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DNA/SANDIA SOIL PENETRATION EXPERIMENT AT DRES: RESULTS AND ANALYSIS

Sandia Laboratories
P.O. Box 5800
Albuquerque, New Mexico 87115

16 October 1975

Final Report for Period 1 December 1973—30 November 1974

DNA Order No. 74-835

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Prepared for
Director
DEFENSE NUCLEAR AGENCY
Washington, D. C. 20305



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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER SAND-75-0001	2. GOVT ACCESSION NO.	3. REPORT'S CATALOG NUMBER
4. TITLE (and Subtitle) DNA/SANDIA SOIL PENETRATION EXPERIMENT AT DRES: RESULTS AND ANALYSIS.		5. PERIOD COVERED Final Report, 1 Dec 73 - 30 Nov 74
6. AUTHOR(s) W. J. Patterson R. D. Bentley W. R. Wood		7. PERFORMING ORG. REPORT NUMBER
8. ADDRESS (Organization Name and Address) Sandia Laboratories P. O. Box 5800 Albuquerque, New Mexico 87115		9. CONTRACT OR GRANT NUMBER(s) DNA Order No. 74-835
10. CONTROLLING OFFICE NAME AND ADDRESS Director Defense Nuclear Agency Washington, D. C. 20305		11. REPORT DATE 16 October 1975
12. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		13. NUMBER OF PAGES 62
(12) 64p.		14. SECURITY CLASS (of this report) UNCLASSIFIED
		15. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Penetration 8-Inch Gun Terradynamics Instrumentation Deceleration Data		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This report describes the field test portion of a DNA-formulated program for conducting state-of-the-art studies of earth penetrating weapons and their design. The field penetration tests were in a medium with well-defined mechanical properties and they provided a comparison between empirical and theoretical calculations and field test results. This report includes a description of the test site, which was located at The Defense Research Establishment Suffield (DRES), Ralston, Alberta, Canada, projectile, instrumentation, test procedures, test results, data received, and data analysis.		

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received, and data analysis. The comparison of actual field test data results to pretest predictions made by various contractor and government laboratories will be covered in a separate DNA report.

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PREFACE

The "Instrumentation of 8-inch Gun Fired Penetrators" section of this report was written by R. D. Bentley and W. R. Wood of Instrumentation Applications Division II 8482.

CONTENTS

	<u>Page</u>
Introduction	5
Test Programs	5
Objectives	5
Test Procedure and Set-up	6
Test Site	6
Projectile Description	8
Instrumentation of 8-Inch Gun Fired Penetrators	8
Instrumentation of Air Gun Fired Penetrators	11
Test Results	11
Penetration Measurements and Recovery	11
Deceleration Data	11
Data Received	11
Data Reduction	21
Comments on Data	24
Data Analysis	24
Conclusions	26
References	27
APPENDIX A -- 200 Hz Filtered Processed Data	29

ILLUSTRATIONS

<u>Figure</u>		<u>Page</u>
1	Location of Test Nos. 454014-01 and -06 through -09, and Test Nos. 740718A through 740718E	7
2	Location of Test Nos. 454014-01 through -04	7
3	DNA 6.5-inch penetrator	9
4	Test R454014-01, 7/13/74, low g accelerometer (memory calibrated), deceleration vs. time	13
5	Test R454014-01, 7/13/74, low g accelerometer, 10.5 kHz (real time calibrated), 450 Hz LPF, deceleration vs. time	14
6	Test 454014-02, 7/13/74, low g accelerometer (memory calibrated), deceleration vs. time	15
7	Test 454014-02, 7/13/74, low g accelerometer, 10.5 kHz (real time calibrated), 450 Hz LPF, deceleration vs. time	16
8	Test R454014-06, 7/15/74, low g accelerometer (memory calibrated), deceleration vs. time	17
9	Test R454014-06, 7/15/74, low g accelerometer, 10.5 kHz (real time uncorrected), 450 Hz LPF, deceleration vs. time	18
10	Test R454014-07, 7/15/74, low g accelerometer (memory calibrated), deceleration vs. time	19
11	Test R454014-07, 7/15/74, low g accelerometer, 10.5 kHz (real time calibrated), 450 Hz LPF, deceleration vs. time	20
12	Deceleration-time validity check	21
13	a. Test R454014-06, 7/15/74, low g accelerometer (memory calibrated), displacement vs. time	22
	b. Test R454014-06, 7/15/74, low g accelerometer (memory calibrated), 200 Hz LPF, displacement vs. time	22
14	a. Test R454014-06, 7/15/74, low g accelerometer, 10.5 kHz (real time uncorrected), 450 Hz LPF, displacement vs. time	23
	b. Test R454014-06, 7/15/74, low g accelerometer, 10.5 kHz (real time uncorrected) 200 Hz LPF, displacement vs. time	23
15	R-454014-02, real time, 200 Hz, LPF, deceleration-displacement with dashed line representing idealized curve	24

TABLES

<u>Table</u>		<u>Page</u>
I	Projectile Description	8
II	Penetrator and Penetration Data	12
III	Layer Data Derived from Deceleration-Displacement Curves	26
IV	Penetration Prediction Using Tests -02 and -06 Deceleration Data	26

DNA/SANDIA SOIL PENETRATION EXPERIMENT AT DRES: RESULTS AND ANALYSIS

Introduction

As a result of recent improvements in weapon delivery accuracy it appears that low yield earth penetrating weapons can, in many cases, replace high yield air burst weapons with significant reduction in collateral effects and with no degradation of desired weapon effects.

Recognizing the potential of earth penetrators, DNA assigned a project officer in October 1973 to survey past efforts and current interest in earth penetration and assess current state-of-the-art. The survey, conducted during the period October through December 1973, pointed out that while several empirical methods were available for predicting projectile penetration depth and deceleration, very little work had been done to develop pure analytical solutions such as finite-difference techniques based on first principles of mechanics. Due to these findings, DNA formulated a program for FY 1974 to develop state-of-the-art studies for penetrating weapons and design, to award contracts to industrial and government laboratories for making empirical and theoretical calculations for a given projectile's performance in a medium with well defined mechanical properties, and to conduct actual field penetration tests in that medium for comparison between calculations and field test results.¹

In addition to the penetration tests for calculation comparison, tests to obtain data on possible scaling effects were conducted using projectiles with four different diameters and weights.

This report, which describes the field test portion of the program, includes location and description of the test site, projectile description, instrumentation, test procedures, test results, data received, and data analysis. The comparison of actual field test data results to pretest predictions made by various contractors and government laboratories will be covered in a separate DNA report.

Test Program

Objectives

The objectives of the test program were to:

1. Penetrate 35 to 50 feet into the glacial lake bed located in the vicinity of the Prairie Flat HEST Test site with a 8.5-inch-diameter 400-pound instrumented projectile and obtain a complete rigid body deceleration-time profile of the penetration event.

2. Measure stress levels in the soil during penetration with the use of lithium niobate stress gages.²

3. Conduct penetration tests with 6.0-, 4.125-, 3.06-, and 1.56-inch-diameter projectiles to obtain scaling data.

Test Procedure and Set-Up

An 8-inch-diameter, smooth bore recoilless rifle barrel mounted in vertical position for projectile impact normal to surface accelerated the 6.5-, 6.0-, and 4.125-inch-diameter projectiles to velocities up to 500 fps. An air gun accelerated the 3.06- and 1.56-inch diameter projectiles to velocities up to 500 fps.

Image motion and streak cameras measured impact velocity on each test. A Fastax camera (approximately 3000 frames/sec) recorded the firing. In addition to the photographic methods, an electromechanical method measured impact velocity. This system consists of two printed circuit (PC) boards, spaced one foot apart (vertically) and set over the impact point. Projectile travel time between the boards is measured with an electronic counter that starts when the projectile impacts the top PC board breaking continuity in that circuit and stops when the projectile impacts the bottom PC board. Since the distance between boards is one foot, the reciprocal of the measured time is the projectile velocity. The two pulses resulting from loss of continuity as the PC boards shatter are also recorded on magnetic tape for permanent storage in case the counter should malfunction.

Test Site

The penetration tests were conducted in the vicinity of the Prairie Flat HEST Test site at the Defense Research Establishment Suffield, Ralston, Alberta, Canada. Figures 1 and 2 show the location of each test by test number and relate the test points with the range reference points. This particular area was selected because a comprehensive soil investigation had been conducted there for the HEST test event and thus the mechanical properties of the target material needed for the calculations were available.

The site is located on an old glacial lake bed and the near surface deposits consist of thin alternating layers of sand, silt, and clay sized particles.³ (Although the vertical profile of the target is layered, it was expected that the materials would be similar in the horizontal direction and that comparisons could be made with tests conducted along a line within a total distance of approximately 100 feet.)

	RANGE COORDINATES METERS	
	EAST	NORTH
E-1	526,553.09	5,592,621.01
SILO	526,770.65	5,592,279.99
TRANS SETUP	526,780.68	5,592,985.84

RANGE BENCH MARK, E-1

CONCRETE SILO

MAG. NORTH

TRANS SETUP POINT

740718A

740718E

300' @ 161°30'

108.2' @ 116°46'

91.7' @ 105°32'

83.3' @ 94°21'

78.5' @ 79°52'

80' @ 63°36'

65°36'

2°35'

67' @ 2°35'

64.93'

DNA CANADIAN TEST SERIES
A34014-01 THRU -04

E-1 TRANS
SETUP POINT
116° 46'

106° 3' @ 116° 46'
119° 38'
127° 0'

-01
-02
-03

96''
31''
24''
36''
96''

T

Projectile Description

Figure 3 shows the 6.5-in. projectile (with instrumentation and telemetry components) which was used in the tests for calculation comparisons. The projectile with components weighed 400 pounds. The center of gravity was located 32.1 in. (53.5 percent of body length) from the nose tip. The nose was a 9.25 caliber radius head tangent ogive (length to diameter ratio of 3).⁴ The projectile was fabricated from D6AC steel which was heat treated to a Rockwell C hardness of 42 with a resulting tensile yield strength of 180,000 to 190,000 psi. Table I gives a description of all of the projectiles.

TABLE I
Projectile Description

<u>Test No.</u>	<u>Diameter (in.)</u>	<u>Length (in.)</u>	<u>Weight (lb)</u>	<u>C.G. From Nose (in.)</u>	<u>Nose Shape</u>
454014-01	6.0	48	283	25.0	6.0 CRH
454014-02	6.5	60	400	32.1	9.25 CRH
454014-03	6.0	48	283	25.0	6.0 CRH
454014-04	6.0	48	283	25.0	6.0 CRH
454014-05	6.5	60	400	32.1	9.25 CRH
454014-06	6.5	60	400	32.1	9.25 CRH
454014-07	6.5	60	400	32.1	9.25 CRH
454014-08	4.13	60	200	30.0	9.25 CRH
454014-09	4.13	60	200	30.0	9.25 CRH
740717A	1.56	19.4	9.3	10.5	L/d = 2 Cone
740718A	3.06	36.8	30.7	15.8	6.0 CRH
740718B	1.56	19.0	9.3	10.1	6.0 CRH
740718C	3.06	36.8	30.7	15.8	6.0 CRH
740718D	1.56	19.0	9.3	10.1	6.0 CRH
740718E	3.00	37.3	57.3	19.5	6.0 CRH

Instrumentation of 8-Inch Gun Fired Penetrators -- The deceleration data from the 6.0- and 6.5-in. -diameter penetrators was transmitted through the soil via a 10.5 kHz $\pm$ 500 Hz frequency modulated carrier. These data were transmitted by two methods: a real time, single channel, continuous transmission and a delayed time, multichannel, sampled data transmission. During gun launch and subsequent deceleration, the output of a low range accelerometer was used to modulate the low frequency carrier directly. This allowed the continuous recording of the penetration data in real time, with a maximum frequency response of 1 kHz. The data transmittal time was controlled by the data window chosen for the delay time transmission scheme.

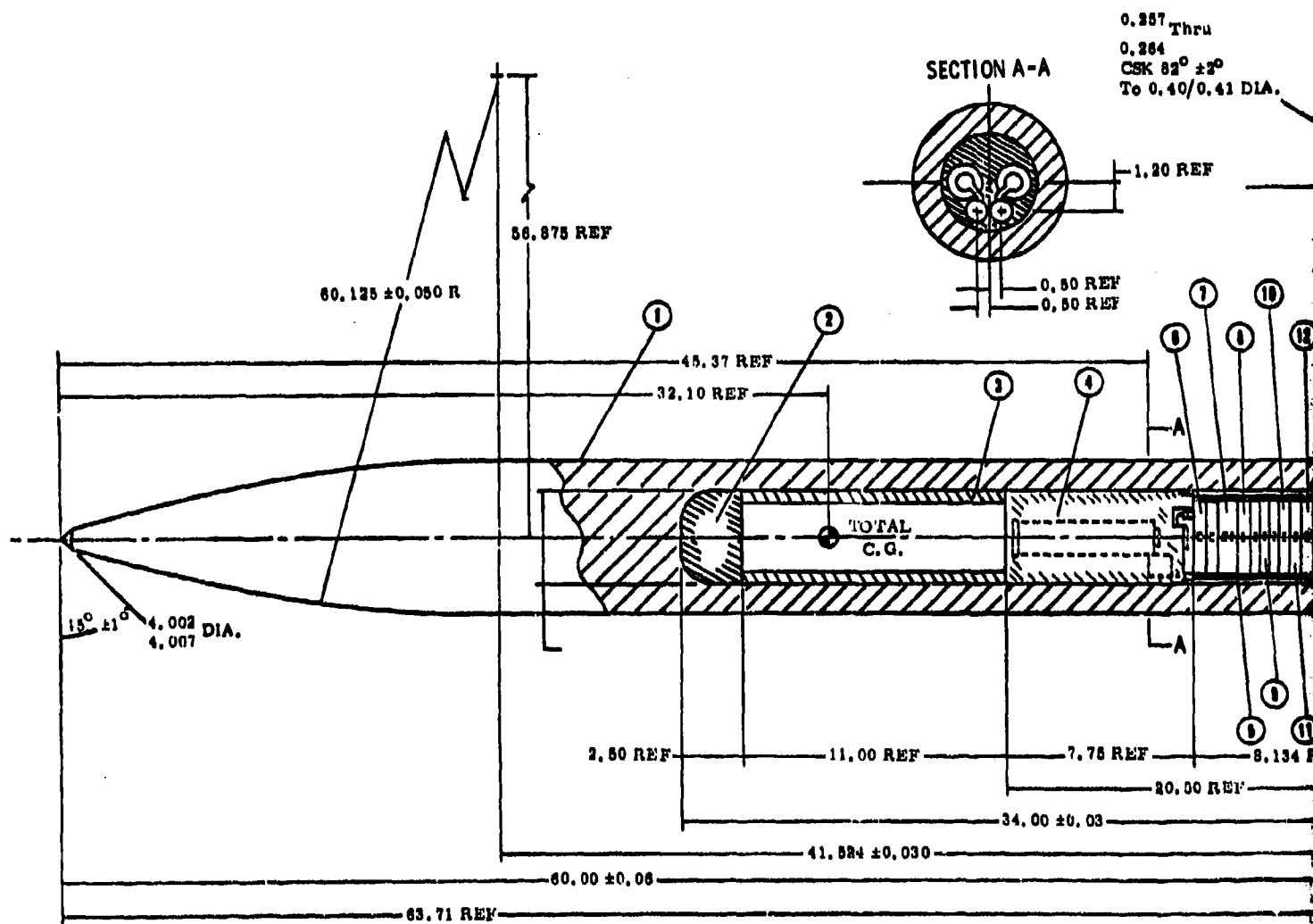
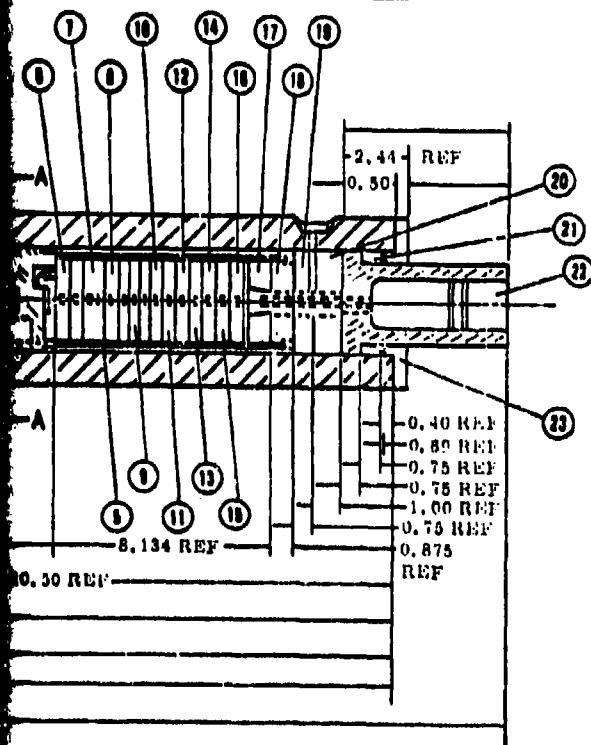
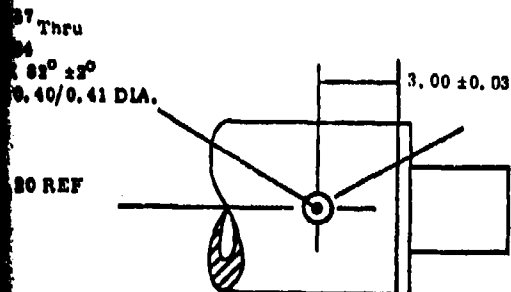


Figure 3. DNA 6.5-inch penetrator



MASS PROPERTIES

ITEM	PART IDENTIFICATION	MATERIAL	WEIGHT
1	PENETRATOR SHELL	STEEL	367 LBS.
1	PLUG	ALUMINUM	3 LBS.
3	SPACER	ALUMINUM	6 LBS.
4	BATTERY PACK	ALUMINUM	9.5 LBS.
5	ELECTRONICS HOUSING	ALUMINUM	2 LBS.
6	EXPLOSIVE SWITCH P.W.B.	ELECTRONICS PLUS 20psi FOAM	2 LBS.
7	SIGNAL CONDITIONING P.W.B.		
8	JUNCTION BOARD		
9	MULTIPLEXER P.W.B.		
10	A/D CONVERTER P.W.B.		
11	TIMING MODULE P.W.B.		
12	SHIFT REG. MEMORY P.W.B.		
13	" " " "		
14	" " " "		
15	" " " "		
16	POWER SUPPLY P.W.B.		
17	TRANSMITTER P.W.B.		
18	TM COVER	ALUMINUM	3/4 LBS.
19	PRELOAD PLATE W/TERM. BD.	ALUMINUM	3/4 LBS.
20	PRELOAD PLATE	STEEL	3 LBS.
21	ANTENNA PRELOAD RING	STEEL	1 LBS.
22	ANTENNA CORE	POLYCARBONATE	3 LBS.
23	O-RING PRELOAD RING	STEEL	2 LBS.

The multichannel delayed transmission method utilized a pulse code modulator (PCM) coupled to a semiconductor memory. The output of the low range accelerometer, a high range accelerometer, and a battery monitor formed the data base for this technique. The PCM encoded the time multiplexed data from these three channels with six bit accuracy at a maximum rate of 250K bits/sec (or 42K samples/sec) and these data were inputted to the memory during deceleration.

When the projectile experienced 300g launch acceleration, the memory load cycle was initiated and the memory accepted data until its capacity was exhausted. The time to load the memory was controlled by the data rate (maximum of 250K bits/sec) and the size of the memory (49,152 bits for this test series). This memory load time also controlled the data window for the real time transmission. Once the memory was filled no new data could be entered and the output of the memory became the modulating signal for the low frequency transmitter. The contents of the memory, a "snap-shot" of the launch, and deceleration time, were repetitively transmitted through the soil at 1K bits/sec until the battery power was depleted. During the 30-minute battery life following penetration the deceleration data were transmitted to the surface 360 times.

The selection of the memory load cycle time (data window) required a compromise between the "safety factor" used to insure that the window was sufficiently wide to cover the projectile acceleration in the barrel and the deceleration event, and the quality of the sampled data acquired. Operation at 250K bits/sec would provide a data window of only 200 ms, but would result in sufficient samples to reconstruct the sampled data with a 2K Hz response. Reduction of the bit rate to 167K bits/sec would result in a data window of 300 ms, but would result in samples sufficient only to reconstruct the data with a frequency response of 1.4K Hz. Selection of a 600 ms window would have resulted in data reconstruction with a 700 Hz frequency response. The selection of the data window is also dependent on the frequency content of the data base and must be chosen to prevent aliasing in the data reconstruction. This was the limiting factor in this test series.

Based on preliminary penetration estimates the telemetry systems were designed to provide a 200-ms window. Final preshot calculations refined this estimate and indicated the deceleration event would encompass 230 ms. It was possible to modify three of the four test units to provide a 300-ms window; however, time did not permit the modification of the fourth unit and its data window remained at 200 ms (Test No. 454014-06). Since approximately 30 ms of time elapses between memory load cycle initiation (300g launch acceleration) and impact, 270 ms of penetration data could be received for the 300-ms window and 170 ms of data for the 200-ms window.

Two piezoresistive accelerometers were used to sense the deceleration event. One of these was ranged to provide a full-scale output compatible only with the deceleration through the soil and was overranged during launch. This low range accelerometer, an Endevco 2261-M4, was ranged to provide a 250g, full-scale, deceleration monitor. The sensitivity of the second accelerometer was selected to monitor both the high acceleration launch environment and comparatively lower deceleration through the soil. This high range accelerometer, an Endevco 2261-M6, was biased to give a 2500 g range for launch acceleration with a 500g range for deceleration.

Instrumentation of Air Gun Fired Penetrators -- The 3.08-in. -diameter air gun penetrators were fitted with a telemetry package which yielded real-time acceleration data. It utilized a crystal accelerometer, usable from 5 to 1000g's. Data transmission for this system is in the 230 to 280 MHz band in a conventional FM/FM telemetry scheme, using a simple subcarrier. Real-time acceleration data, along with timing and velocity data, is recorded on magnetic-tape and oscillographic recorders. This system provides a usable signal down to approximately eight feet in dry soils, and somewhat less in saturated soils.

Test Results

Penetration Measurements and Recovery -- Impact conditions and penetration results for all tests are given in Table II. Included in the table are the three different impact velocity measurements (PC board, image motion camera, and streak camera) made for each of the 8-in. recoilless gun shots. The powder charge for Test 454015-05 failed to ignite properly and thus the projectile exited the gun so slowly that none of the impact velocity methods worked.

Penetration depth was determined by probing the penetration holes with 2-in. -diameter drill stems. A local drilling company was hired to do the probing. A truck mounted derrick lowered approximately 30-foot sections of 2-in. -diameter drill stem into the hole. With water flowing through the drill stem, it was lowered into the hole under its own weight until it hit the back of the projectile. After hitting the back of the penetrator, the operator raised and dropped the stem to be sure it was in contact with the penetrator. The length of pipe in the hole was then measured to obtain penetrator depth.

Two projectiles were recovered with a "fishing" technique used by the oil industry to recover tools and casings. Bear Tool Co. Ltd., Edmonton, Canada, was contracted to do the fishing. In order to recover the projectiles, a 6-5/8 in. regular bit was used to open the hole. Then a 7-3/8-in. wash overshoe was used to increase the diameter of the hole further and to go over the projectile and flush the attached soil from the penetrators. The washover tool was then removed and an overshot (catcher unit) tool with grapples was lowered into the hole and over the penetrator. The grapples secured the penetrator to the overshot tool and was then pulled from the hole. The 454014-02 and -07 penetrators were recovered with the above method.

Deceleration Data -- The 8-in. recoilless gun fired penetrators used in Tests 454014-01, -02, -05, -06, -07, and the air gun propelled penetrators used in Tests 740718A and C were instrumented to measure rigid body deceleration during penetration. The -05 penetrator, reworked after the unsuccessful powder ignition, was used for Test -07.

Data Received -- The memory and real-time data (deceleration time) for each test are shown in Figures 4 through 11. The data from the memory system are shown exactly as received after digital-to-analog conversion. The real-time data have been processed through a 450 Hz low pass filter.

