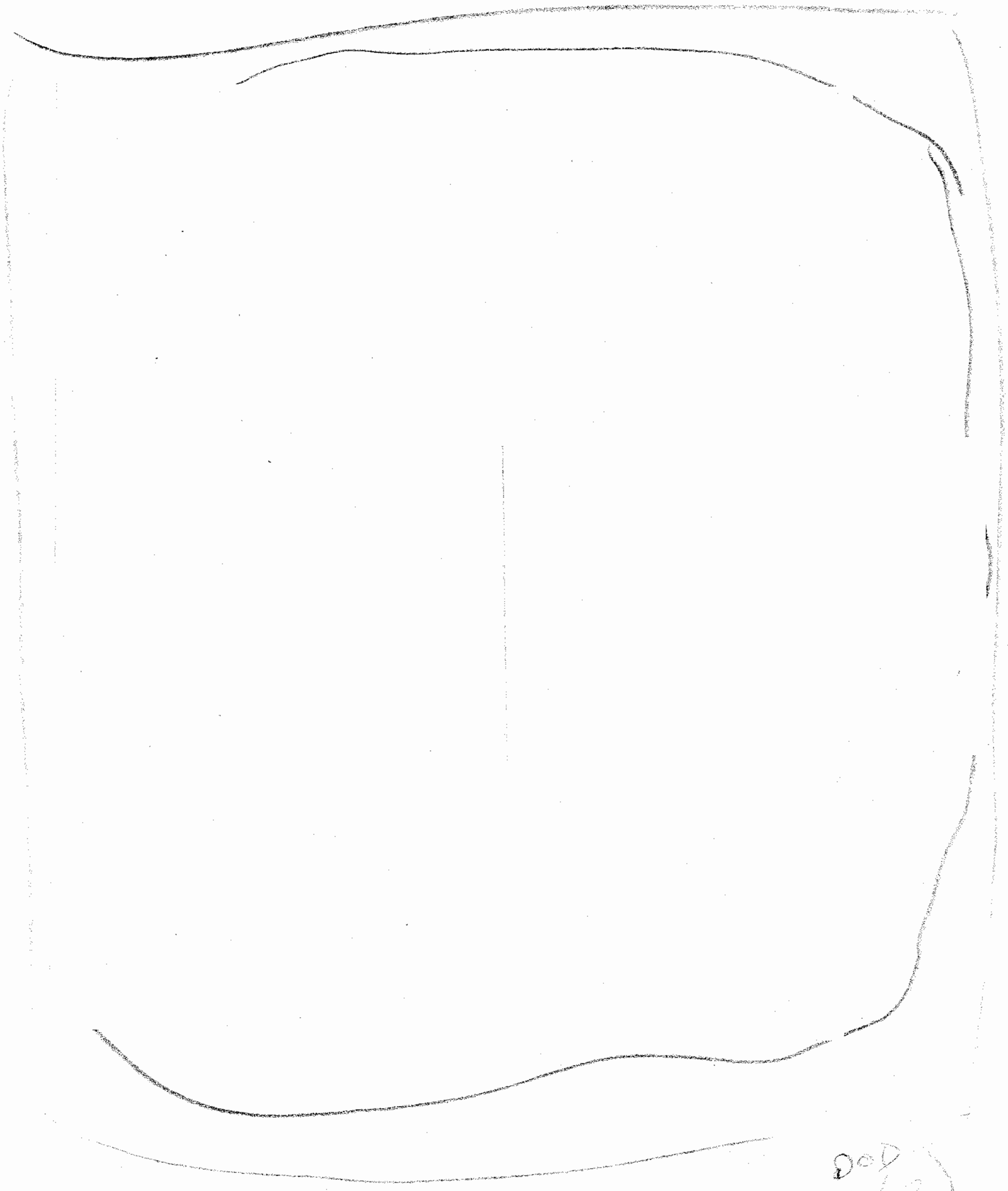
DOE b(3)

Figure 18: DSP-307 impact conditions and trajectory



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DOD b(3)

Figure 19: DSP-310 impact conditions and trajectory

DOE b(3)

Figure 20: DSP-312 impact conditions and trajectory

3.4 DSP-312 and 316 Results

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DOE

[2] The lateral (yaw) deviation observed in this test may have been influenced by (1) pusher plate impact with the penetrator aft end, and (2) improper alignment of the penetrator in the gun barrel. The DSP-312 penetrator/sabot assembly rotated while raising the assembly in the Davis gun. This changed the penetrator preset angle of attack from 2° (pitch)/0° (yaw) to about 1.9° (pitch)/0.5° (yaw).

