Pendulum Impact Testing of Steel W-Beam Guardrail, FOIL Test Numbers: 94P023-94P027, 94P030, and 94P031

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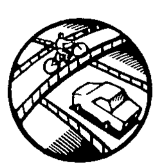

FOREWORD

This report documents the test results from a series of seven pendulum impact tests conducted at the Federal Outdoor Impact Laboratory (FOIL) located at the Turner-Fairbank Highway Research Center (TFHRC). The Federal Highway Administration (FHWA), in cooperation with the Catholic University of America, has been evaluating advanced materials as a possible alternative to conventional steel guardrail systems. Several studies have been sponsored by FHWA to determine the feasibility of composite materials for the use in roadside safety structures. The purpose of this study was to develop a testing procedure for the steel rails that could be used for the comparison testing of composite material rails under development.

This report (FHWA-RD-98-018) contains test data, photographs taken with high-speed film, and a summary of the test results. These tests were full-scale crash tests using a modified pendulum test fixture. The test fixture has been developed as a lower cost alternative to full-scale vehicle crash testing for the comparison and evaluation of composite rail systems.

This report will be of interest to all State departments of transportation; FHWA headquarters; region and division personnel; and highway safety researchers interested in the crashworthiness of roadside safety hardware.

A. George Ostensen, Director
Office of Safety and Traffic
Operations Research and Development

NOTICE

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16. Abstract
This test contains the test results from a series of seven pendulum impact tests conducted at the Federal Outdoor Impact Laboratory (FOIL) pendulum facility located at the Turner-Fairbank Highway Research Center (TFHRC) in McLean, VA. The purpose of this study was to develop an optimal testing procedure to determine the dynamic response for steel guardrail sections so that the behavior of a rail can be evaluated without conducting full-scale vehicle crash tests with automobiles. Standard steel w-beam rail sections were tested in this study; however, the test procedure eventually developed is expected to be used for the evaluation of rails composed of other materials, such as glass fiber-reinforced composite materials.

17. Key Words	18. Distribution Statement
Impact testing, pendulum testing, w-beam guardrail, composite materials.	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161.

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Unclassified	Unclassified	65	

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3

NOTE: Volumes greater than 1000 l shall be shown in m^3.

Symbol	When You Know	Multiply By	To Find	Symbol
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised September 1993)

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BACKGROUND

The Federal Highway Administration (FHWA) in cooperation with The Catholic University of America has been evaluating advanced materials as a possible alternative to conventional steel guardrail systems. One of the alternatives currently under investigation is a rail element composed of fiber-reinforced composite materials. Several studies have been sponsored by FHWA to determine the feasibility of composite materials for the use in roadside safety structures.[1-3] Energy absorption, localized damage zones, simplified field installation and replacement, low maintenance, and ease of fabrication are some of the advantages of composite materials.[4] The purpose of this research effort is to evaluate the relative performance of steel w-beam guardrail material. The results will serve as baseline data which will be compared to similar tests on the prototype composite rails under development.

SCOPE

This report documents the test results from seven impact tests conducted at the Federal Outdoor Impact Laboratory's (FOIL) pendulum facility located at the Turner-Fairbank Highway Research Center (TFHRC) in McLean, Virginia. The tests were conducted using a modified pendulum test fixture. The test fixture was developed as a lower cost alternative to full-scale vehicle crash testing for the comparison and evaluation of composite rail systems. One of the modifications was replacing the pendulum's crushable nose with a rigid nose. The test article foundation was modified to allow for the testing of a two-post section of guardrail. Strain gauges were attached to monitor the stress in the fixture to ensure that the fixture's structural integrity was not compromised during testing. It was determined during testing that the pendulum did not have adequate travel for the 35-km/h tests; wood spacers were used in between the pendulum mass and the nose. This solved the problem of the pendulum overriding the w-beam rail. The purpose of this study was to develop an optimal testing procedure to determine the dynamic response of steel rails and to compare the response of composite material rails under development. As the testing proceeded, various parameters of the testing conditions were altered to determine the optimal test setup. This approach allowed researchers to solve limitations arising in the setup.

TEST MATRIX

Seven pendulum tests were conducted on a single 1.9-m section of w-beam guardrail. The nominal impact velocities ranged from 10 km/h to 35 km/h. The pendulum mass varied depending on whether spacers were used behind the nose or not. During testing, it was discovered that the pendulum nose overrode the rail. As a countermeasure, spacers were used to increase the contact time between the pendulum and the rail. The bolt connection between the blockout and the strong post were either real world (i.e., connected in an actual standard guardrail system) or symmetric (i.e., the bolts on the blockout on one end were placed symmetric to those on the other end). Table 1 presents a summary of test conditions for each test in this study.

Table 1. Summary of test conditions.

Test number	Test date	Impact velocity (km/h)	Pendulum mass (kg)	Blockout-to-post bolt connection	Spacer behind pendulum nose(mm)
94P023	10-6-94	10	880	real world	none
94P024	10-7-94	20	880	real world	none
94P025	10-12-94	30	880	real world	none
94P026	10-13-94	35	880	real world	none
94P027	10-18-94	35	880	symmetric	none
94P030	11-2-94	35	894	symmetric	133
94P031	11-15-94	35	912	symmetric	325

PENDULUM MASS

The test vehicle was FOIL's 880-kg pendulum. The actual test weight varied depending on the test conditions as shown in table 1. The pendulum consisted of a reinforced concrete mass suspended from a steel structure by four steel cables. Within the concrete mass were two aluminum guide sleeves. A wood nose attached to the two guide tubes was inserted into the guide sleeves. Two accelerometers centered vertically on the rear of the pendulum were used to collect data. The velocity vs. time, displacement vs. time, force vs. displacement, and force vs. time traces were obtained from the accelerometers. Figure 1 depicts the pendulum mass with a solid wood nose.

TEST ARTICLE

The test article was a 1.9-m span of steel w-beam guardrail connected to two strong posts and blockouts. The posts were 711 mm

Figure 1. Pendulum mass.

high, and the center of the guardrail was 533 mm high, which are both typical heights for standard w-beam guardrail systems. Four strain gauges were placed on the middle of the w-beam rail. The strain gauges were placed vertically on the middle of the w-beam and midway laterally between the posts and the impact location.

DATA ACQUISITION

For each of the tests, speed trap, accelerometer, and strain gauge data were collected. In addition, strain gauge rosettes were placed on the support structure of the guardrail posts to measure the stress, and ensure that the integrity of the test fixture was not compromised.

a. Speed Trap. A speed trap, consisting of multiple LED infrared scanners placed a known distance apart, were used to measure the pendulum speed before impact. Signals from the sensors were recorded on a Honeywell model 5600 E analog tape recorder. The signals were stored on analog tape for future analysis.

b. Accelerometers. Two longitudinal (x-axis) 100-g accelerometers were mounted at the center of the rear face of the pendulum. The accelerometer signals were recorded by the FOIL on-board data acquisition system (ODAS) III/8. The ODAS III/8 is a self-contained data acquisition system providing transducer excitation, signal conditioning, 4000 Hz prefiltering, 12,500 Hz digital sampling, and digital storage for up to eight channels. The data was collected then downloaded to a portable computer.

C. Stain Gauge Rosettes. A total of three strain gauge rosettes were placed on the guardrail post mounting fixture to determine loading on the pendulum fixture. The purpose of this was to ensure that the fixture was not stressed beyond its design limit. Figure 2 illustrates the test fixture assembly and rosette placement. The test fixture stress for test 94P030 is shown in figure 3. This figure shows that the peak strain occurring in the test fixture was 80 $\mu\varepsilon$, and it is apparent that the fixture performed as intended. For further information on the design of this test fixture,refer to reference 5.

d. Rail Strain Gauges. Data from four single-gauge strain gauges were recorded during the pendulum tests. The four single-gauge strain gauges were attached to the w-beam specimen. Two gauges were placed on the front and two gauges were placed on the back of the guard rail. Each front and back pair was placed at the same location vertically and laterally. The gauges were placed at the same locations for each test. The gauges were positioned in the middle of the valley of the w-beam vertically and midway between the impact point and the I-section

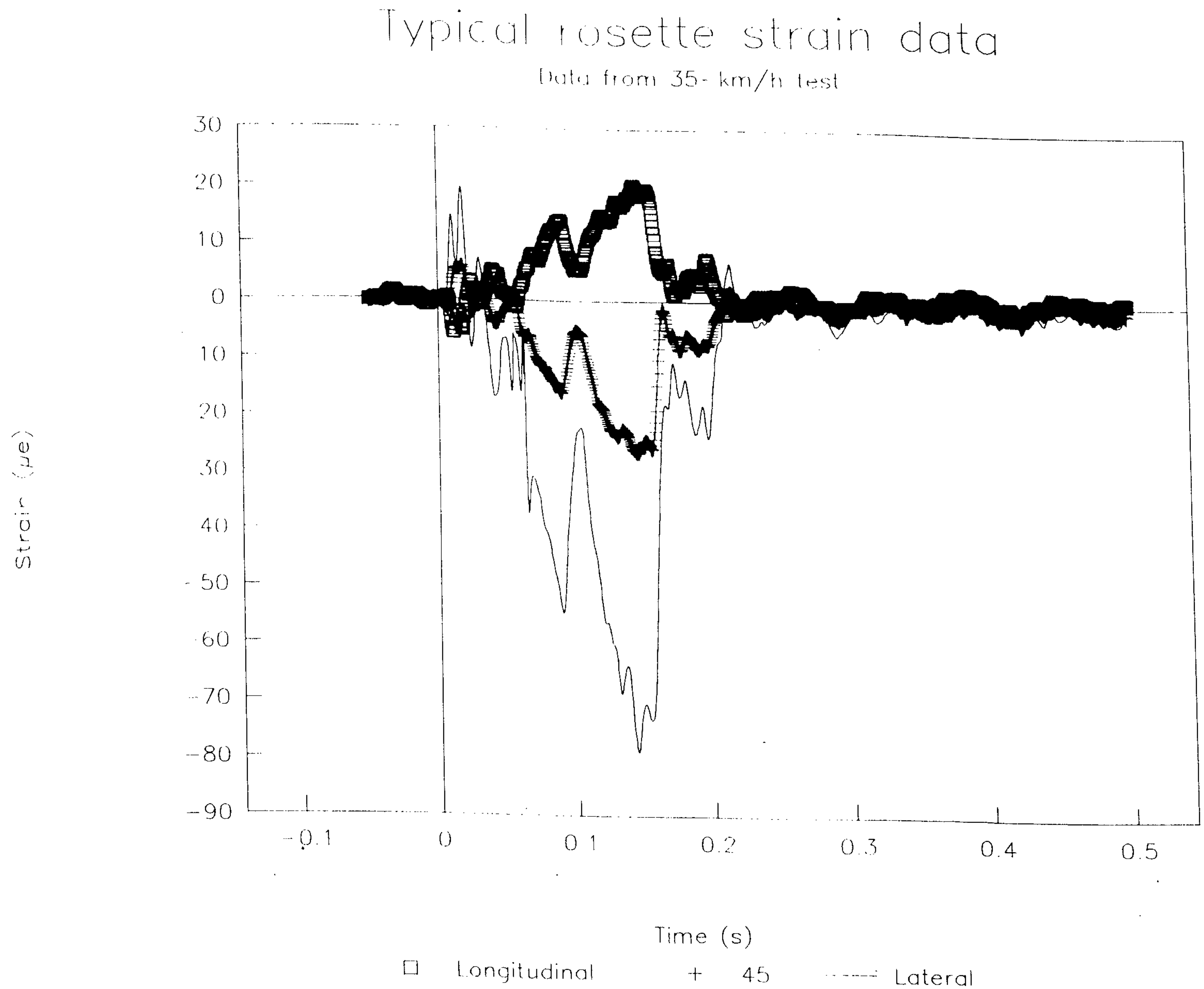


Figure 3. Test fixture strain for test 94P030.

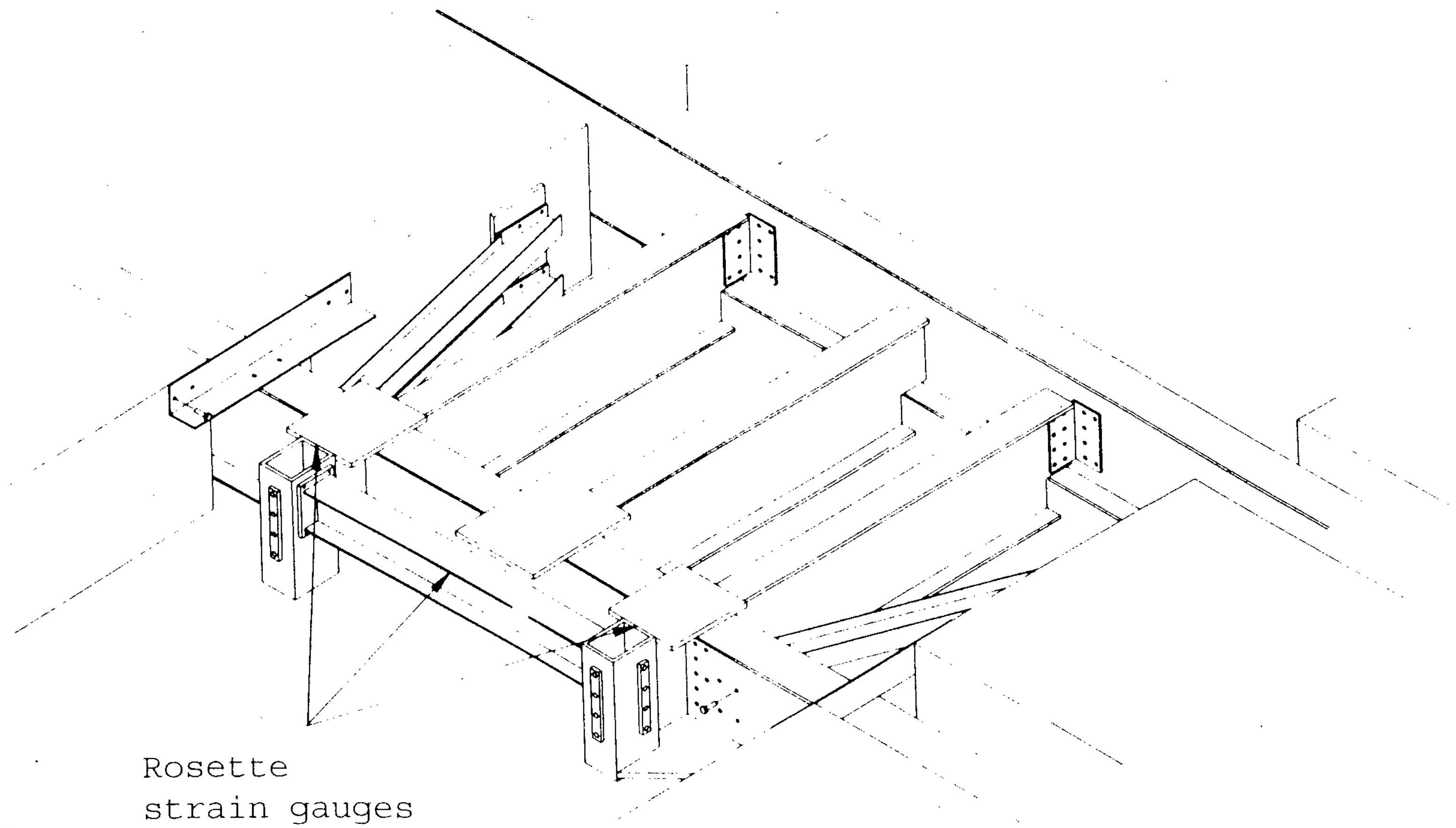


Figure 2. Test fixt e illustrating strain gauge rosette placement.

strong posts laterally. The w-beam strain gauge data was recorded by the FOIL ODAS III system.

e. High-Speed Photography. The crash tests were photographed using five high-speed cameras with an operating speed of 500 frames/s. All high-speed cameras used Kodak 2253 daylight film. The high-speed film was analyzed for impact speed data. In addition to the high-speed cameras, one real-time camera loaded with Kodak 7239 daylight film and two 35-mm still cameras were used to document the test. Table 2 summarizes the cameras used and their respective placements.

Table 2. Summary of camera placement.

Camera	Type	Film speed (frames/s)	Lens (mm)	Location
1	LOCAM II	500	100	Right 90° to impact
2	LOCAM II	500	16	Overall
3	LOCAM II	500	50	Right side 45° to impact
4	LOCAM II	500	50	Left side 45° to impact
5	LOCAM II	500	25	Overhead
6	BOLEX	24	ZOOM	Documentary
7	CANNON AE-1	still	ZOOM	Documentary
8	CANNON AE-1	still	ZOOM	Documentary

DATA ANALYSIS

Data were collected via the FOIL analog tape recorder system, including speed-trap data; the FOIL ODAS III on-board data acquisition system; and high-speed film.

a. Speed Trap. The speed trap consisted of a set of four LED infrared emitter/receiver pairs fastened on opposite sides of the pendulum's swing path at 152-mm intervals. One set was positioned before the impact area to measure the pre-impact pendulum velocity. As the pendulum passed through the infrared scanners, electronic pulses were recorded on analog tape. The tape was played back through a Data Translation A/D converter and the time between pulses was determined. The time-distance data was entered into a computer spreadsheet and a linear regression was performed on the data to determine the pendulum speed before impact.

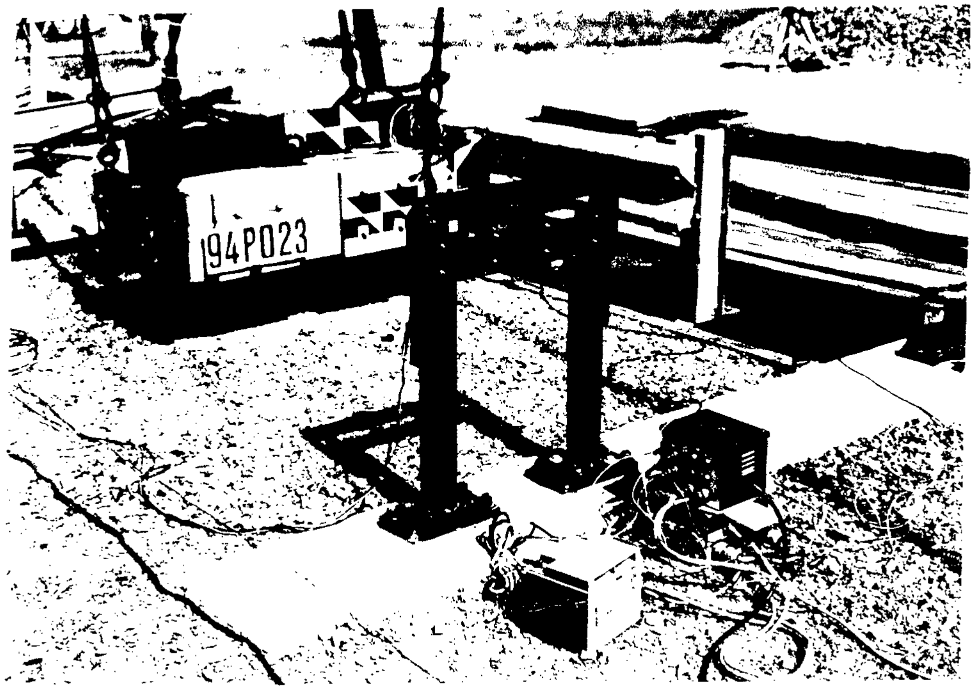
b. Accelerometers and Strain Gauges. The data from the accelerometers and strain gauges were digitally recorded and converted to the ASCII format. The sampling rate during data acquisition was 2000 Hz for data recorded via the FOIL umbilical cable (rosette strain gauges) and 12,500 Hz for data recorded via the ODAS III on-board system (accelerometers and w-beam strain gauges). The ASCII files were processed, which included removal of zero-bias, storing the region of interest, and digitally filtering the data to 300 Hz (Class 180). The rosette data was filtered at 100 Hz. The data was imported into a spreadsheet for plotting and analysis.

c. High-Speed Photography. Films obtained from the high-speed cameras were used for visual inspection of the impact event and were available for use in cases in which there was a failure in electronic data collection.

RESULTS

A summary of test results is presented in table 3. Included in the table are the pertinent data from all tests and the maximum front- and back-rail strain data from tests 94P030 and 94P031. Pre- and post-test photographs illustrating each test are presented in figures 4-17. Accelerometer data from the tests, including acceleration vs. time, velocity vs. time, displacement vs. time, force vs. time, and energy vs. time, are presented for all seven tests in appendix A

The peak force occurring in tests 94P023-27 is attributed to the fact that no wood spacer was used for the tests. This inertial ring was reduced somewhat in the two tests with wood spacers (tests 94P030 and 94P031). The wood spacer also allowed for better contact between the pendulum and the rail. It was discovered during testing at 35 km/h (tests 94P026 and 94P027) that the pendulum overrides the rail. Initially, a 133-mm spacer was installed to solve the problem (as in test 94P030). This was found to be inadequate, so a spacer of 325 mm was used in test 94P031. Even with this improvement, the rail was not completely failed by the 35-km/h impact of the pendulum. Instead, a bolt failed during maximum loading. Testing was halted at this point in order to revaluate the test setup.



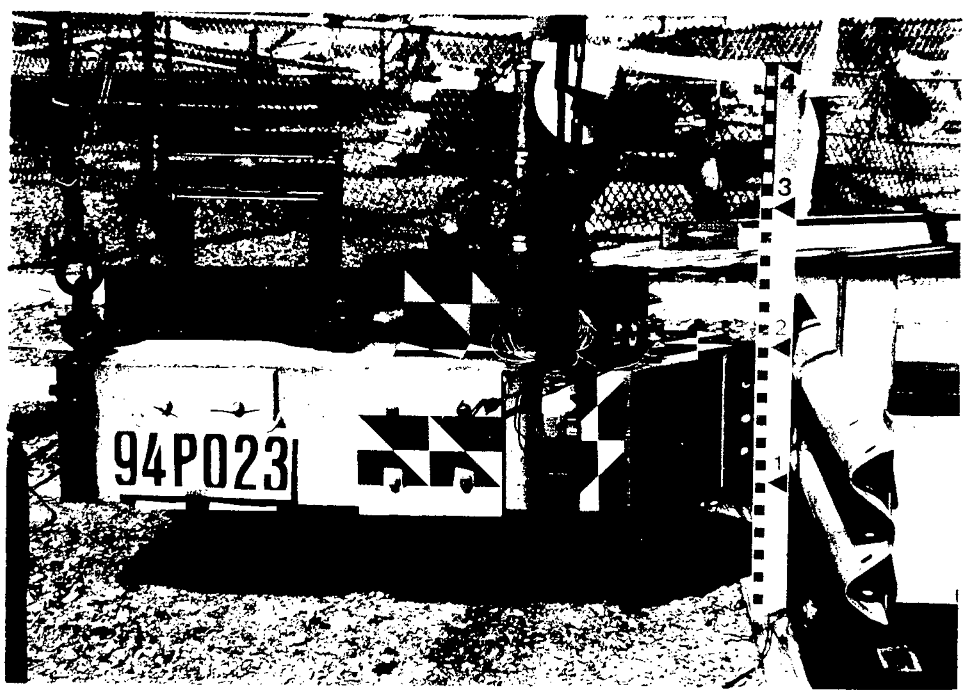


Figure 4. Pre-test photographs. test 94P023.