TABLE II
Penetrator and Penetration Data

Test Number	Test Date	Projectile Diameter (in.)	W/A (lb/in. ²)	Depth to Nose Tip (ft)	Impact Velocity (fps)			Average S Number
					P. C. Board	Image Motion	Streak	
454014-01	7-13-74	6.0	10.00	73.2	583	571	583	15.5
454014-02	7-13-74	6.5	12.05	48.3	429	410	403	13.5
454014-03	7-14-74	6.0	10.20	39.8	409	402	405	13.0
454014-04	7-15-74	6.0	10.20	65.7	529	512	521	15.5
454014-05	7-15-75	6.5	12.05	-	-	-	-	-
454014-06	7-16-74	6.5	12.05	67.9	493	478	495	14.6
454014-07	7-16-74	6.5	12.05	29.8	306	305	293	12.2
454014-08	7-17-74	4.13	15.00	99.0	Malfunction	650	663	13.6
454014-09	7-17-74	4.13	15.00	86.1	611	619	N.G.	12.6
740717A	7-17-74	1.56	4.87	15.6	Not Used	516	Not Used	5.1
740718A	7-18-74	3.06	4.49	10.3	Not Used	416	Not Used	5.0
740718B	7-18-74	1.56	5.23	10.1	Not Used	455	Not Used	4.0
740718C	7-18-74	3.06	4.49	6.5	Not Used	312	Not Used	4.7
740718D	7-18-74	1.56	5.23	6.5	Not Used	342	Not Used	3.8
740718E	7-18-74	3.06	7.61	9.9	Not Used	307	Not Used	5.6

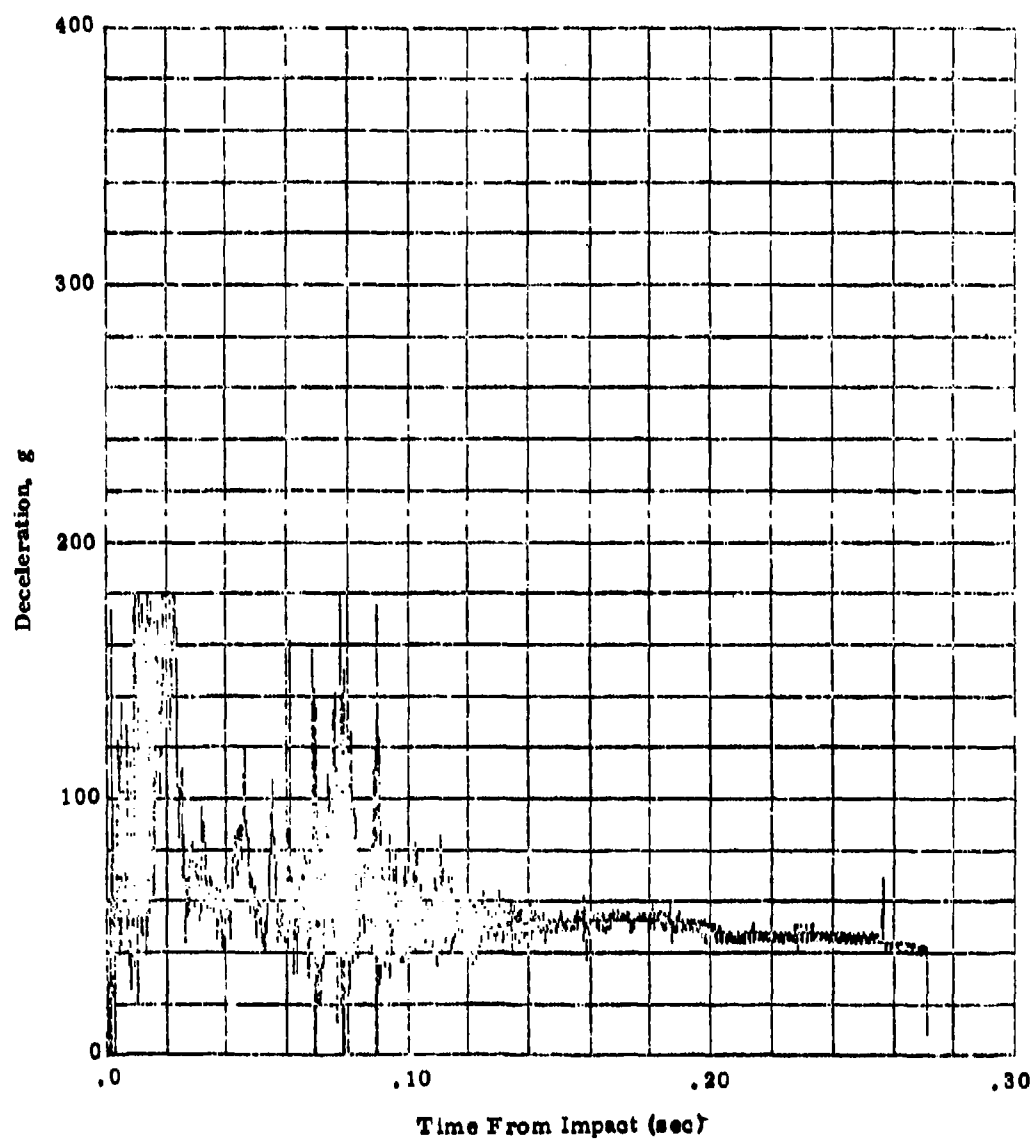


Figure 4. Test R454014-01, 7/13/74, low g accelerometer, (memory calibrated), deceleration vs. time

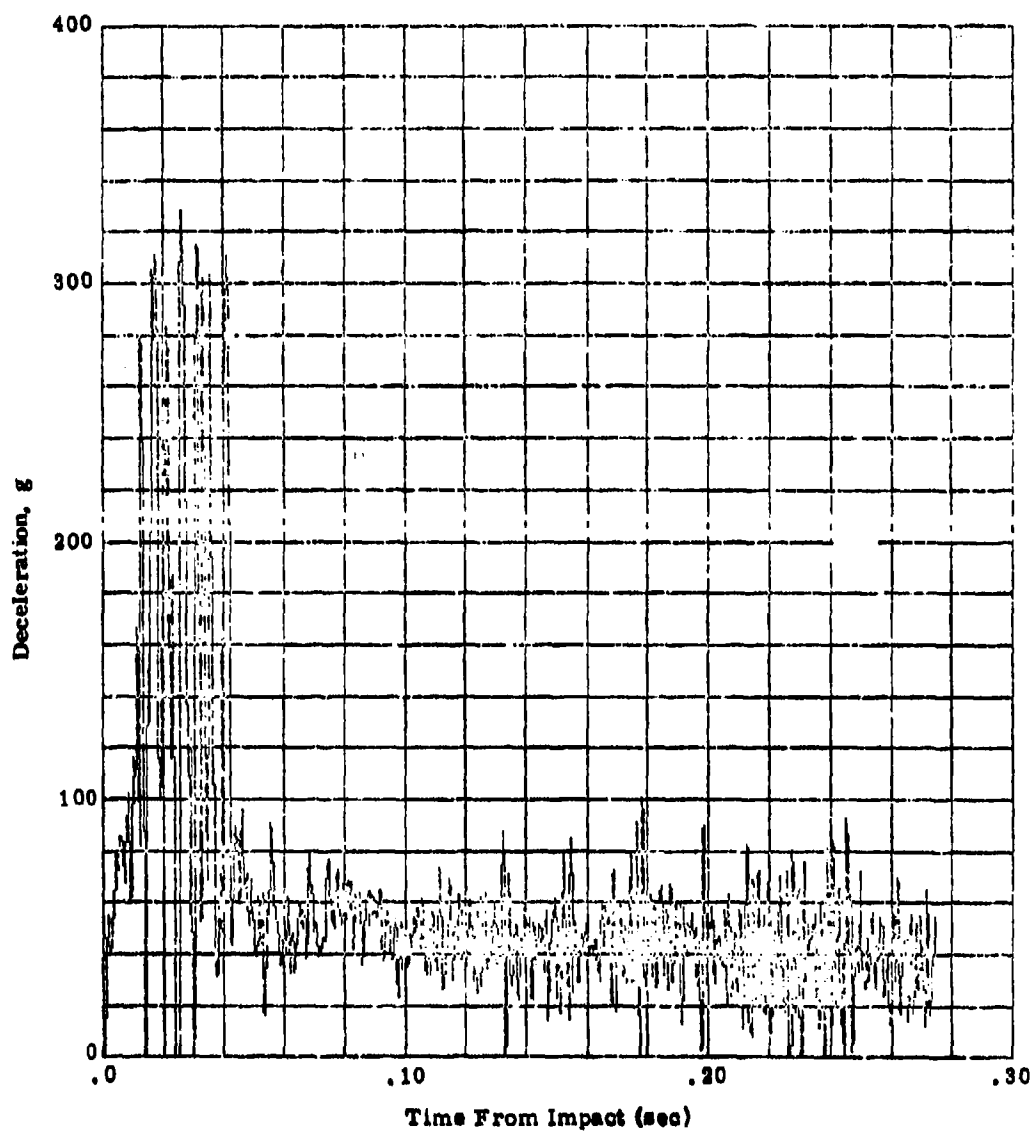


Figure 5. Test R454014-01, 7/13/74, low g accelerometer, 10.5 kHz (real time calibrated), 450 Hz LPF, deceleration vs. time

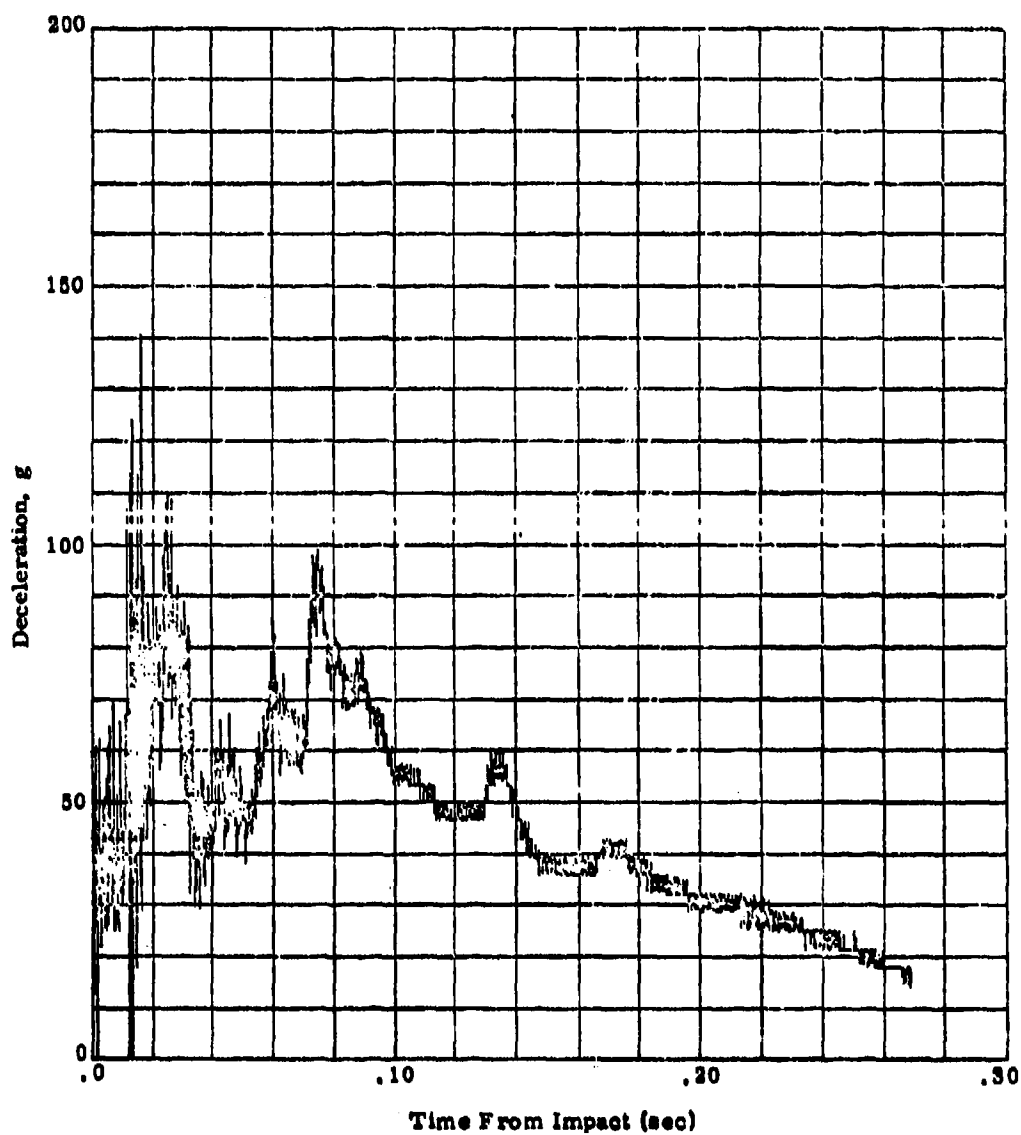


Figure 6. Test R454014-02, 7/13/74, low g accelerometer (memory calibrated), deceleration vs. time

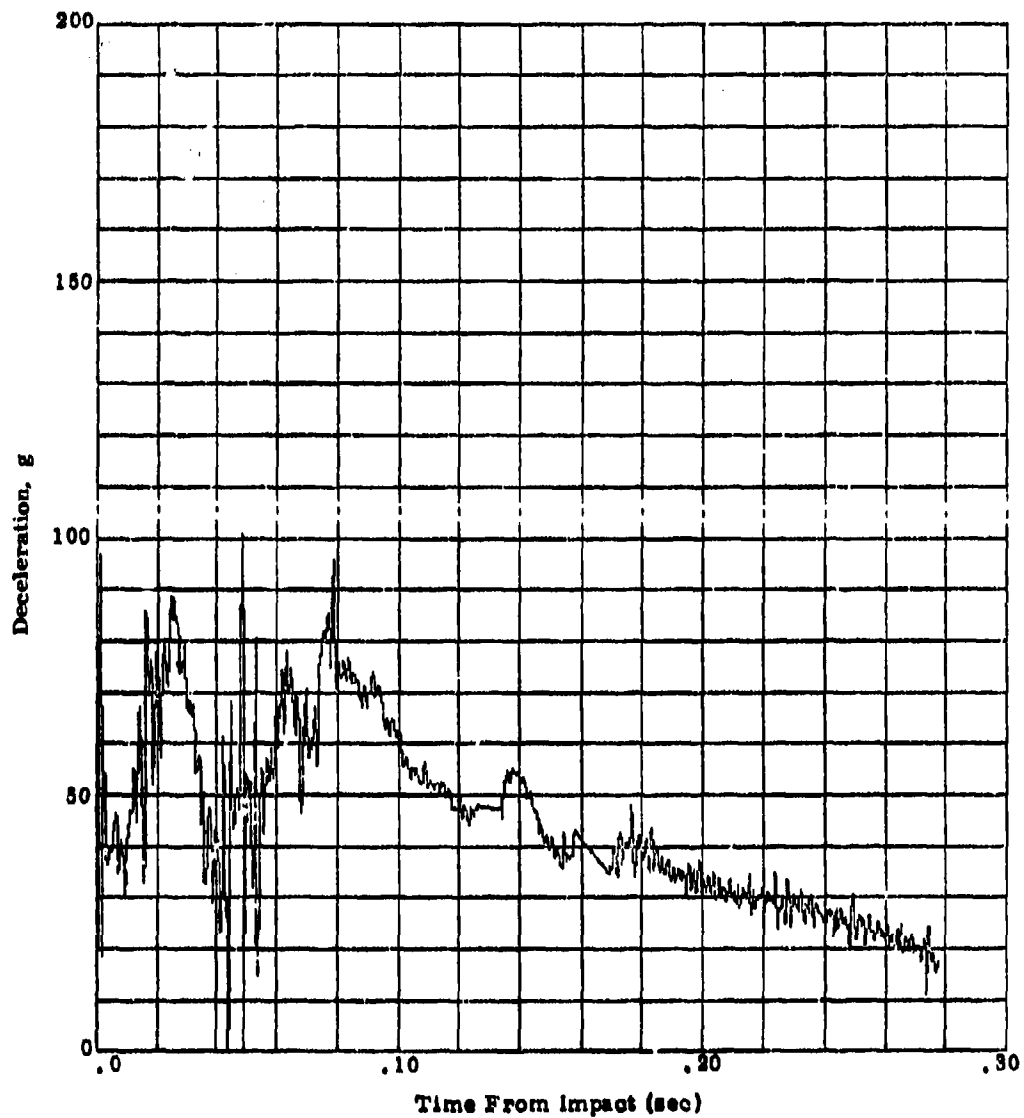


Figure 7. Test R484014-02, 7/13/74, low g accelerometer, 10.5 kHz
(real time calibrated) 450 Hz LPF, deceleration vs. time

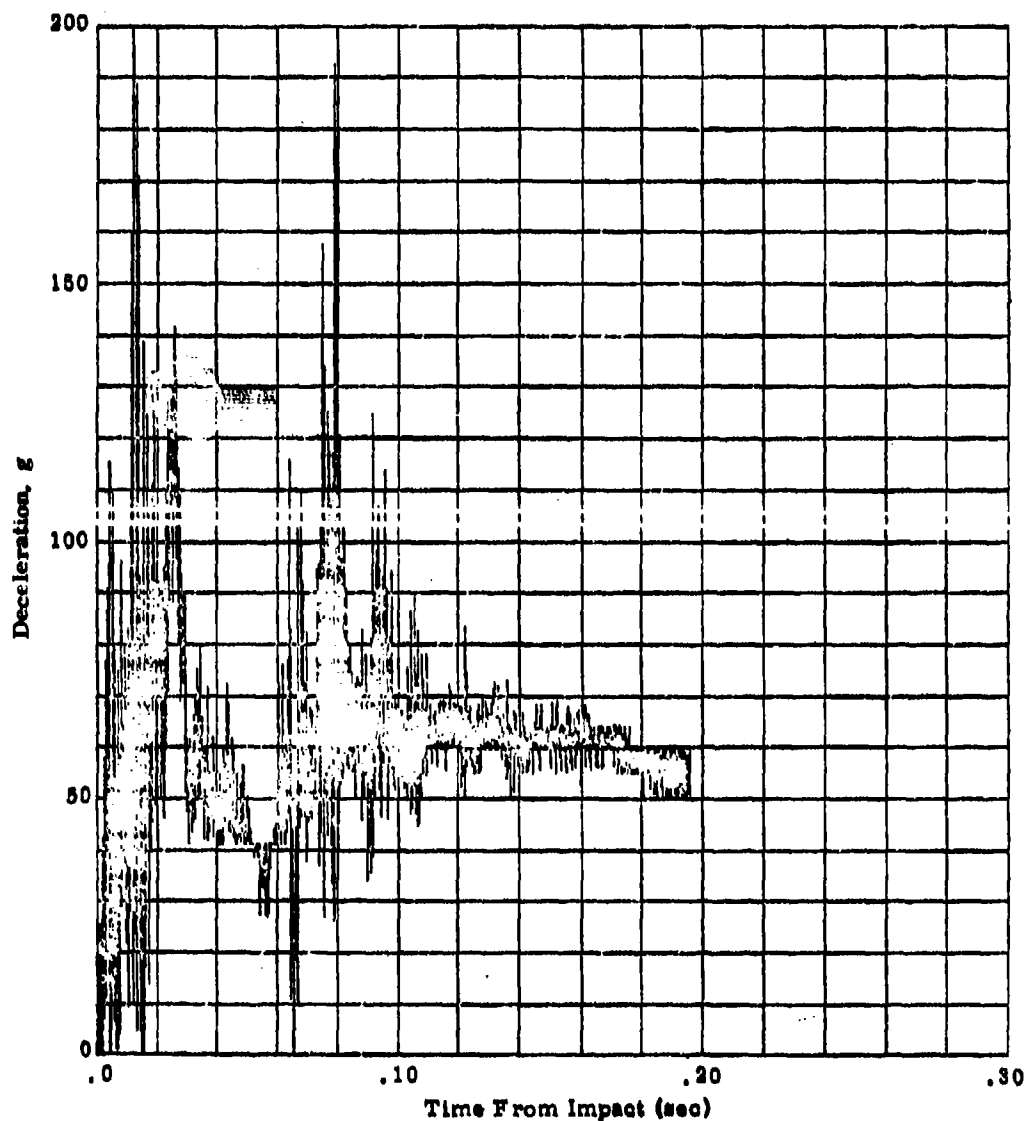


Figure 8. Test R454014-06, 7/15/74, low g accelerometer
(memory calibrated) deceleration vs. time

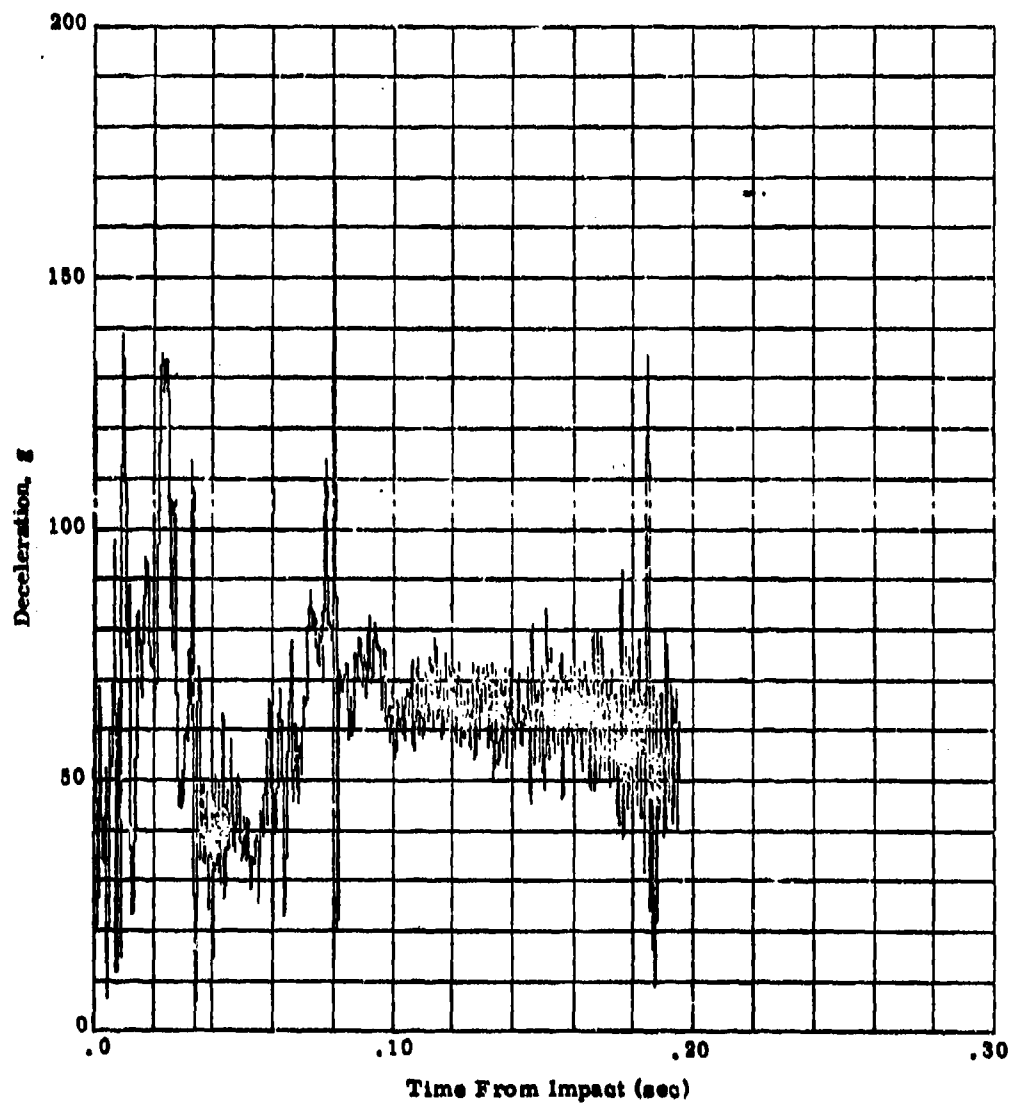


Figure 9. Test R454014-06, 7/15/74, low g accelerometer, 10.5 kHz
(real time uncorrected) 450 Hz LPF, deceleration vs. time