[redacted] UNCLASSIFIED

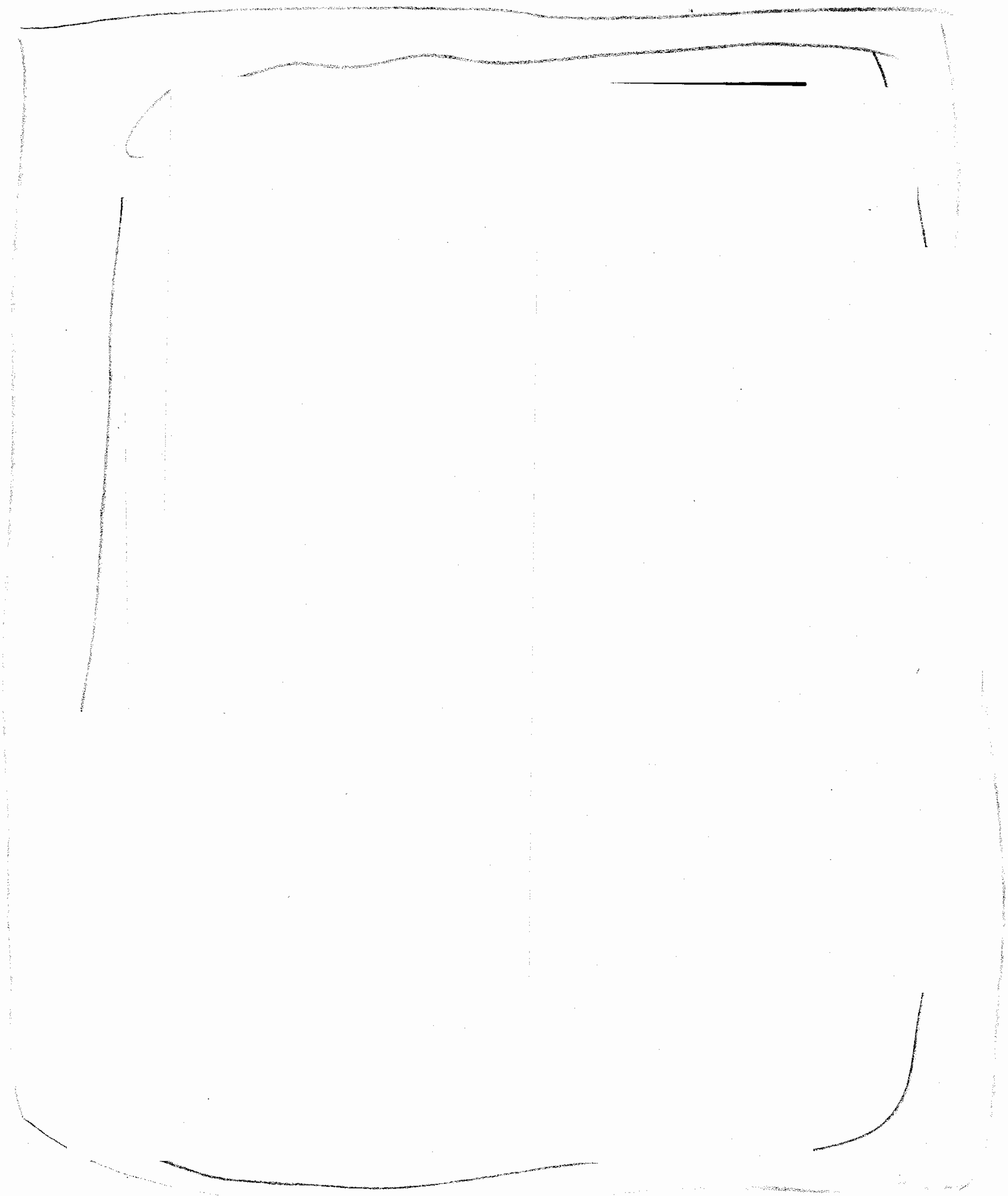

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Figure 21: DSP-316 impact conditions and trajectory