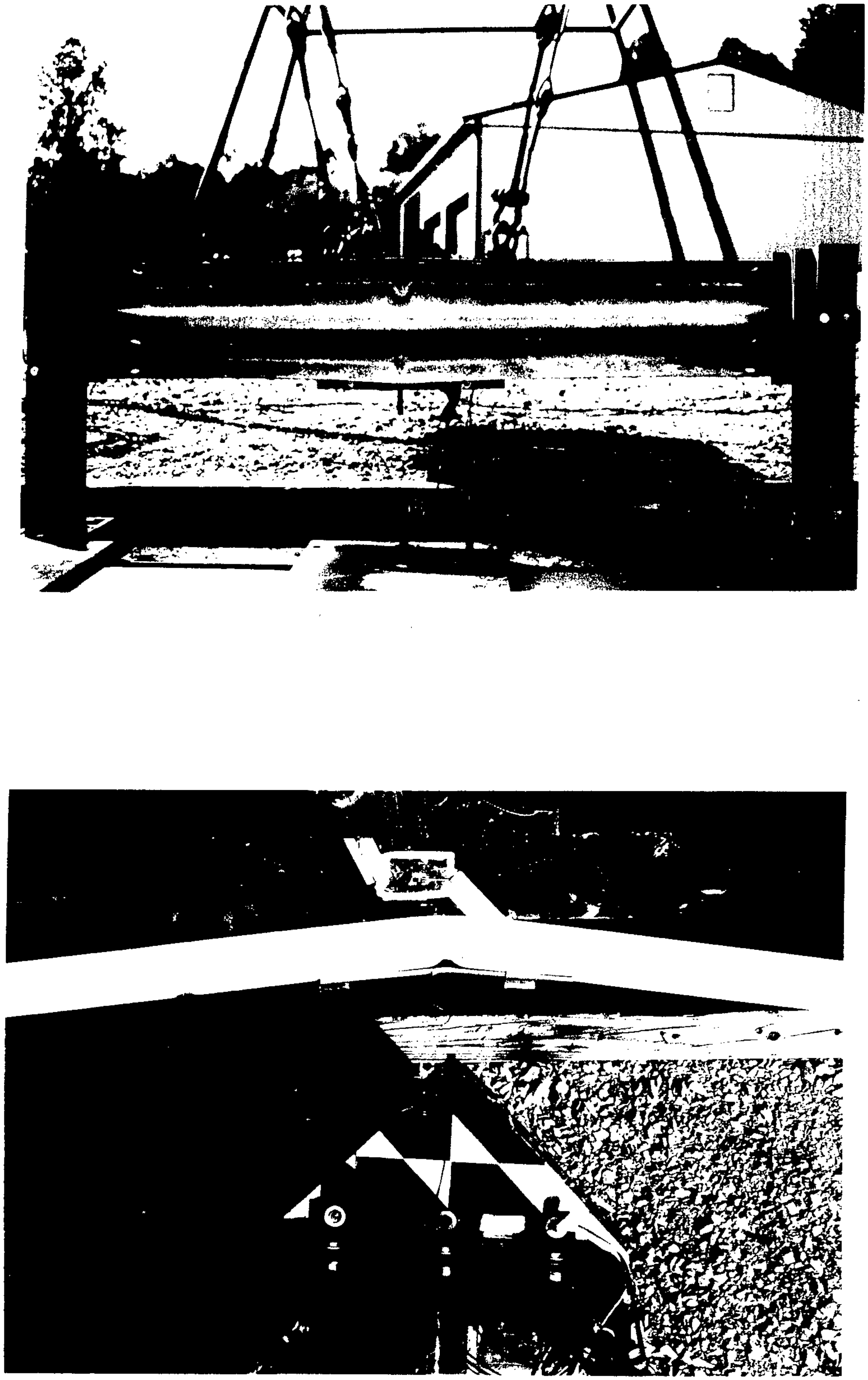
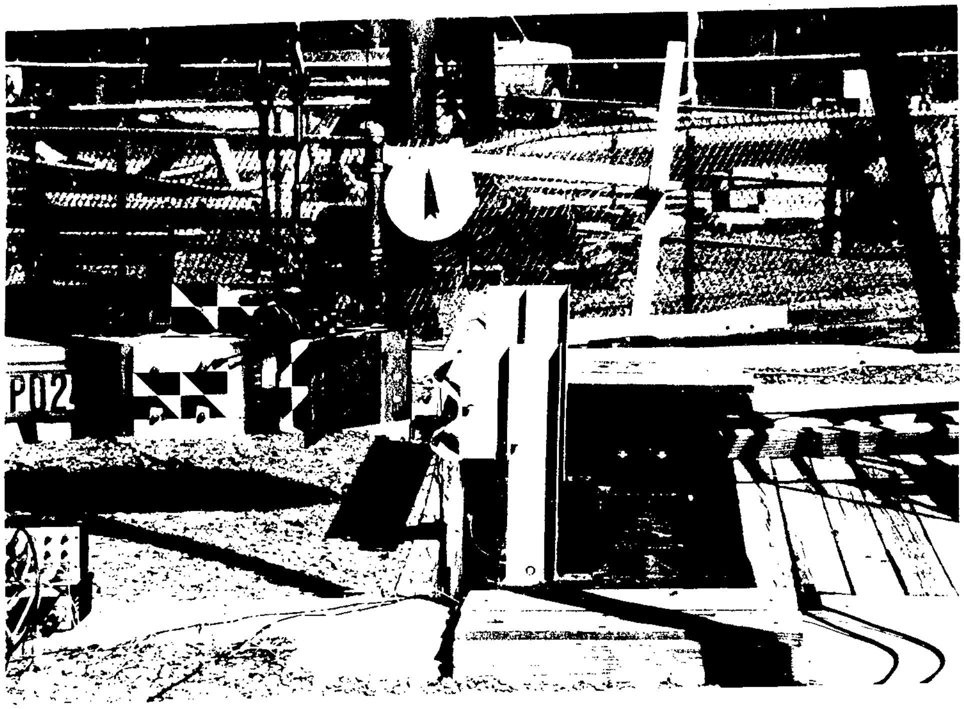


Figure 5. Post-test photographs, test 94P023.



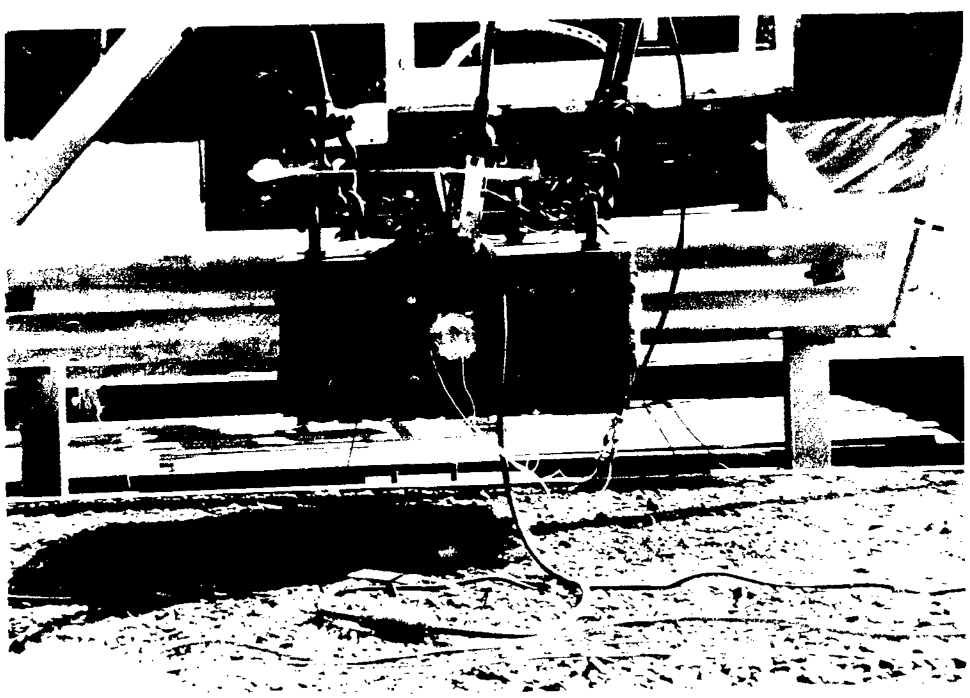


Figure 6. Pre-test photographs, test 94P024.

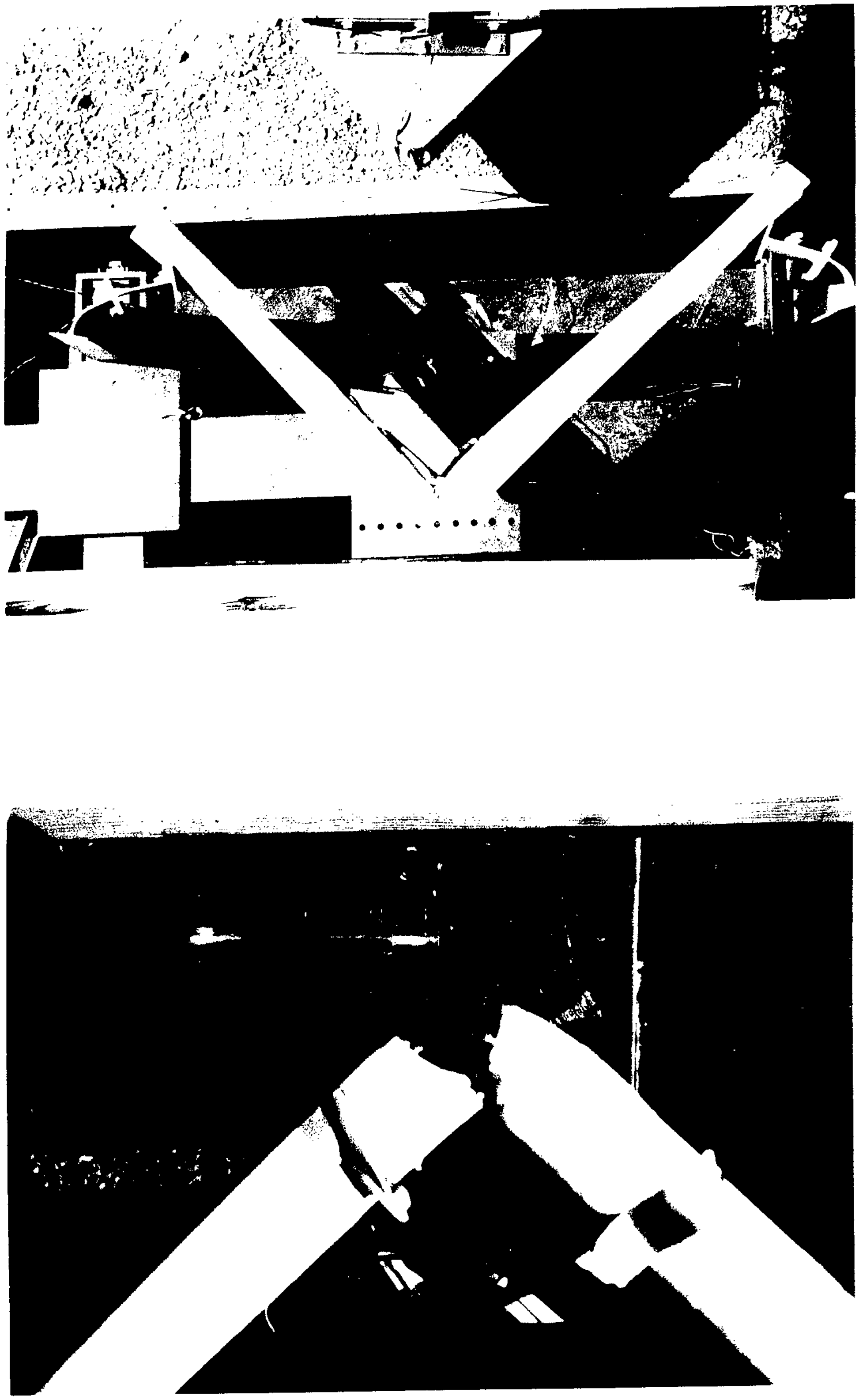
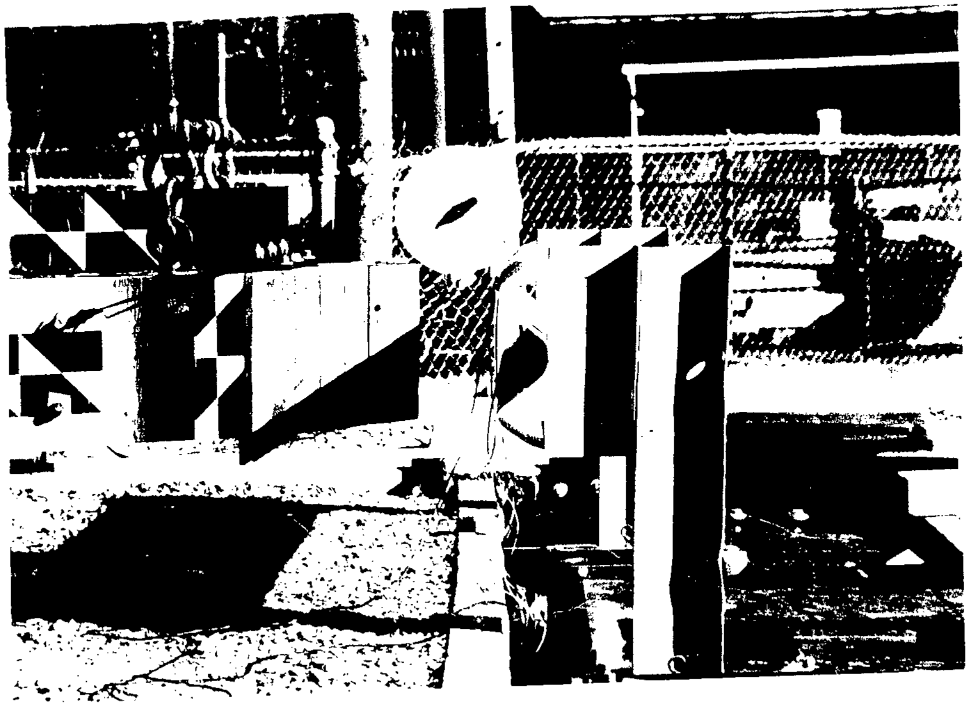


Figure 7. Post-test photographs, test 94P024 .



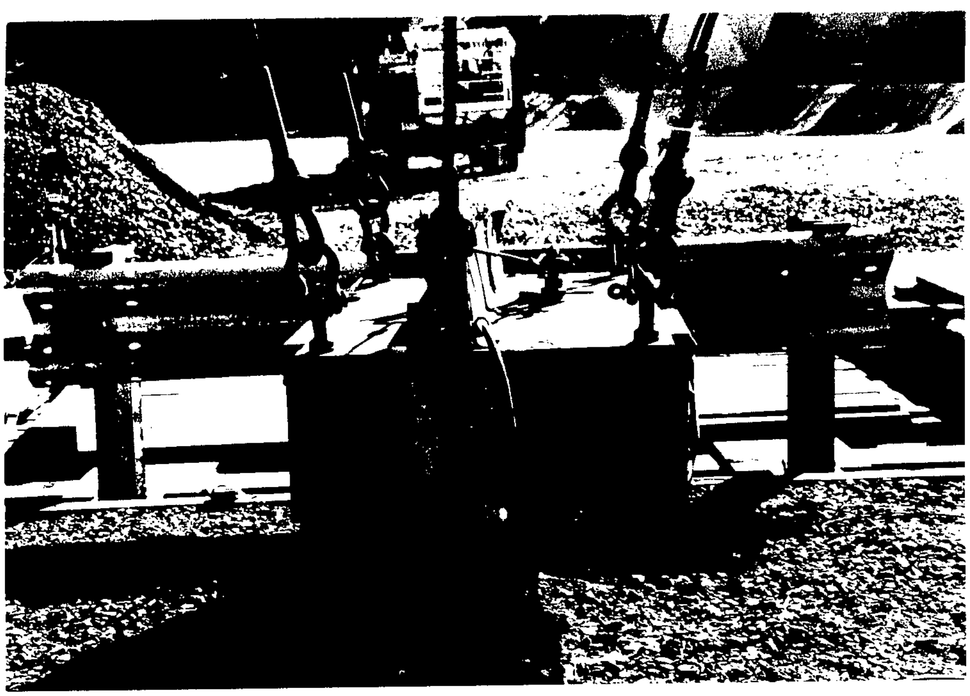


Figure 8. Pre-test photographs, test 94P025 .

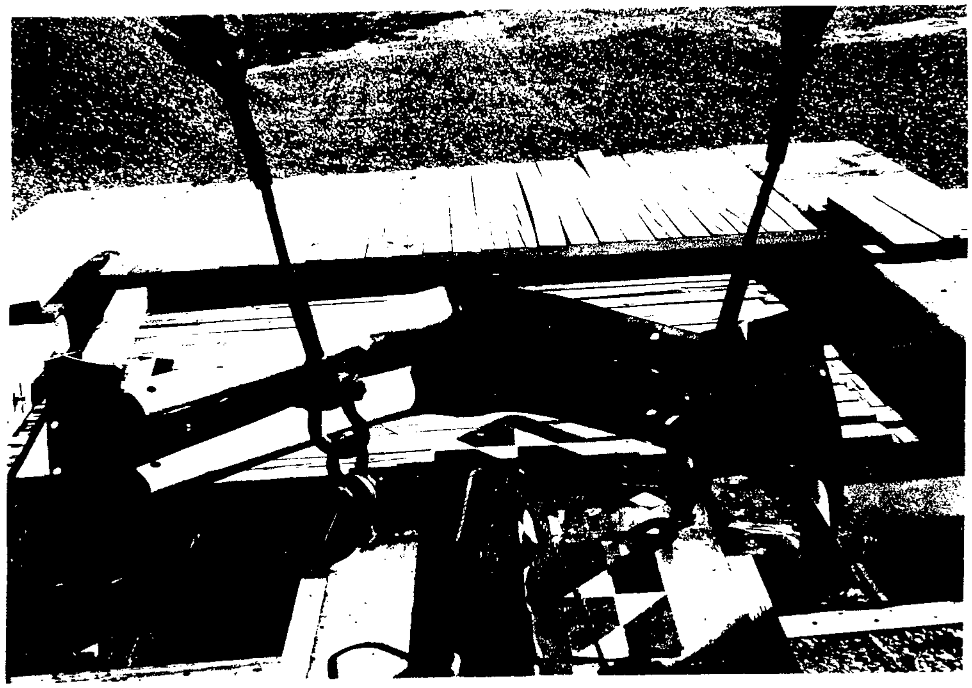


Figure 9. Post-test photographs, test 94P025.

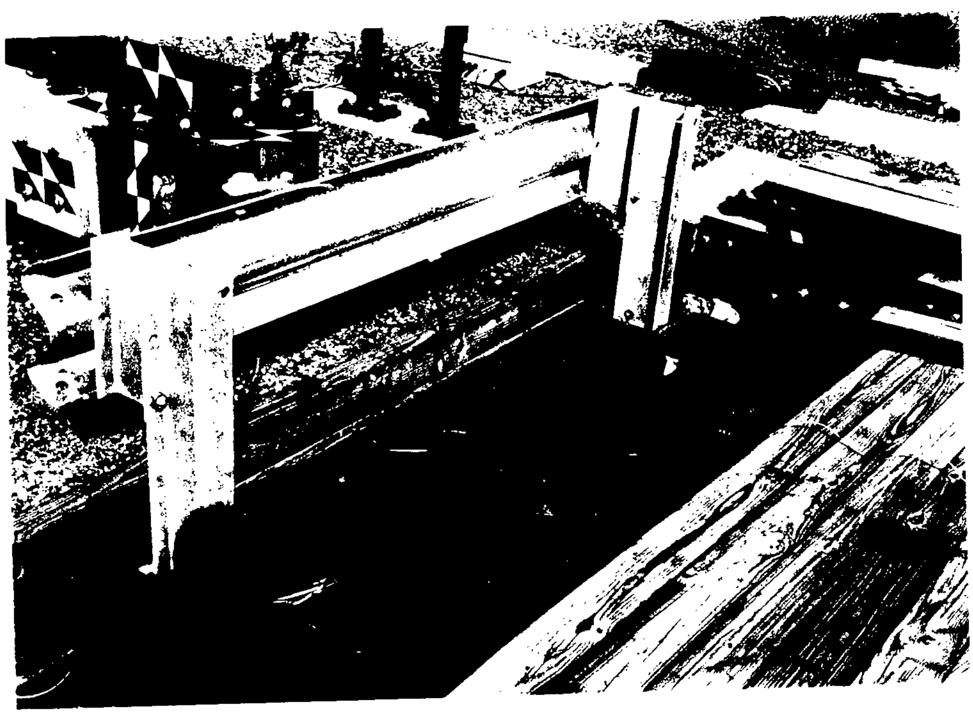


Figure 10. Pre-test photographs, test 94P026.

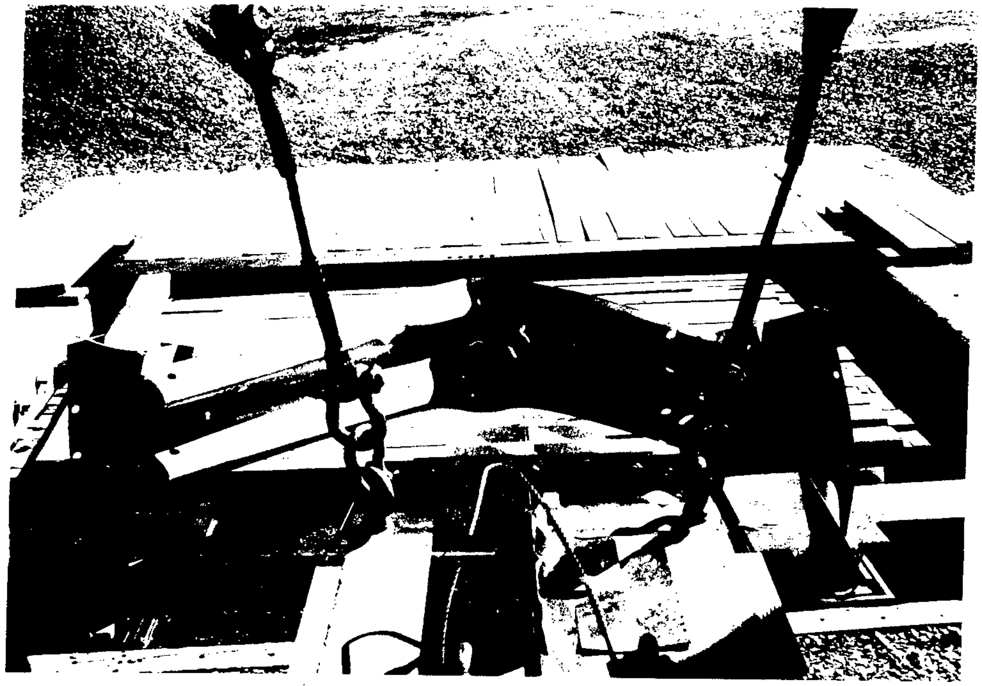


Figure 11. Post-test photographs, test 94P026.

Figure 12. Pre-test photographs, test 94P027.