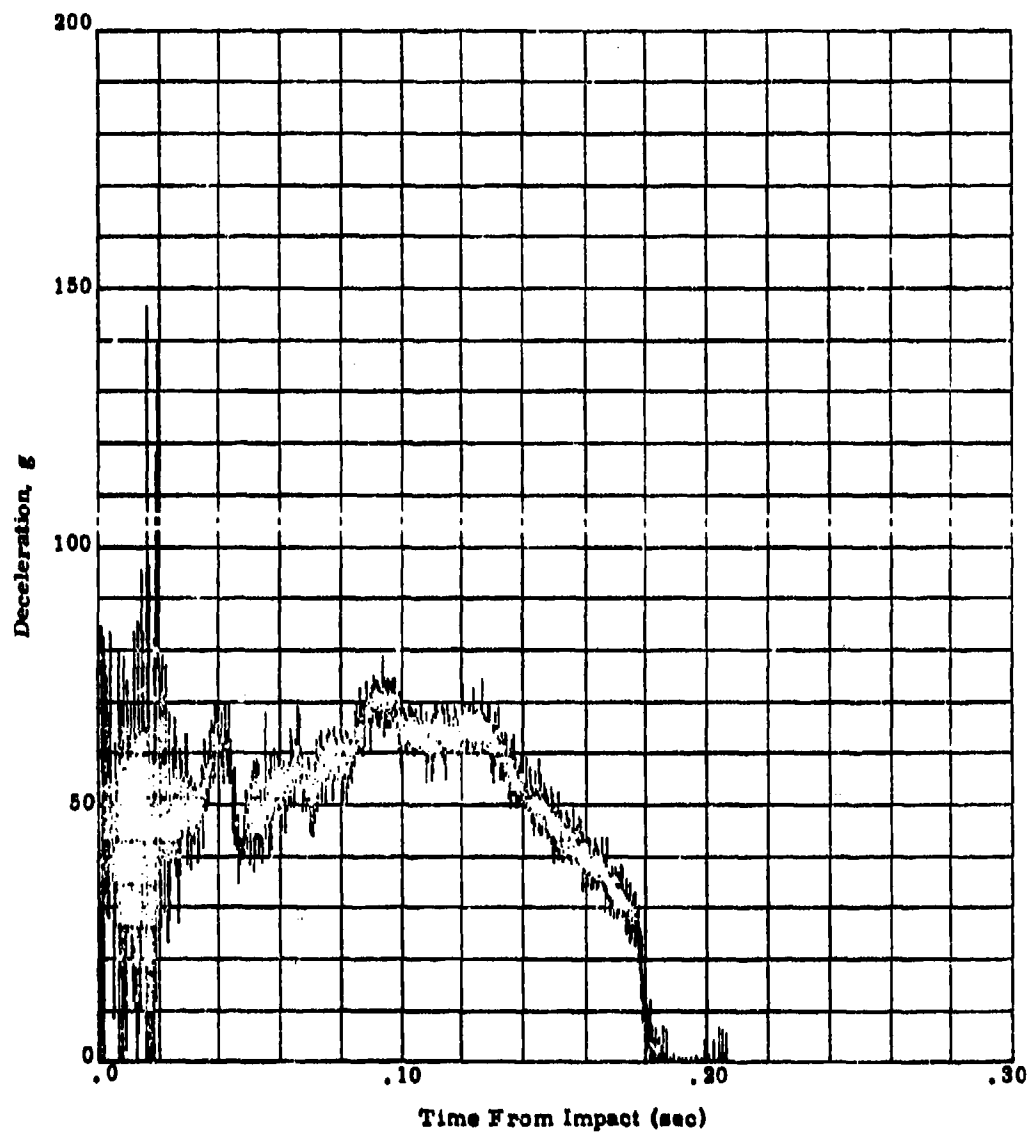


Figure 10. Test R454014-07, 7/16/74, low g accelerometer (memory calibrated) deceleration vs. time

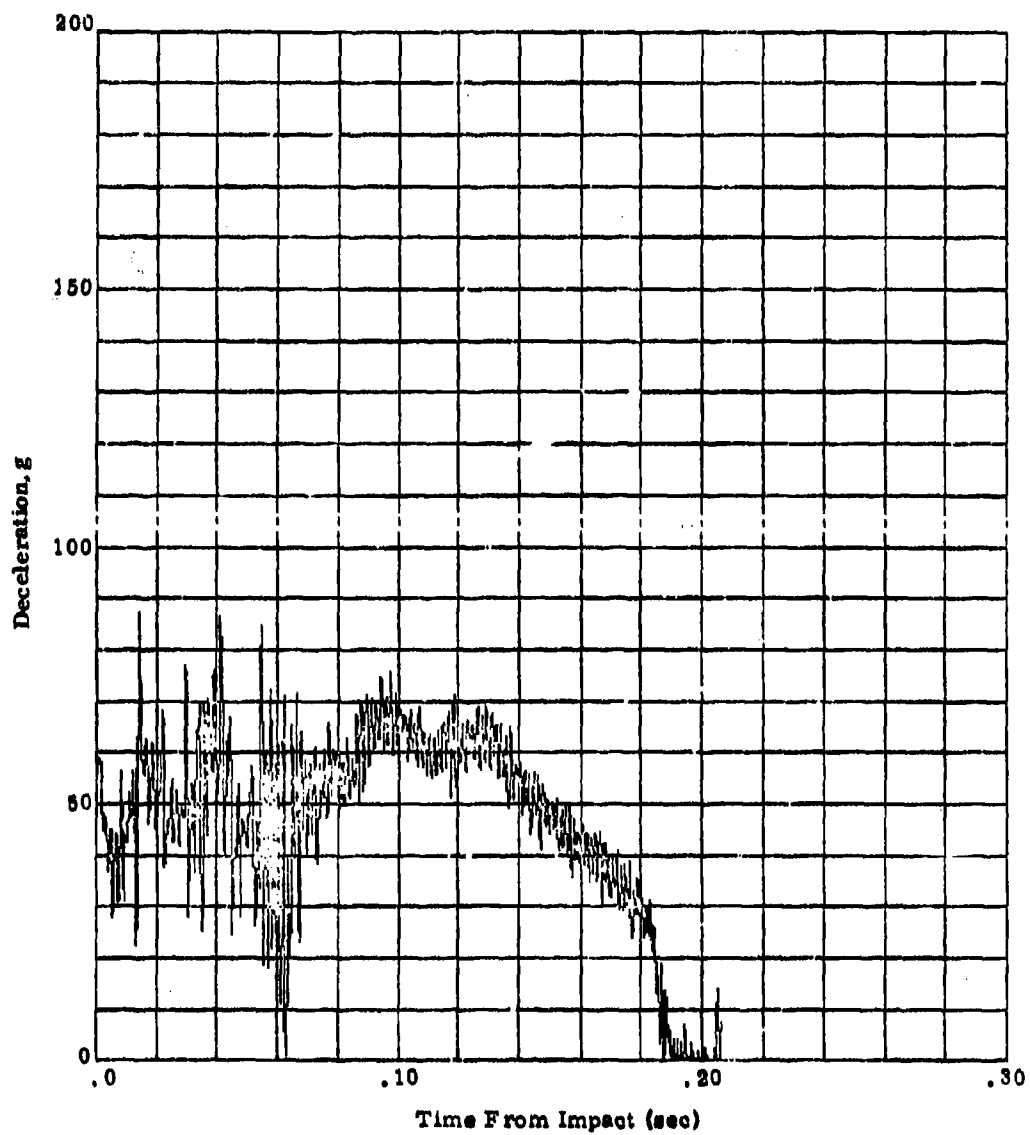
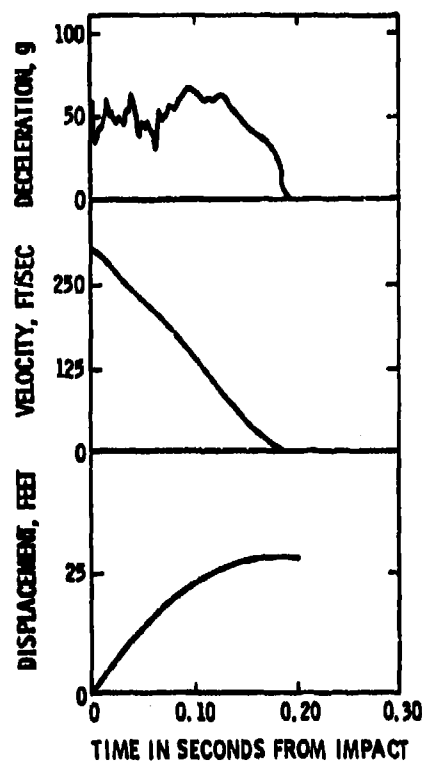


Figure 11. Test R464014-07, 7/16/74, low g accelerometer, 10.5 kHz
(real time calibrated) 450 Hz LPF, deceleration vs. time

Data Reduction -- The curves in Figure 12 show how the deceleration-time record is checked for validity. Only deceleration traces with no zero shift can be used. A preliminary calibration of the accelerometer/telemetry system is conducted in the laboratory before the test (usually on a drop table) to determine the ratio of the accelerometer output (voltage) to the applied deceleration. Using the laboratory calibration, the deceleration-time trace recorded during penetration is then integrated which gives the projectile impact velocity.

Figure 12. Deceleration-time validity check



The first check of the data validity is to compare the impact velocity determined from the telemetry data with the impact velocity measured by an independent method such as impact cameras. If the two velocities do not agree and the deceleration trace did return to zero at the termination of the penetration event, an adjustment of the laboratory calibration is required. For final dynamic calibration, the ordinate scale (deceleration) is increased or decreased (the shape of the curve is not changed) until the integral of the deceleration time curve agrees with the independently measured impact velocity. A velocity-time curve is then constructed by graphical integration of the new deceleration-time curve. The velocity-time curve is then integrated to obtain projectile depth which is then compared to the actual projectile depth measured in the field.

If both the impact velocity and depth determined from the motion curves constructed from the recalibrated deceleration-time curve agree with the independent measurements, the accelerometer is now properly calibrated and the shape of the curve is assumed to be correct. However, if both velocity and depth do not agree with the independent measurements, it must be assumed that a non-linear shift did occur in the accelerometer output and that the data are questionable.

After the validity of the data has been established, cross plots of velocity-depth and deceleration-depth are constructed. The deceleration-depth curve is most useful in studying penetration because deceleration levels displayed on the curve at a given depth can be compared with field data on the material penetrated at that depth.

The only 8-in. gun test where a complete deceleration pulse was received was 454014-07. These data were calibrated by the above method and the displacement determined by double integration of the calibrated deceleration-time record differed from the probed depth by 6 percent for the real time data and 10 percent for the memory data. The 4 percent difference between real time and memory data is within expected system tolerances and may be attributed to the different transmission frequencies of the two techniques. The 6 percent difference between probed depth and integrated depth is within the tolerance of the velocity measurement.

In order to show the rigid body motion of the projectiles more clearly, the memory and real-time deceleration-time data were processed through a 200 Hz low pass filter. To insure that the filtering did not affect the rigid body data, the 200 Hz filtered data were processed exactly like the unfiltered memory and 450 Hz filtered real-time data. Both sets of processed data (velocity-time and displacement time) for a typical test, 454014-06, are given in Figures 13 and 14.

A comparison of these figures shows that the 200 Hz filtered data yield the same results as the unfiltered data. The data for all of the tests were processed in the above manner and the filtering did not affect the results. The 200 Hz filtered processed data for the other tests is included in Appendix A.

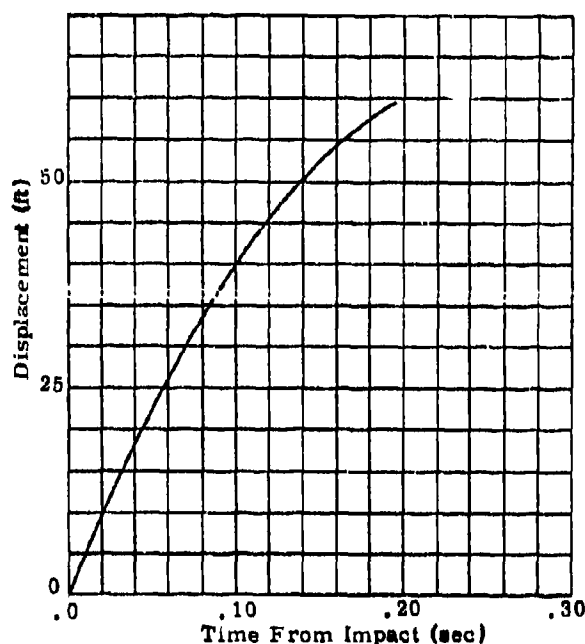


Figure 13a. Test R454014-06, 7/15/74, low g accelerometer (memory calibrated) displacement vs. time

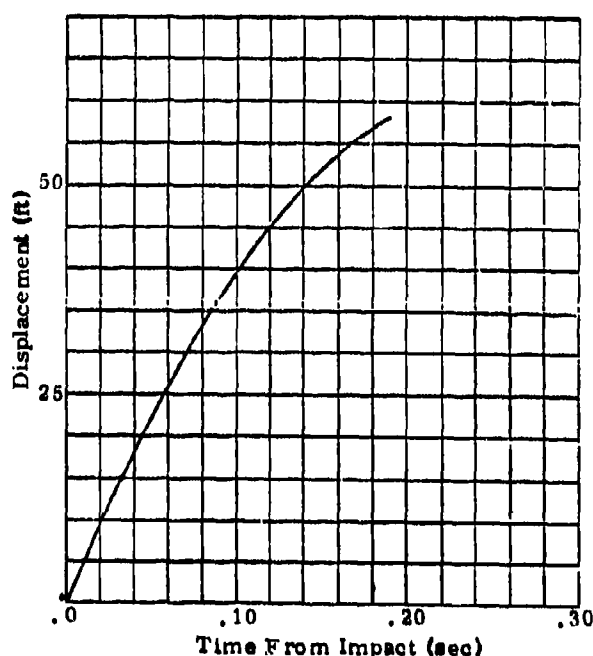


Figure 13b. Test R454014-06, 7/15/74, low g accelerometer (memory calibrated) 200 Hz LPF, displacement vs. time

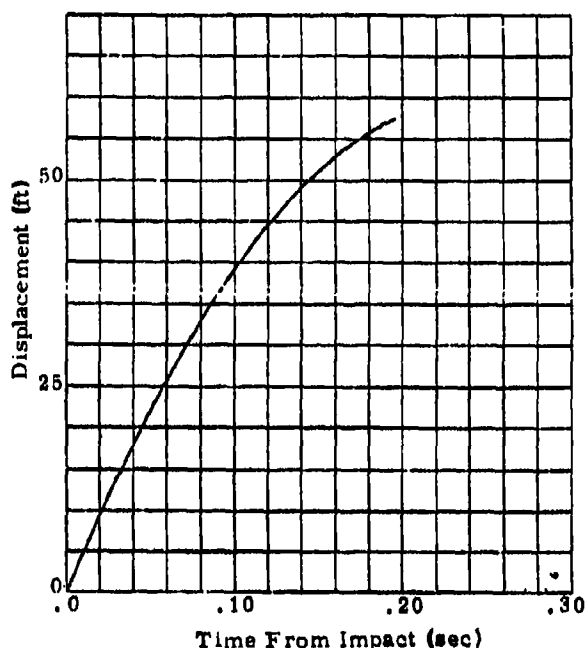


Figure 14a. Test R454014-06, 7/15/74, low g accelerometer, 10.5 kHz (real time uncorrected) 450 Hz LPF, displacement vs. time

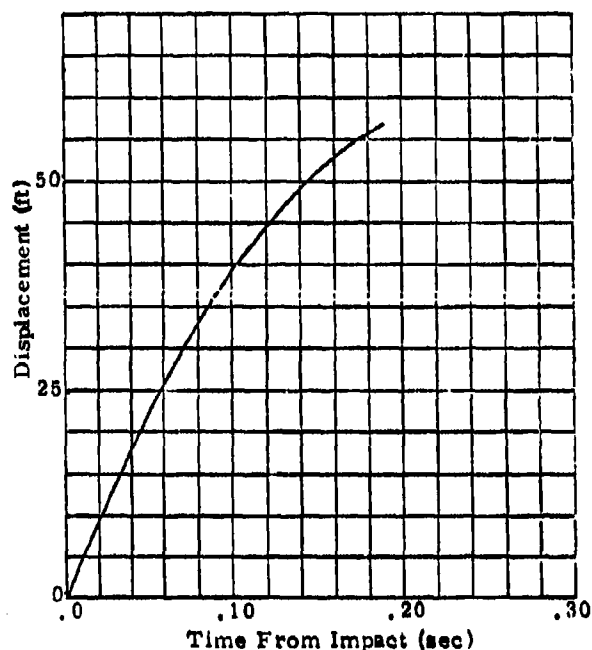


Figure 14b. Test R454014-06, 7/15/74, low g accelerometer, 10.5 kHz (real time uncorrected) 200 Hz LPF, displacement vs. time

Complete deceleration pulses were not obtained on Tests 454014-01, -02, and -06 because the time duration of the penetration event exceeded the data window acquisition time. (See instrumentation section.) Since a complete pulse was not obtained in the -01, -02, and -06 tests, there is no way to be absolutely sure that no zero shift occurred; however, no zero shift occurred in either tests -07 or any of the tests conducted in preparation for the Canadian test series. Assuming that no zero shift occurred, the partial records were calibrated in the following manner:

1. The recorded deceleration-time pulse, using the laboratory calibration of the ratio of accelerometer output voltage to the applied deceleration, was integrated to obtain a velocity-time curve. The initial velocity used in constructing the v-t curve was the velocity measured with impact cameras.
2. The velocity-time curve was then integrated to obtain a displacement-time curve.
3. Cross plots were then constructed to obtain velocity-depth and deceleration-depth curves.
4. The velocity-depth curve was then studied to determine if an extrapolation of the curve to zero velocity yielded a depth within 6 to 10 percent of the probe measured depth. If these depths did not agree, a linear calibration of the recorded deceleration-time record was made and the process was repeated.

Comments on Data -- The memory and real-time data for Test -01 could not be calibrated by the above technique. All of the curves are included (Figures A-1 through A-10), but must be considered questionable data. It appears that a burst of noise, perhaps caused by the receiving coils being located at a null point for the depth of penetration, gave a false deceleration in the real time data.

The calibration worked well for Test -02 and, as can be seen in Figures A-14, A-15, A-19, and A-20, data were received for approximately 98 percent of the penetrator depth and 270 ms out of the approximately 290 to 300 ms of penetration. No calibration was required for Test -03.

Data Analysis -- Cross plots of deceleration-displacement for Tests 454014-02 and -06 were analyzed to determine depth, thickness, and penetrability of each layer of the penetrated medium at each of the two locations. Impact points for Tests -02 and -06 were approximately 100 feet apart. The analysis assumed that an increase or decrease in rigid body penetrator deceleration occurred when the penetrator nose entered a layer. It further assumed that the penetrator rigid body deceleration was constant after the nose was completely into the layer and remained constant until the nose began to exit that layer to enter the next layer. It was necessary to idealize the deceleration-displacement curves so that the depths where rigid body deceleration changed and the displacements where deceleration remained constant could be determined.

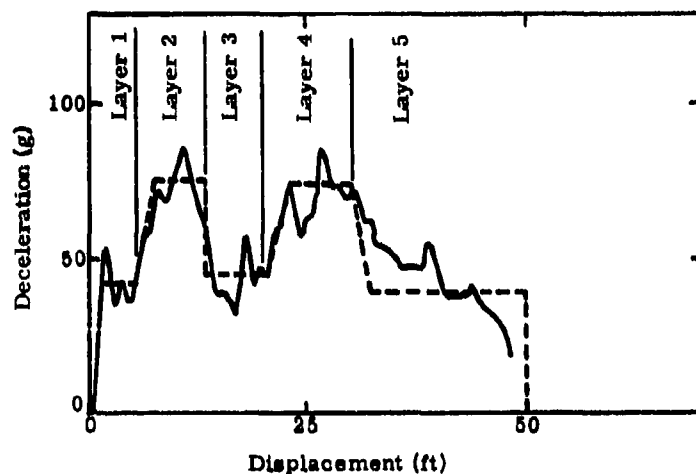


Figure 15. R-454014-02, real time, 200 Hz, LPF, deceleration-displacement with dashed line representing idealized curve.

The dashed line in Figure 15 is the idealized curve for Test -02. The thickness of the layers and their depths were determined using the above assumptions and the idealized curves. Projectile rigid body deceleration in each layer was then obtained from the idealized curves. The results are recorded in Table III. These results were then used for inputs into the Sandia Empirical Depth Prediction Equation,⁵ and "S" numbers (index of soil penetrability) were calculated. Calculated S numbers for each layer are recorded in Table III.

Once the S numbers were calculated for Test -02, they were used with the empirical depth prediction equation of Reference 5 to calculate depth of penetration for all of the other 8-in. gun fired tests. Then the S numbers calculated from Test -06 data were used to calculate depth of penetration for all of the other 8-in. gun fired tests. Table IV gives the results of the analysis and the percent difference between predicted depths using the experimentally determined S numbers and the actual measured depths. The results are well within the published 20 percent prediction accuracy stated for the prediction equation for all tests except -08 and -09. Since the penetration depths for these two tests were 86.1 and 99.0 feet, while the penetration depths for the tests used to determine S numbers (Tests -02 and -06) were only 48.3 and 67.9 feet, good correlation could only be expected if the last layer from Test -02 or -06 was of constant penetrability. The actual penetration results of Tests -08 and -09 indicate that there was a harder layer of material below the 68-foot depth.

TABLE III
Layer Data Derived From Deceleration-Displacement Curves

<u>Test No.</u>	<u>Layer No.</u>	<u>Thickness (ft)</u>	<u>Depth to Layer (ft)</u>	<u>Deceleration (g)</u>	<u>S Number</u>
454014-02	1	5	0	42	16.7
	2	8	5	77	9.6
	3	7	13	42	18.7
	4	10	20	73	11.6
	5	Assumed Infinite	30	37	26.0
454014-08	1	6	0	65	12.5
	2	6	6	105	8.1
	3	15	12	42	20.7
	4	7	27	84	11.7
	5	Assumed Infinite	34	50	21.0

TABLE IV

Penetration Prediction Using Tests -02 and -06 Deceleration Data

Test No.	Measured Depth/Velocity (ft/fps)	Calculated Depth -02 S Nos.	% Diff.	Calculated Depth -06 S Nos.	% Diff.
-01	73.2/583	80.6	9	70.6	4
-02	48.3/403	48.3	0*	46.2	5
-03	39.8/410	39.3	1	38.1	4
-04	65.7/529	67.6	3	60.3	9
-06	67.9/493	76.3	12	67.9	0*
-07	29.8/306	27.2	10	29.7	0.3
-08	99.0/650	142.2	44	119.6	21
-09	88.1/619	131.8	53	111.3	29

*S numbers were calculated from this test and therefore the calculated and measured depths are equal.

Conclusions

Data from all of the tests except 454014-01 are believed to be correct and to be a correct representation of the rigid body deceleration of the penetrators. The deceleration-time data recorded in Test 454014-01 is questionable because a burst of noise during the first 40 ms of penetration gave a false deceleration pulse on the record. Due to this apparent deceleration, the data could not be calibrated.

Analysis of the data derived from the Deceleration-Displacement curves of Tests 454014-02 and -06 indicates that five different layers of penetrability occur in the first 68 feet of depth. The indices of penetrability (S numbers) derived from the -02 and -06 data adequately describe the penetrability of the overall test area. Calculated penetration depths, using the Sandia Empirical Depth Penetration Equation and soil penetrability numbers derived from Tests 454014-02 and -06 data, compared with actual measured depths within less than 12 percent for all tests where penetrator depths did not exceed the 68-foot depth for which deceleration data were available. For the two tests with penetrator depths greater than 68-foot (-08 and -09) calculated depths were greater than measured depths by 21 to 53 percent. This large variation leads to the conclusion that another, less penetrable layer, exists below the 68-foot level.

References

1. T. D. Stong, Major, USA, Earth Penetrating Weapons, Defense Nuclear Agency, Washington, D.C., Project Officer's Progress Report No. 1, March 14, 1974.
2. G. A. Carlson, Stress Wave Measurements in Earth Penetrator Experiments, Sandia Laboratories, Albuquerque, New Mexico, SAND74-0257, November 1974.
3. J. G. Jackson, Jr., Physical Property and Dynamic Compressibility Analysis of the Watching Hills Blast Range, U. S. Army Engineer Waterways Experiment Station, Technical Report S-73-4, April 1972.
4. W. J. Patterson and C. W. Young, Physical Properties of Solid Tangent Ogive Shapes, Sandia Laboratories, Albuquerque, New Mexico, SC-TM-68-2810, December 1972.
5. C. W. Young, Empirical Equations for Predicting Penetration Performance in Layered Earth Materials for Complex Penetrator Configurations, Sandia Laboratories, Albuquerque, New Mexico, SC-DR-72-0523, December 1972.