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3.5 DSP-309 and 315 Results

Low taper angle physics package envelopes result in earth penetrators having relatively forward CGs and low afterbody taper angles compared to the B1 penetrator. However, based on the previous penetrator technology database, it was speculated that low L/D cylindrical afterbody penetrators were unstable in soil

In order to specifically address the affect on stability of varying the afterbody shape, the DSP-309 penetrator (Figure 7) had an identical CG and weight as the 500SI design, but the afterbody was cylindrical. DSP-309 was the only test where significant damage to the penetrator aft end occurred due to pusher plate impact at the 0° location. This phenomenon probably influenced the peculiar trajectory for DSP-309 shown in Figure 22, where deviation downward from a straight-line path is evident. It is believed that the downward turning trajectory was caused by (1) the penetrator being unstable for these impact conditions, and (2) the pusher plate impact at 0° forcing the penetrator to turn nose dowr

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Figure 22: DSP-309 impact conditions and trajectory

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DOD b(3)

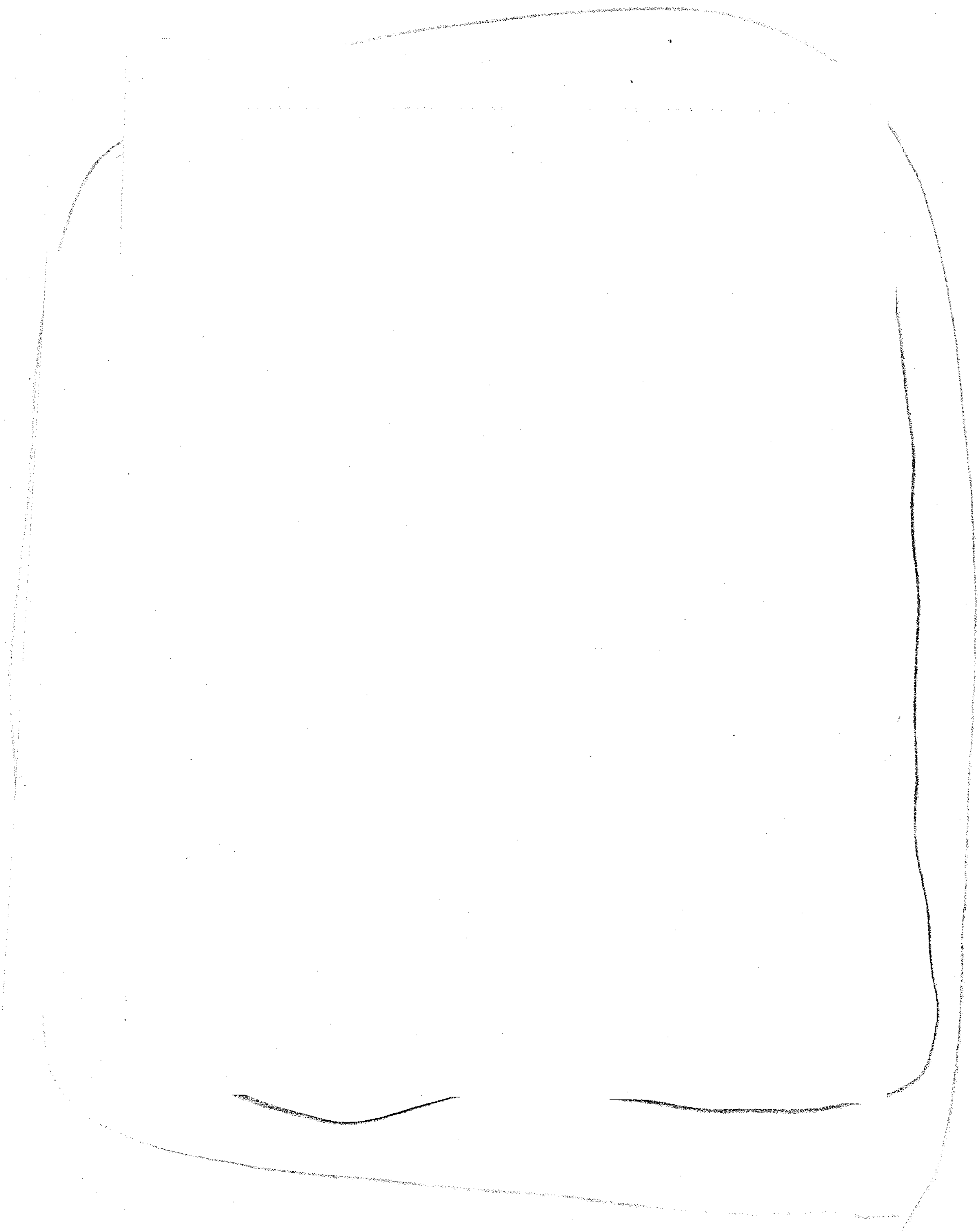

Figure 23: DSP-315 impact conditions and trajectory

3.6 DSP-311 and 317 Results

Packaging a low taper angle physics package envelope resulted in the A2 penetrator, a design of recent interest to both SNLL and LLNL. This penetrator had a L/D=4.9, an afterbody taper angle of 1.05° and a CG=52%. The 1/2-scale model DSP-311/317 design[3] is shown in Figure 9.

DOE b(3)

[3]The taper angle for DSP-311/317 was machined to 1.00° rather than 1.05°.