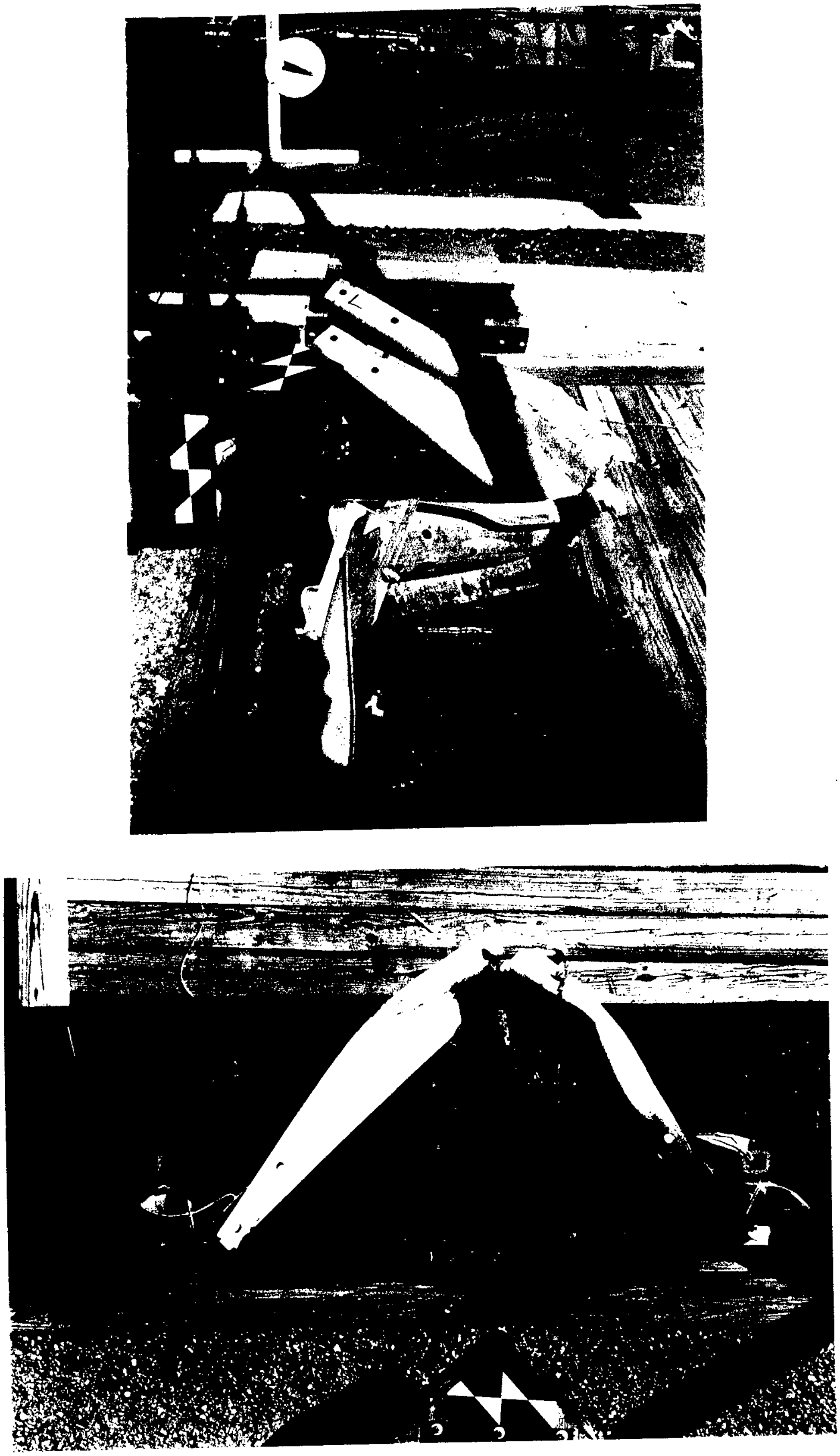


Figure 13. Post-test photographs, test 94P027.

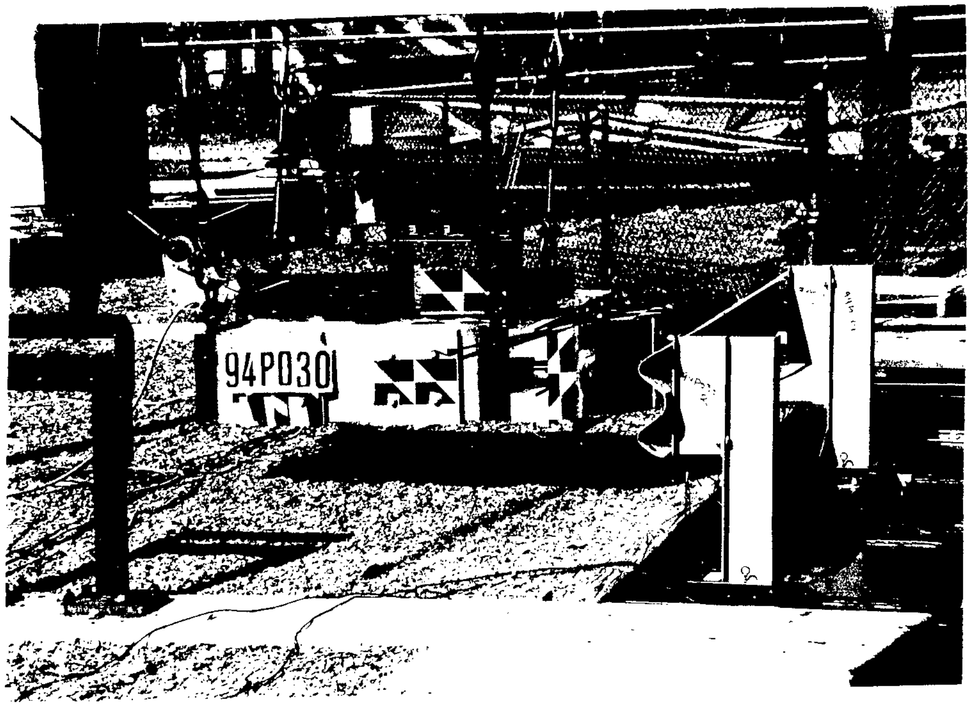


Figure 14. Pre-test photographs, test 94P030.

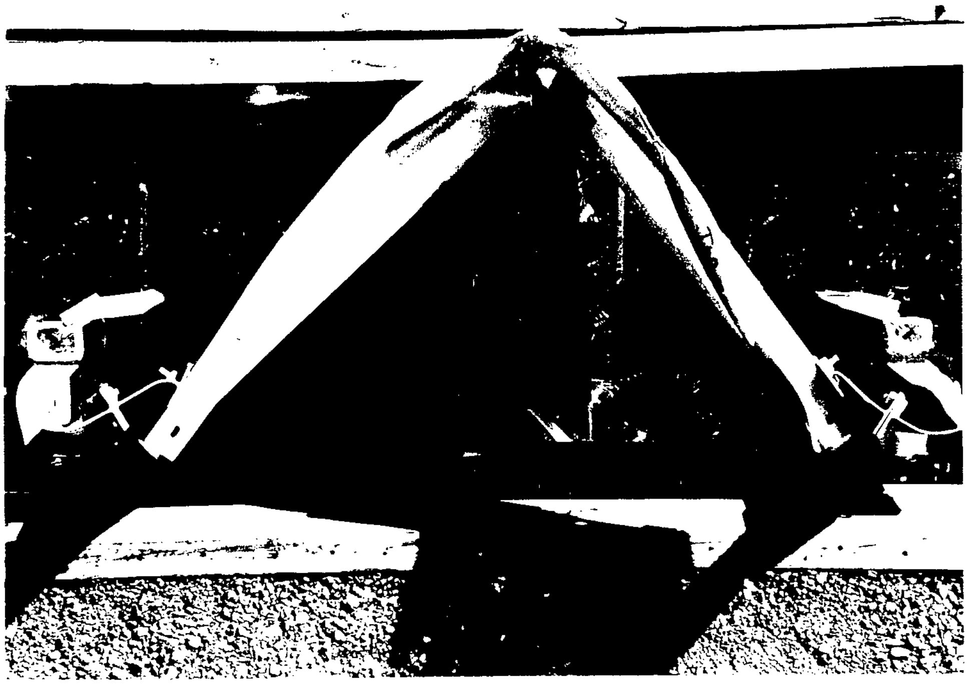


Figure 15. Post-test photographs, test 94P030.

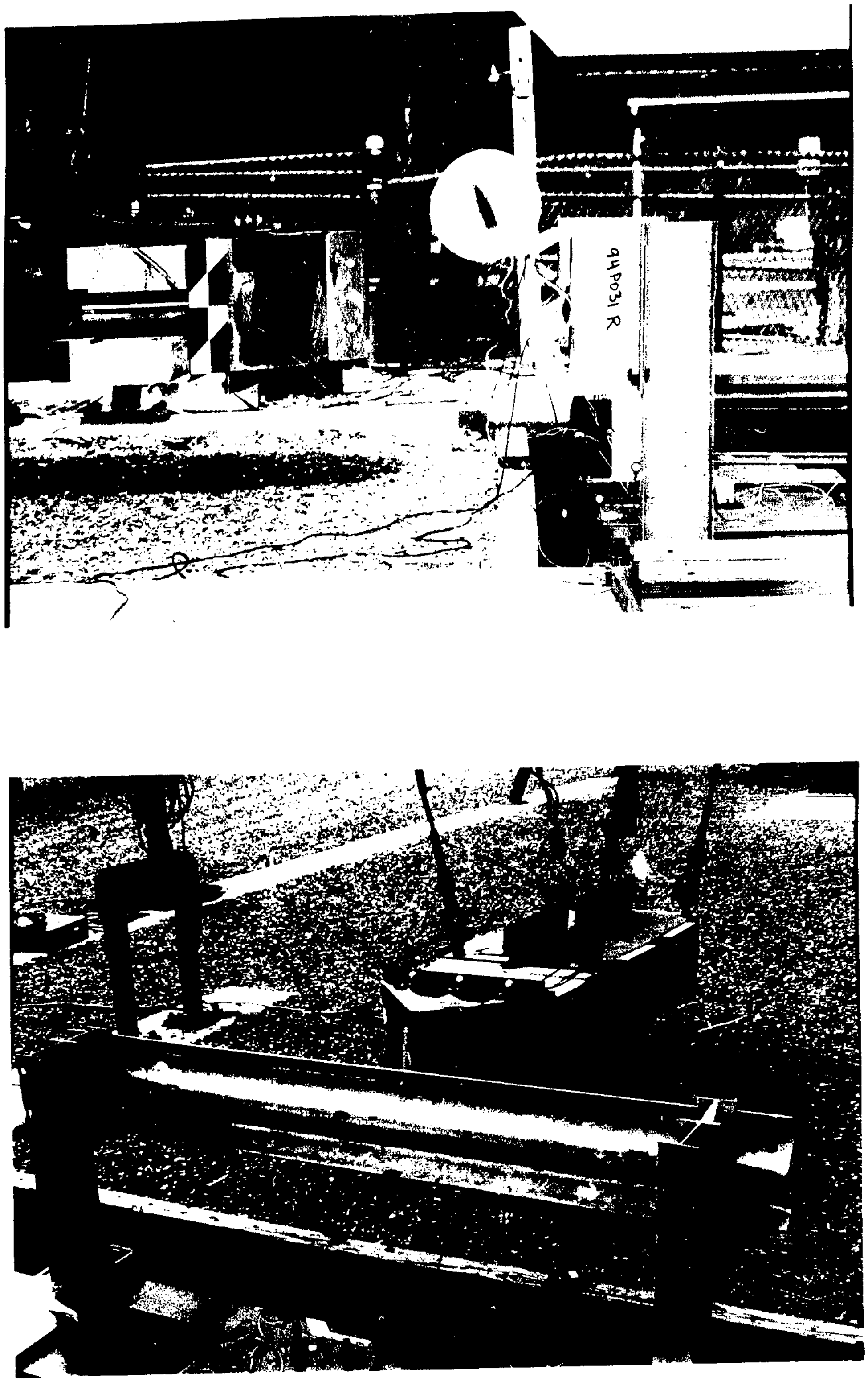


Figure 16. Pre-test photographs, test 94P031.

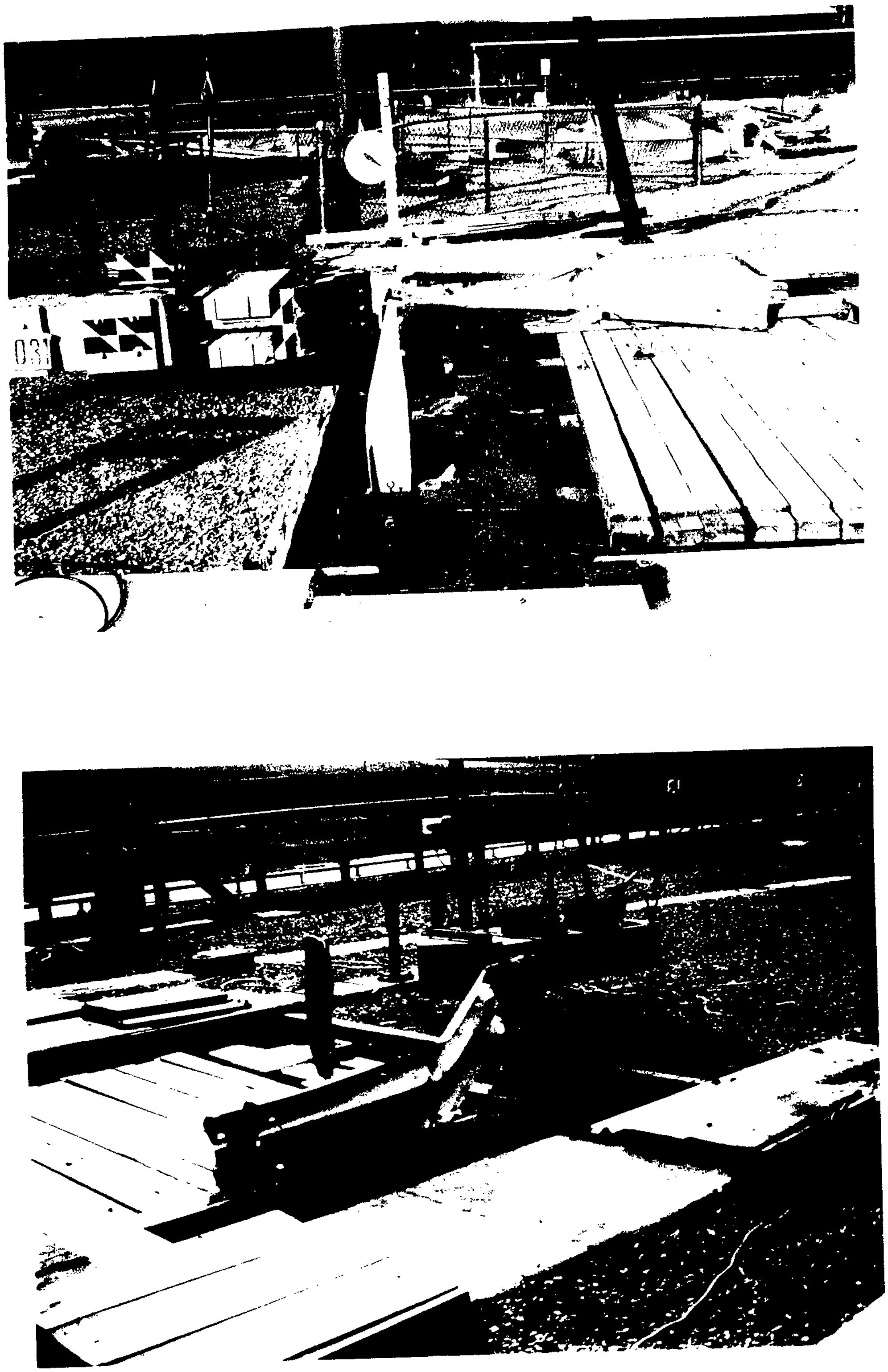


Figure 17. Post-test photographs, test 94P031.

Table 3. Summary of pendulum impact tests.					
Test Number	Speed Trap Data	Accelerometer Data			Strain Gauge Data
	Impact Speed (km/h)	Peak Force (1000 N)	ΔV (m/s)	Maximum Deflection (mm)	Maximum Rail Stain Front/Back ($\mu\epsilon$)
94P023	9.2	29.2	3.2	131	not collected
94P024	20.2	39.7	5.6	995	not collected
94P025	29.9	93.4	8.4	1240	not collected
94P026	34.9	102.5	4.4	1240	not collected
94P027	35.2	93.8	4.4	1300	not collected
94P030	34.8	65.0	5.5	1400	958/1072
94P031	34.8	87.0	3.7	1300	2622/2622

CONCLUSIONS

From the strain gauge rosette data, it was confirmed that there was no problem in the design of the test fixture foundation in terms of over stressing the fixture. Through the course of testing, it was determined that an optimal spacer length of 325 mm was needed to provide the necessary contact time required for a complete impact of the rail. From resulting test data, it was determined that the single span of rail setup was not sufficient to fail the rail at a pendulum impact of 35 km/h. Therefore, in order to determine the force required to break the rail and determine the dynamic response of the rail, a new test setup needed to be developed. It was proposed that end tension applied to the ends of the rail section would better emulate the actual field conditions of a guardrail impact. Also, the use of three spans of rail for testing would reduce the problems encountered with the posts twisting as seen in these series of tests.

APPENDIX A. DATA PLOTS FOR TESTS 94P023, 94P024, 94P025, 94P026, 94P027, 94P030, AND 94P031

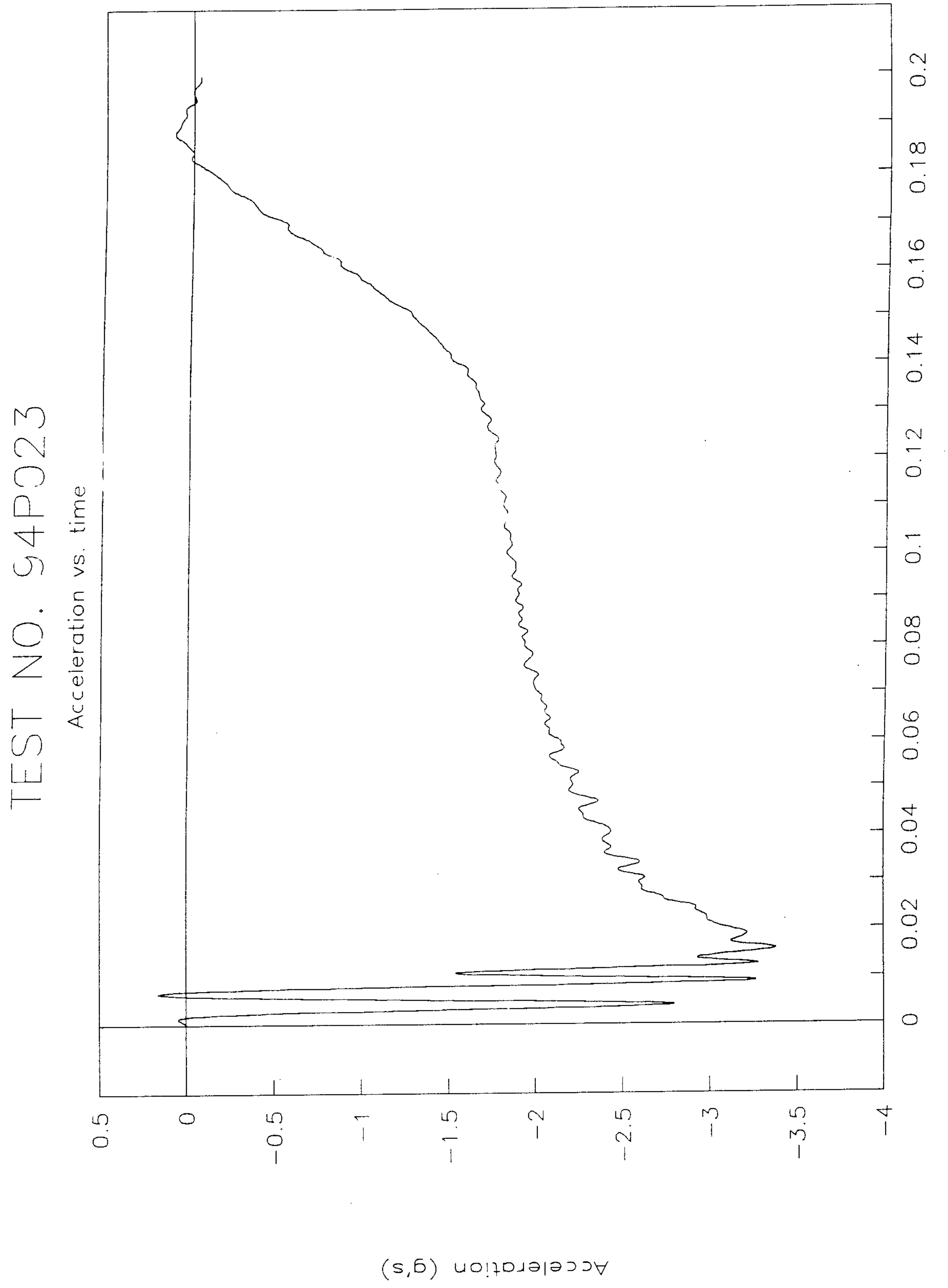


Figure 18. Accelerometer data, acceleration vs. time, test 94P023.

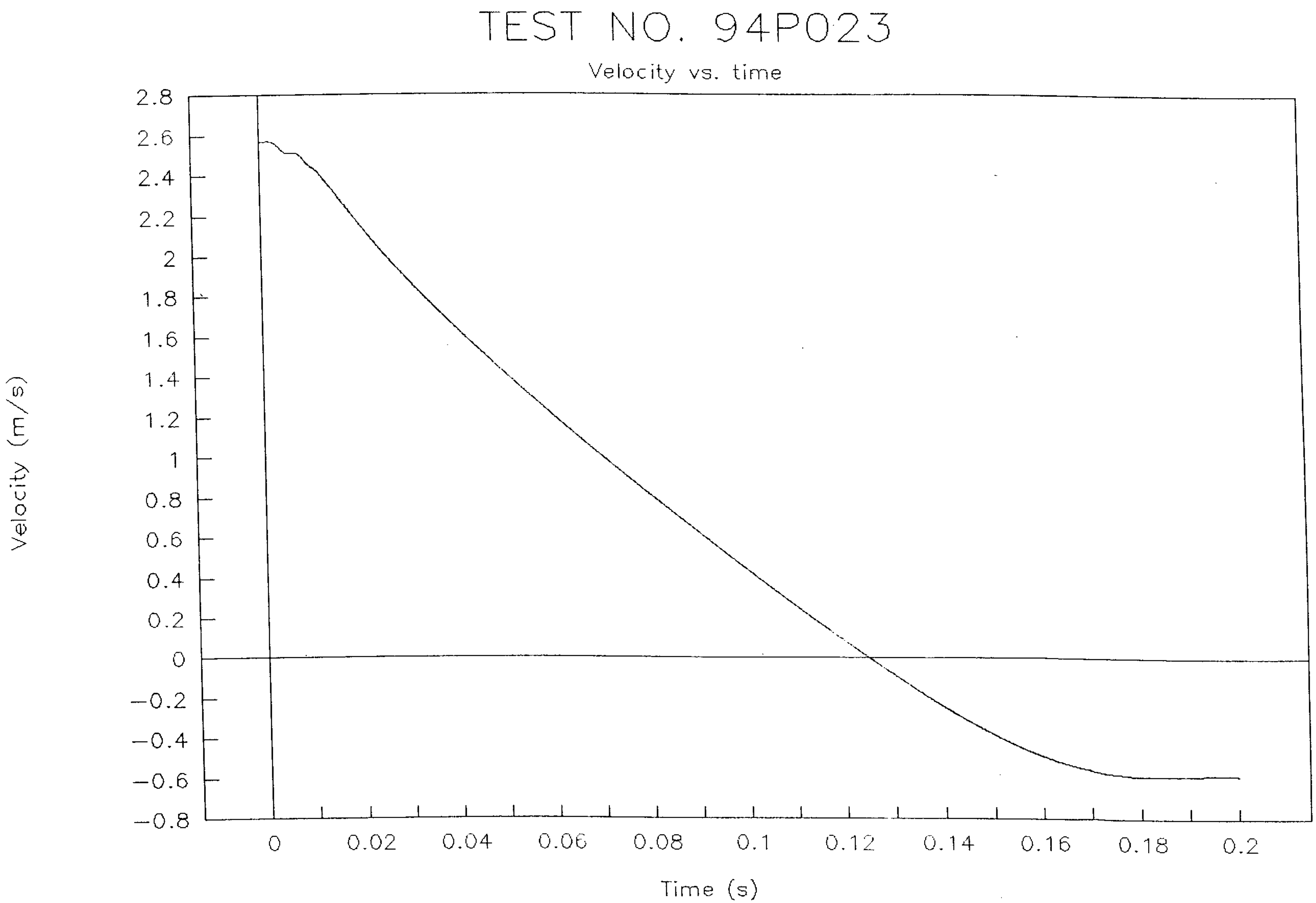


Figure 19. Accelerometer data, velocity vs. time, test 94P023.