APPENDIX A

200 Hz Filtered Processed Data

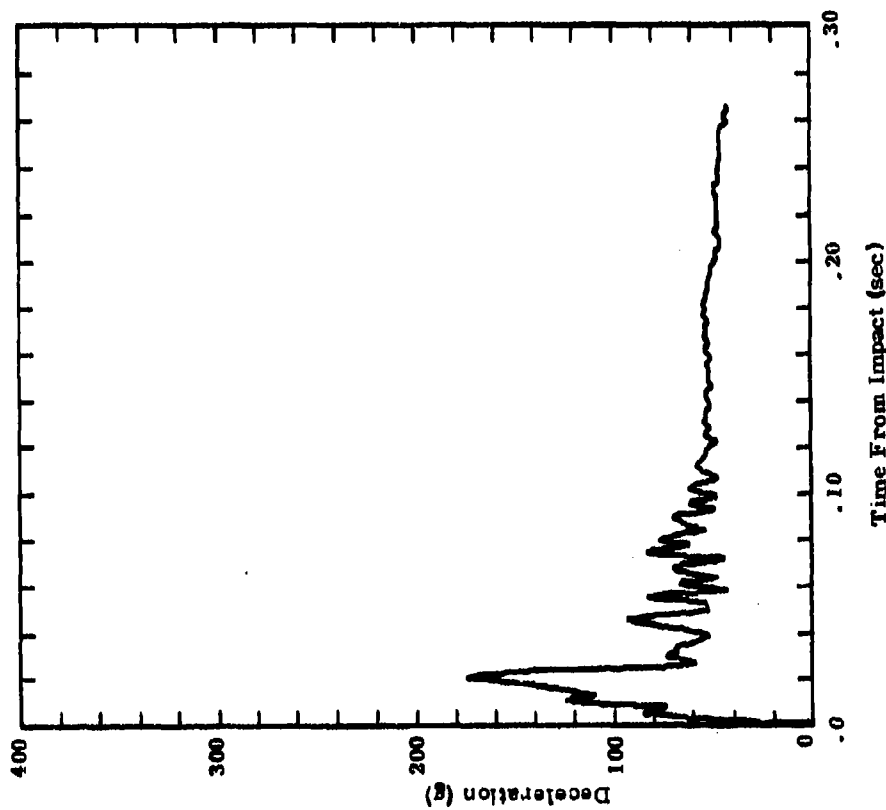


Figure A-1. R454014-01 DNA Canadian Test, test date, 7/13/74,
low g accelerometer (memory calibrated) 200 Hz LPF
deceleration vs. time

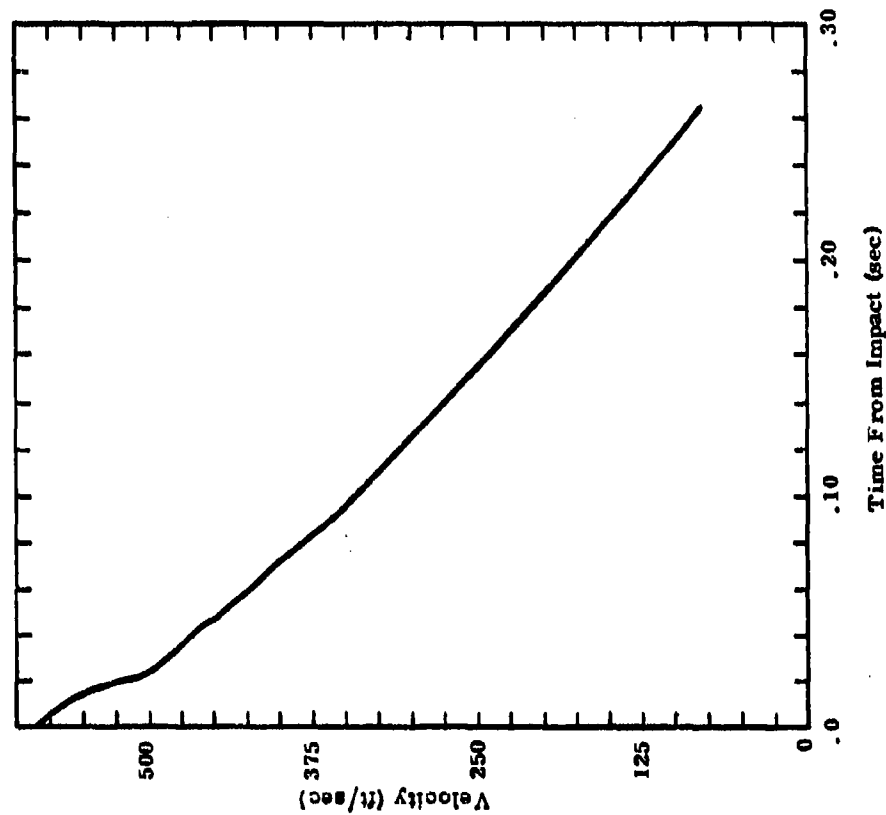


Figure A-2. R454014-01 DNA Canadian Test, test date, 7/13/74,
low g accelerometer (memory calibrated) 200 Hz LPF
velocity vs. time

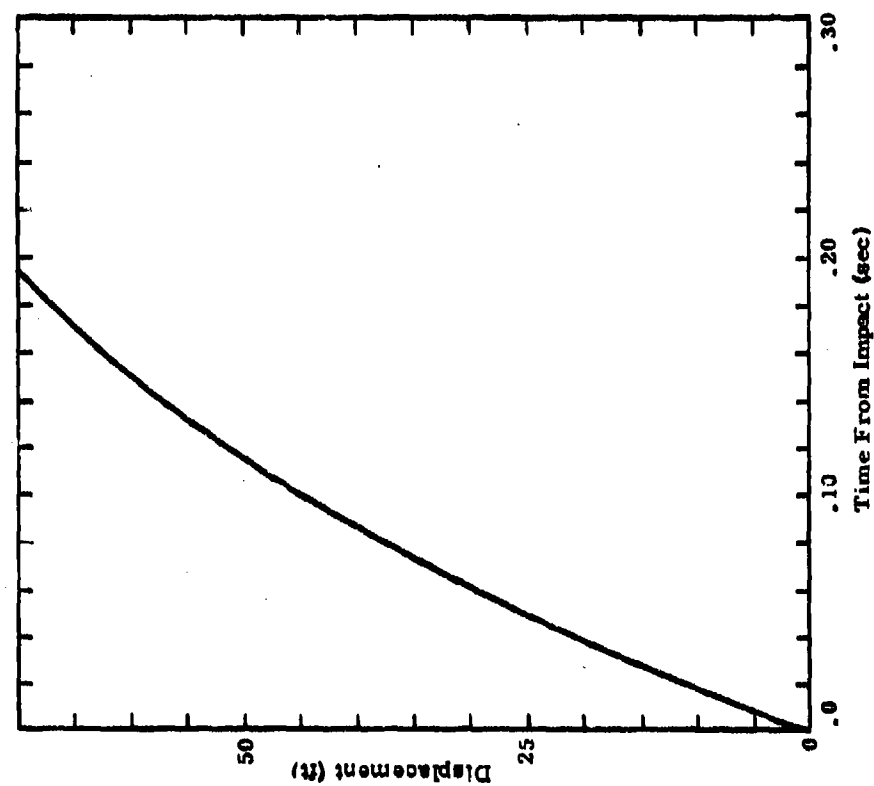


Figure A-3. R45401-01 DNA Canadian Test, test date, 7/13/74
low g accelerometer (memory calibrated) 200 Hz LPF
displacement vs. time

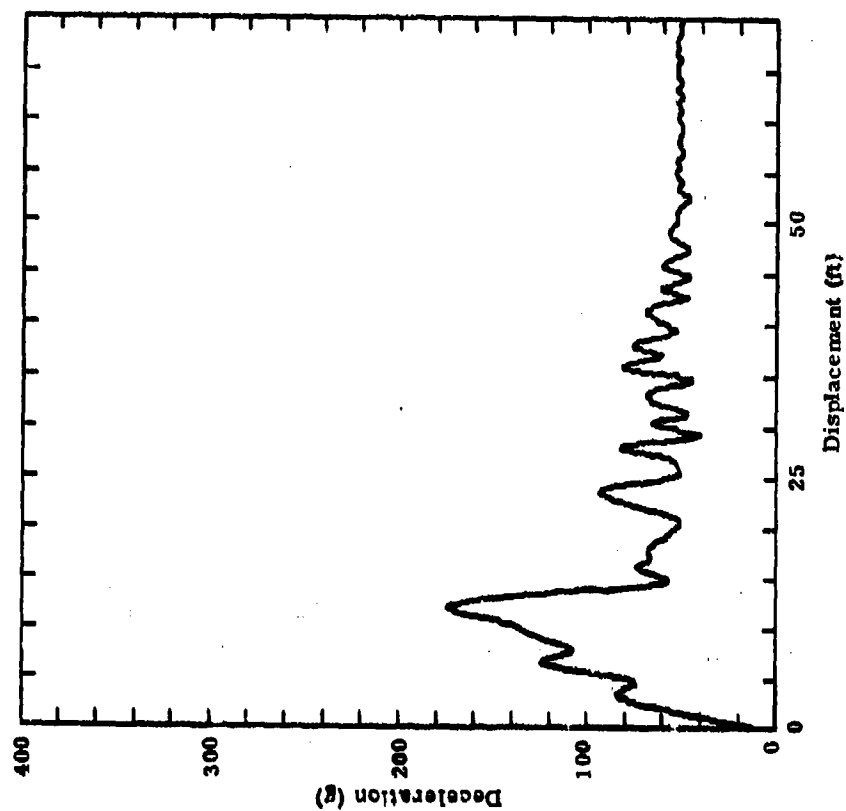


Figure A-4. R454014-01 DNA Canadian Test, test date, 7/13/74,
low g accelerometer (memory calibrated) 200 Hz LPF
deceleration vs. displacement

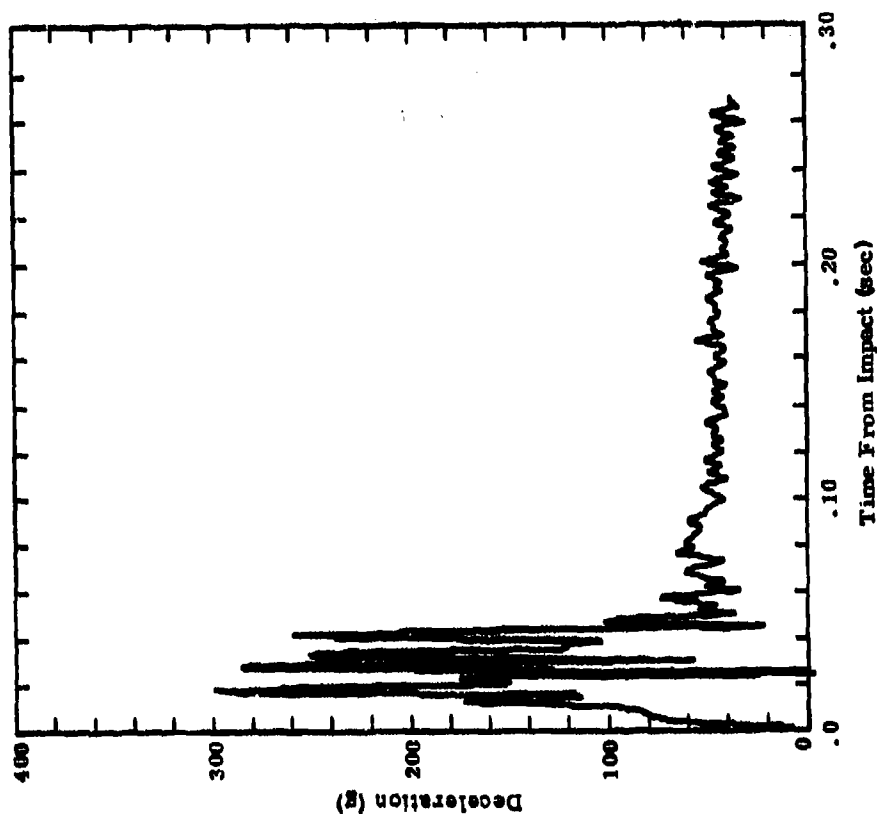


Figure A-5. R454014-01 DNA Canadian Test, test date, 7/13/74,
low g accelerometer (memory calibrated) 200 Hz LPF
Velocity vs. displacement

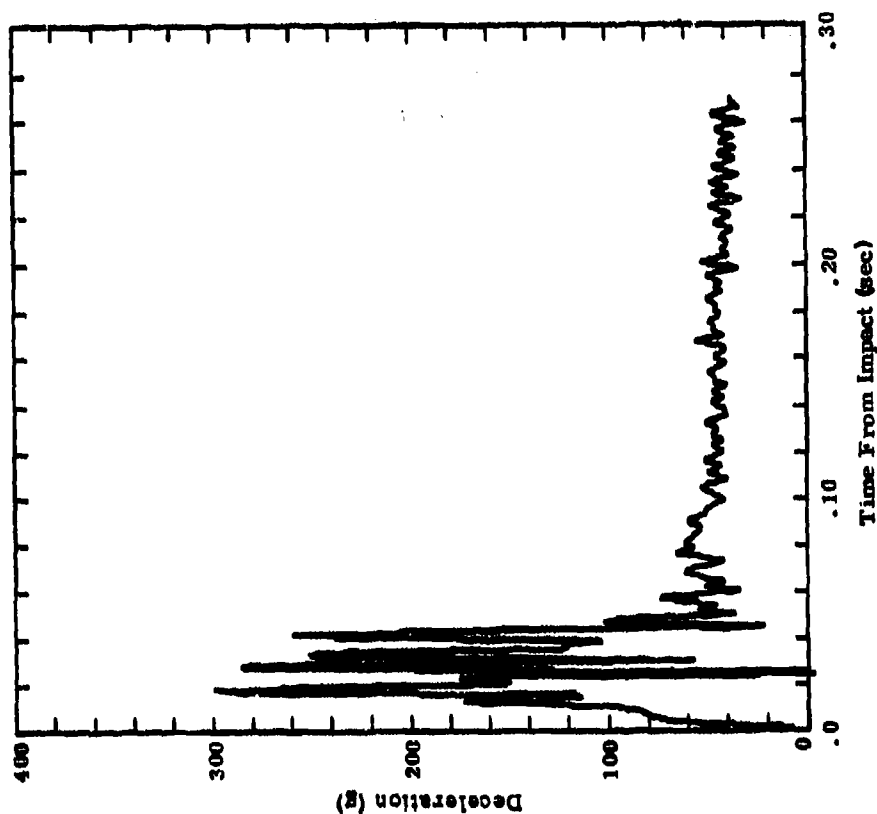


Figure A-6. R454014-01 DNA Canadian Test, test date, 7/13/74
low g accelerometer, 10.5 kHz (real time calibrated)
200 Hz LPF, deceleration vs. time

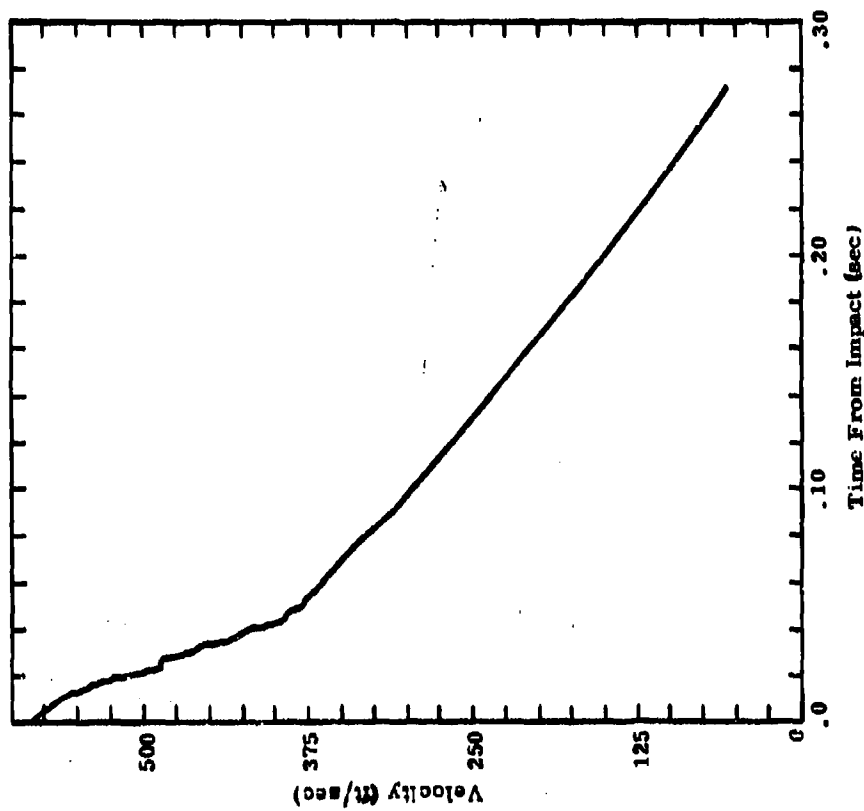


Figure A-7. B454014-01 DNA Canadian Test, test date, 7/13/74, low g accelerometer, 10.5 kHz (real time calibrated) 200 Hz L.P.F., velocity vs. time

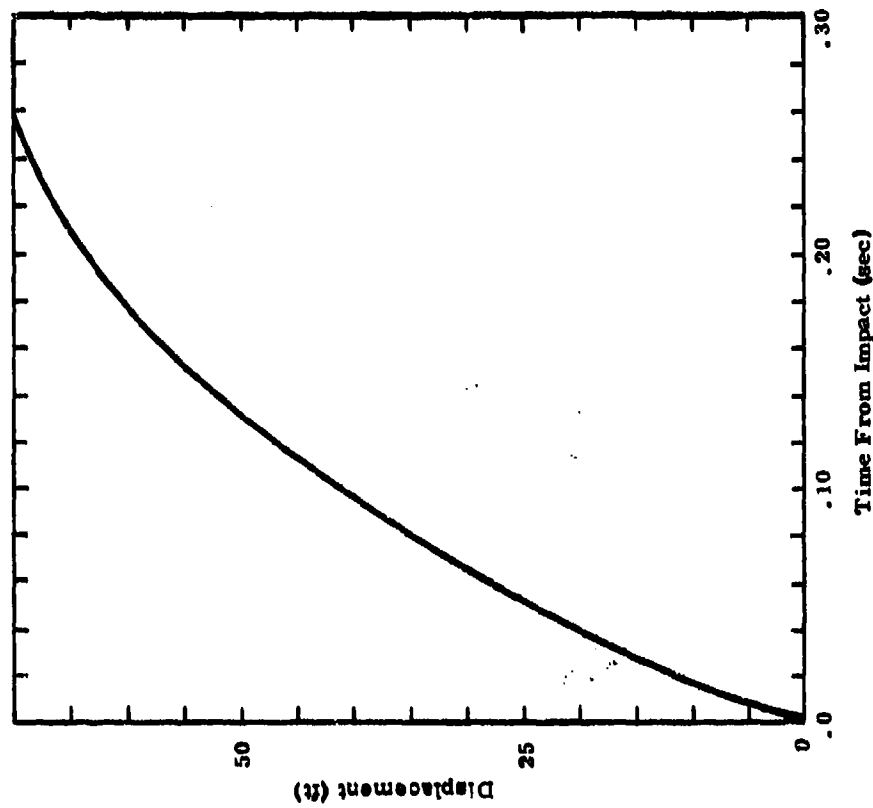


Figure A-8. B454014-01 DNA Canadian Test, test date, 7/13/74, low g accelerometer, 10.5 kHz (real time calibrated) 200 Hz L.P.F., displacement vs. time

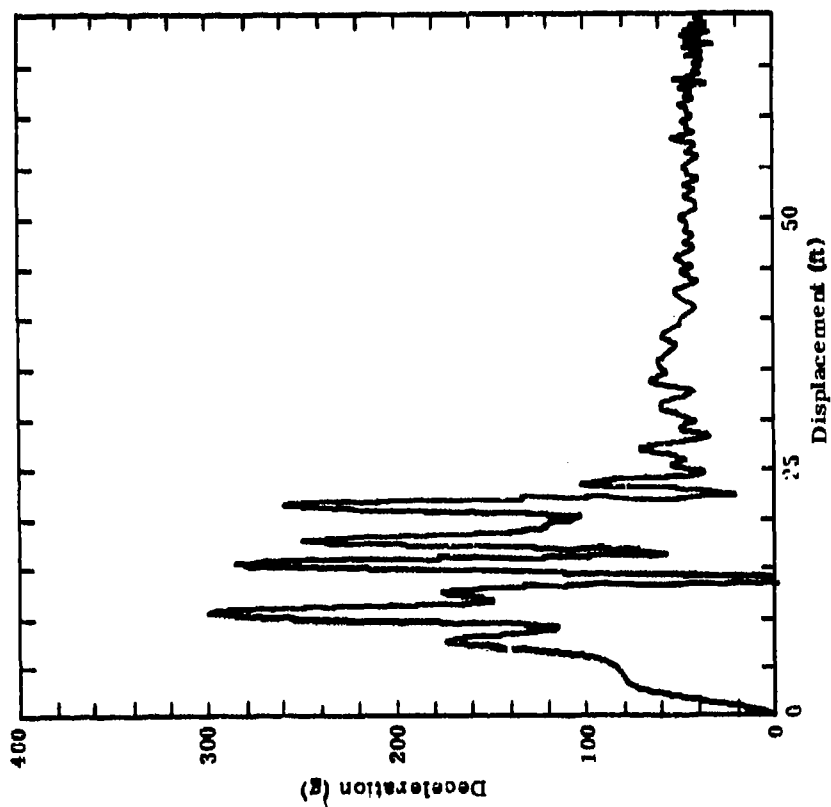


Figure A-9. R454014-01 DNA Canadian Test, test date, 7/13/74,
low g accelerometer, 10.5 kHz (real time calibrated)
200 Hz LPF, deceleration vs. displacement

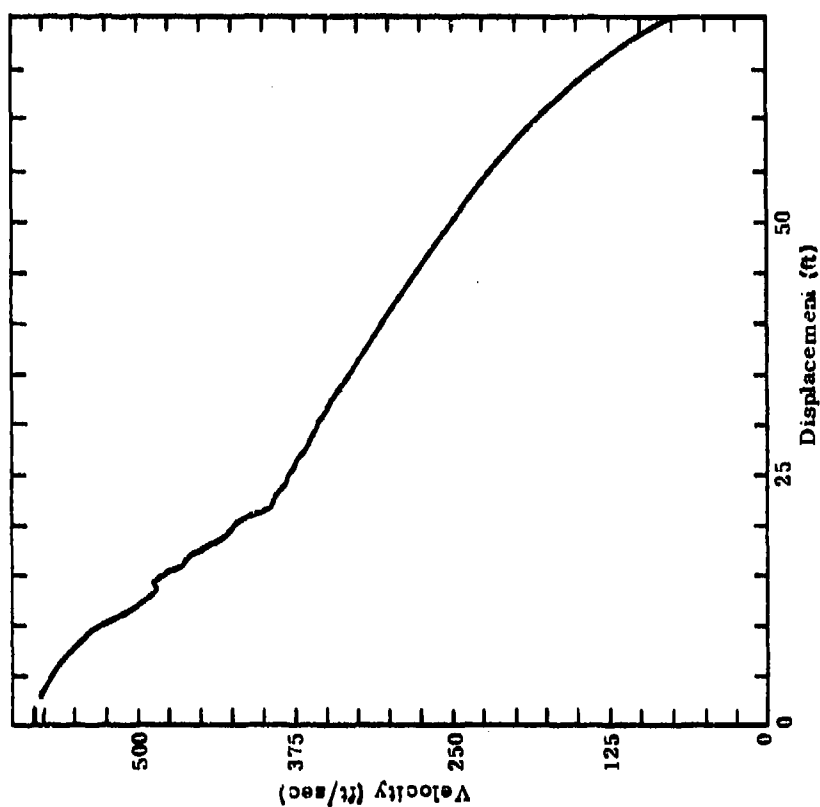


Figure A-10. R454014-01 DNA Canadian Test, test date, 7/13/74,
low g accelerometer, 10.5 kHz (real time calibrated)
200 Hz LPF, velocity vs. displacement