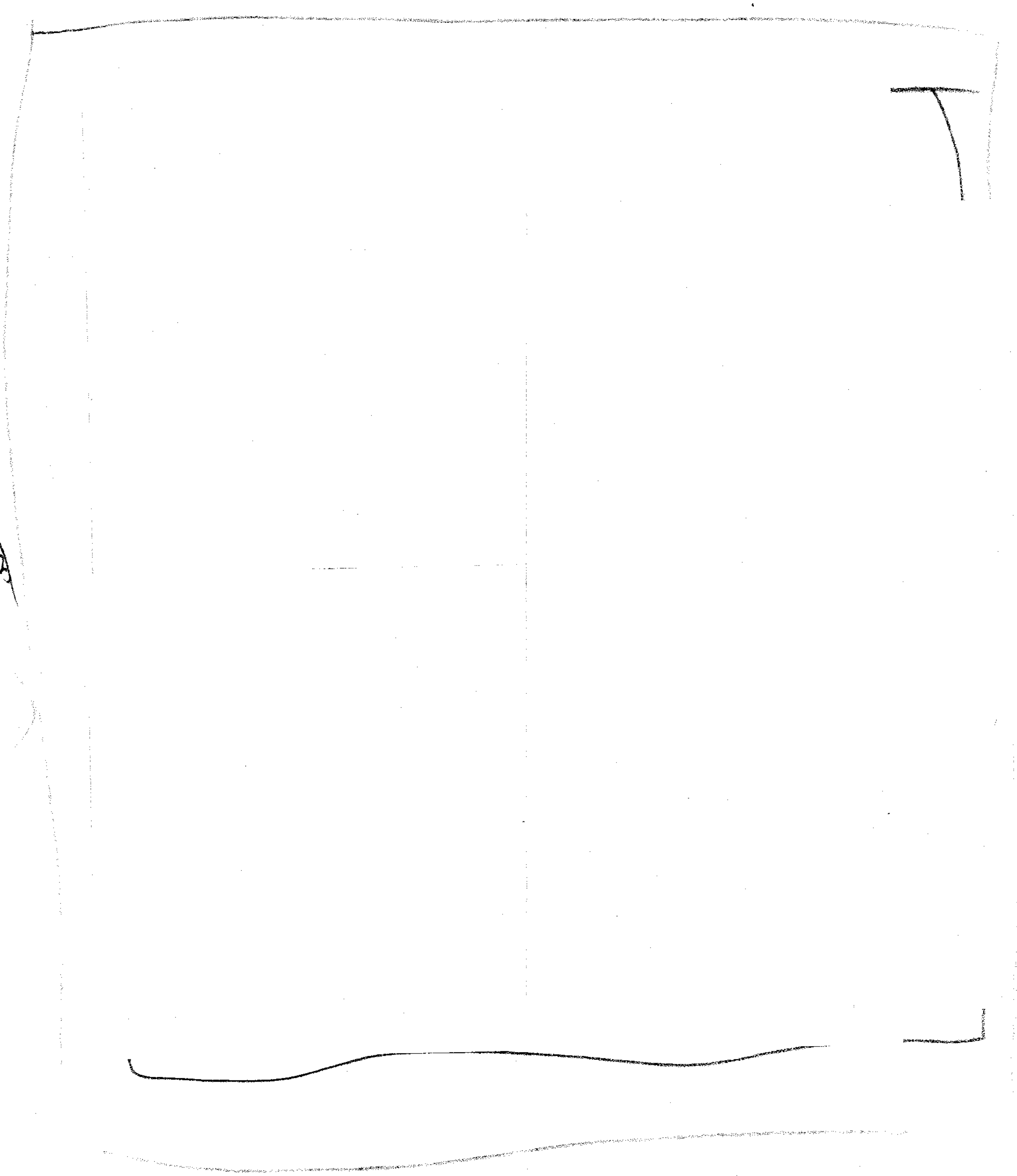

Figure 24: DSP-311 impact conditions and trajectory

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Figure 25: DSP-317 impact conditions and trajectory

4 Conclusion

The stability of low L/D strategic earth penetrators in Antelope Lake, TTR has been reported here. The penetrator designs evaluated in this test series had 3 CRH tangent ogive nose shapes and L/Ds between 4.0 and 5.4. In addition, the CG was varied as far aft as 60% and the penetrator afterbody shape was either cylindrical or tapered (up to 2.85°). The impact conditions were parameterized as follows: impact velocities from 1940 to 2560 ft/sec, impact angles from 20° to 45°, and angles of attack from 0° to 4° (nose up). The penetrator designs and impact conditions investigated in this study resulted in a substantial extension of the previous earth penetrator stability database.

The significant findings of the DSP-300 field test series are enumerated below.

DOE b(3)

5 Appendix A

Table 2: TTR coordinates of DSP-300 series impact points

TEST	TTR Coordinates *	
	X (ft)	Y (ft)