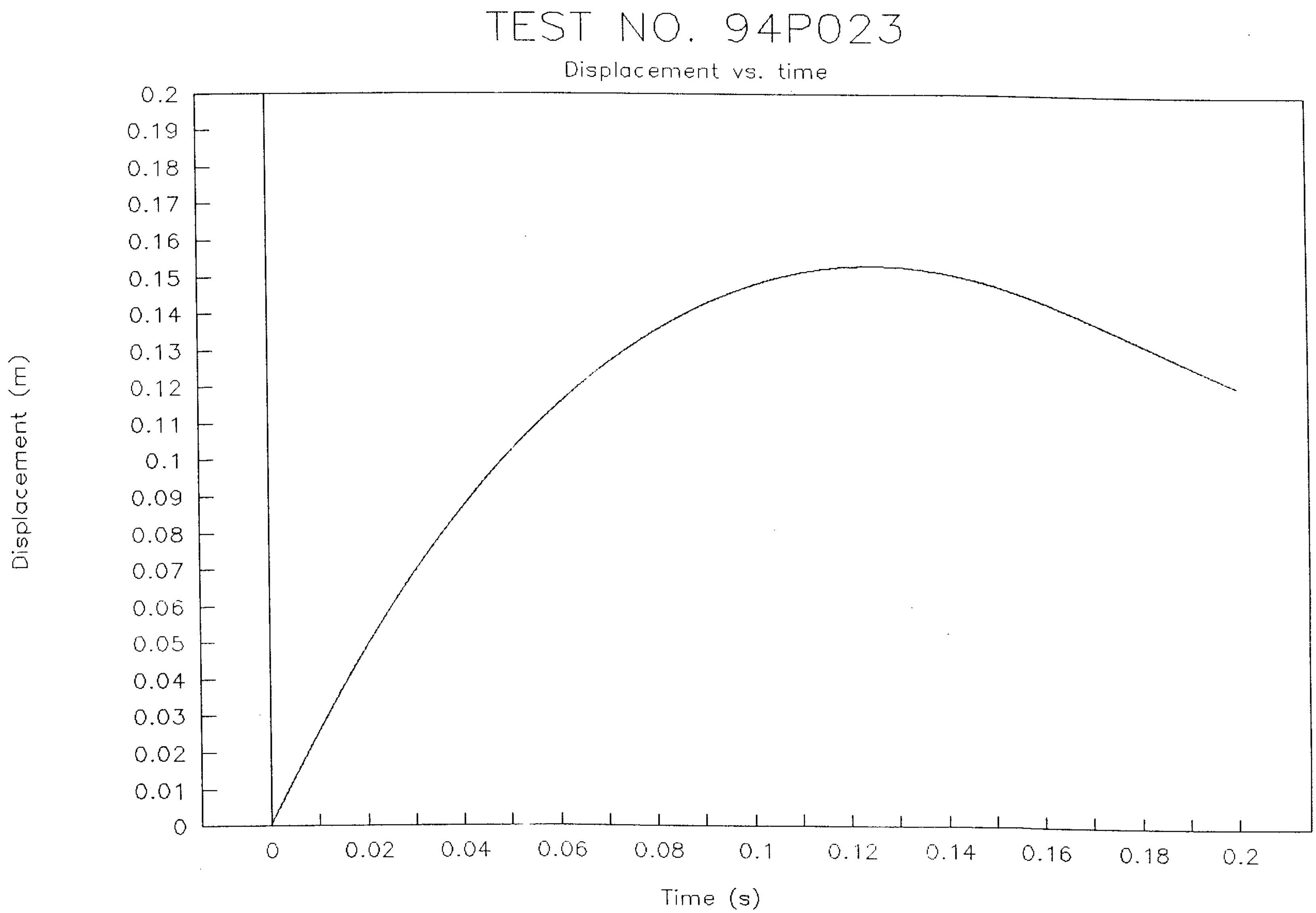


Figure 20. Accelerometer data, displacement vs. time, test 94P023.

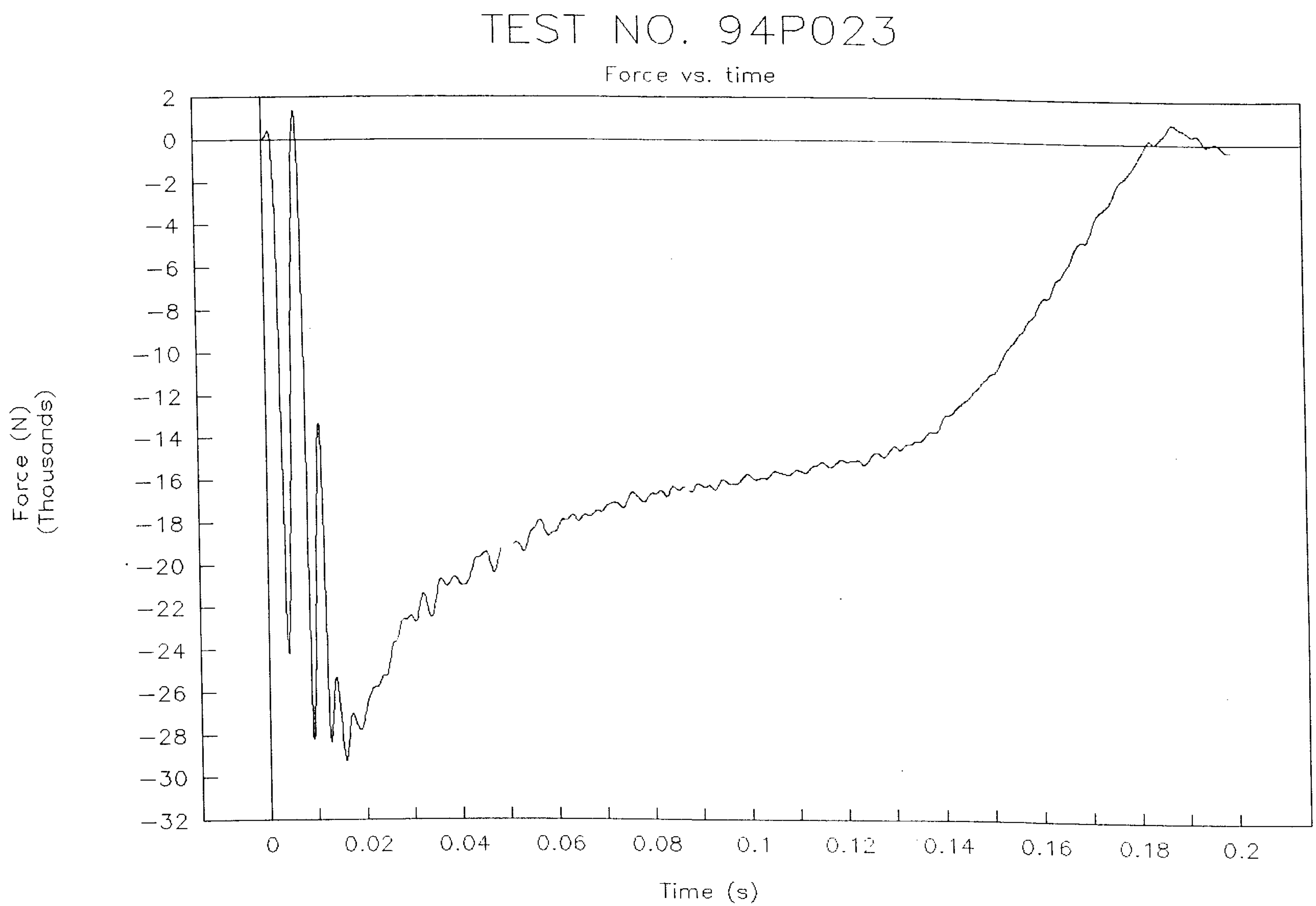


Figure 21. Accelerometer data, force vs. time, test 94P023.

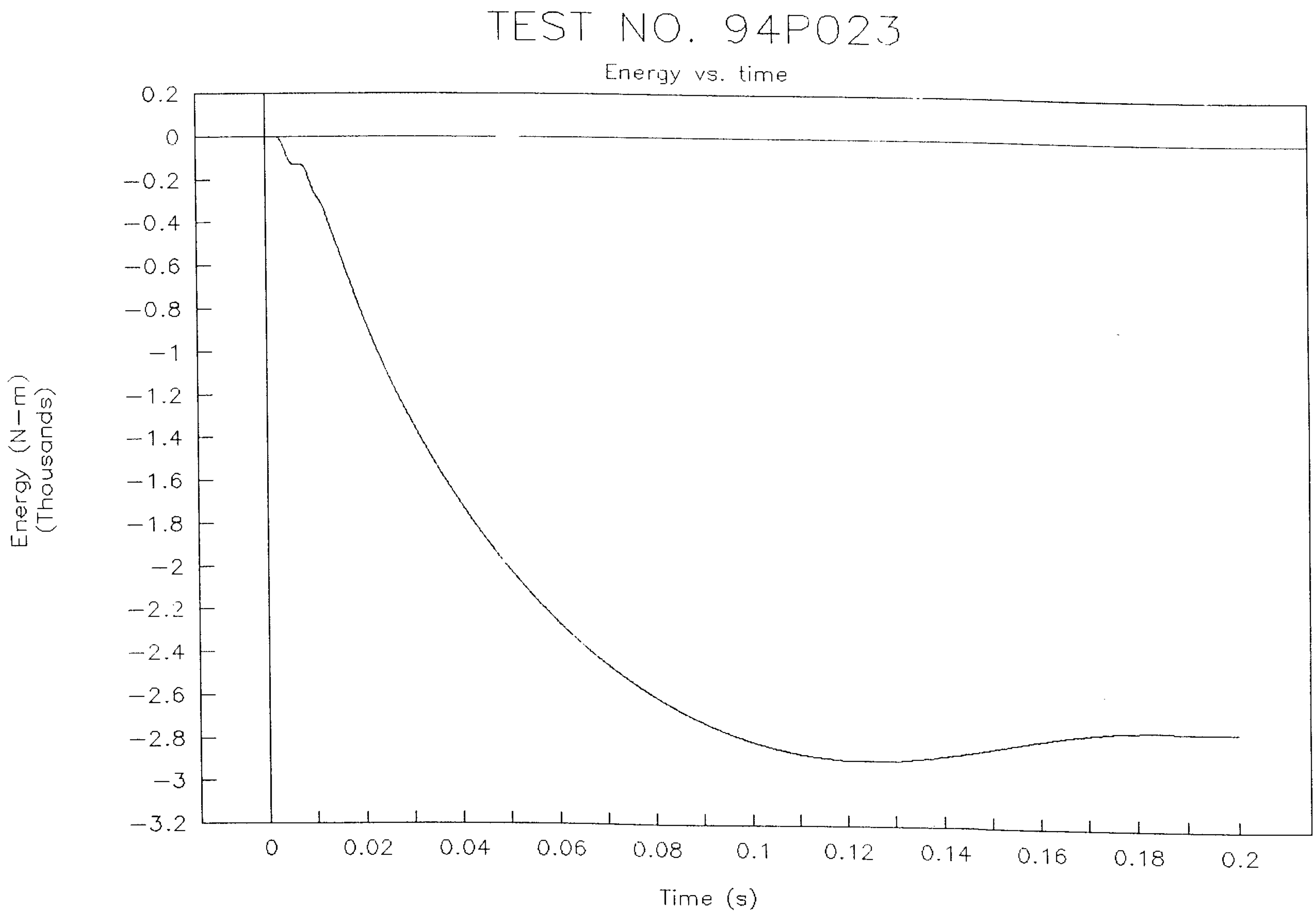


Figure 22. Accelerometer data, energy vs. time, test 94P023.

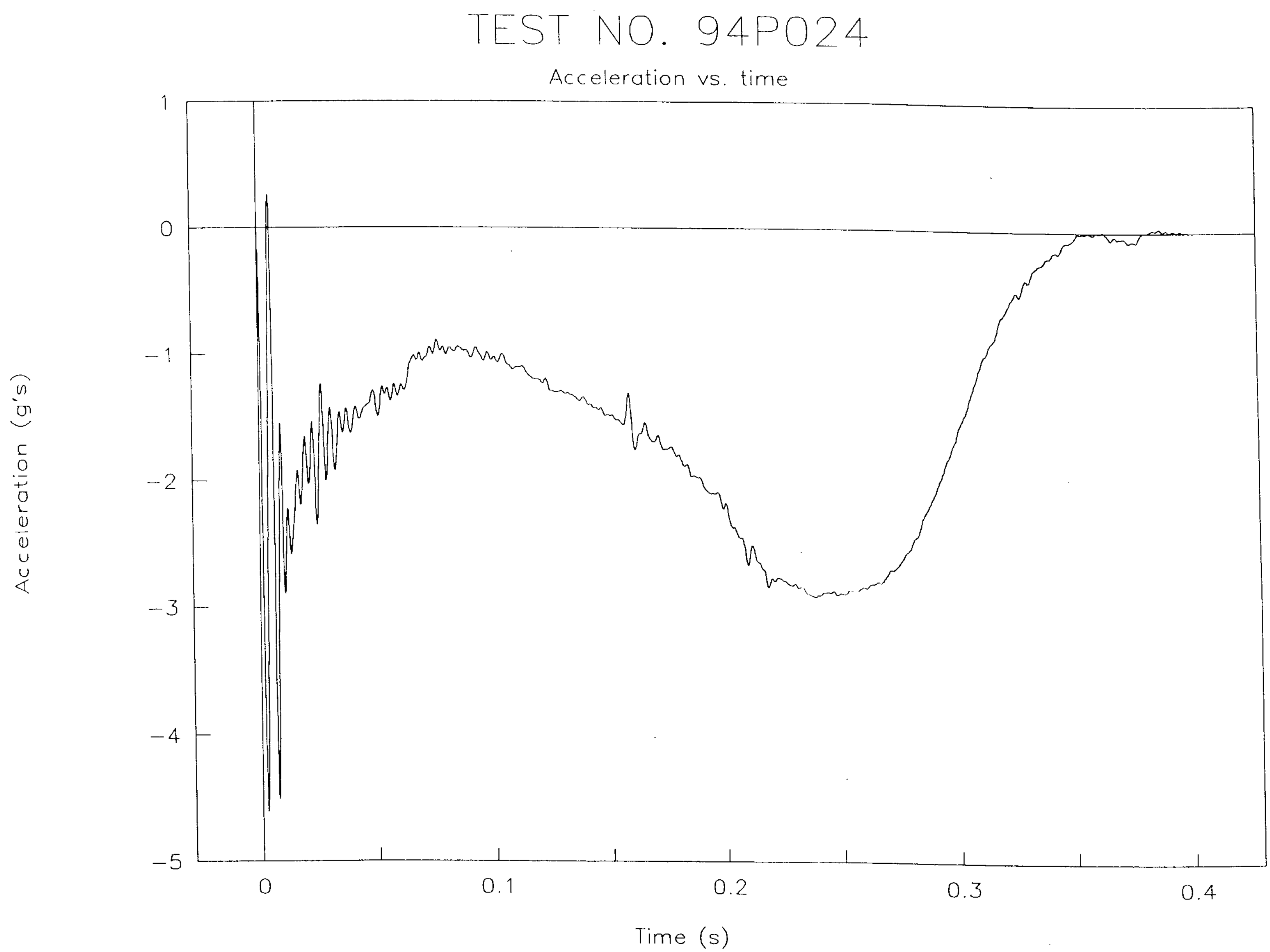


Figure 23. Acceler[illegible]ter data, acceleration vs. time, test 94P024.

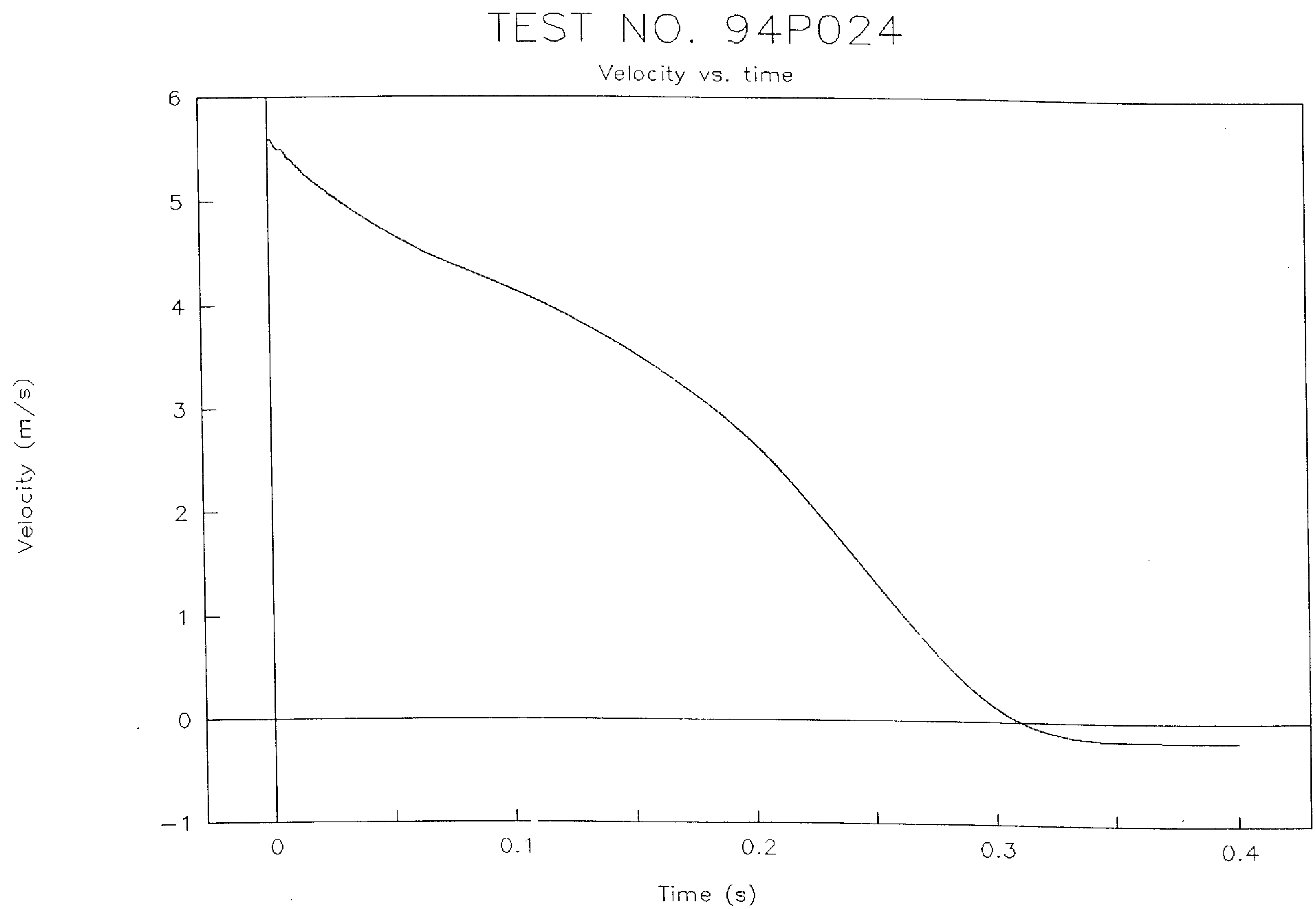


Figure 24. Accelerometer data, velocity vs. time, test 94P024.

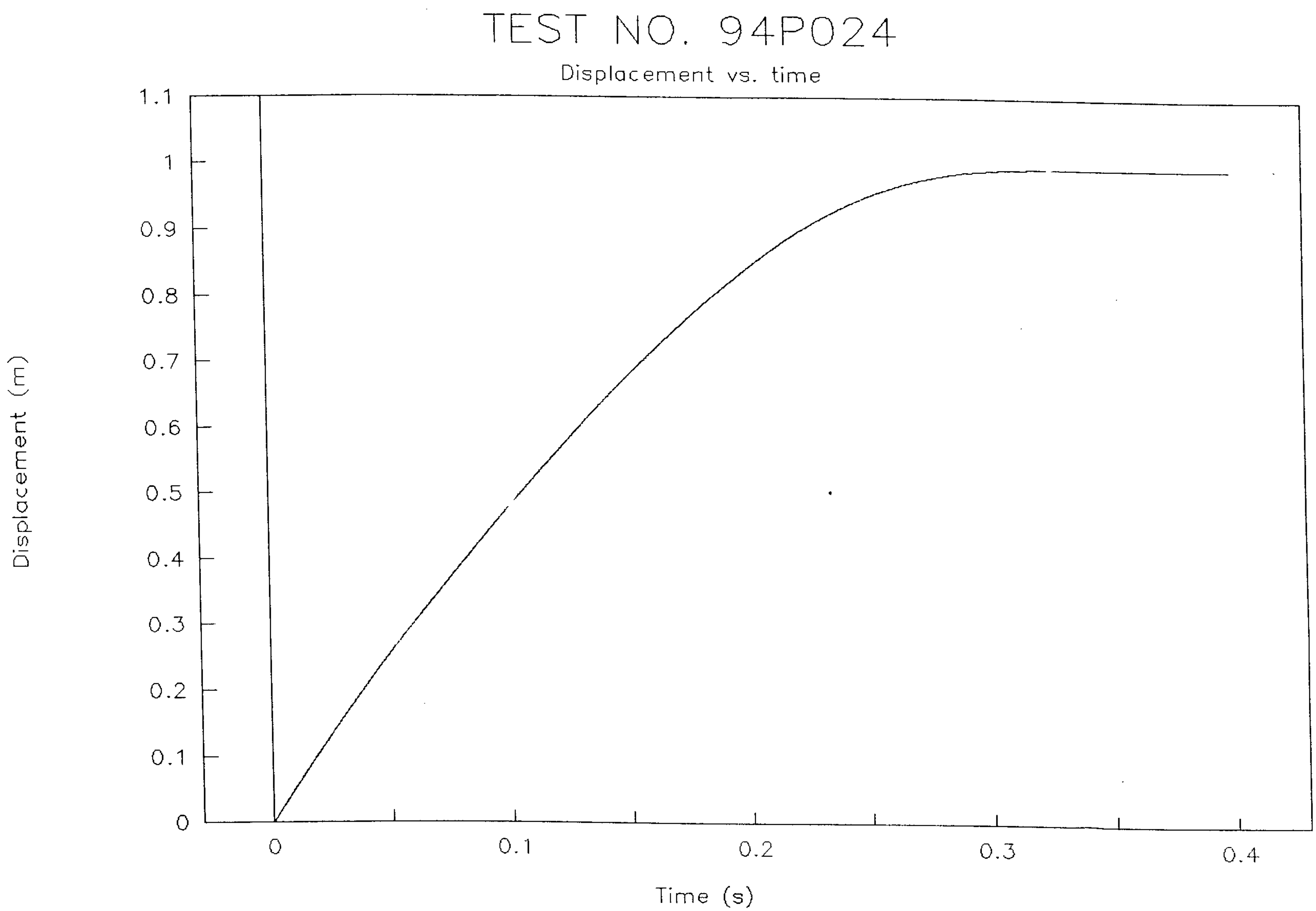


Figure 25. Accelerometer data, displacement vs. time, test 94P024.