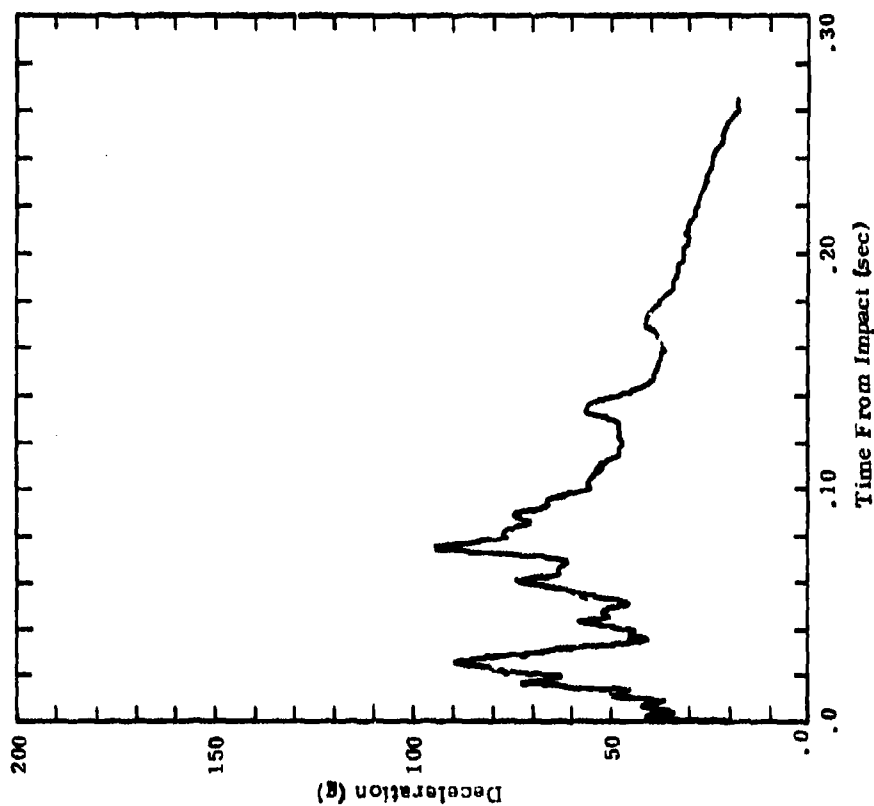


Figure A-11. R454014-02 DNA Canadian Test, test date, 7/13/74.
low g accelerometer (memory calibrated) 200 Hz LPF
deceleration vs. time

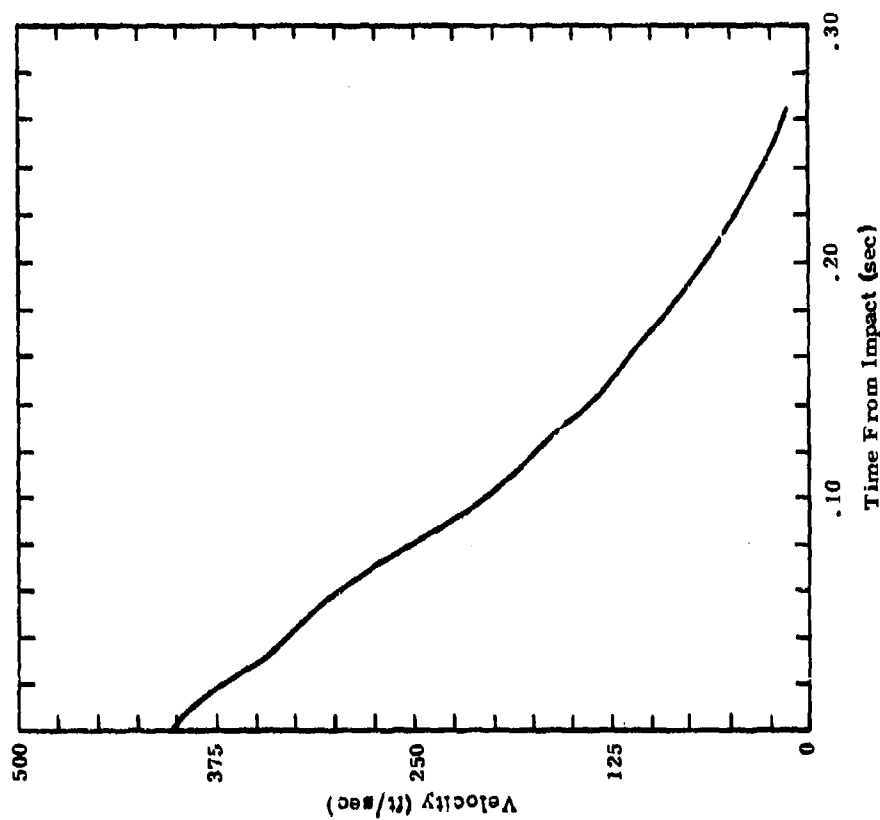


Figure A-12. R454014-02 DNA Canadian Test, test date, 7/13/74.
low g accelerometer (memory calibrated) 200 Hz LPF
velocity vs. time

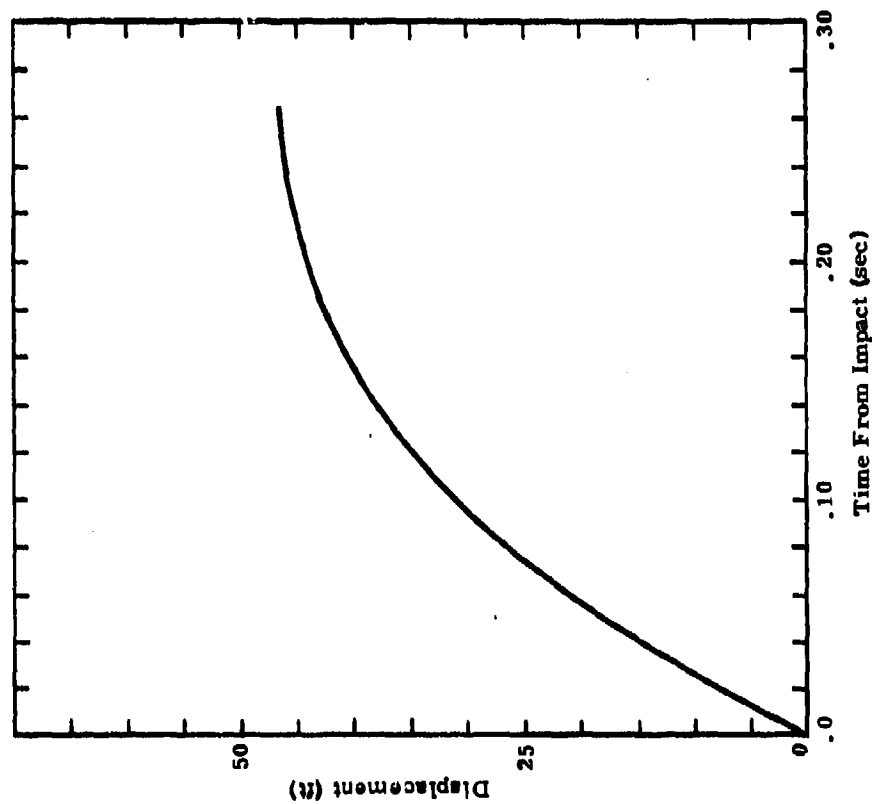


Figure A-13. R454014-02 DNA Canadian Test, test date, 7/13/74.
low g accelerometer (memory calibrated) 200 Hz LPF
displacement vs. time

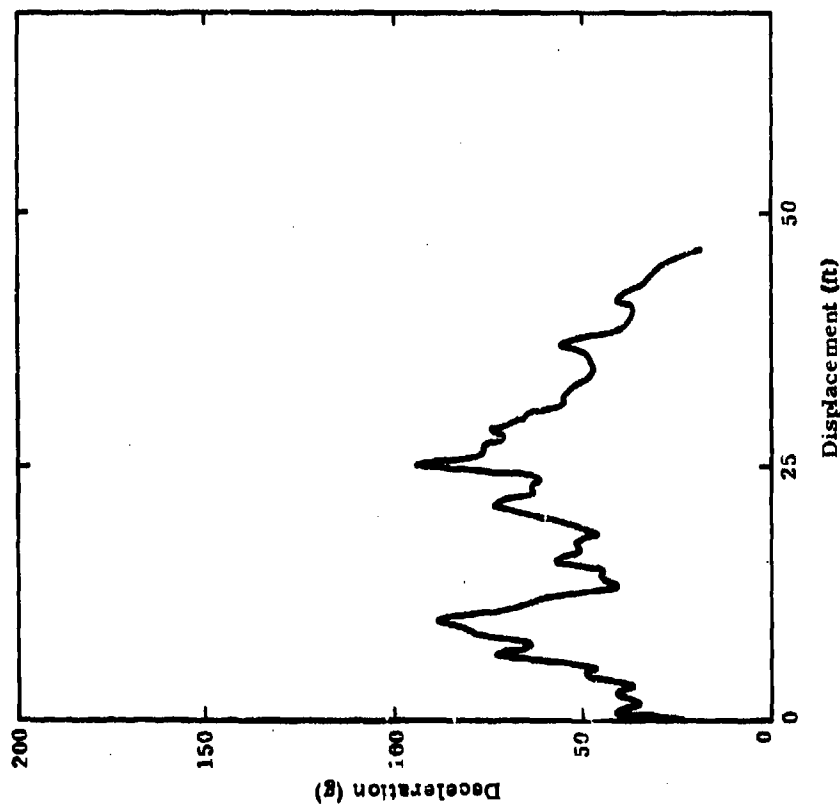


Figure A-14. R454014-02 DNA Canadian Test, test date, 7/13/74.
low g accelerometer (memory calibrated) 200 Hz LPF.
deceleration vs. displacement

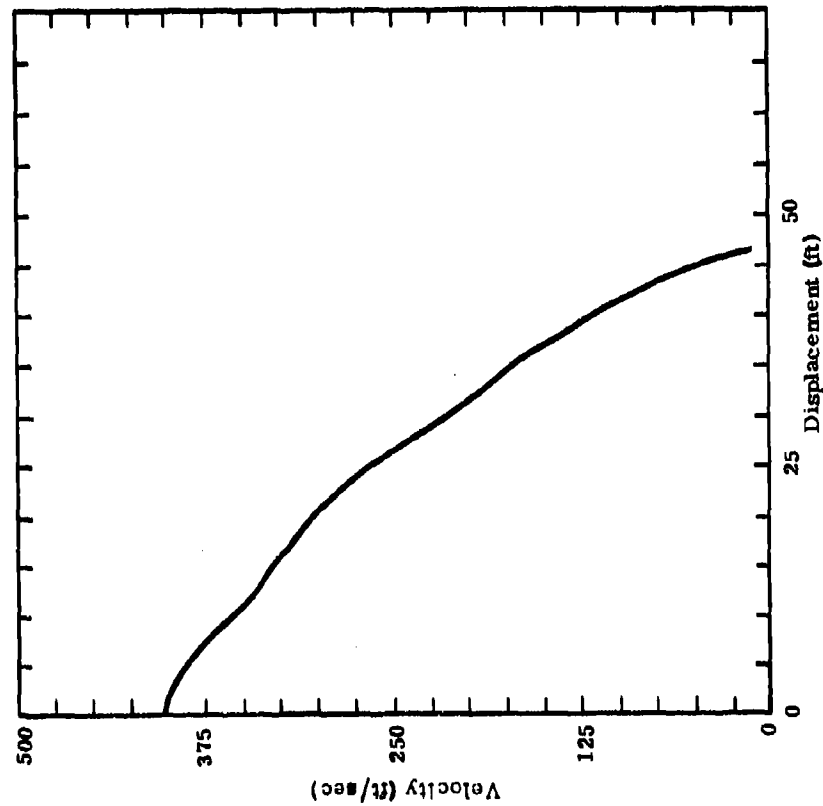


Figure A-15. R454014-02 DNA Canadian Test, test date, 7/13/74, low g accelerometer (memory calibrated) 200 Hz LPF velocity vs. displacement

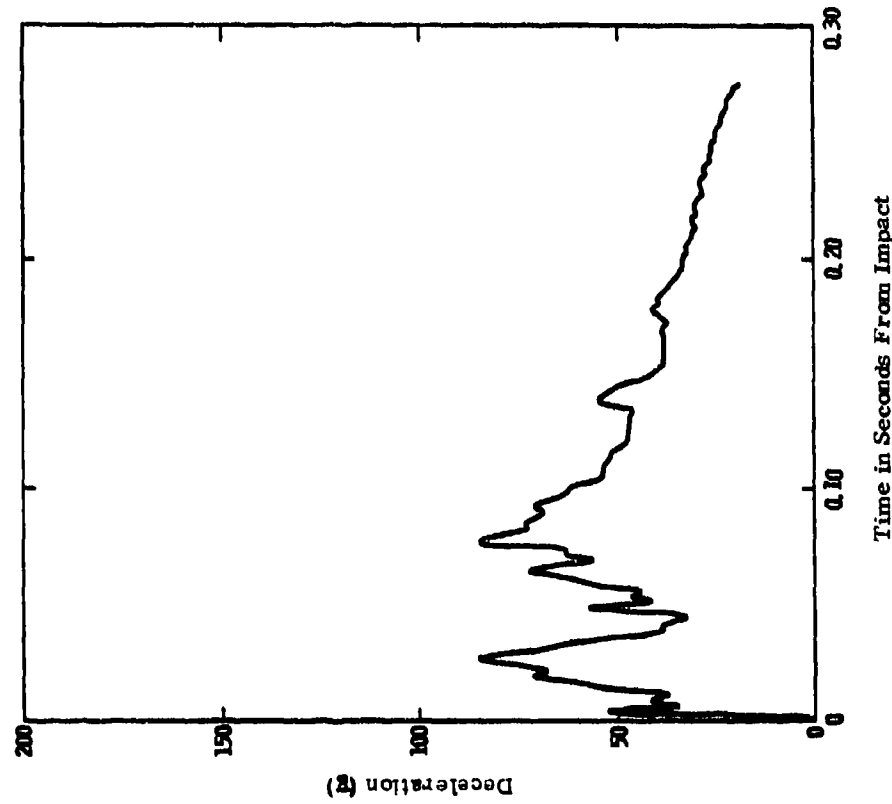


Figure A-16. R454014-02 DNA Canadian Test, test date, 7/13/74, low g accelerometer, 10.5 kHz (real time calibrated) 200 Hz LPF deceleration vs. time

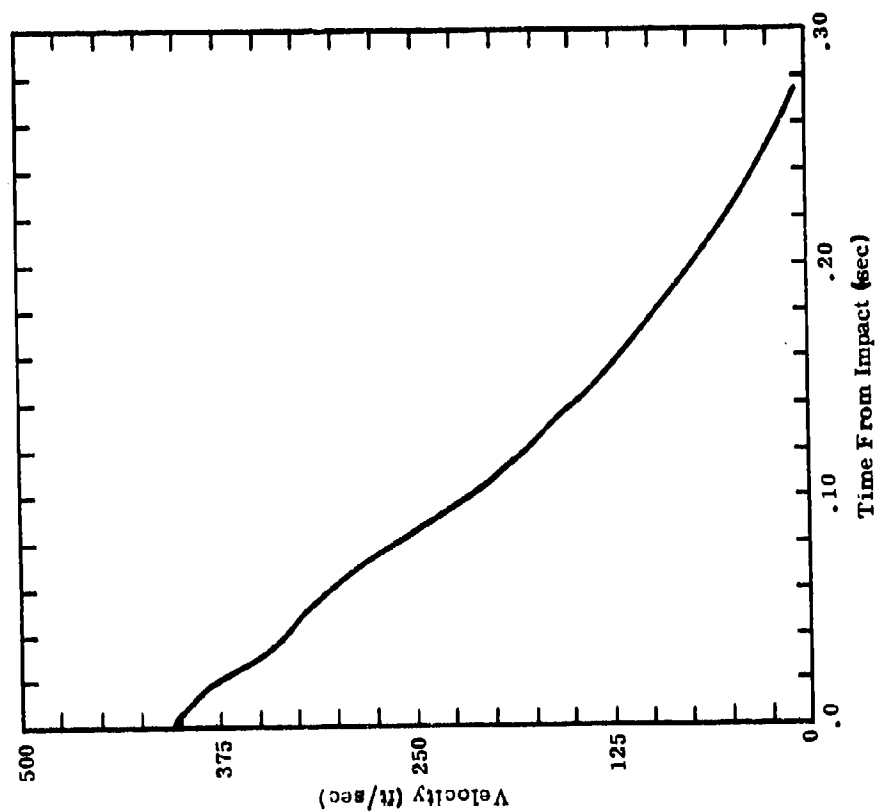


Figure A-17. R454014-02 DNA Canadian Test, test date, 7/13/74,
low g accelerometer, 10.5 kHz (real time calibrated)
200 Hz LPF, velocity vs. time

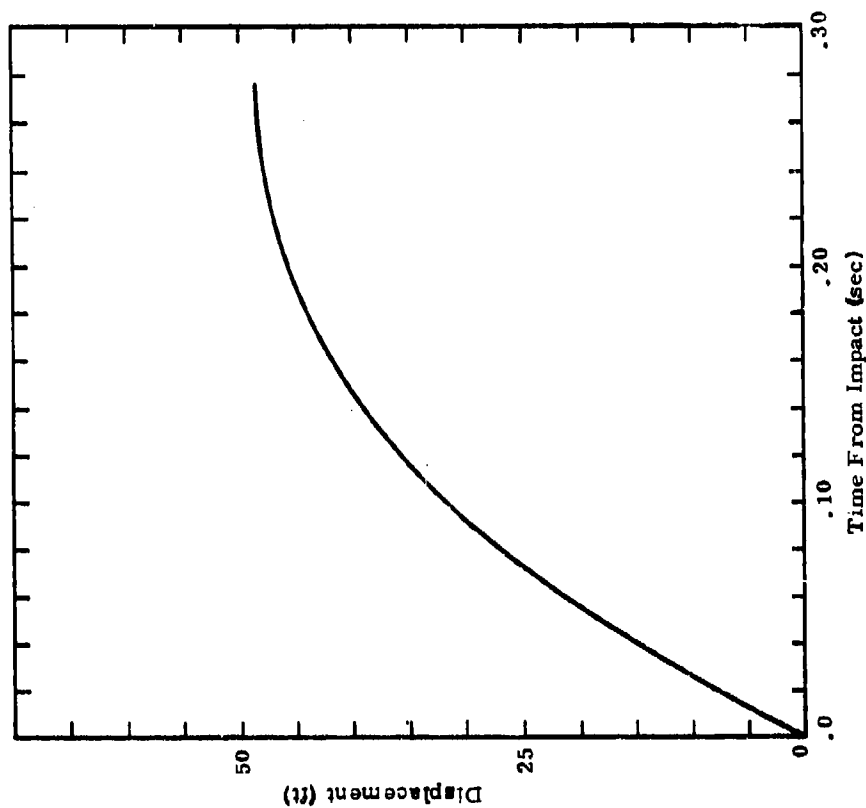


Figure A-18. R454014-02 DNA Canadian Test, test date, 7/13/74,
low g accelerometer, 10.5 kHz (real time calibrated)
200 Hz LPF, displacement vs. time

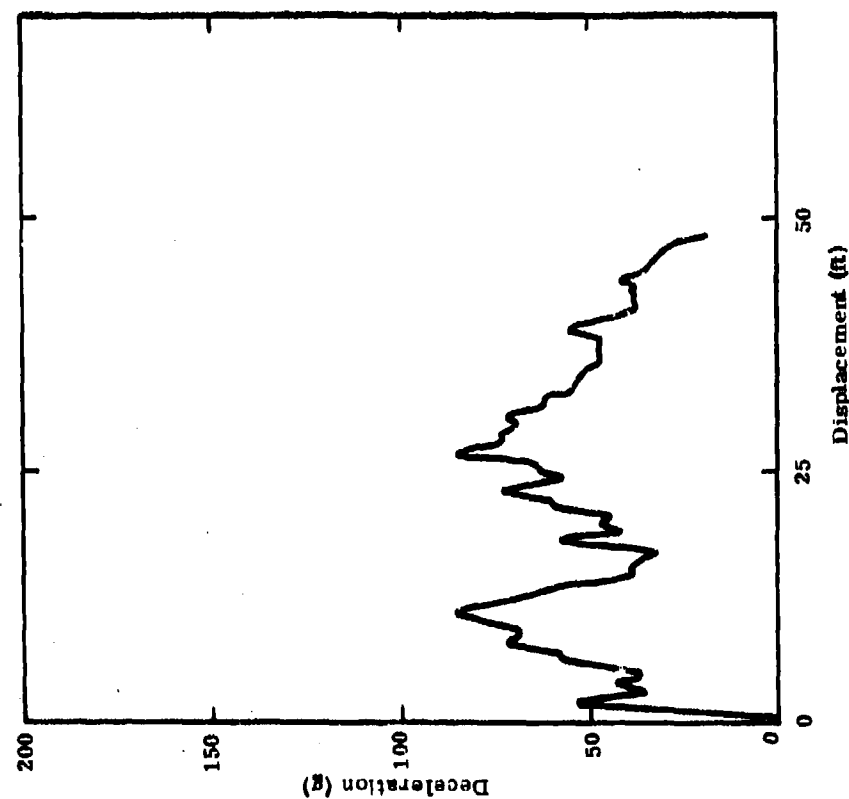


Figure 19. R454014-02 DNA Canadian Test, test date, 7/13/74,
low g accelerometer, 10.5 kHz (real time calibrated)
200 Hz LPF, deceleration vs. displacement

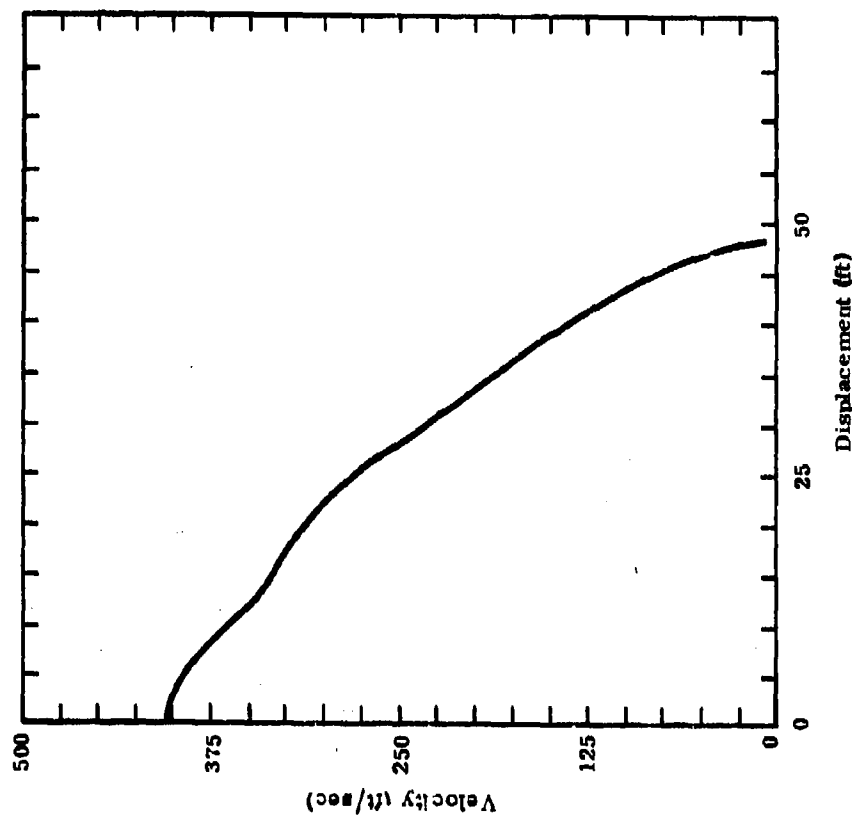


Figure 20. R454014-02 DNA Canadian Test, test date, 7/13/74,
low g accelerometer, 10.5 kHz (real time calibrated)
200 Hz LPF, velocity vs. displacement

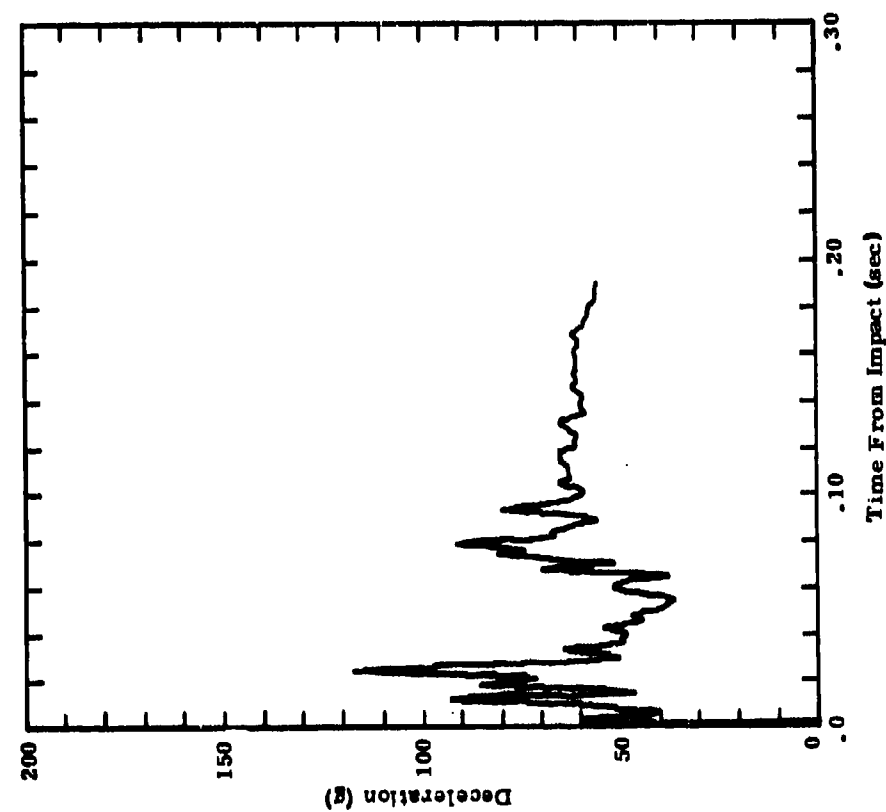


Figure A-21. R454014-06 DNA Canadian Test, test date, 7/15/74,
low g accelerometer (memory calibrated) 200 Hz
LPT, deceleration vs. time