301	14611	-54941
302	14454	-55095
303	14494	-54969
304	14442	-54969
305	14178	-54935
306	14140	-54949
307	14555	-54882
309	14214	-54890
310	14193	-54910
311	14409	-54844
312	14364	-54877
315†	- - -	- - -
316	14086	-54897
317	14048	-54939
coring site	14492	-54877

* x=0, y=0 is center of TTR main target

† Impact point was not surveyed on this test.

6 Appendix B

Summary of Cauchy Scaling Laws

Definitions:

l = length	m = mass
v = velocity	a = acceleration
ρ = density	σ = stress
t = time	$\dot{\varepsilon}$ = strain rate

λ = geometric scale factor; e.g. for $\frac{1}{2}$ - scale, $\lambda = \frac{1}{2}$

superscript * = sub-scale quantity

The following set of independent relationships forms a basis from which other quantities can be generated:

$$l^* = \lambda l \qquad \sigma^* = \sigma \qquad \rho^* = \rho$$

For example, one can derive the expressions shown below:

$$t^* = \lambda t \qquad m^* = \lambda^3 m \qquad a^* = \frac{1}{\lambda} a$$

$$v^* = v \qquad \dot{\varepsilon}^* = \frac{1}{\lambda} \dot{\varepsilon}$$

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