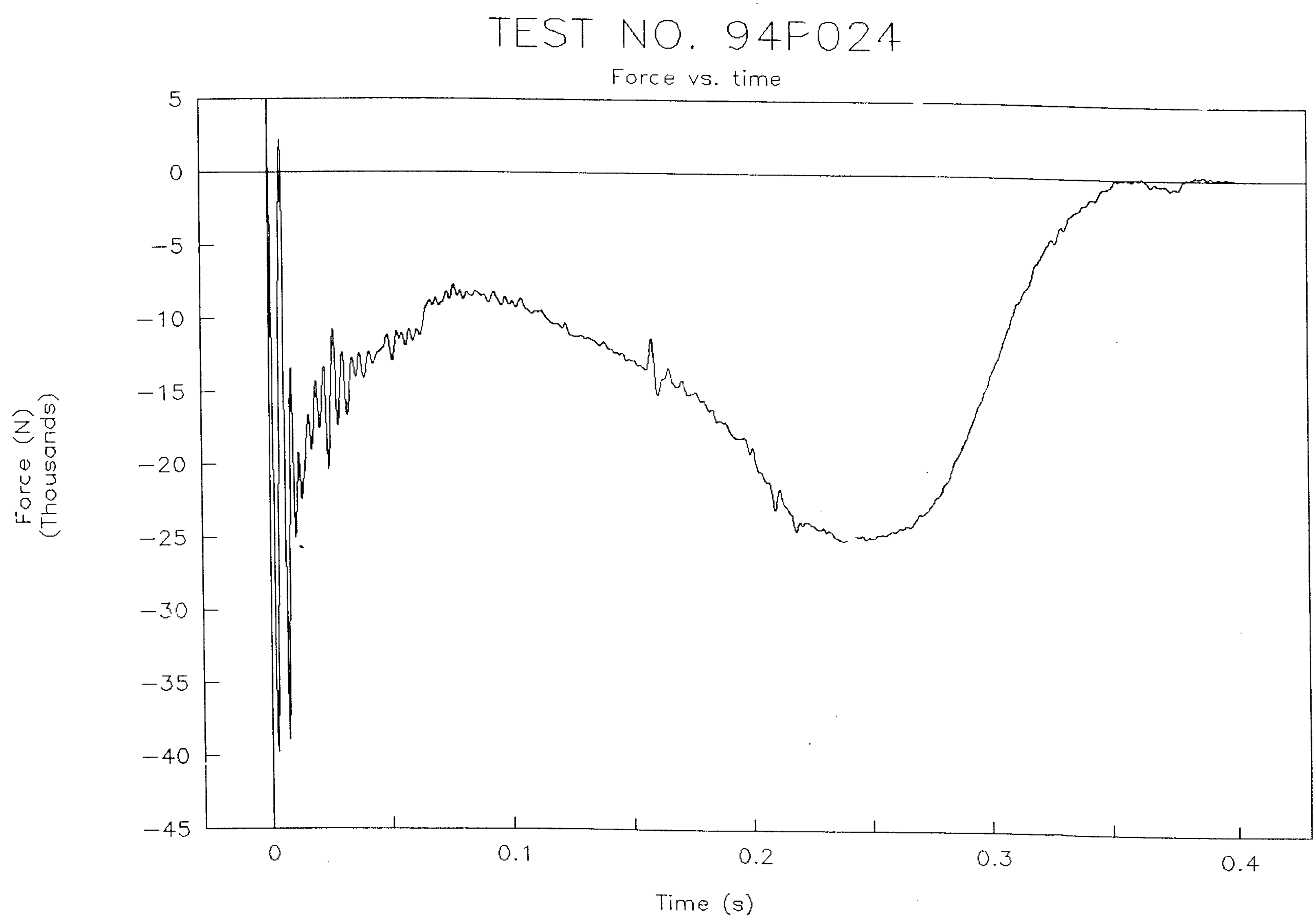


Figure 26. Accelerometer data, force vs. time, test 94P024.

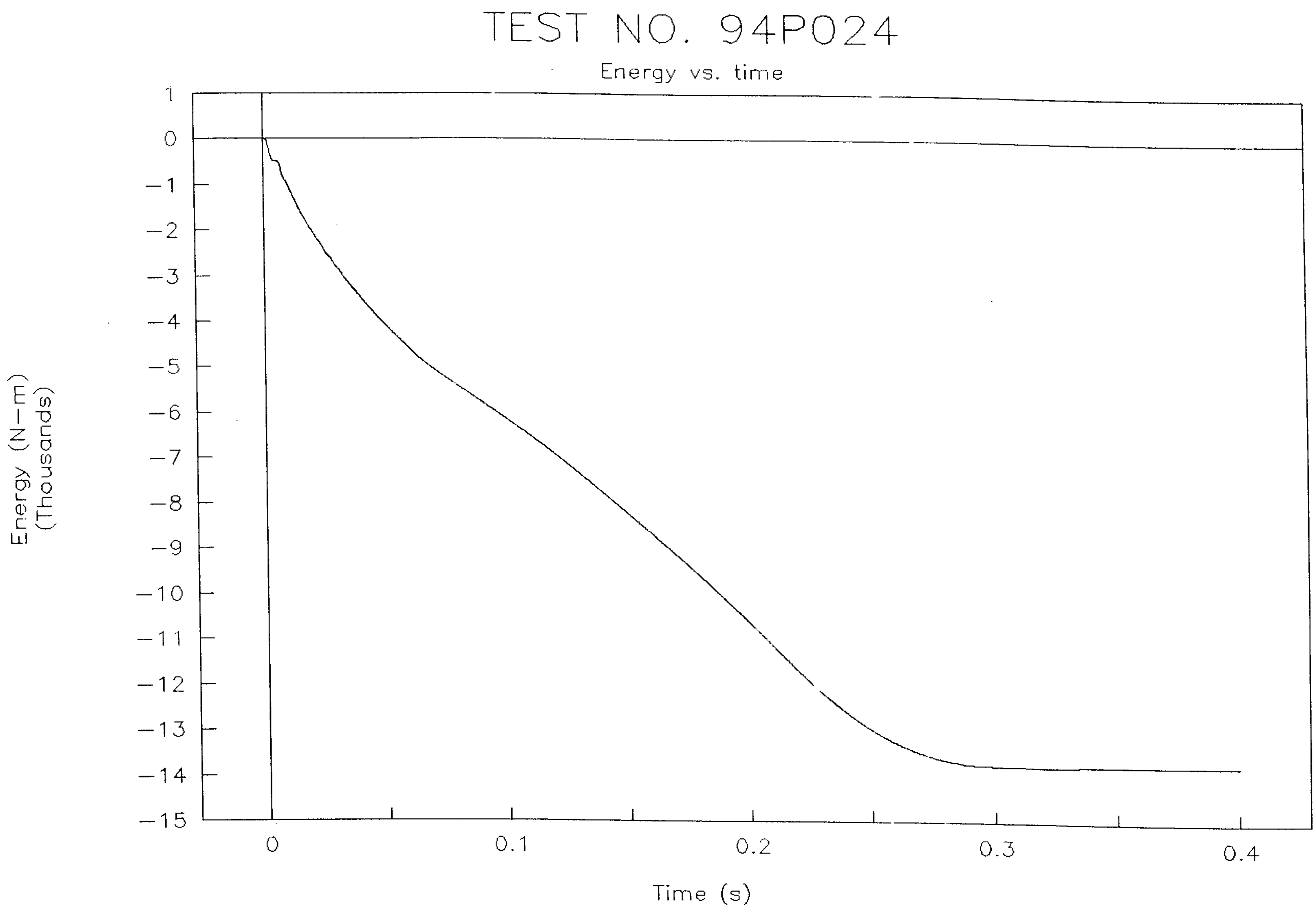


Figure 27. Accel ometer data, energy vs. time, test 94P024.

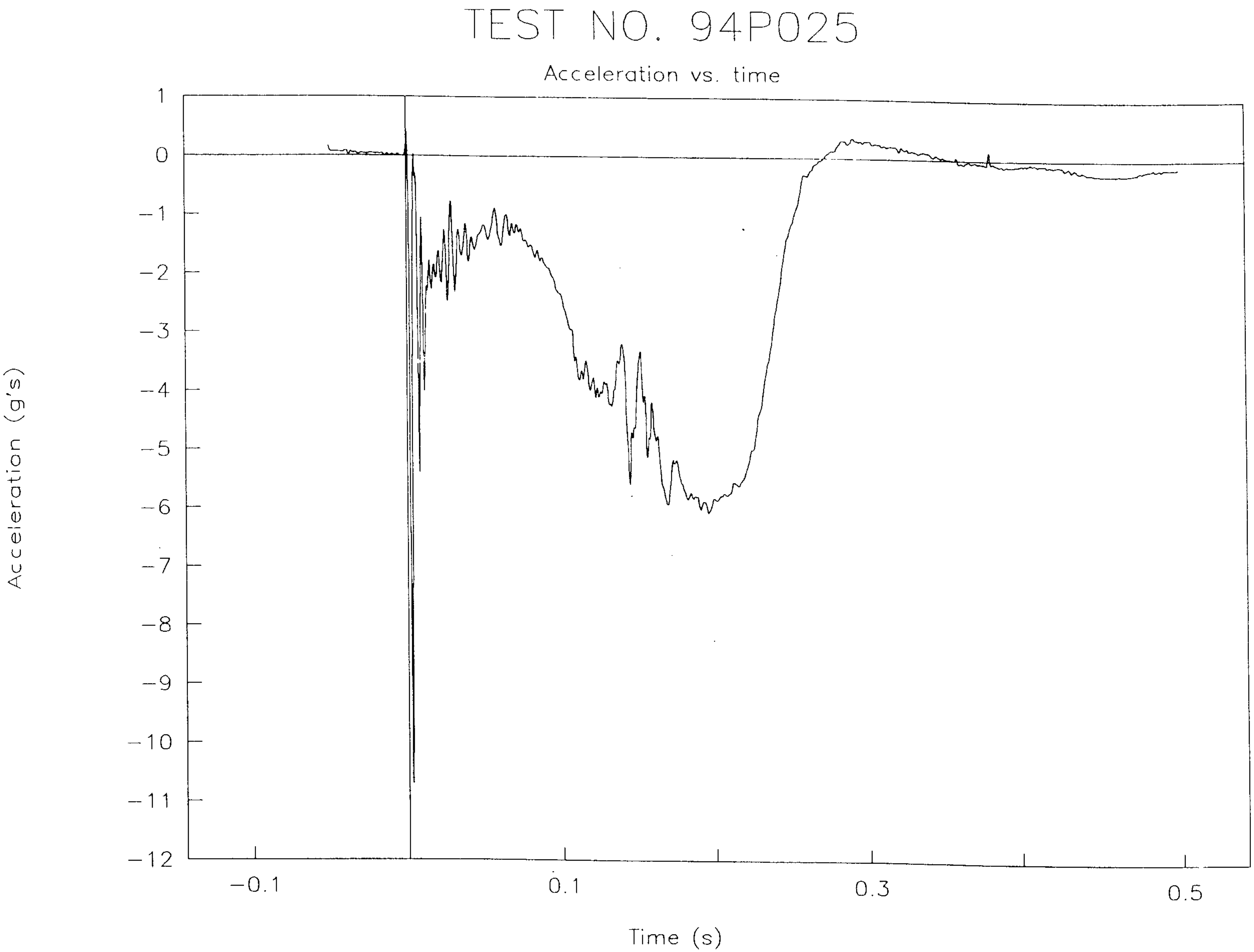


Figure 28. Accelerometer data, acceleration vs. time, test 94P025.

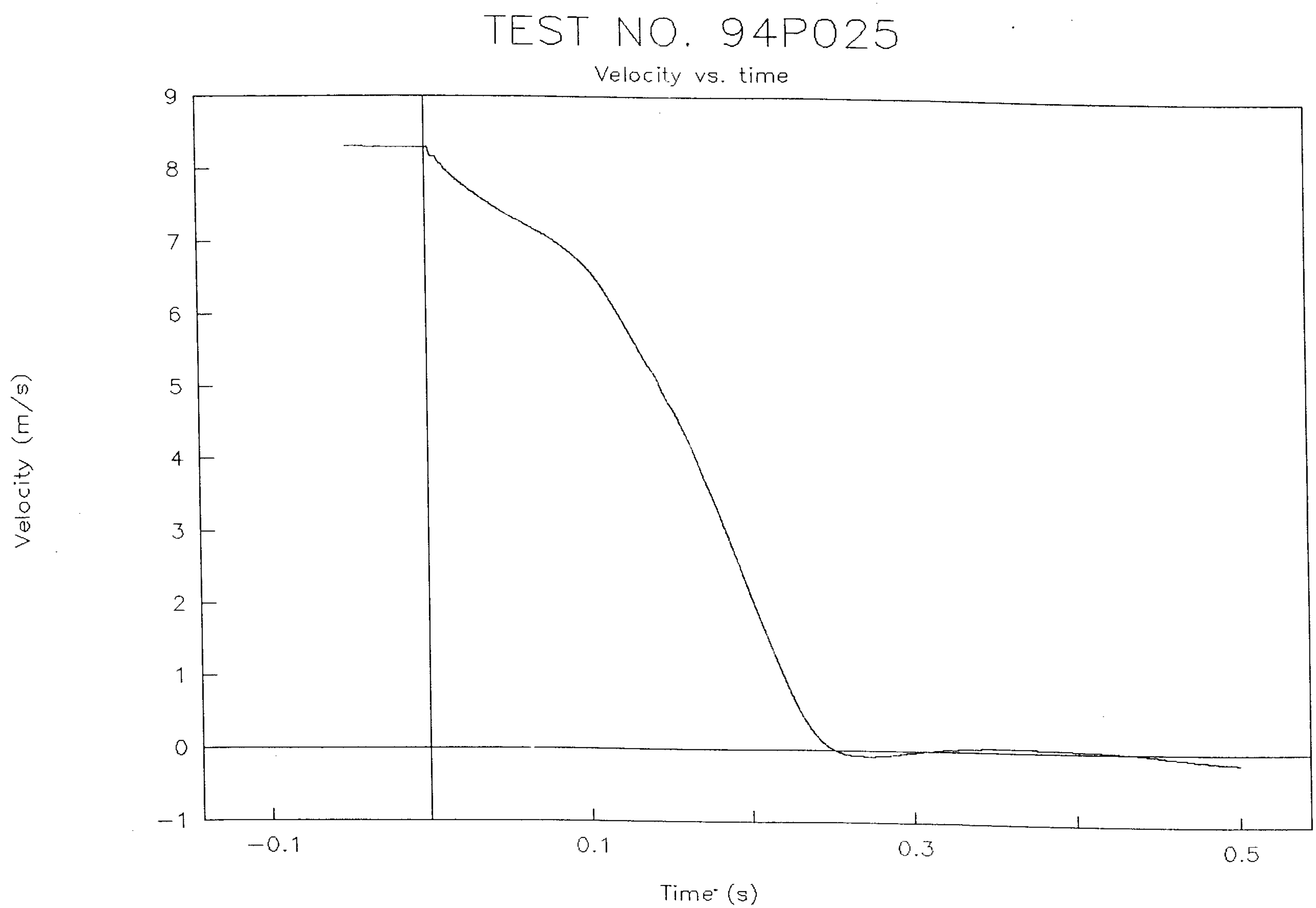


Figure 29. Accelerometer data, velocity vs. time, test 94P025.

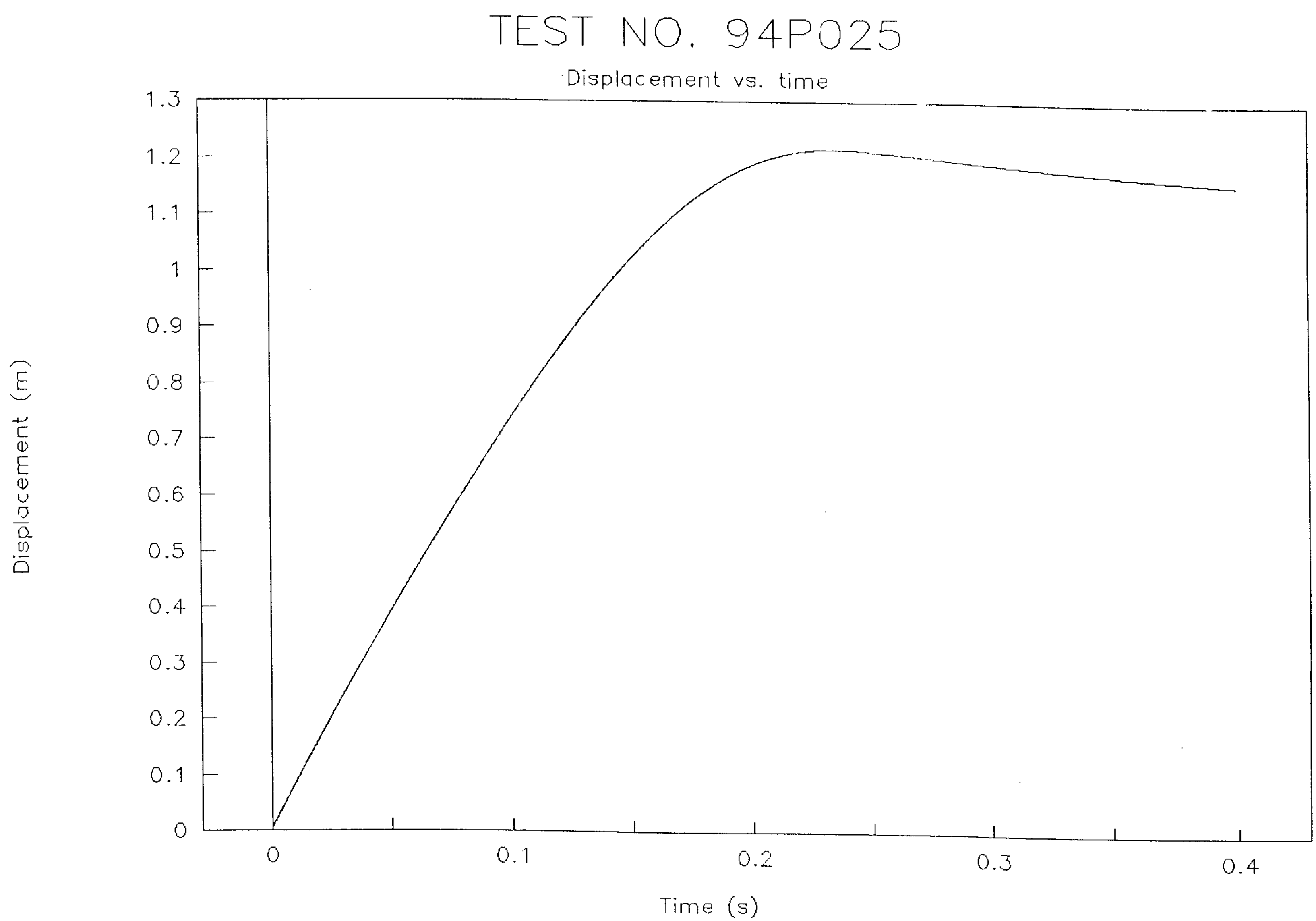


Figure 30. Accelerometer data, displacement vs. time, test 94P025.

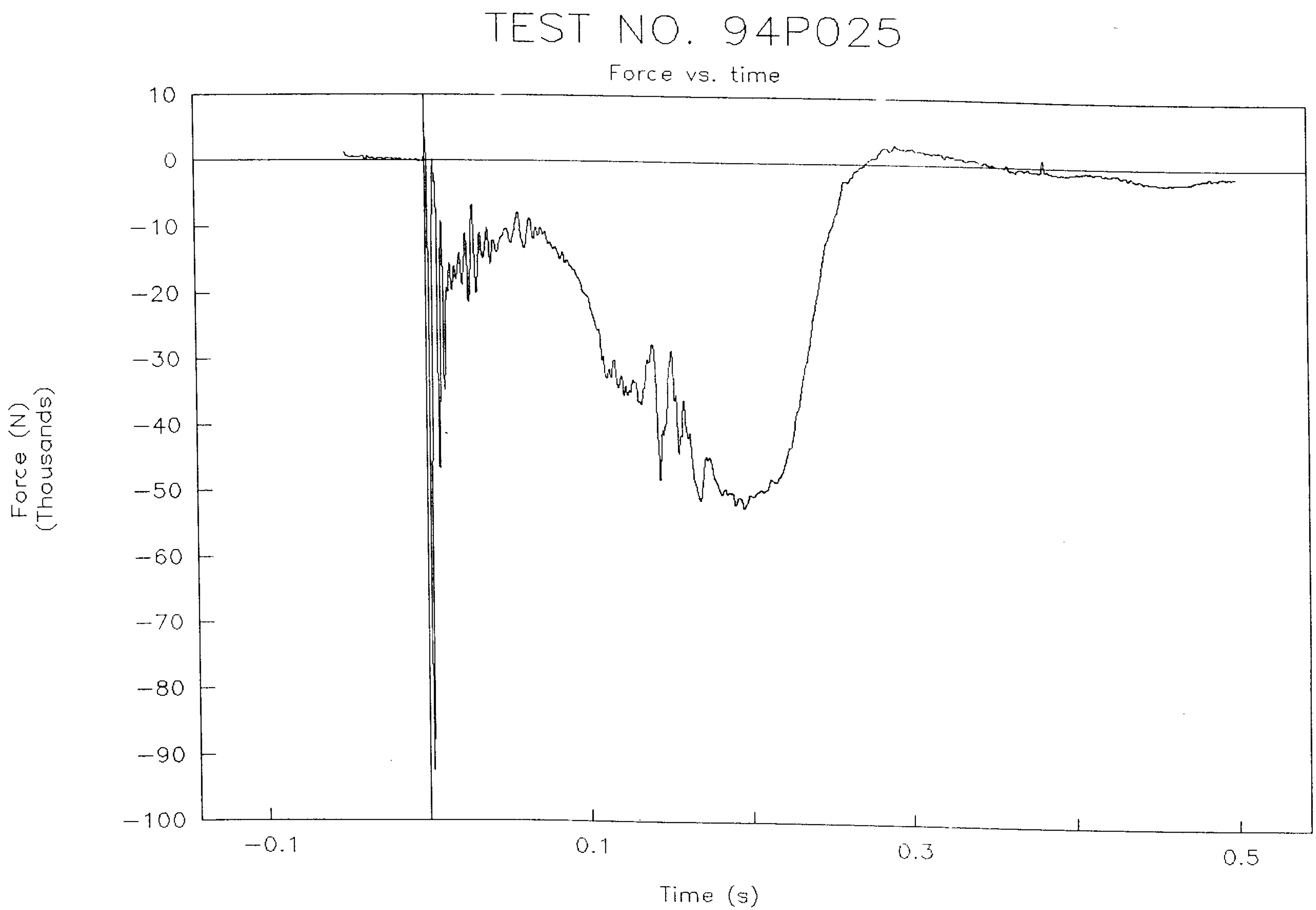


Figure 31. Acce` -ometer data, force vs. time, test 94P025.