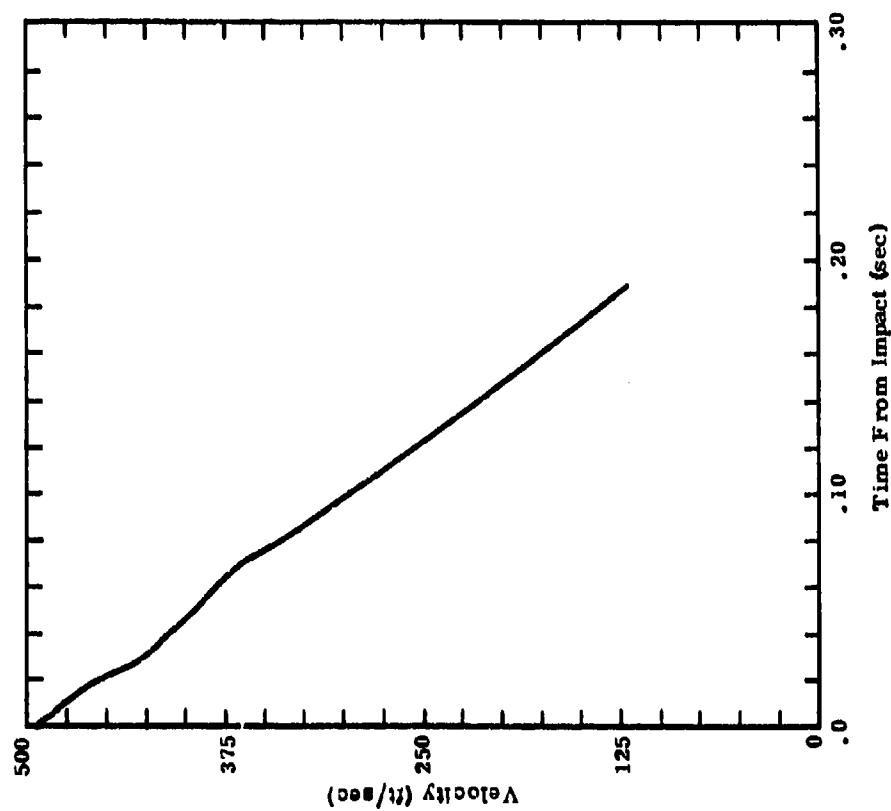


Figure A-22. R454014-06 DNA Canadian Test, test date, 7/15/74,
low g accelerometer (memory calibrated) 200 Hz LPT
velocity vs. time

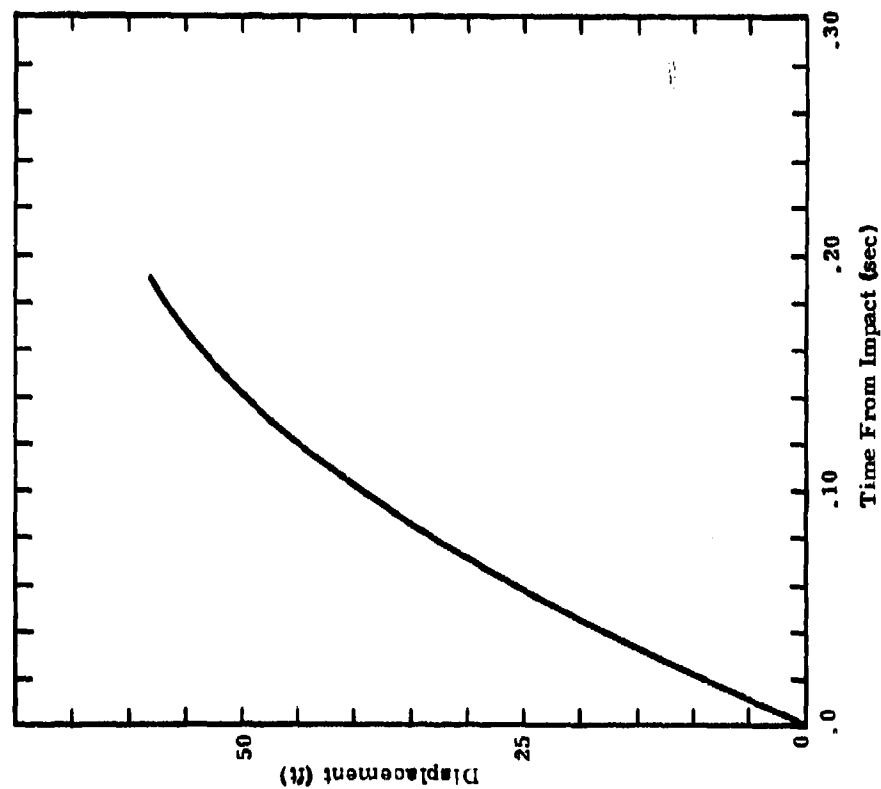


Figure 23. R454014-06 DNA Canadian Test, test date, 7/15/74, low g accelerometer (memory calibrated) 200 Hz LPF displacement vs. time

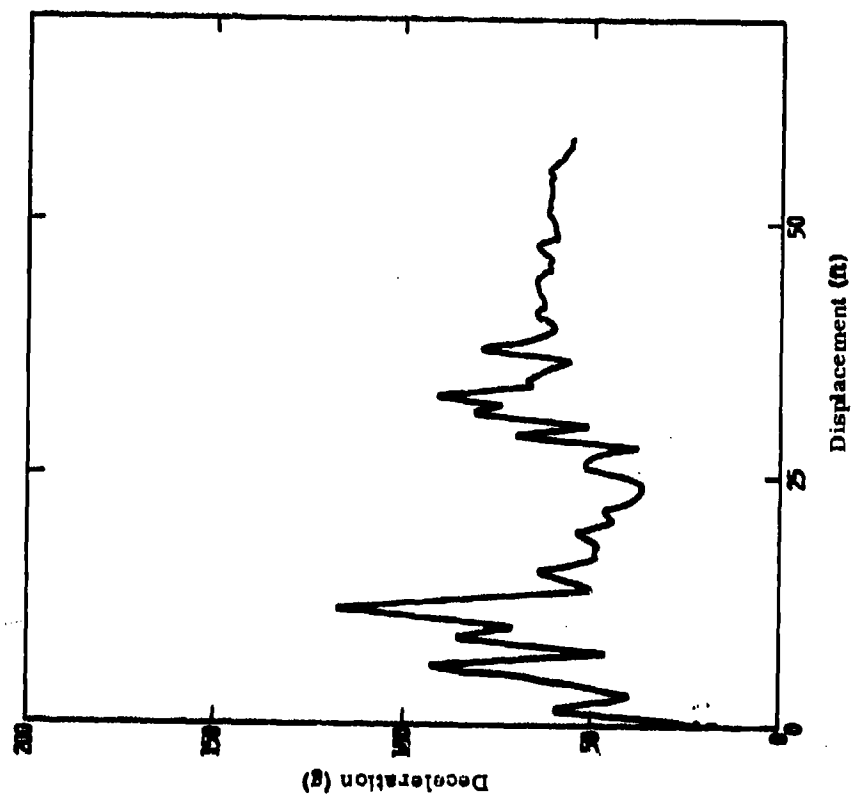


Figure 24. R454014-06 DNA Canadian Test, test date, 7/15/74, low g accelerometer (memory calibrated) 200 Hz LPF deceleration vs. displacement

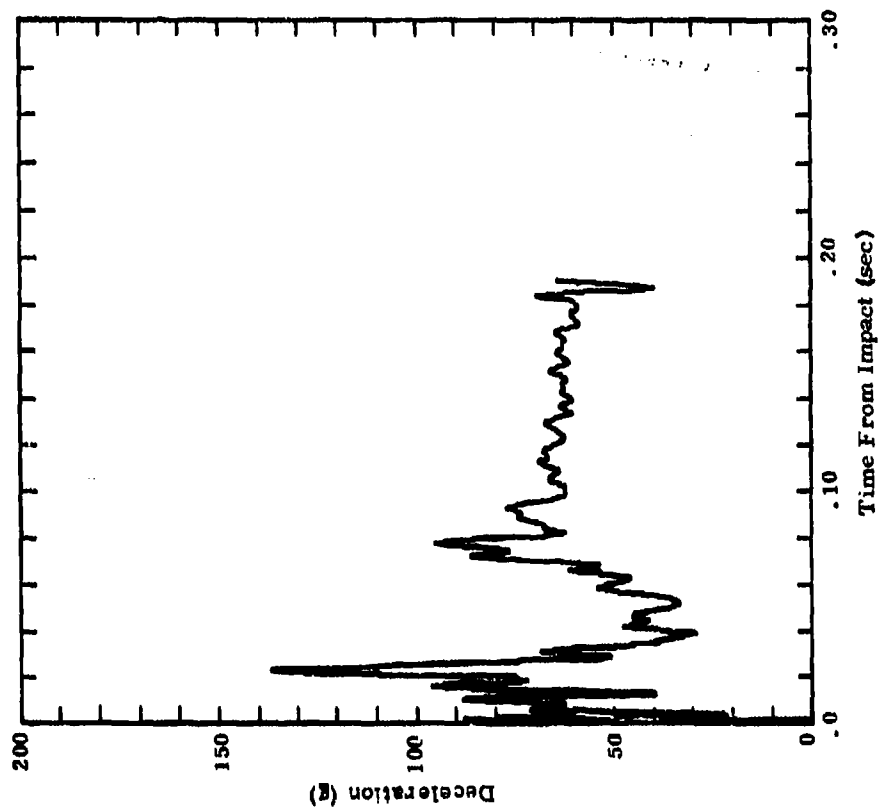


Figure A-25. R454014-06 DNA Canadian Test, test date, 7/15/74, low g accelerometer (memory calibrated) 200 Hz LPF velocity vs. displacement

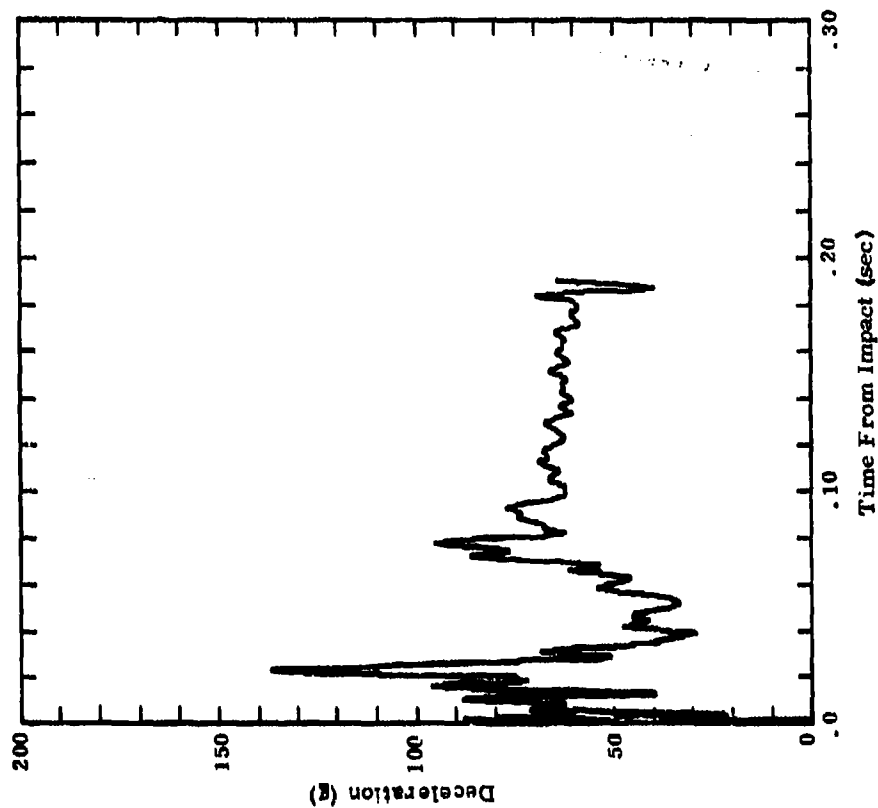


Figure A-26. DNA Canadian Test, test date, 7/15/74, low g accelerometer, 10.5 kHz (real time uncorrected) 200 Hz LPF, deceleration vs. time

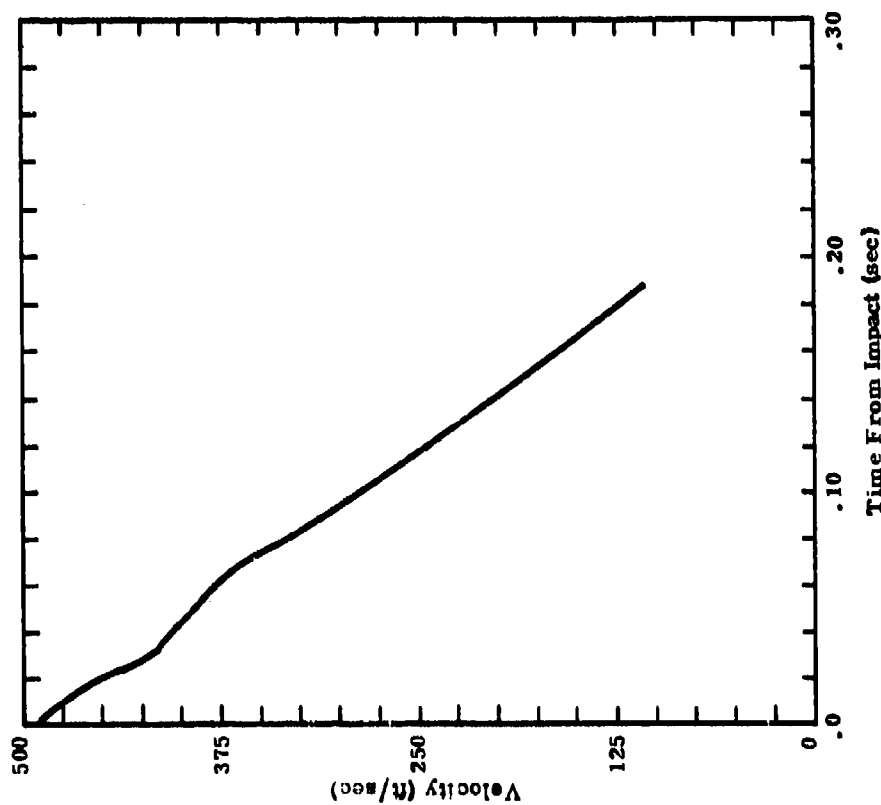


Figure A-27. R454014-06 DNA Canadian Test, test date, 7/15/74,
low g accelerometer, 10.5 kHz (real time uncorrected)
200 Hz L.P.F., velocity vs. time

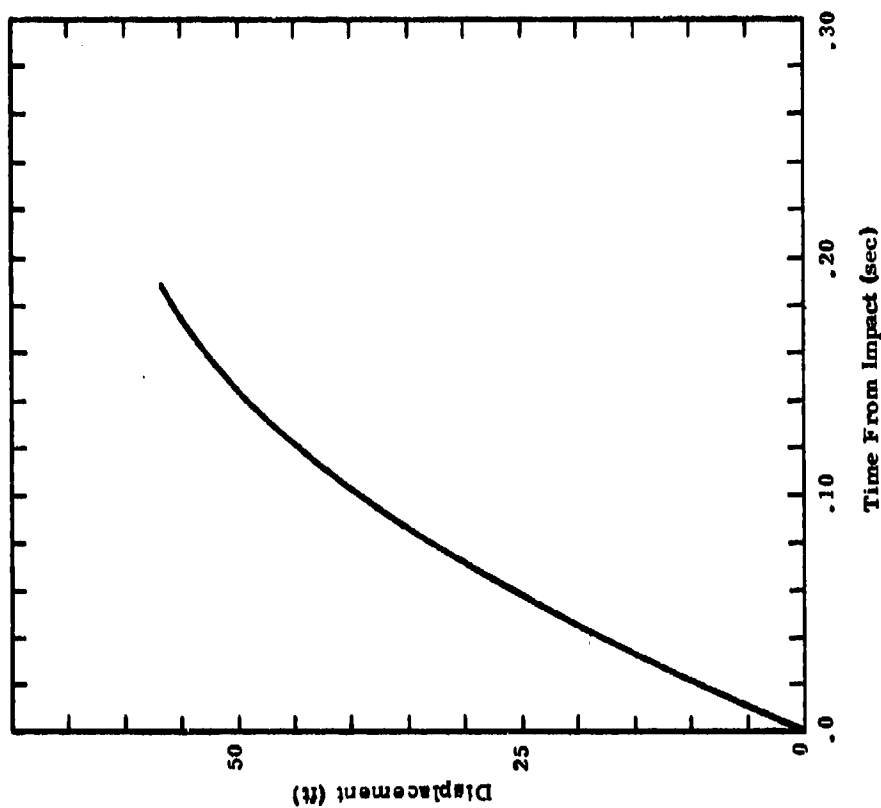


Figure A-28. R454014-06 DNA Canadian Test, test date, 7/15/74,
low g accelerometer, 10.5 kHz (real time uncorrected)
200 Hz L.P.F., displacement vs. time

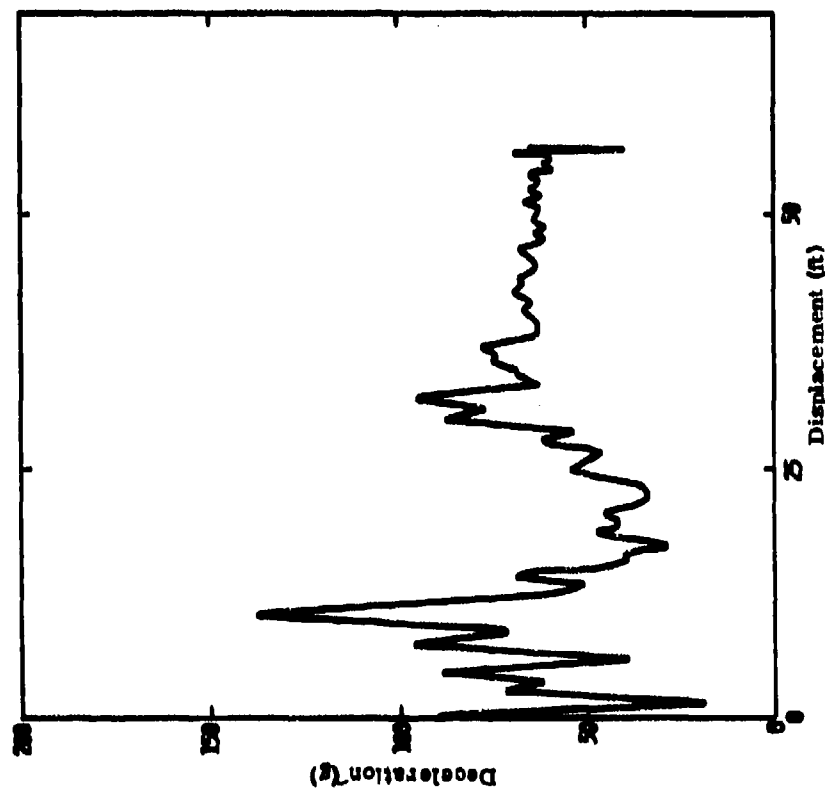


Figure 29. R454014-06 DNA Canadian Test, test date, 7/15/74,
low g accelerometer, 10.5 kHz (real time uncorrected)
200 Hz LPF, deceleration vs. displacement

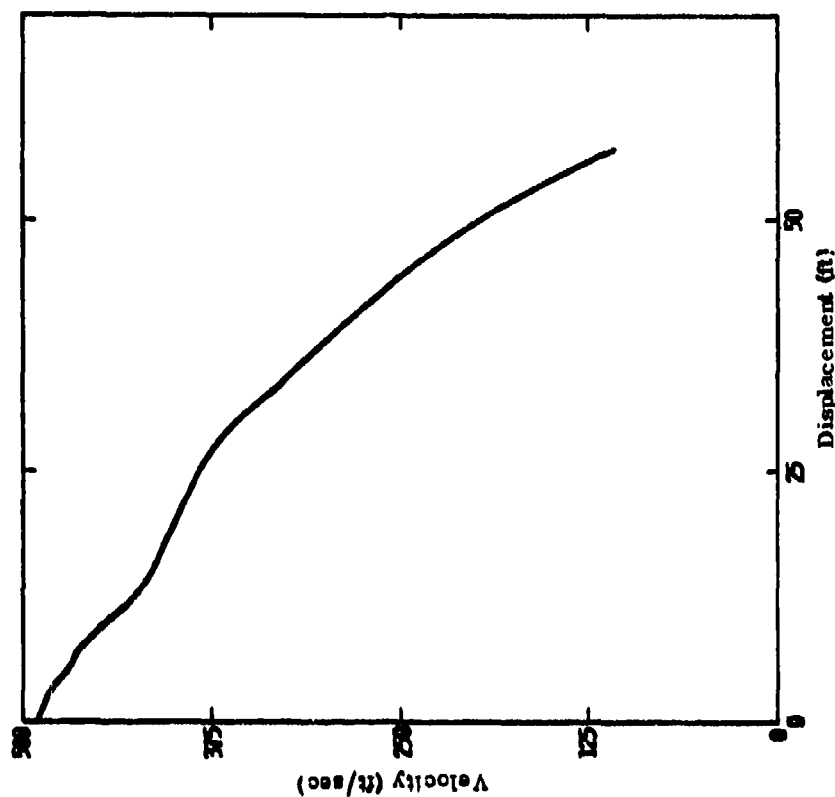


Figure 30. R454014-06 DNA Canadian Test, test date, 7/15/74,
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200 Hz LPF, velocity vs. displacement

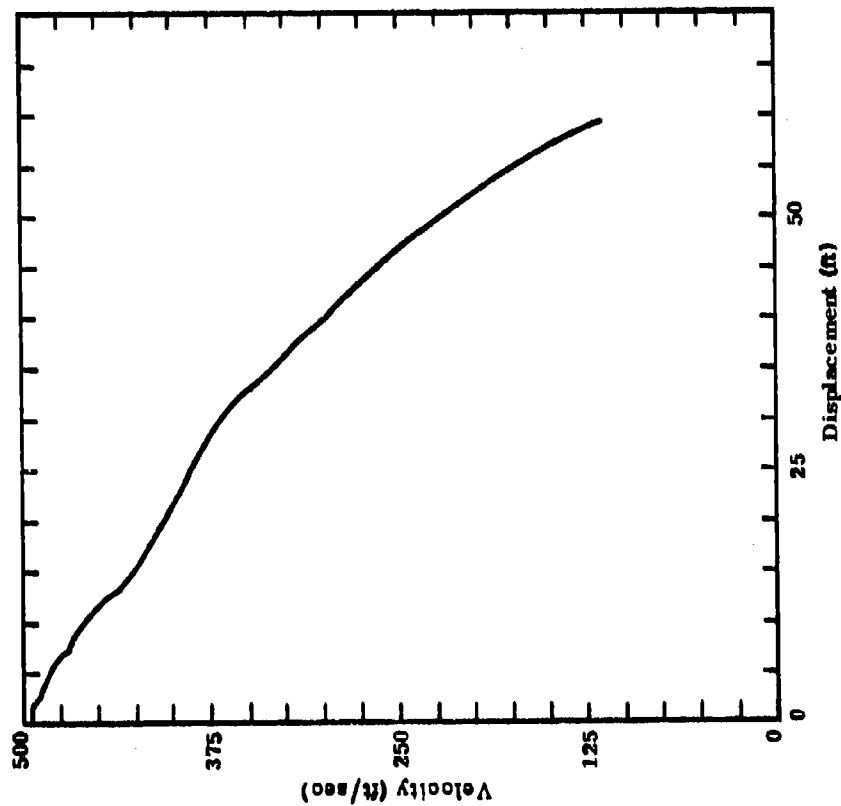


Figure A-31. R454014-06 DNA Canadian Test, test date, 7/15/74, low g accelerometer (memory calibrated) velocity vs. displacement

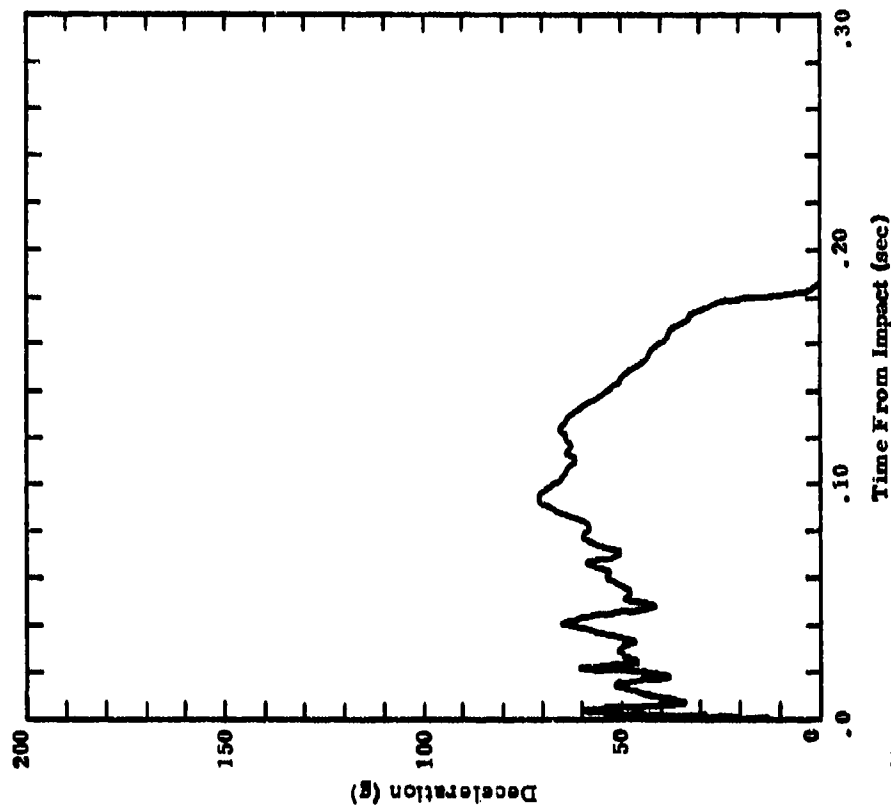


Figure A-32. R454014-07 DNA Canadian Test, test date, 7/16/74, low g accelerometer (memory calibrated) 200 Hz LPF, deceleration vs. time

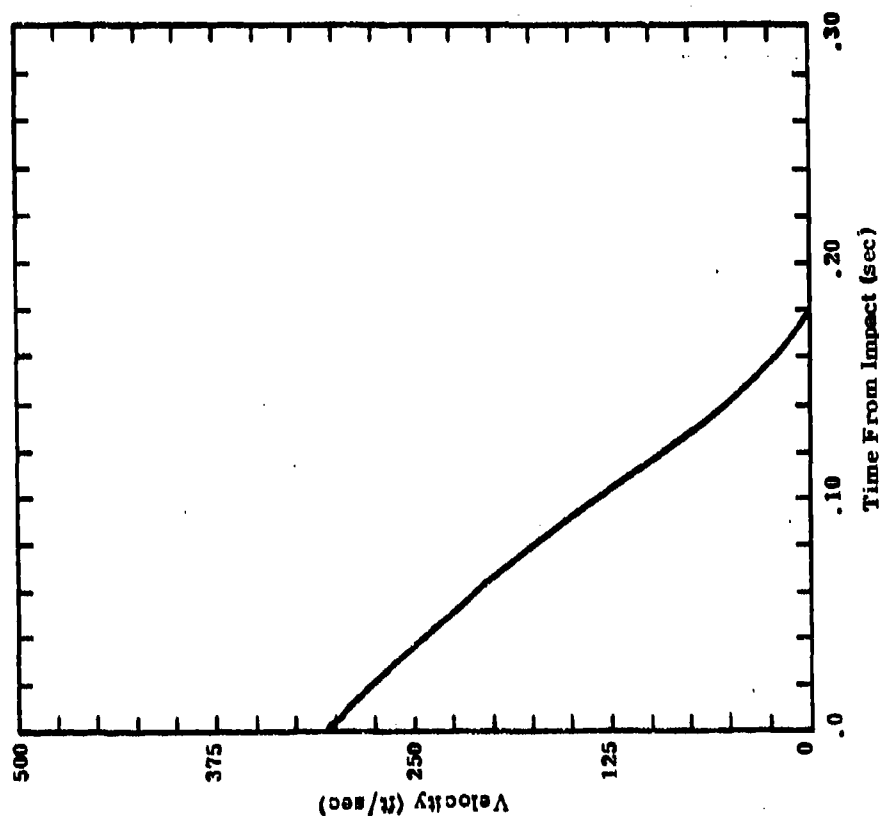


Figure A-33. R454014-07 DNA Canadian Test, test date, 7/16/74, low g accelerometer (memory calibrated) 200 Hz LPF, velocity vs. time

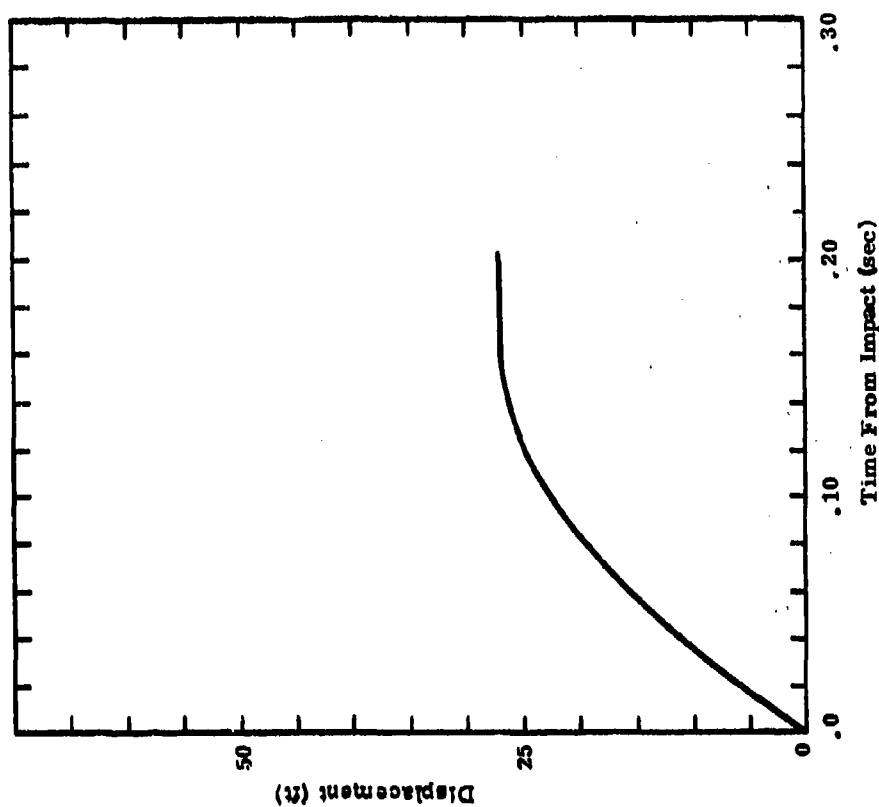


Figure A-34. R454014-07 DNA Canadian Test, test date, 7/16/74, low g accelerometer (memory calibrated) 200 Hz LPF, displacement vs. time

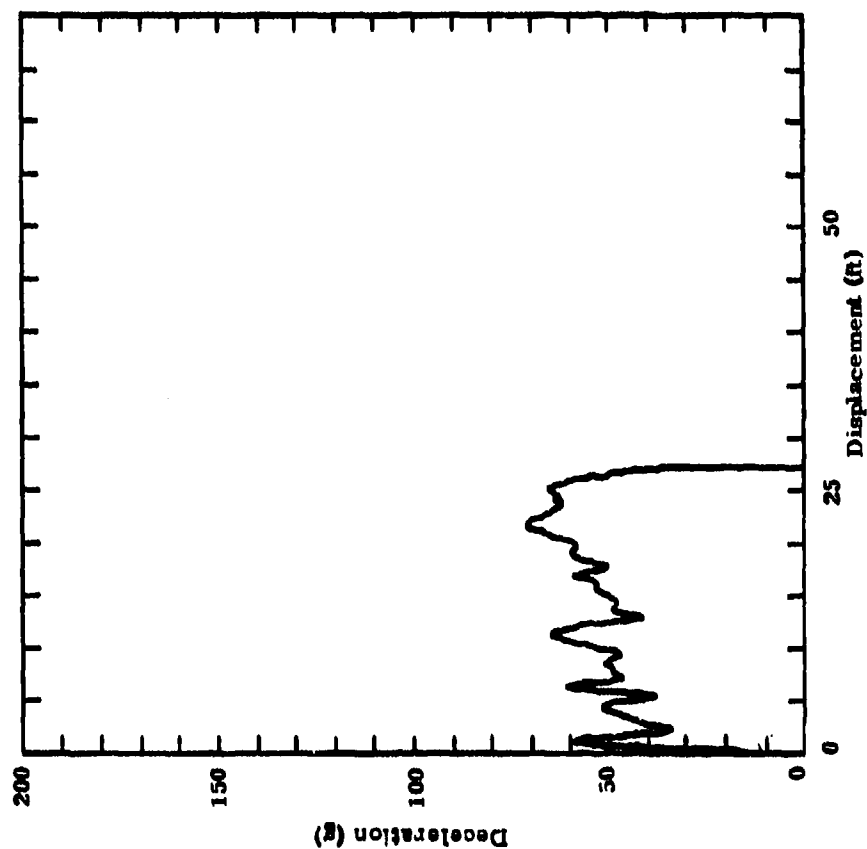


Figure A-35. R454014-07 DNA Canadian Test, test date, 7/16/74,
low g accelerometer (memory calibrated) 200 Hz LPF
deceleration vs. displacement

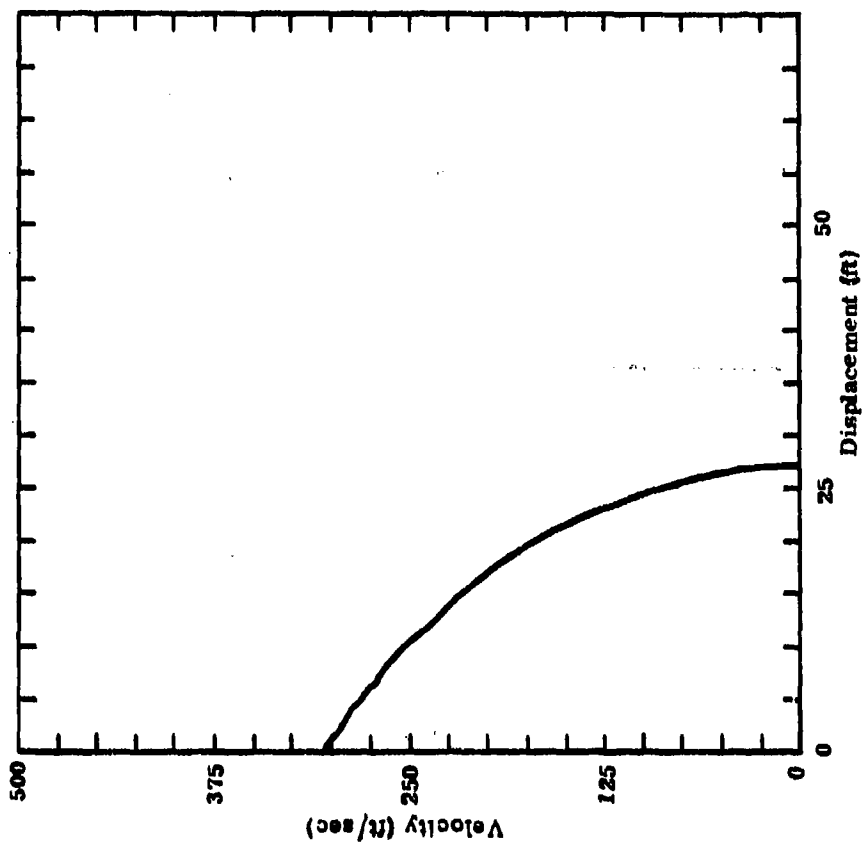


Figure A-36. R454014-07 DNA Canadian Test, test date, 7/16/74
low g accelerometer (memory calibrated) 200 Hz LPF
velocity vs. displacement

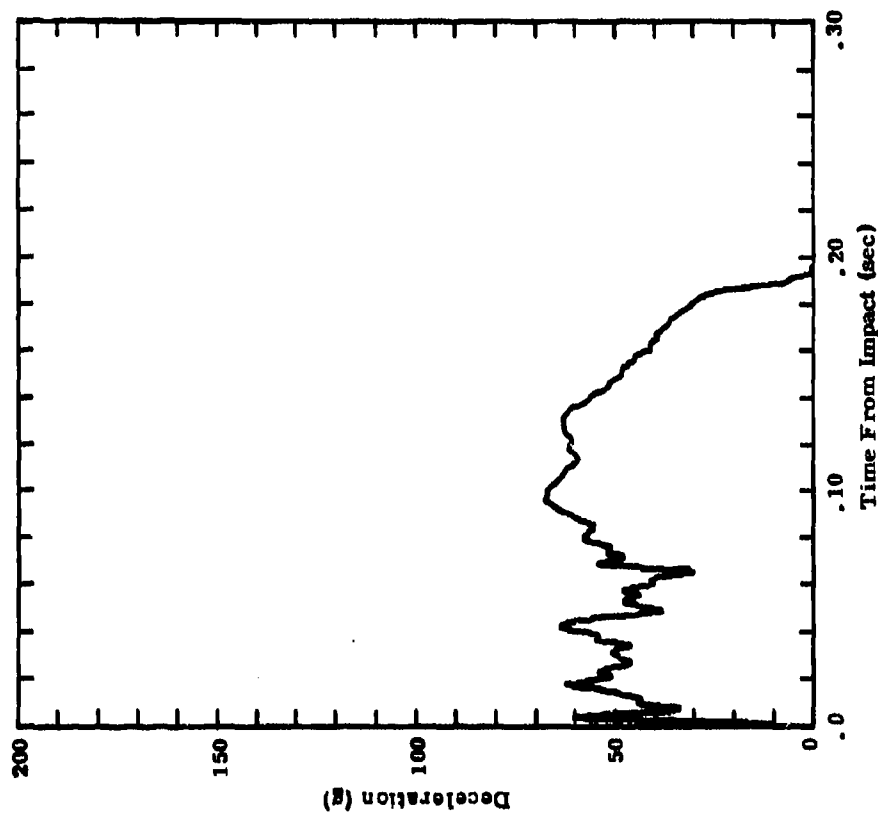


Figure A-37. R454014-07 DNA Canadian Test, test date, 7/16/74,
low g accelerometer, 10.5 kHz (real time calibrated)
200 Hz LPF, deceleration vs. time

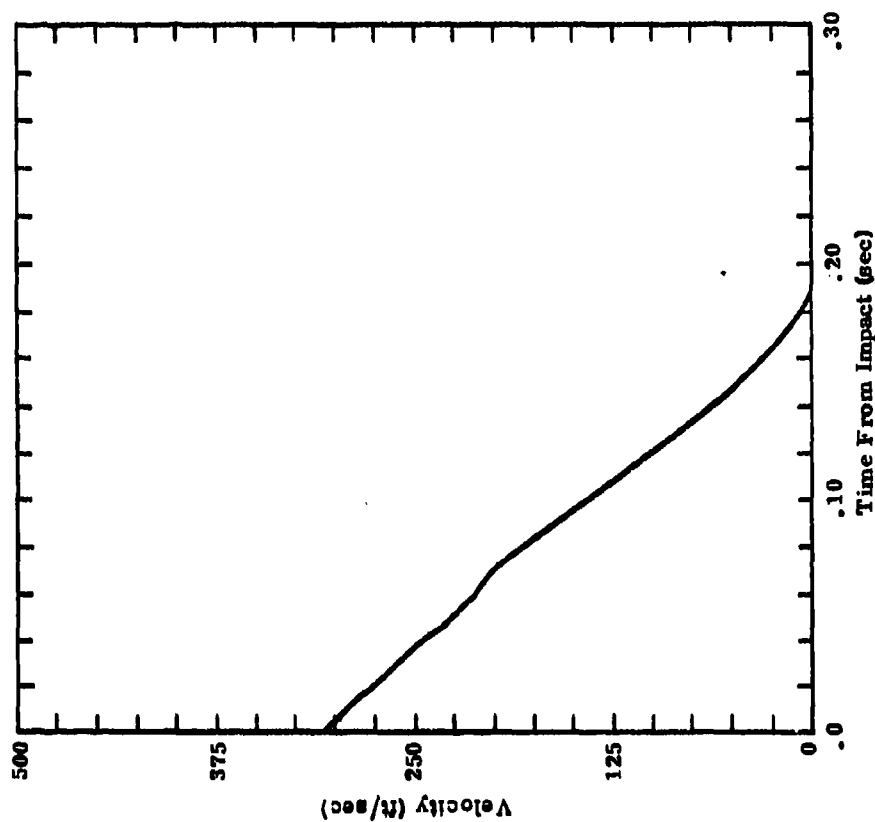


Figure A-38. R454014-07 DNA Canadian Test, test date, 7/16/74,
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200 Hz LPF, velocity vs. time

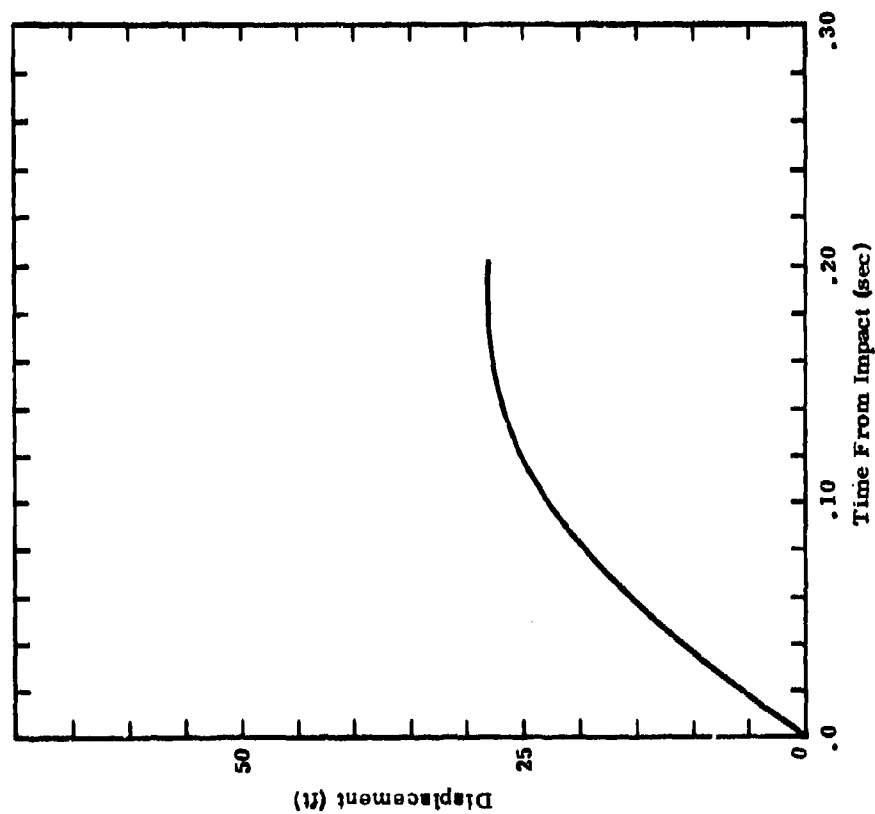


Figure A-39. R454014-07 DNA Canadian Test, test date. 7/16/74,
low g accelerometer, 10.5 kHz (real time calibrated)
200 Hz LPF, displacement vs. time

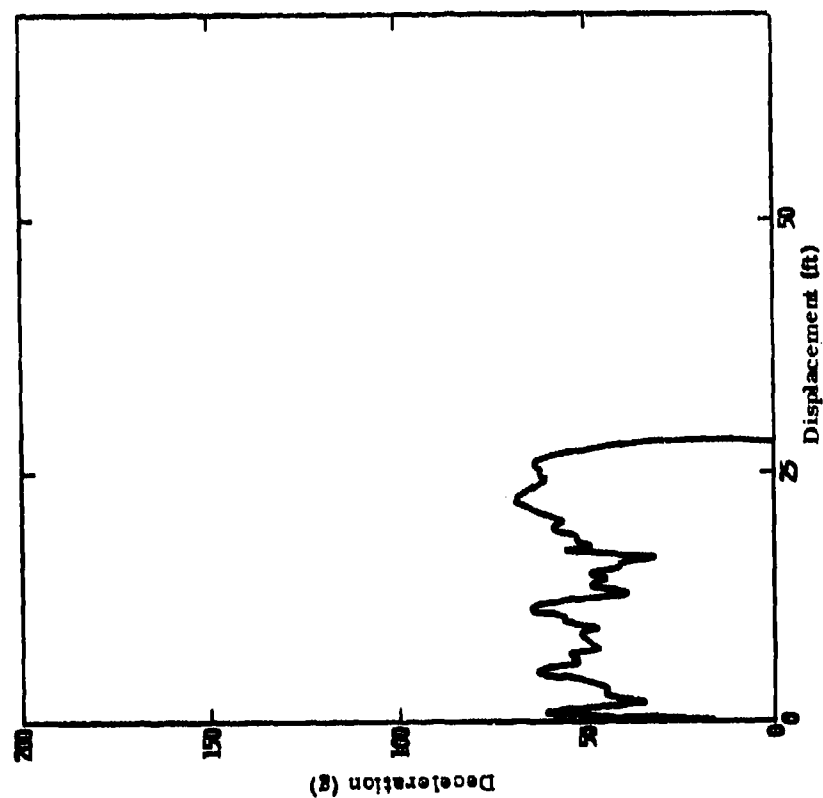


Figure A-40. R454014-07 DNA Canadian Test, test date, 7/16/74,
low g accelerometer, 10.5 kHz (real time calibrated)
200 Hz LPF, deceleration vs. displacement

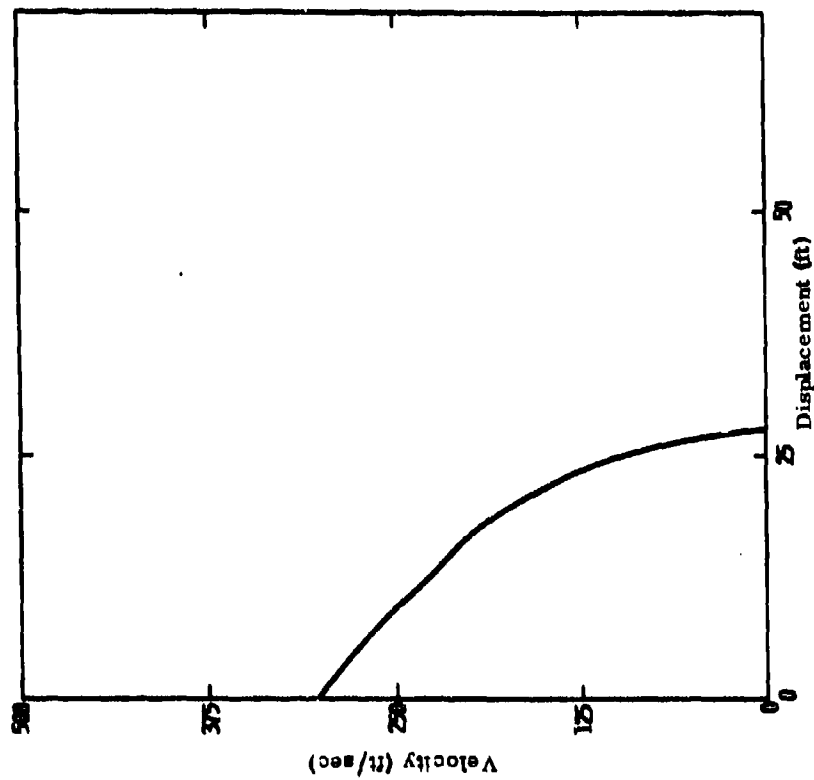


Figure A-41. R454014-07 DNA Canadian Test., test date, 7/16/74,
low g accelerometer, 10.5 kHz (real time calibrated)
450 Hz L.P.F., velocity vs. displacement