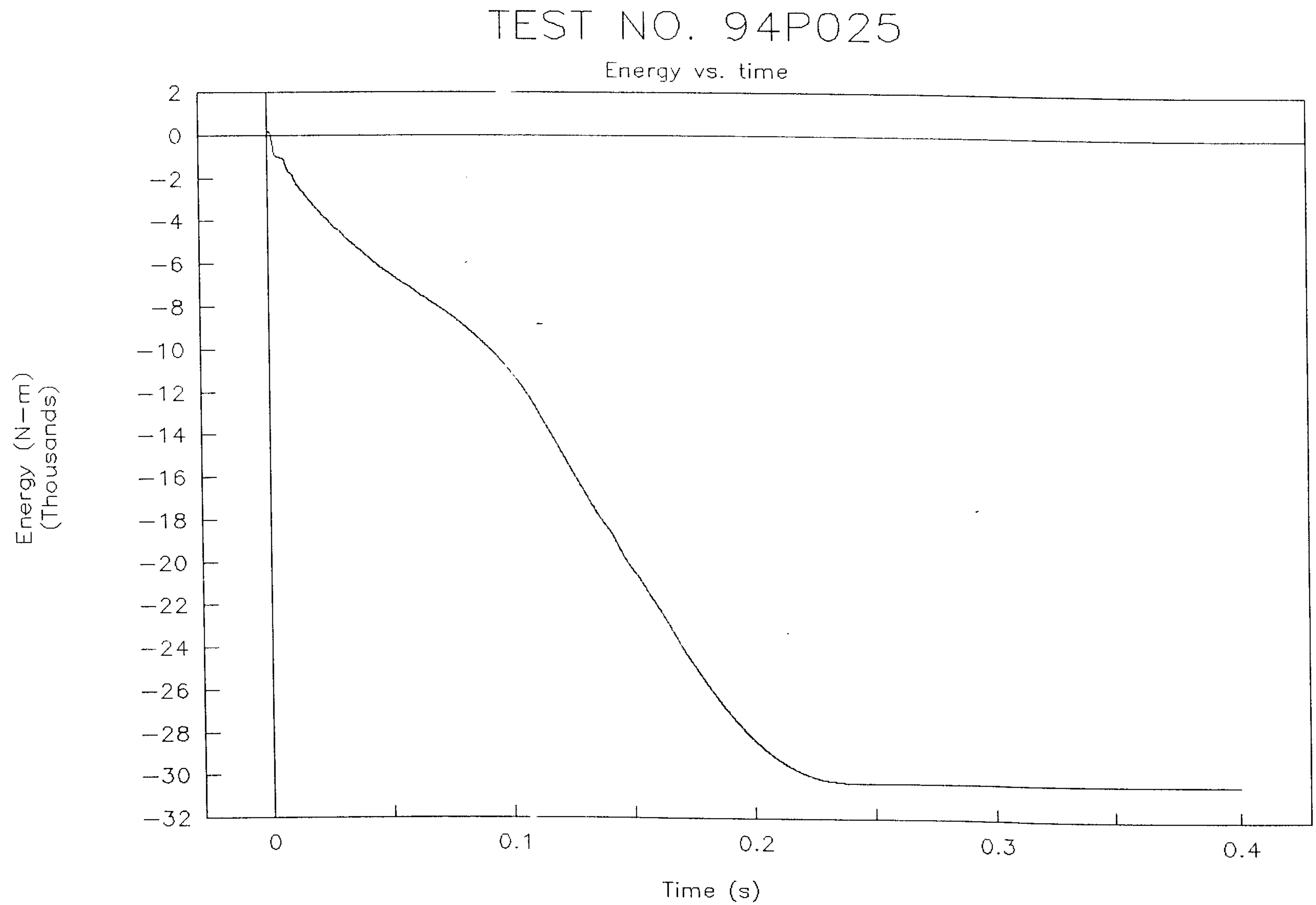


Figure 32. Accelerometer data, energy vs. time, test 94P025.

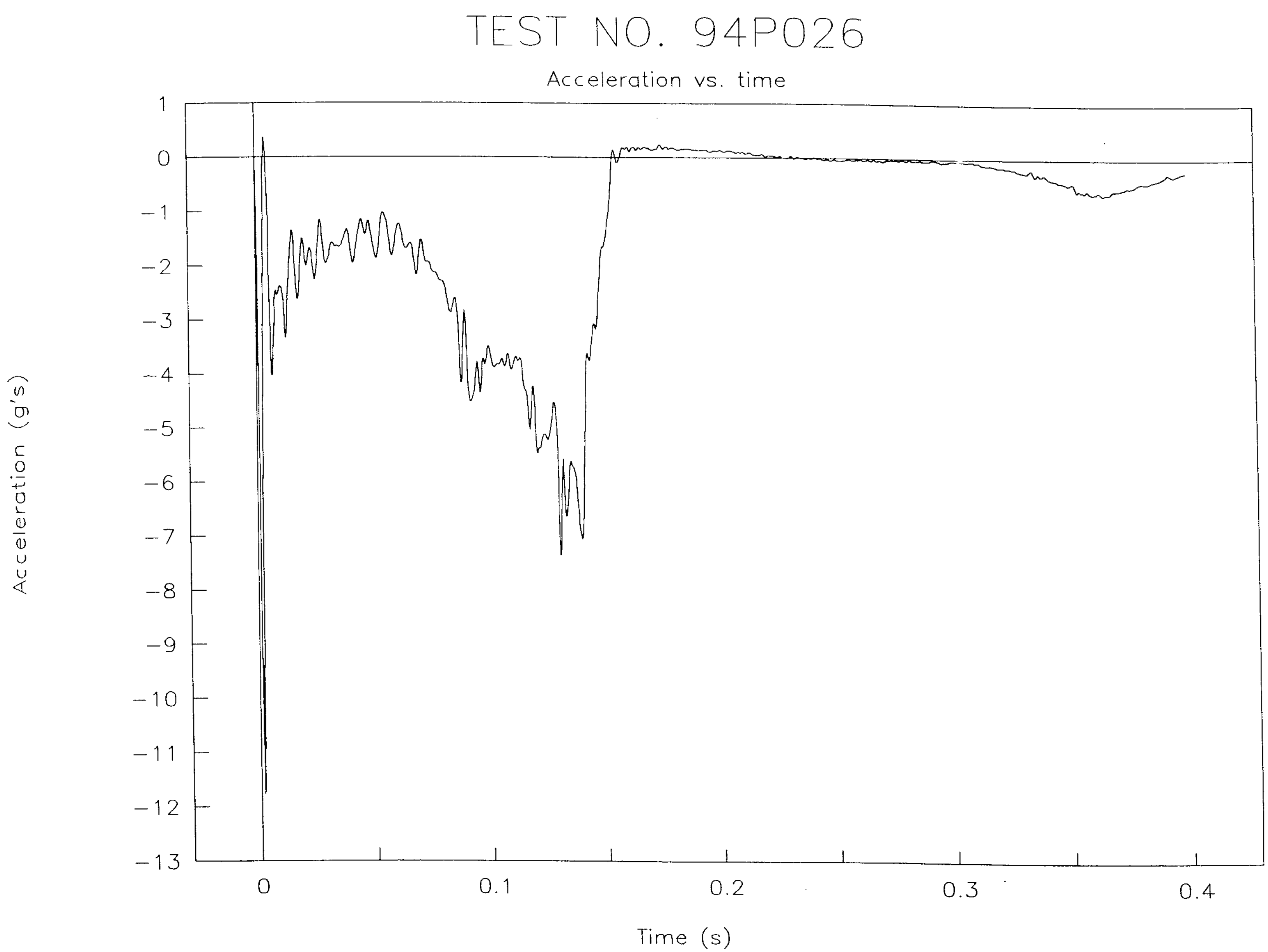


Figure 33. Accelerometer data, acceleration vs. time, test 94P026.

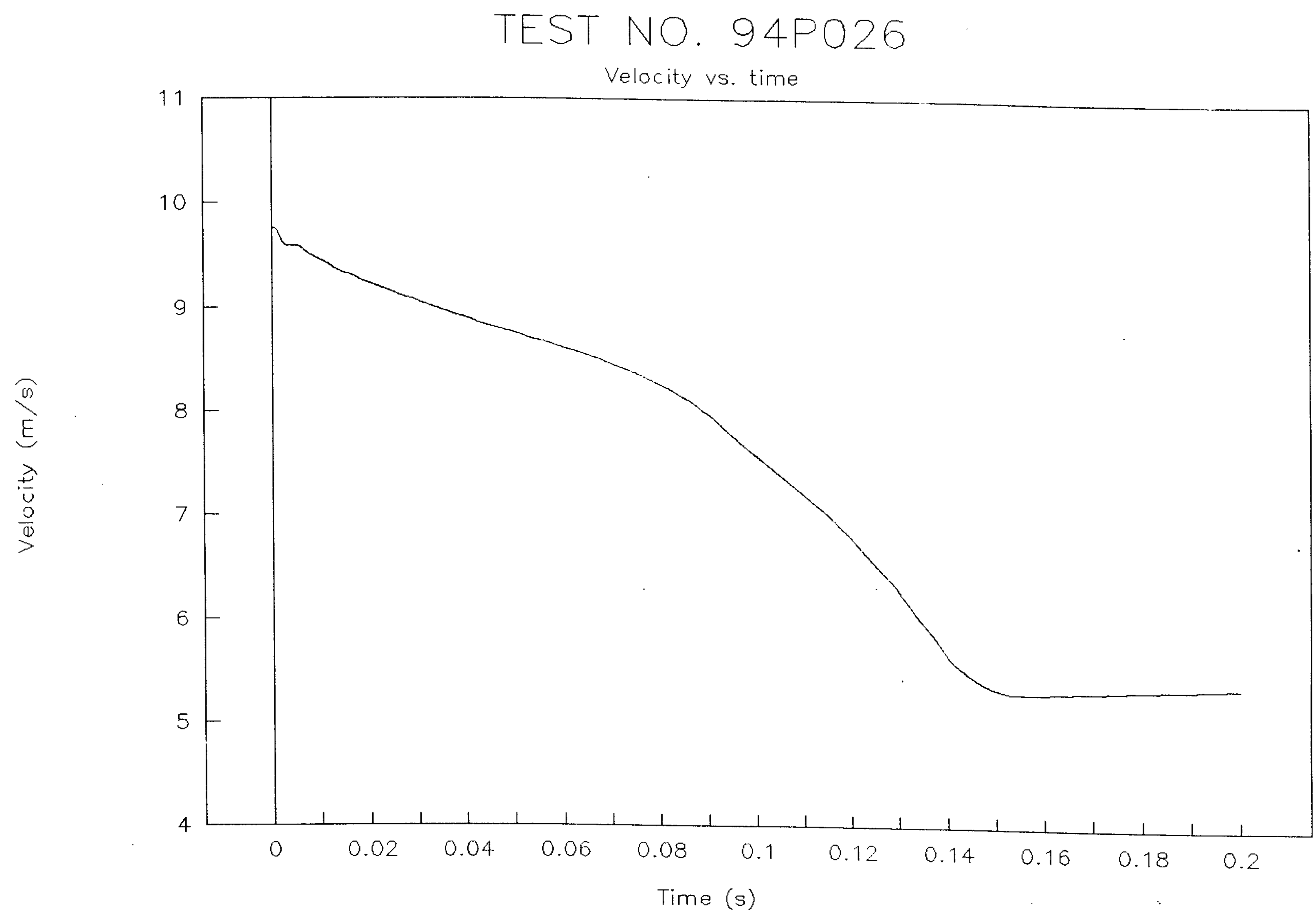


Figure 34. Accelerometer data, velocity vs. time, test 94P026.

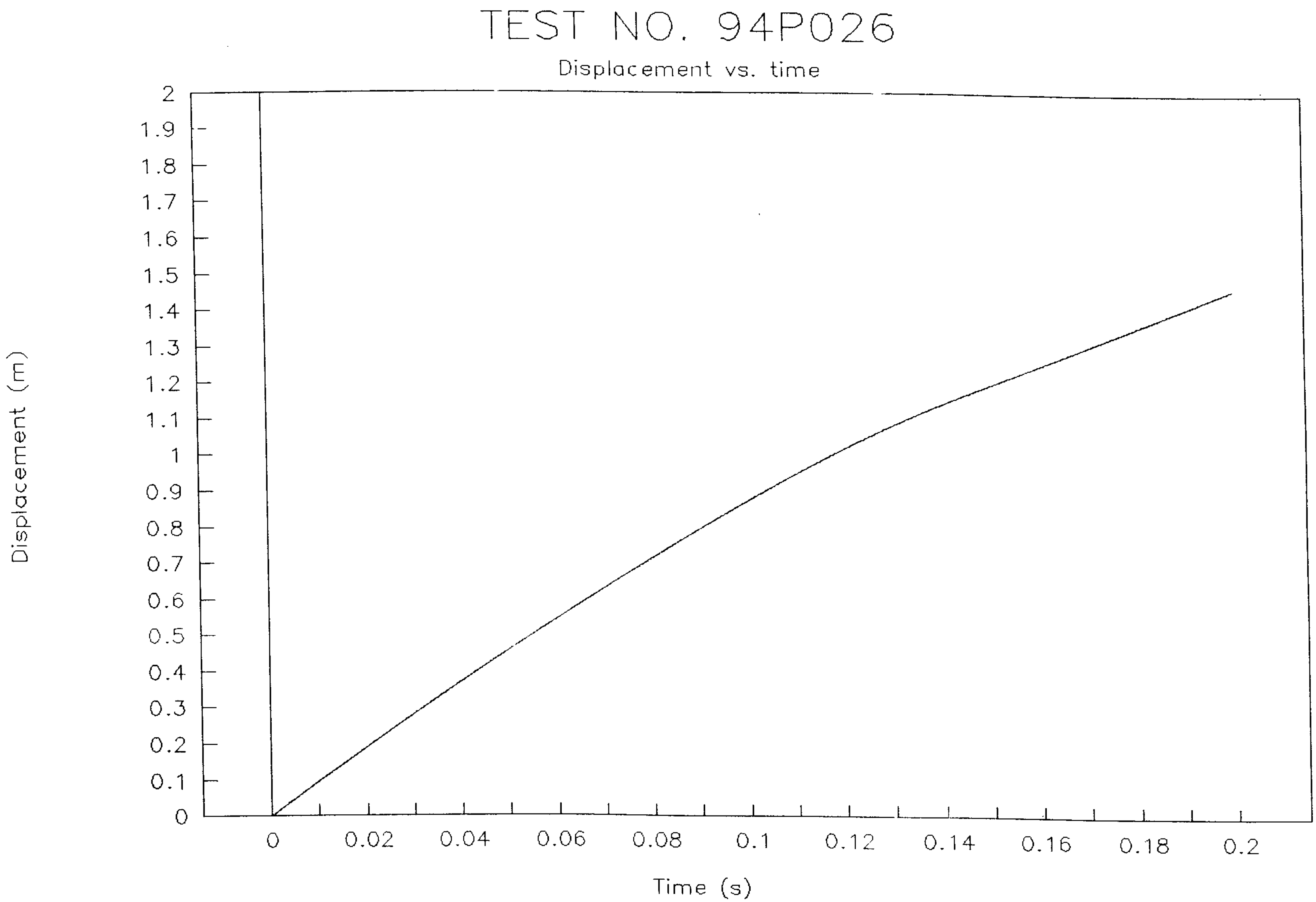


Figure 35. Accel ɔmeter, displacement vs. time, test 94P026.

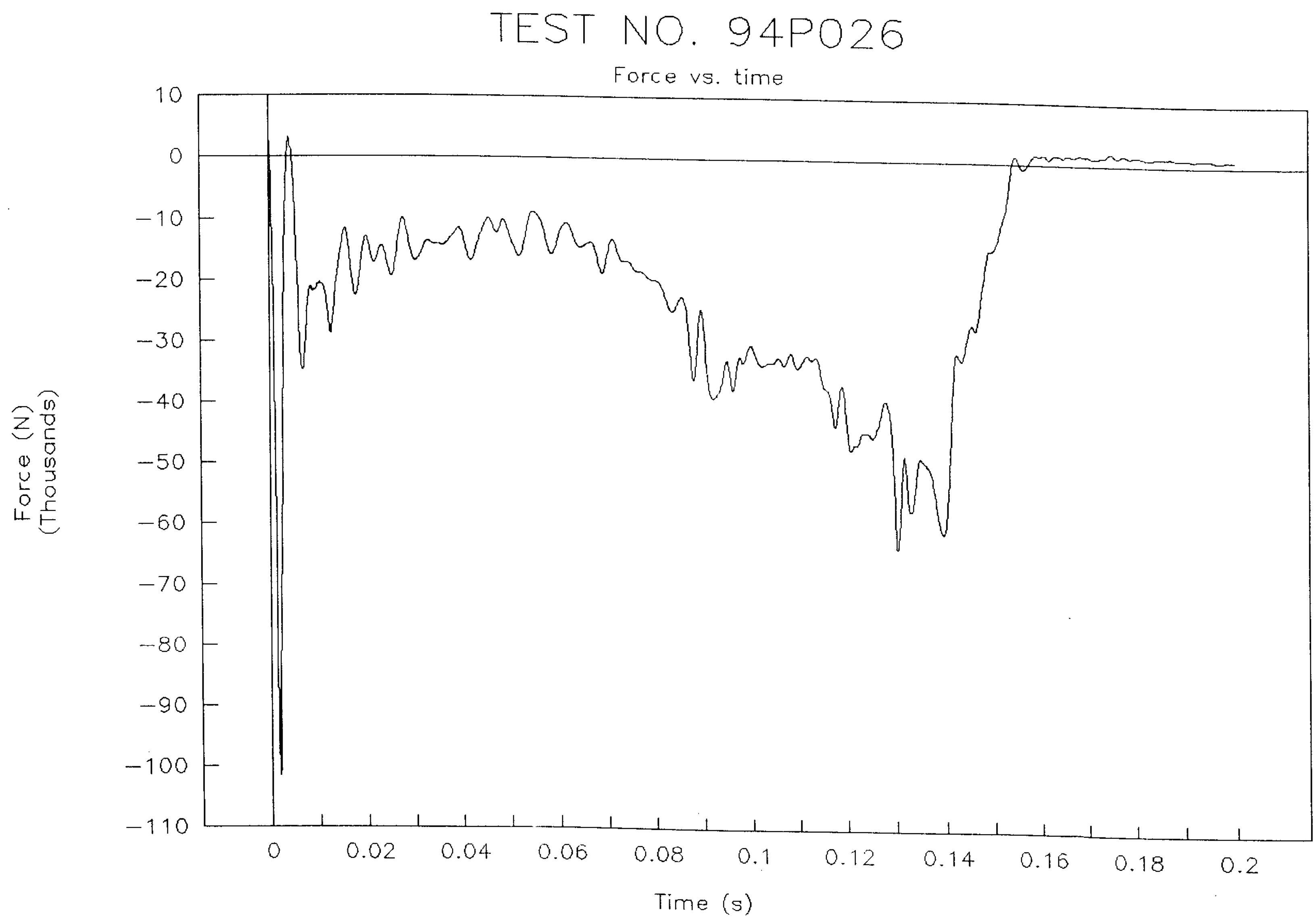


Figure 36. Accelerometer data, force vs. time, test 94P026.

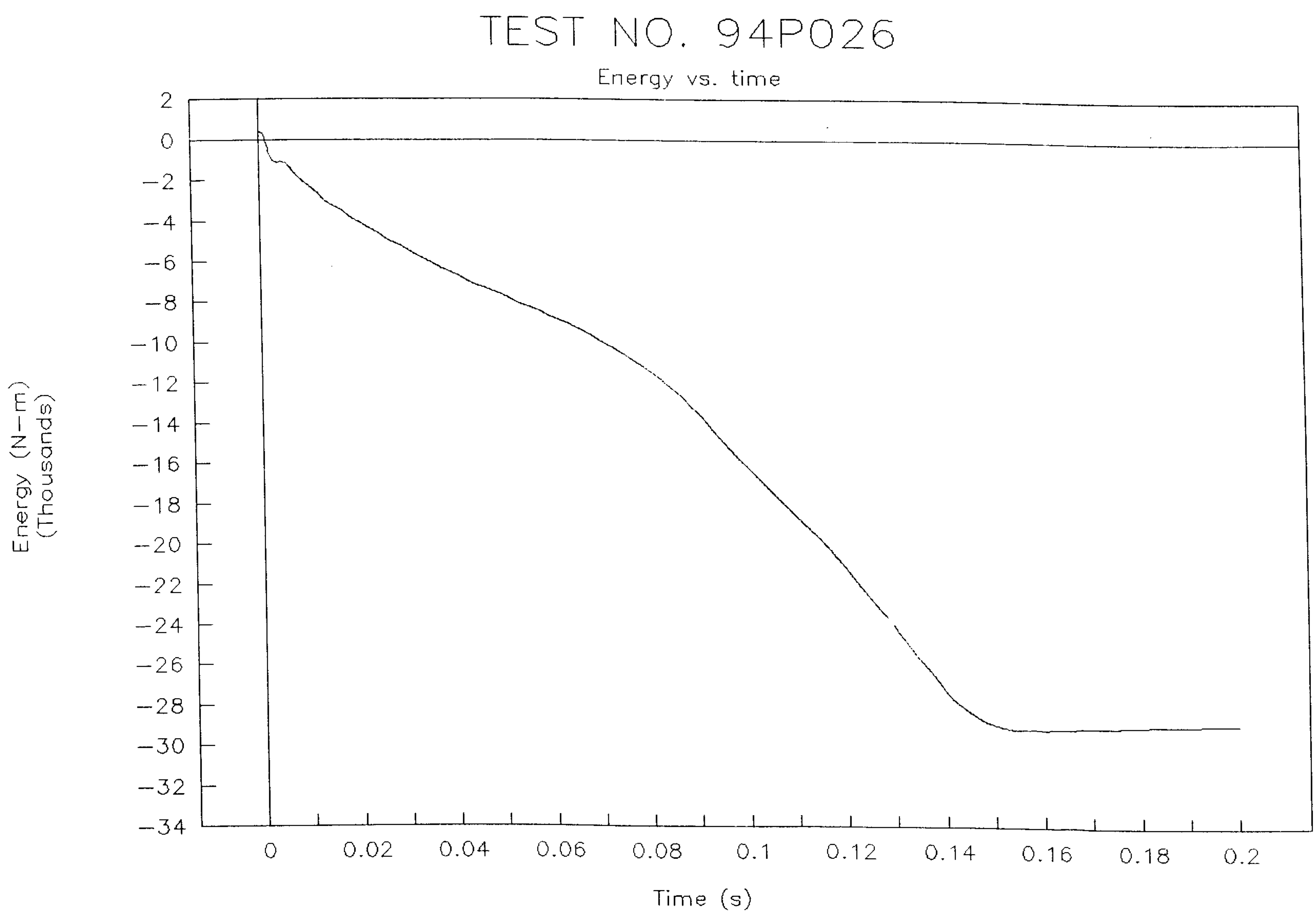


Figure 37. Accelerometer data, energy vs. time, test 94P026.

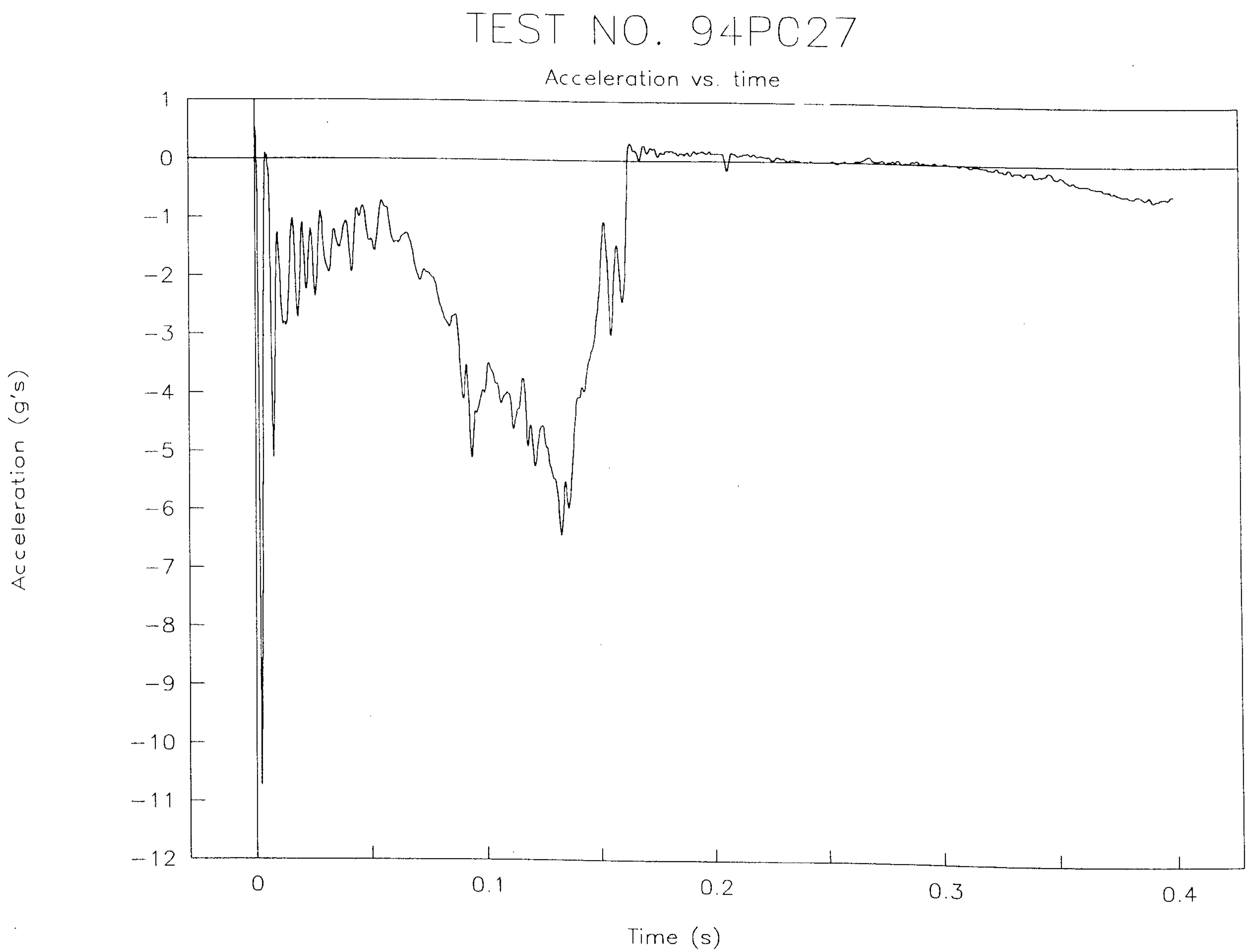


Figure 38. Accelerometer data, acceleration vs. time, test 94P027.

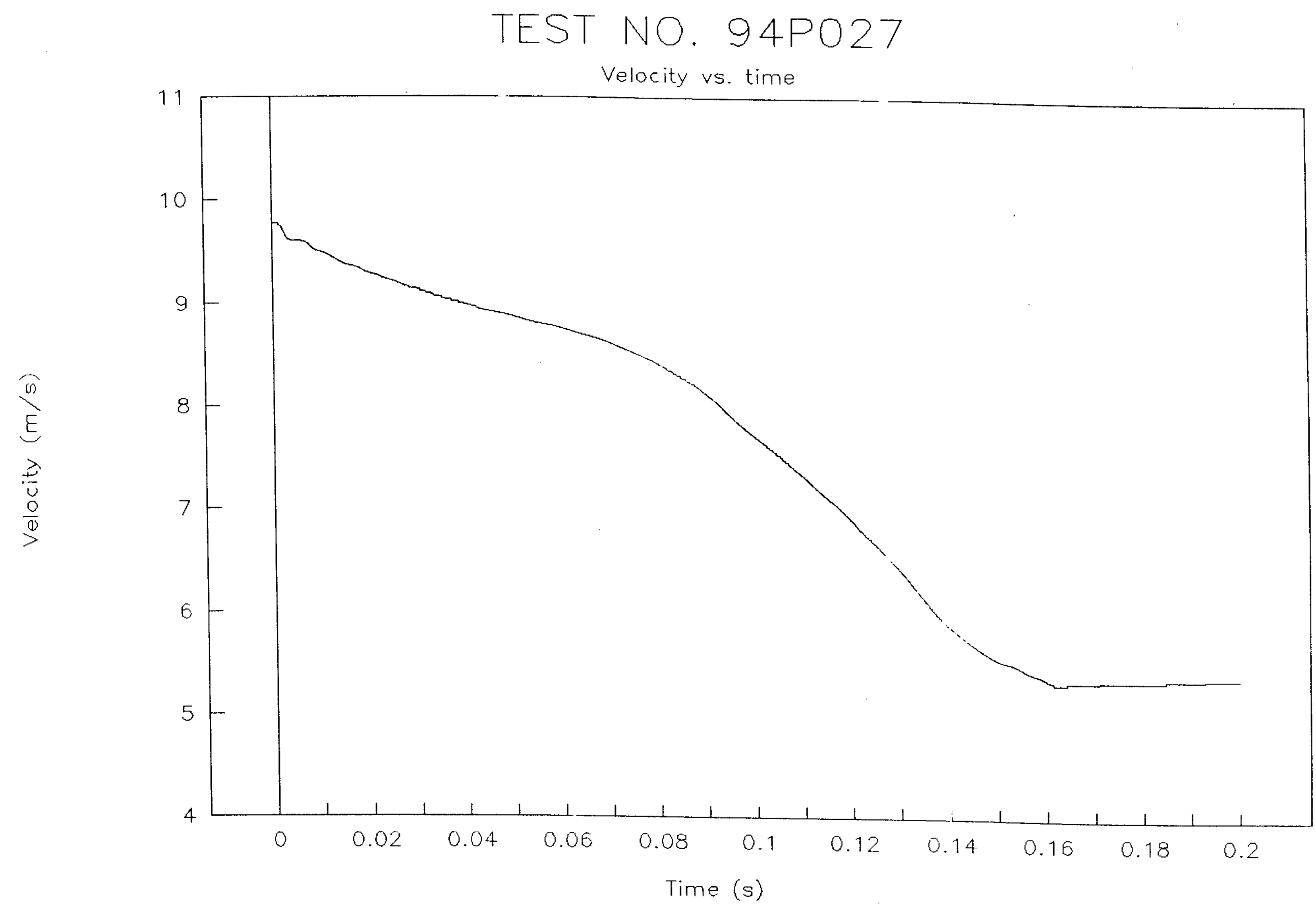


Figure 39. Accele meter data, velocity vs. time, test 94P027.

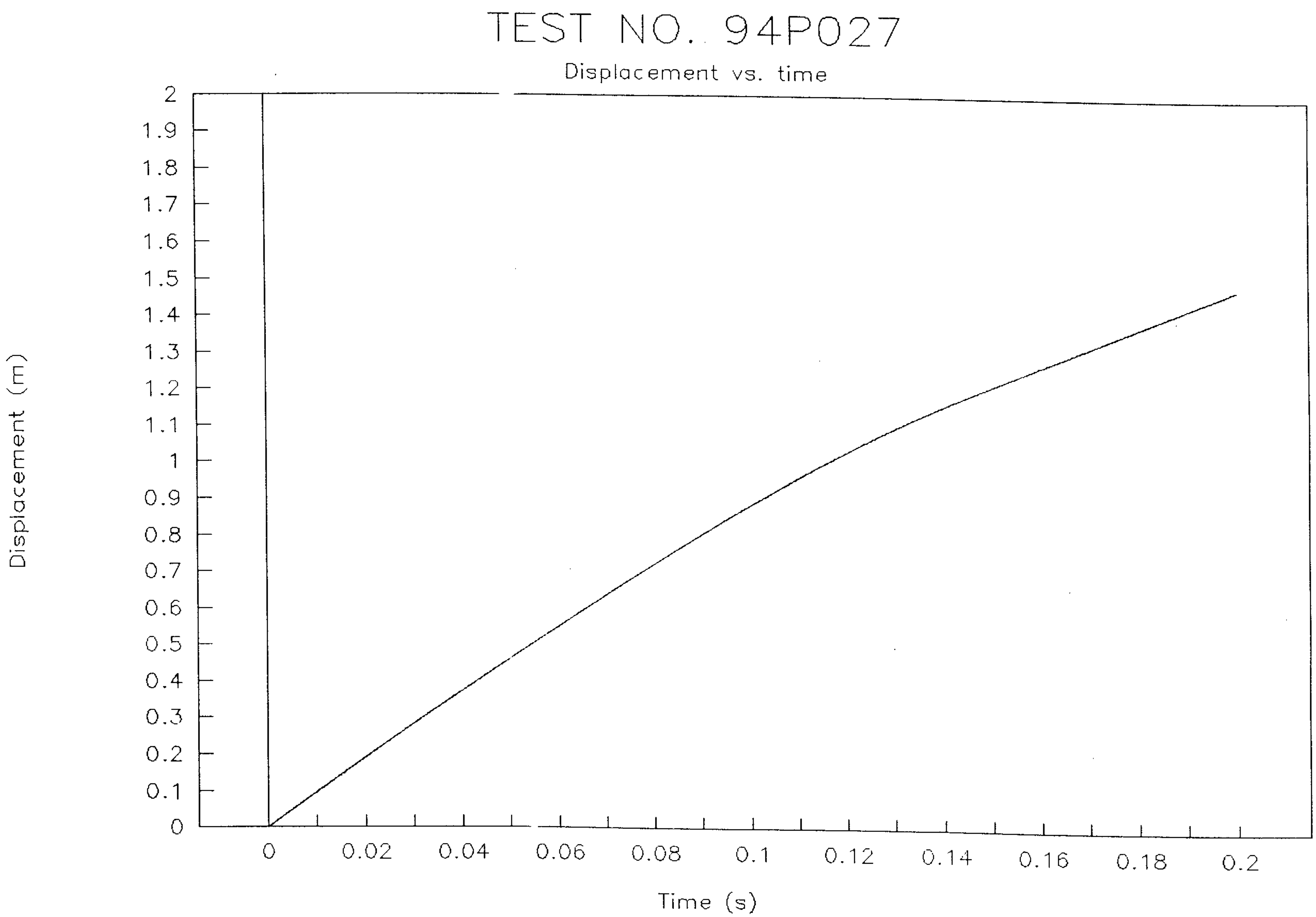


Figure 40. Accelerometer data, displacement vs. time, test 94P027.

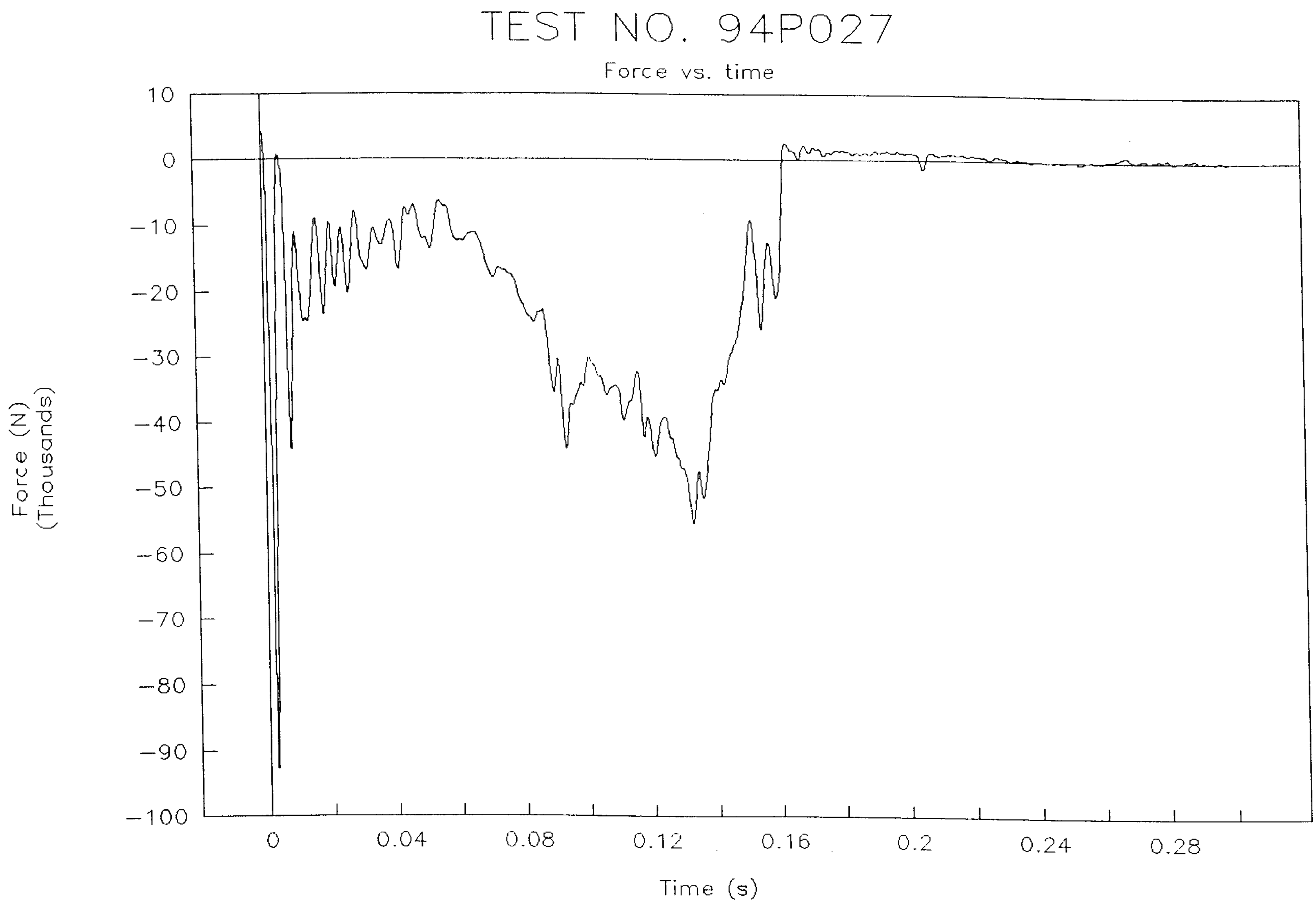


Figure 41. Accelerometer data, force vs. time, test 94P027.

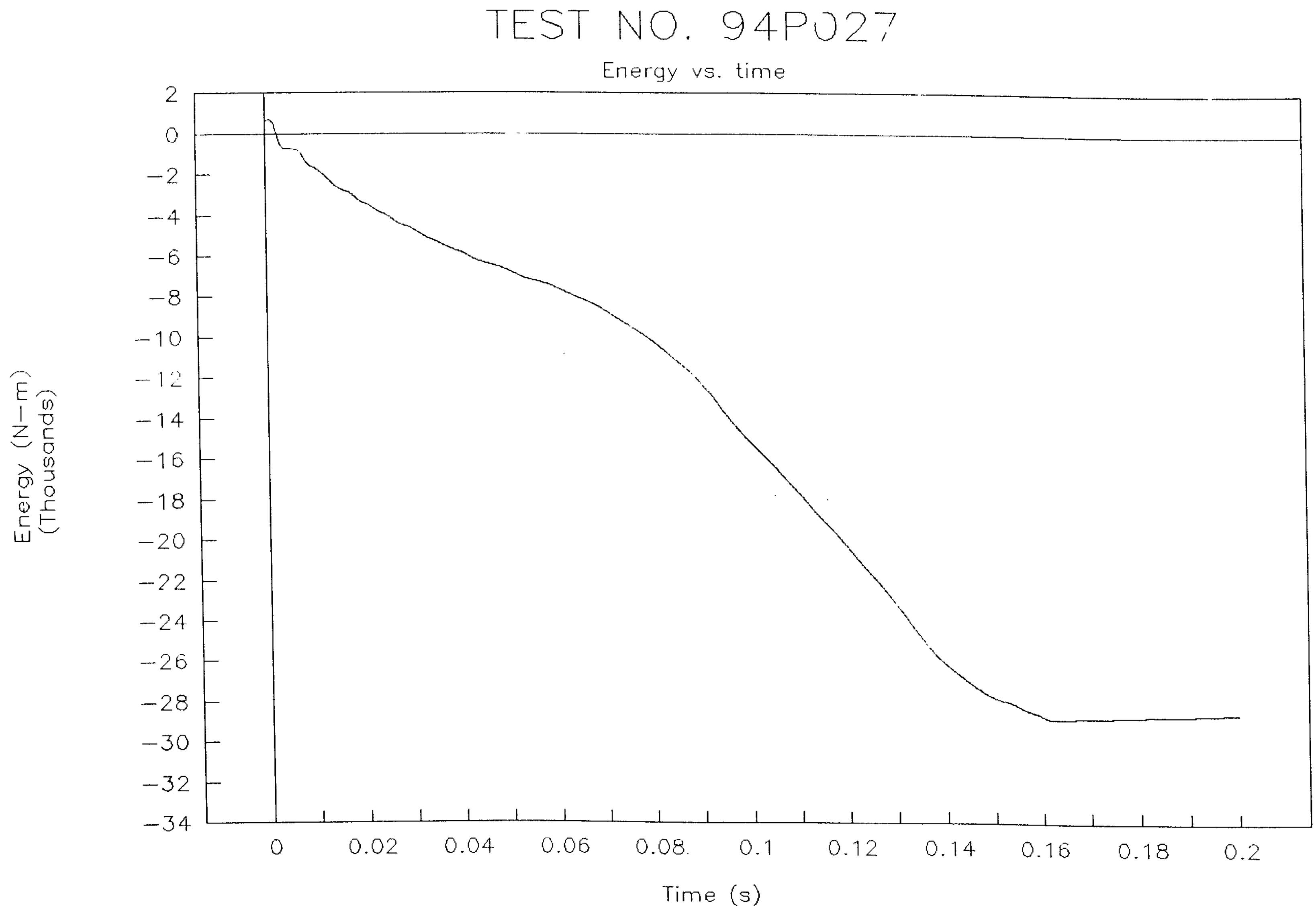


Figure 42. Accelerometer data, energy vs. time, test 94P027.

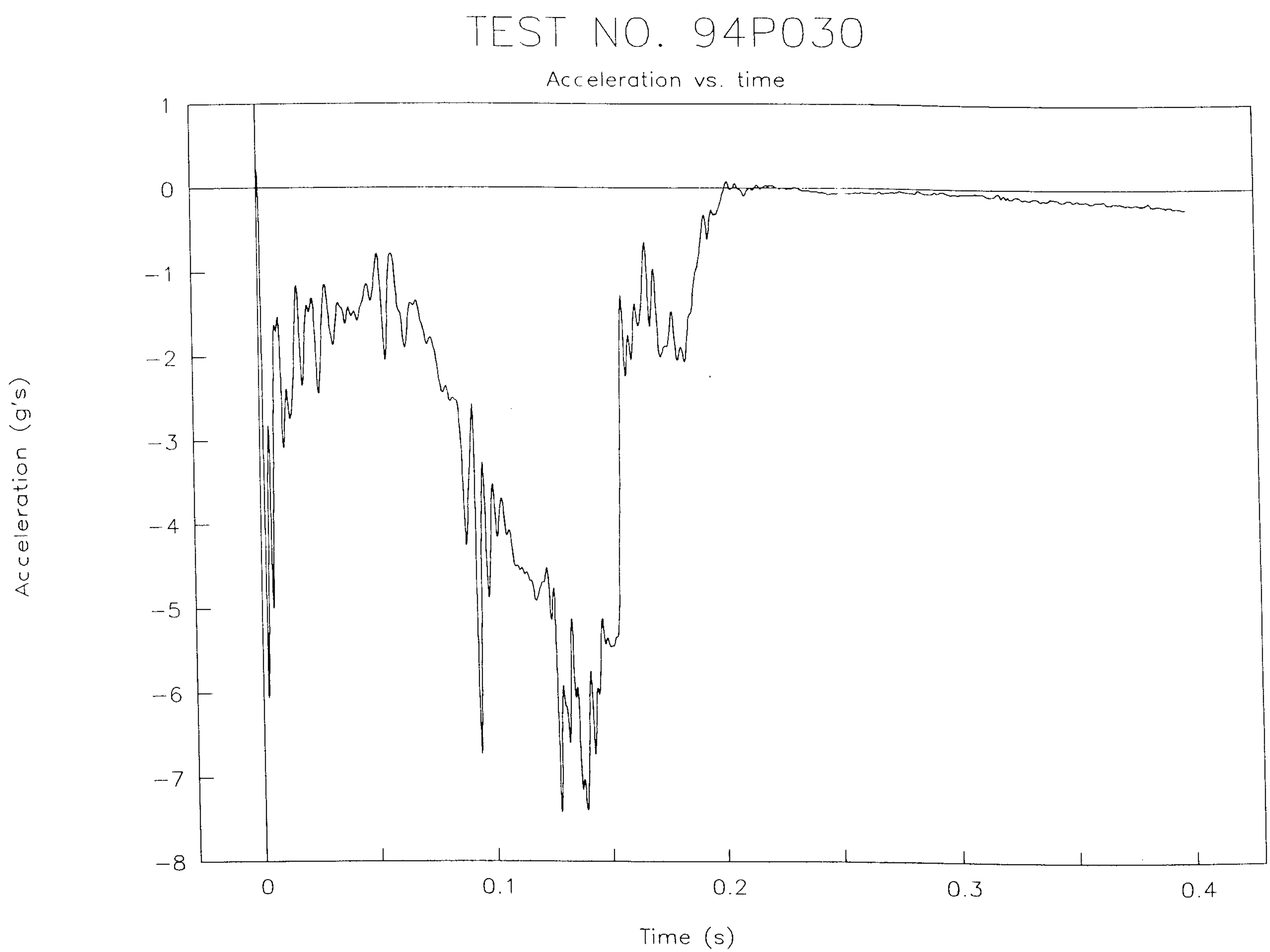


Figure 43. Accelerc ter data, acceleration vs. time, test 94P030.

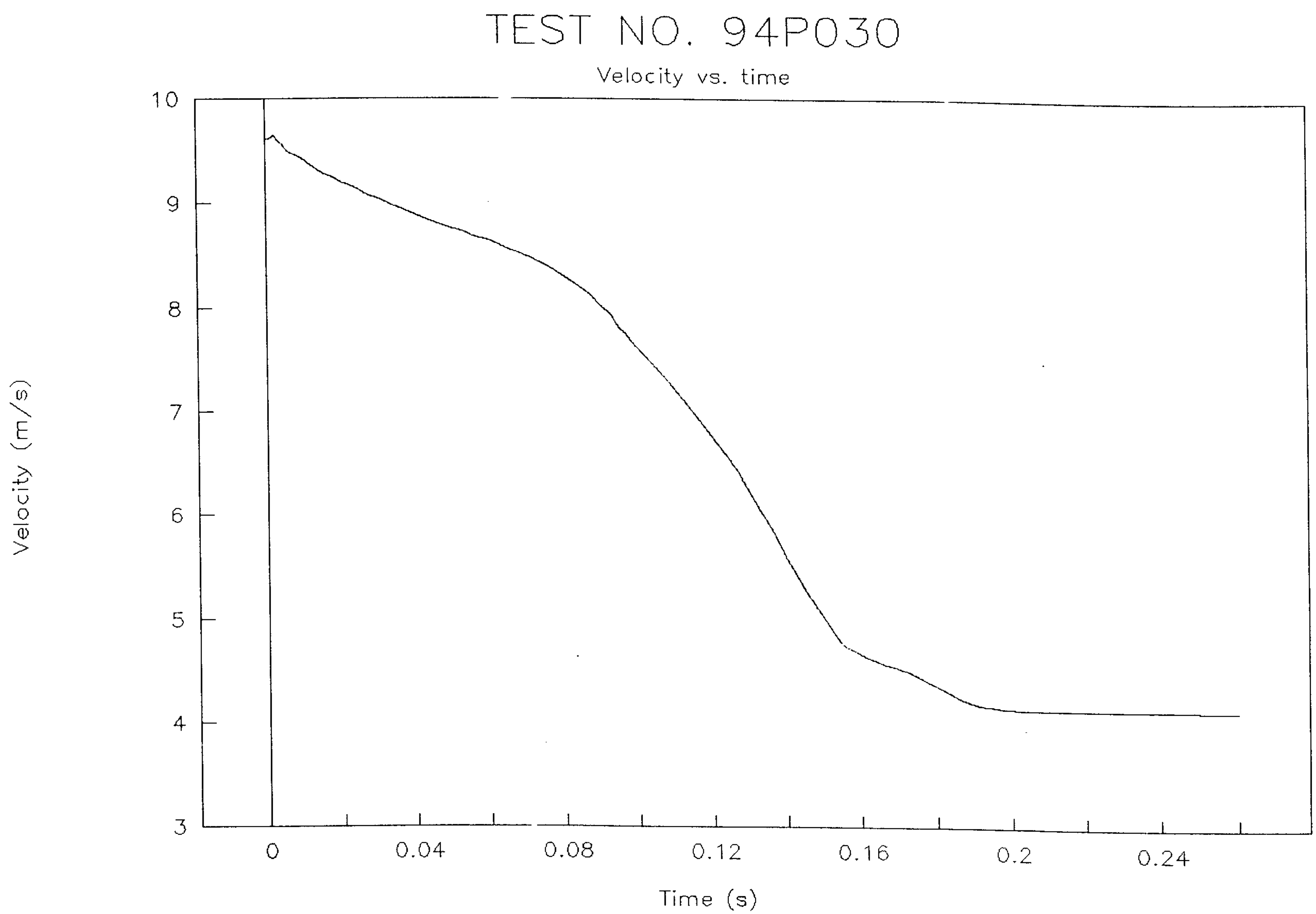


Figure 44. Accelerometer data, velocity vs. time, test 94P030.