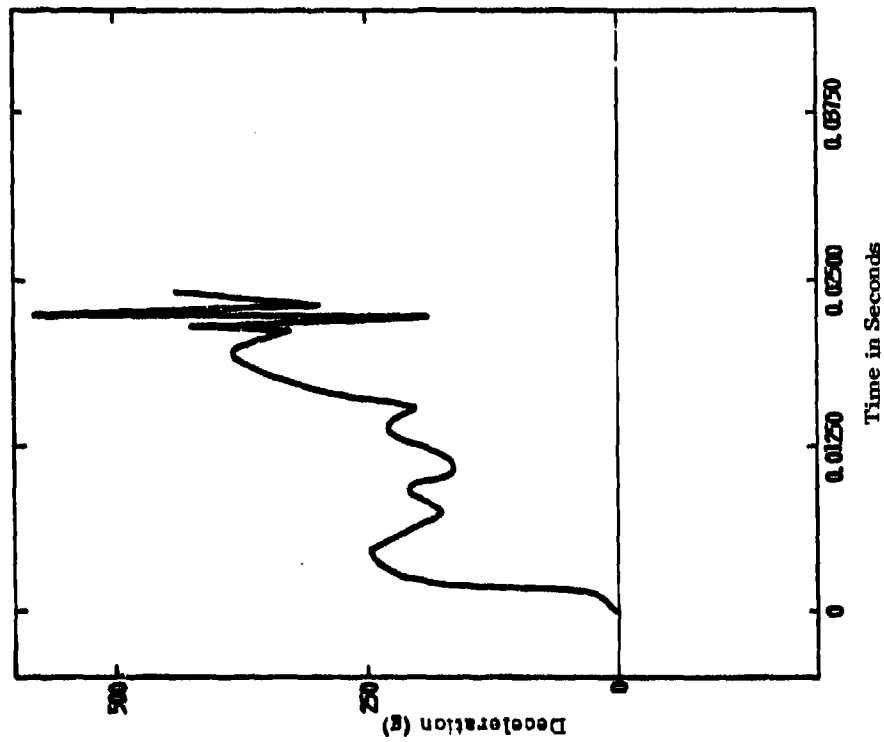


Figure A-42. Air gun penetrometer test 740718 A, deceleration
vs. time

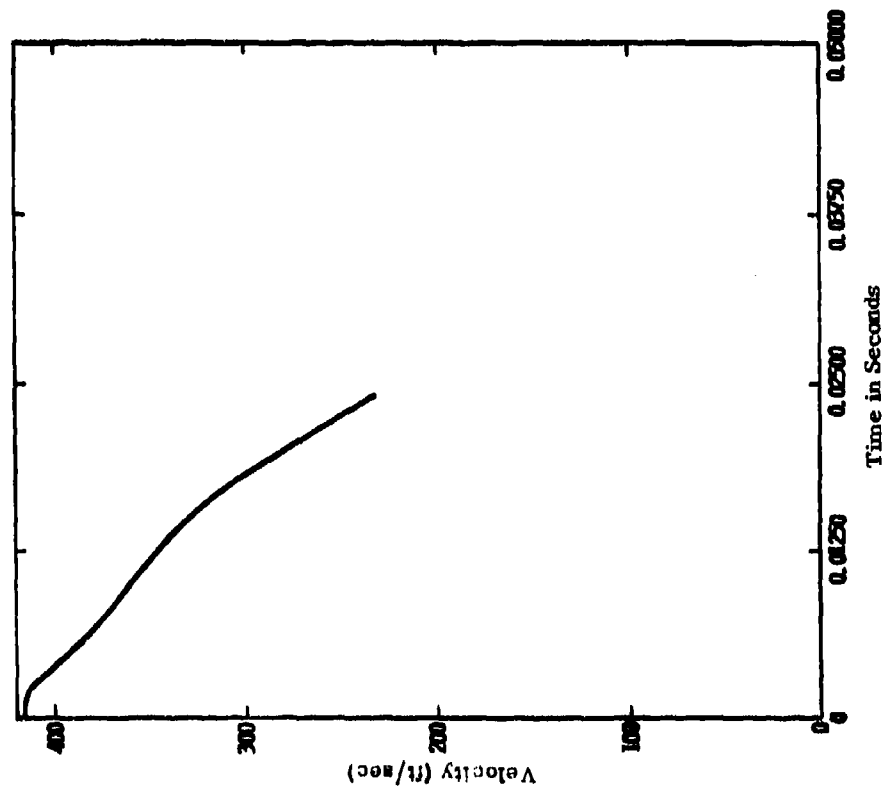


Figure A-43. Air gun penetrometer test 740718A, Velocity vs. time

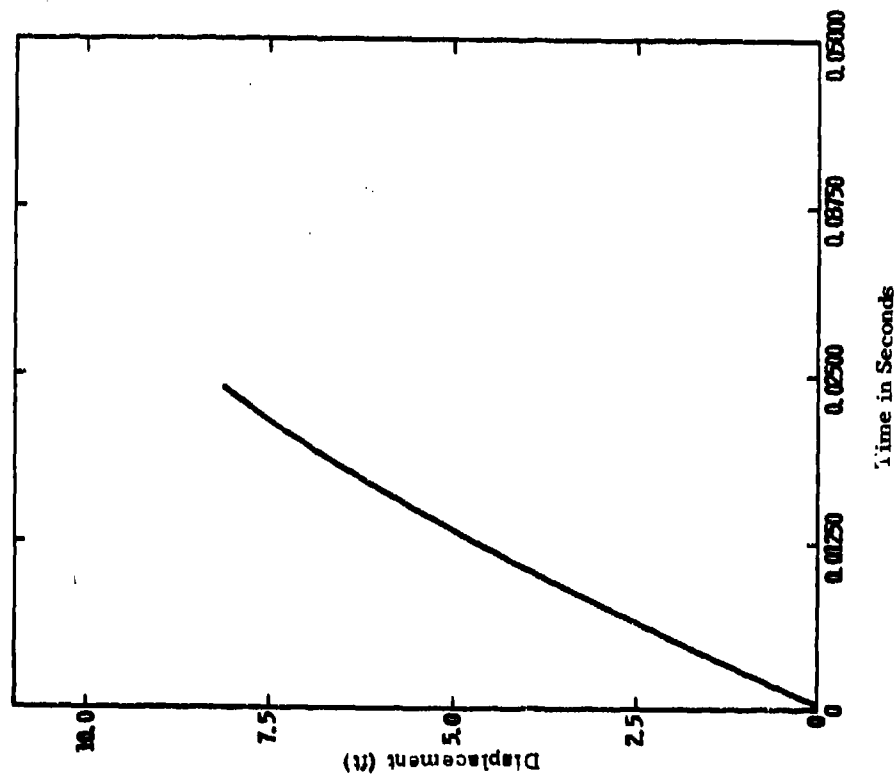


Figure A-44. Air gun penetrometer test, 740718 A, Displacement vs. time

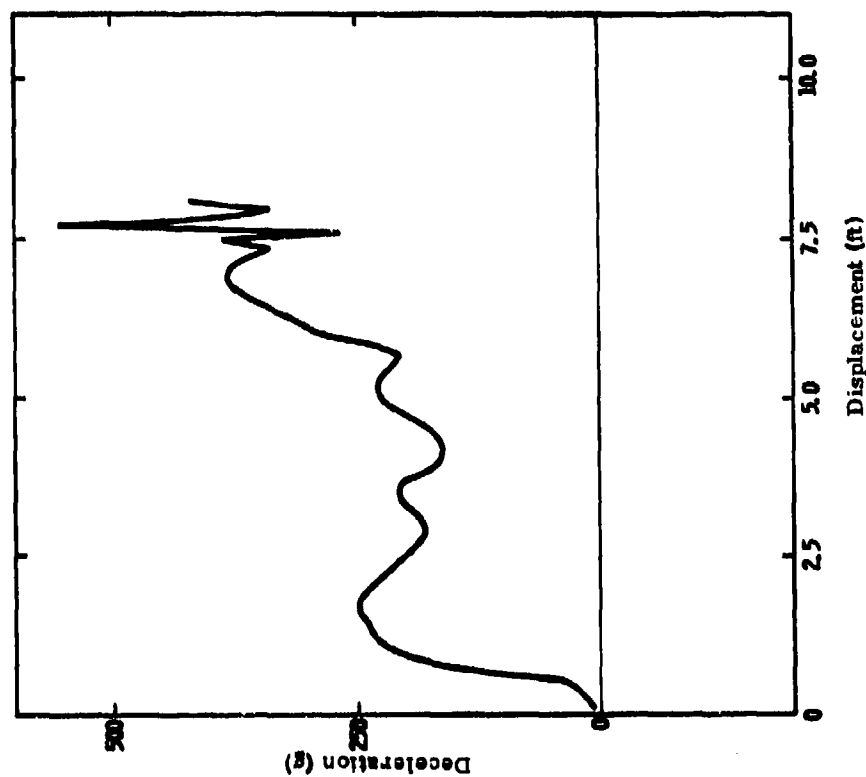


Figure A-45. Air gun penetrometer test, 740718A, Deceleration vs. displacement

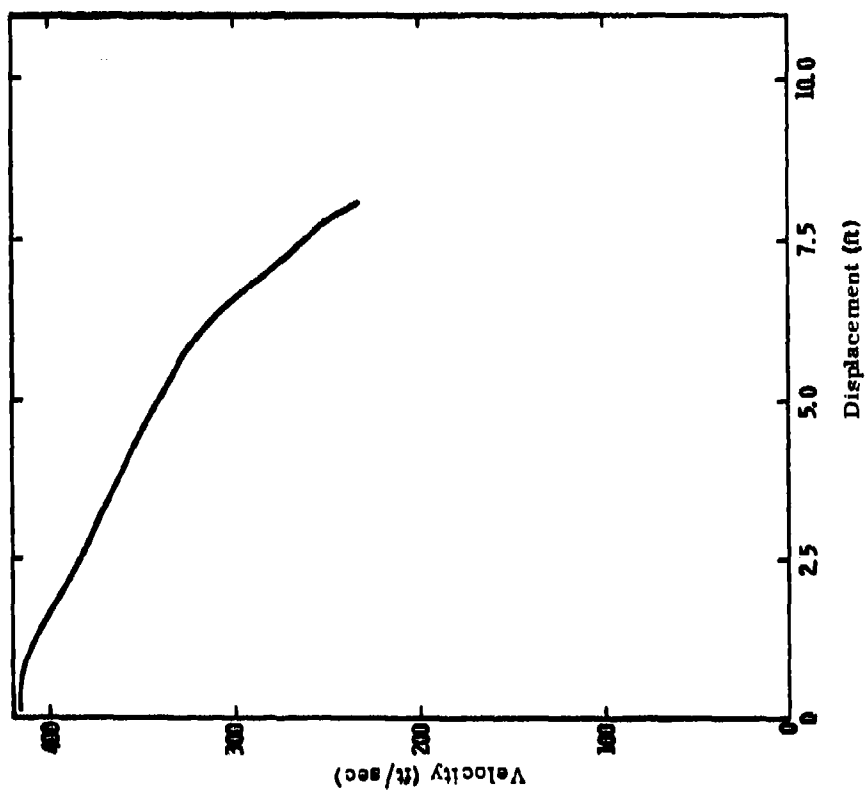


Figure A-46. Air gun penetrometer test, 740718A, Velocity vs. displacement

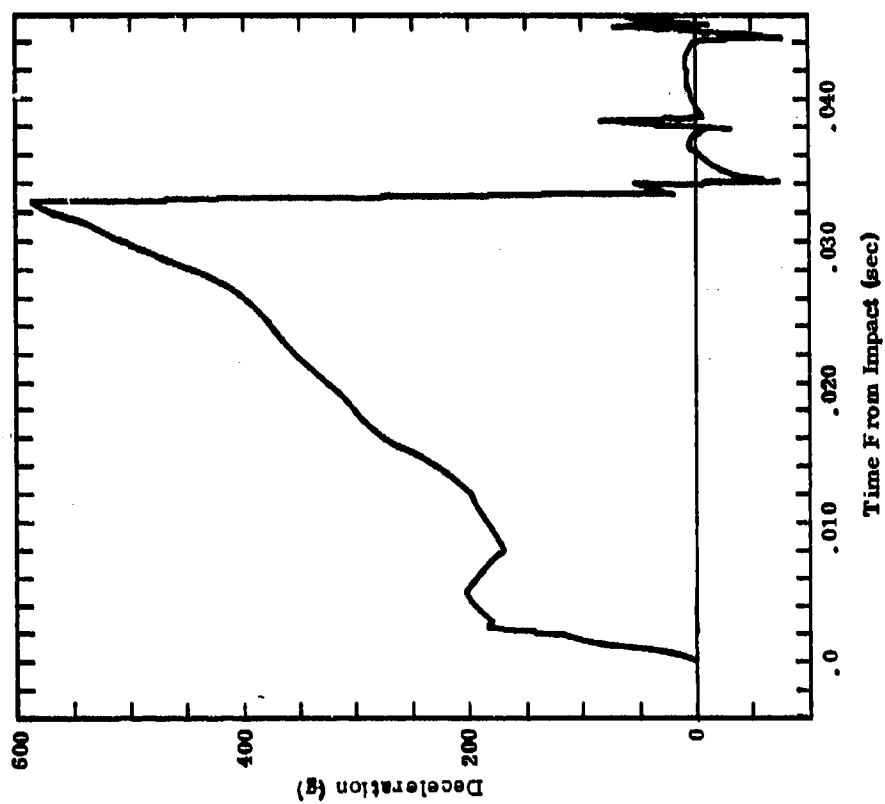


Figure A-48. Air gun penetrometer test 740718C, Deceleration vs. time, calibrated.

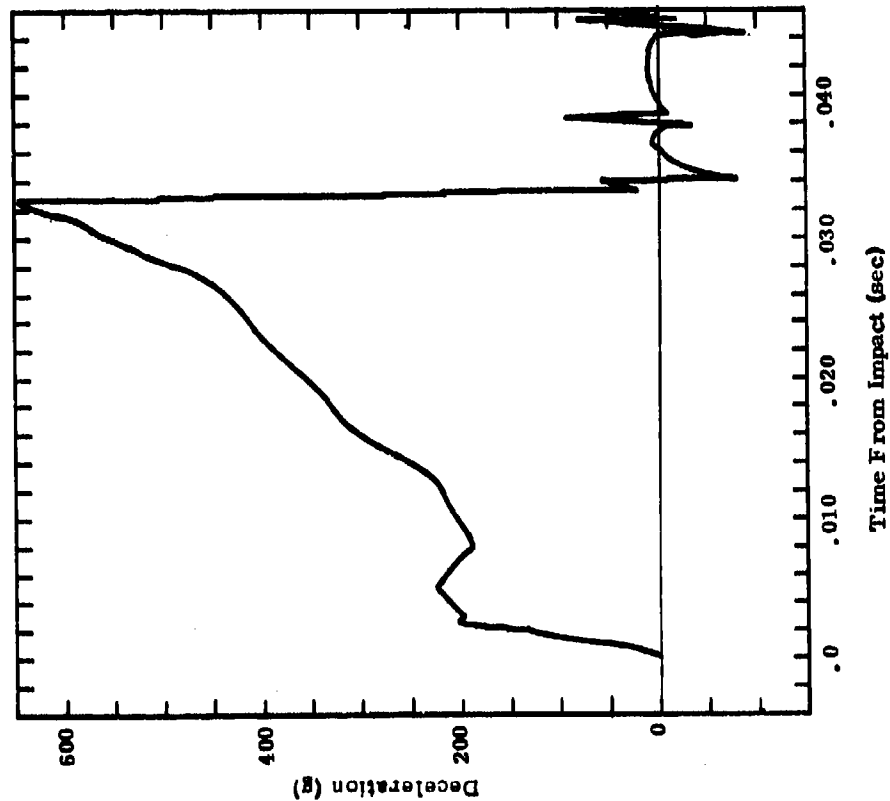


Figure A-47. Air gun penetrometer test 740718C, Deceleration vs. time

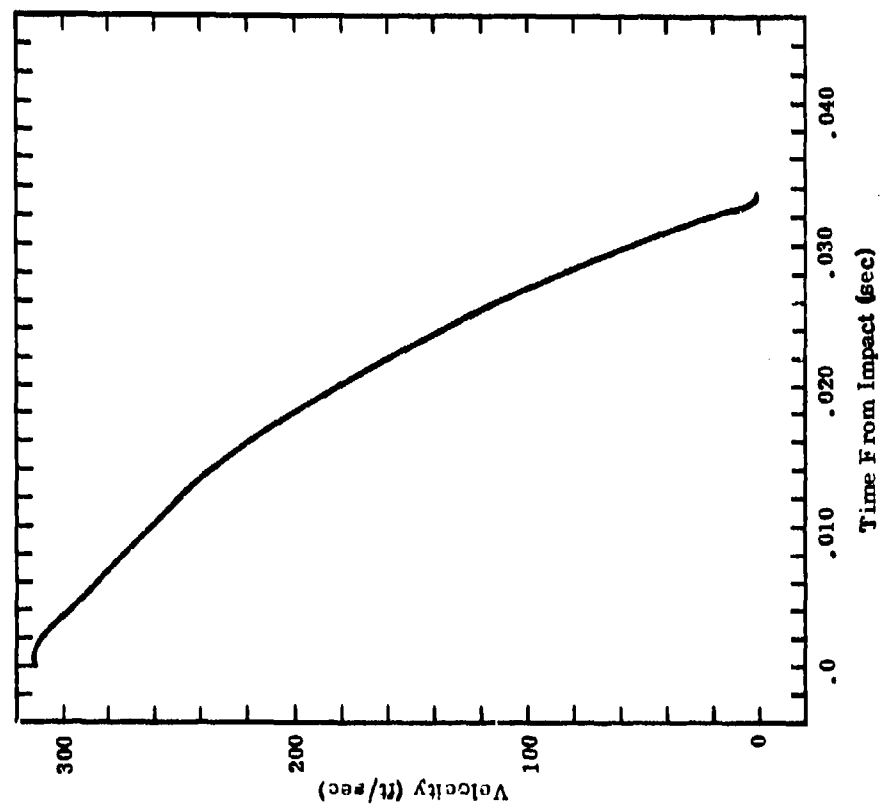


Figure A-49. Air gun penetrometer test, 740718C, Velocity vs. time, calibrated.

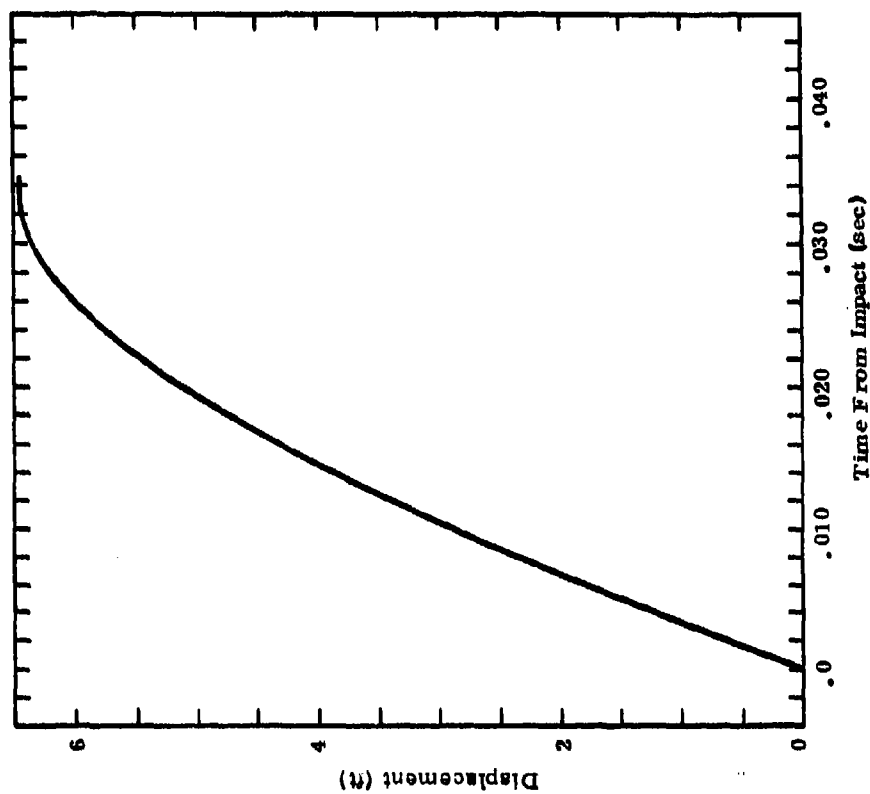


Figure A-50. Air gun penetrometer test, 740718C, Displacement vs. time, calibrated.

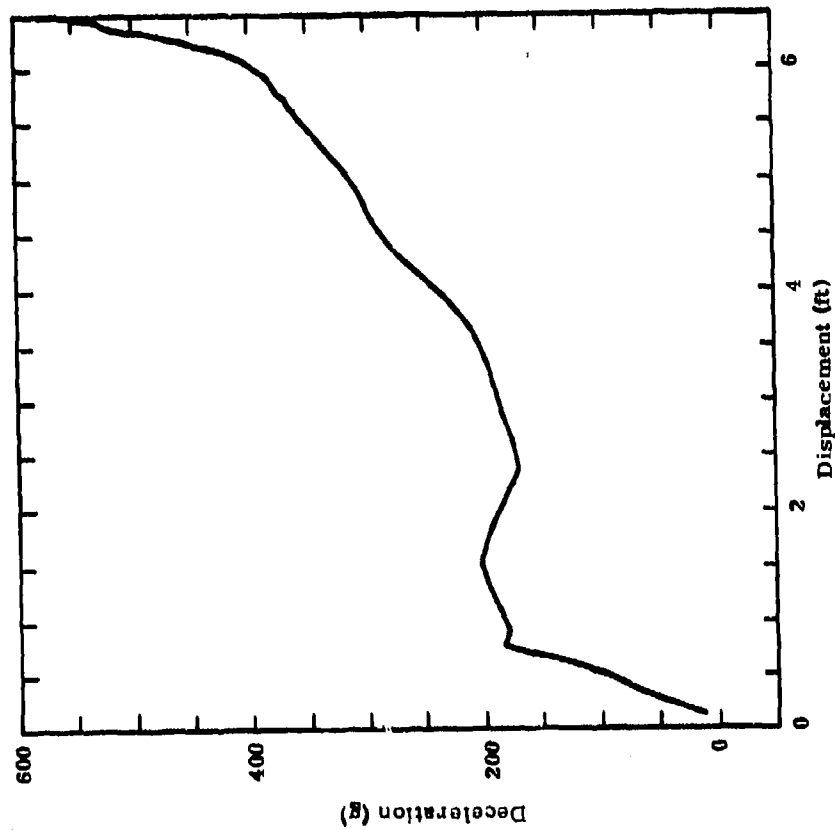


Figure A-51. Air gun penetrometer test, 740718C, Deceleration vs. displacement from calibrated deceleration

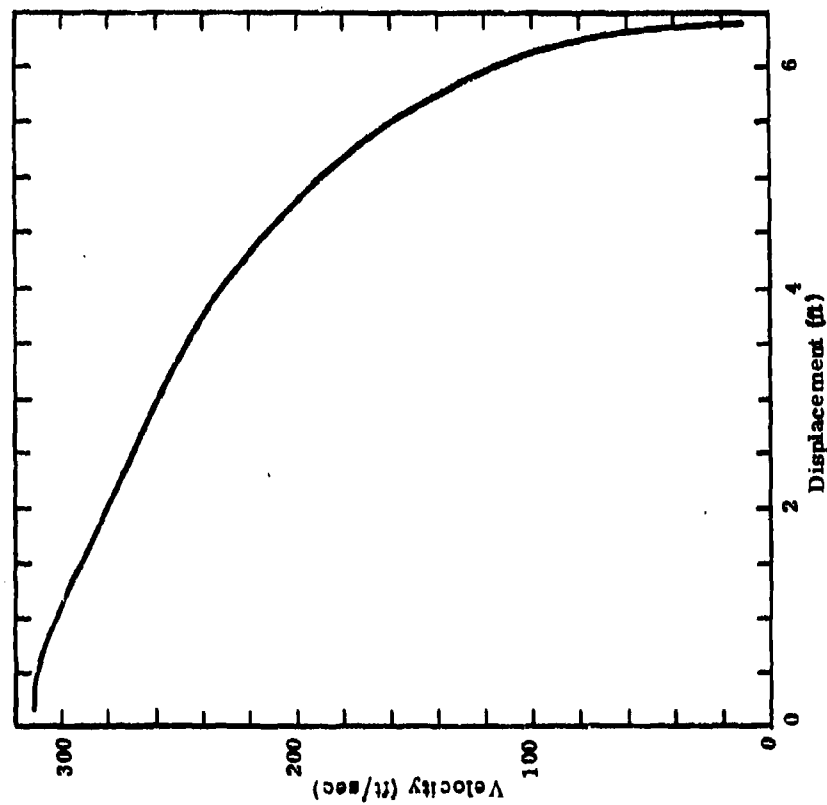


Figure A-52. Air gun penetrometer test, 740718C, Velocity vs. displacement from calibrated deceleration

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