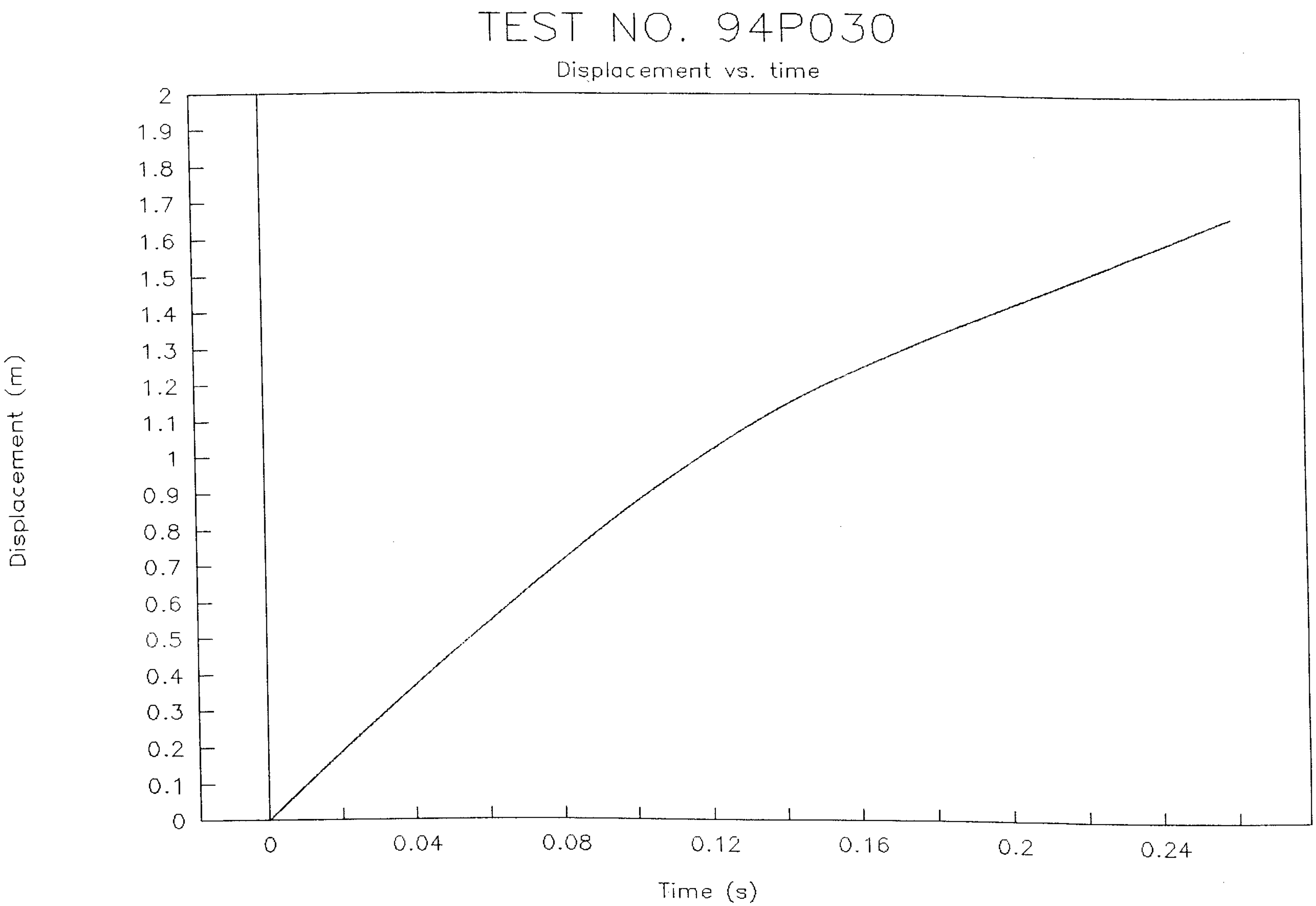


Figure 45. Accelerometer data, displacement vs. time, test 94P030.

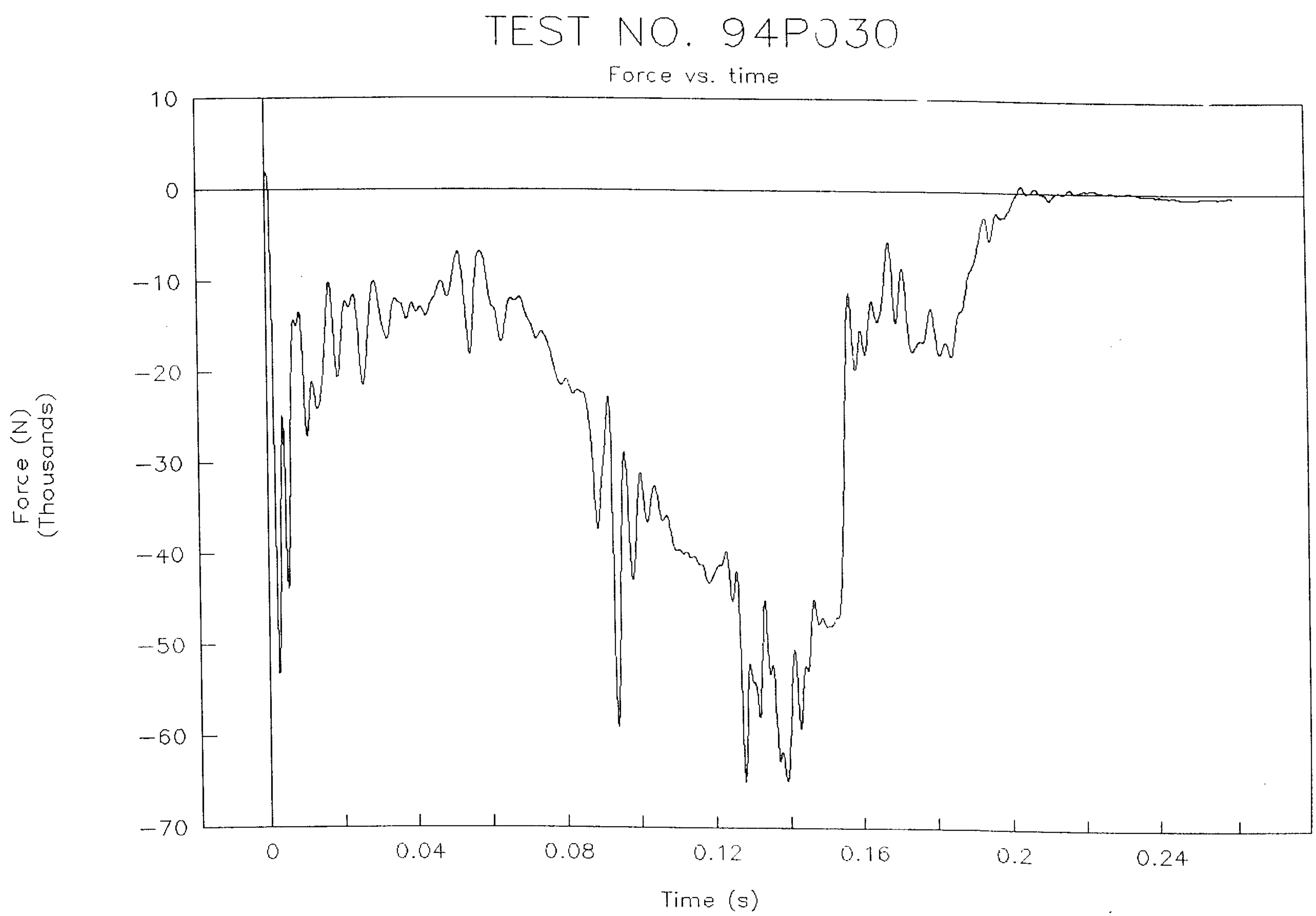


Figure 46. Accelerometer data, force vs. time, test 94P030.

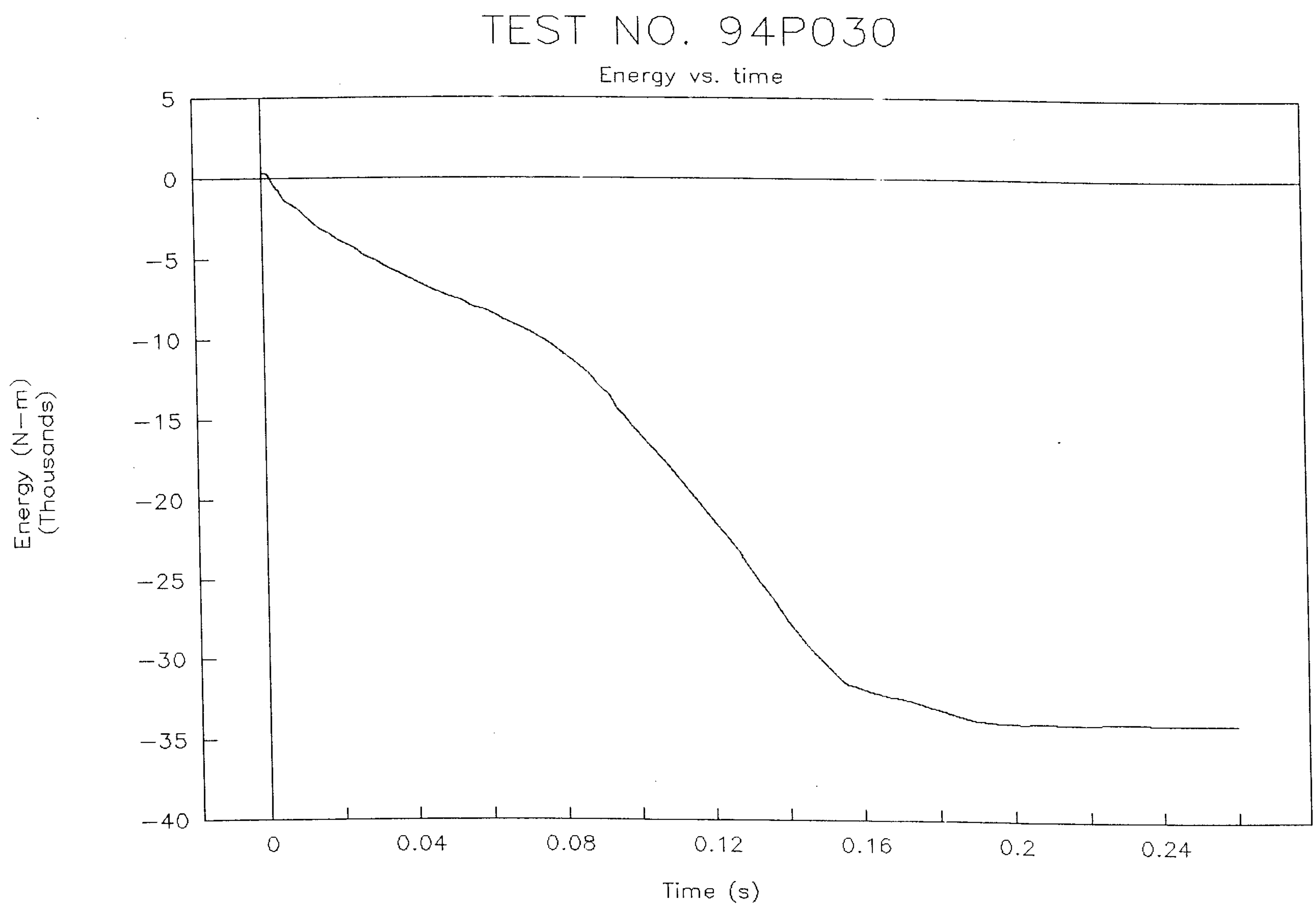


Figure 47. Acce ometer data, energy vs. time, test 94P030.

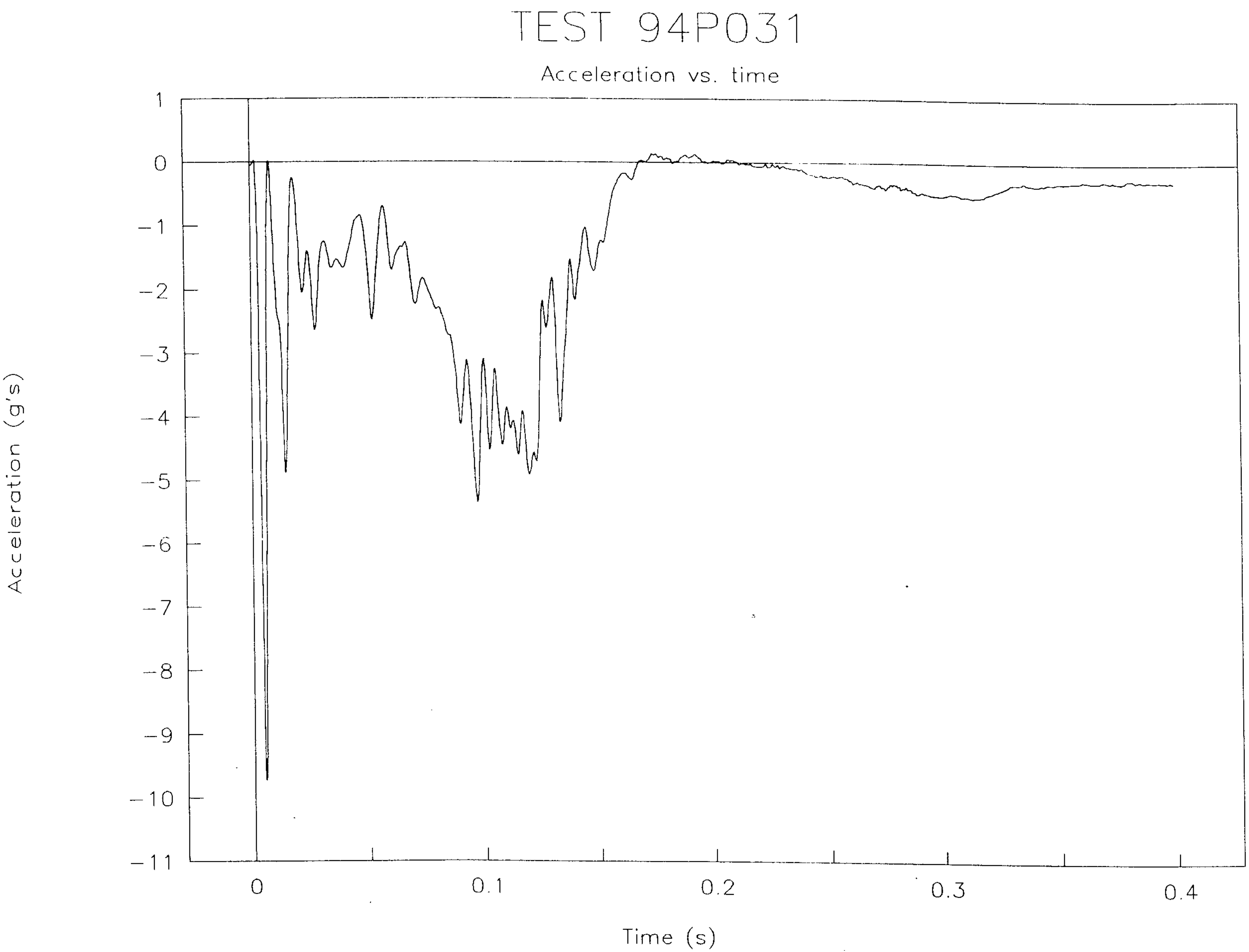


Figure 48. Accelerometer data, acceleration vs. time, test 94P031.

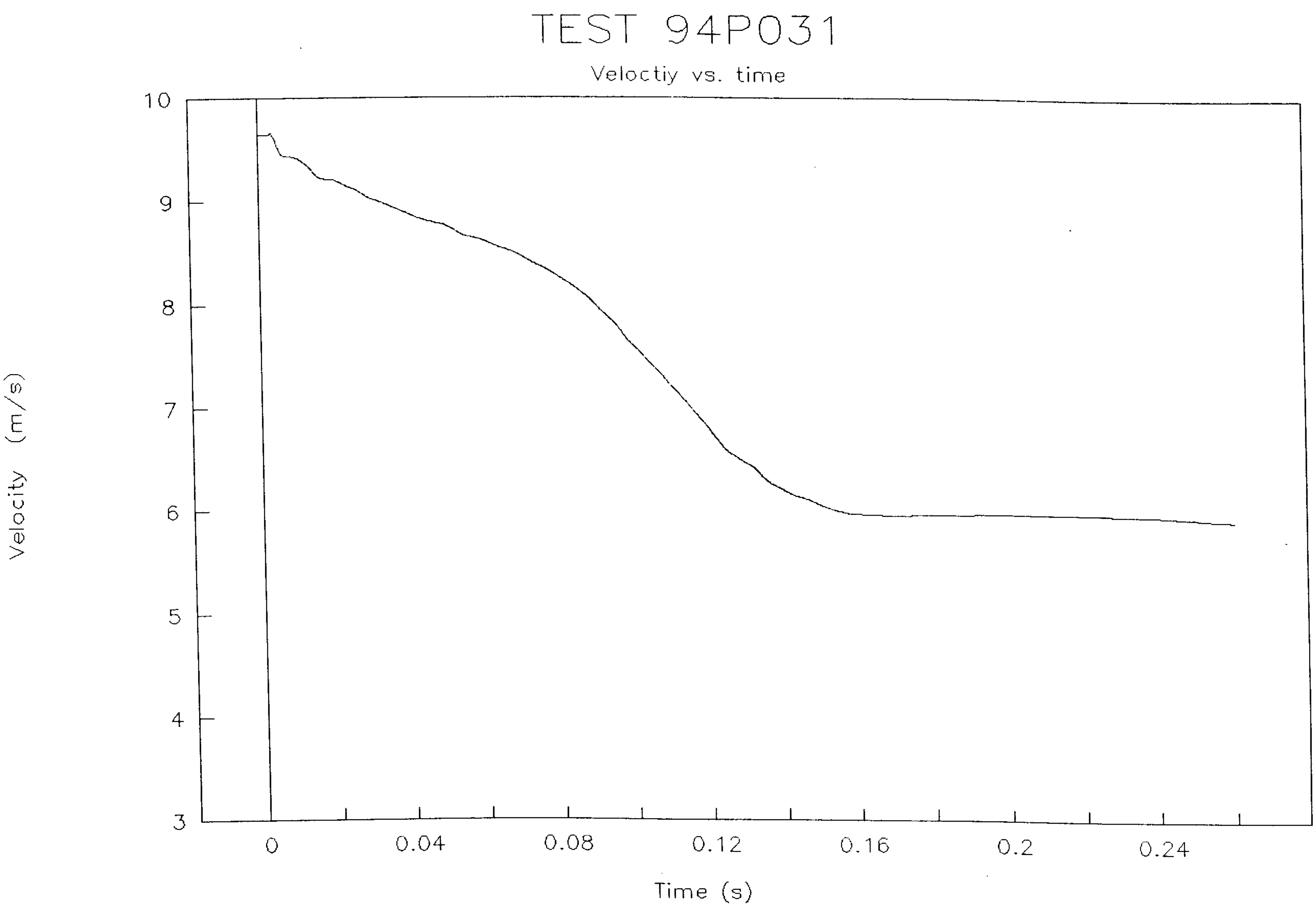


Figure 49. Acceleration data, velocity vs. time, test 94P031.

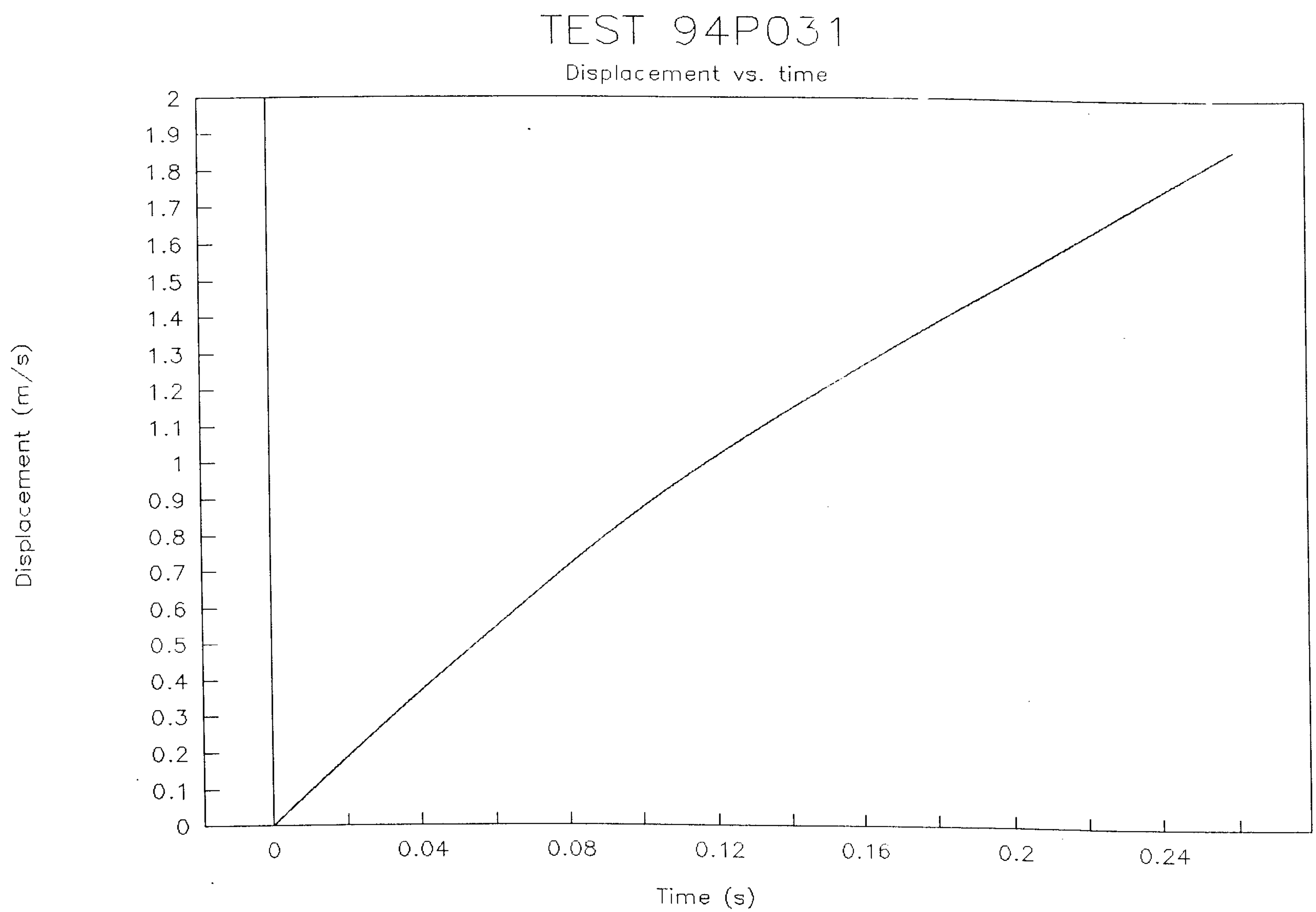


Figure 50. Acceleration data, displacement vs. time, test 94P031.

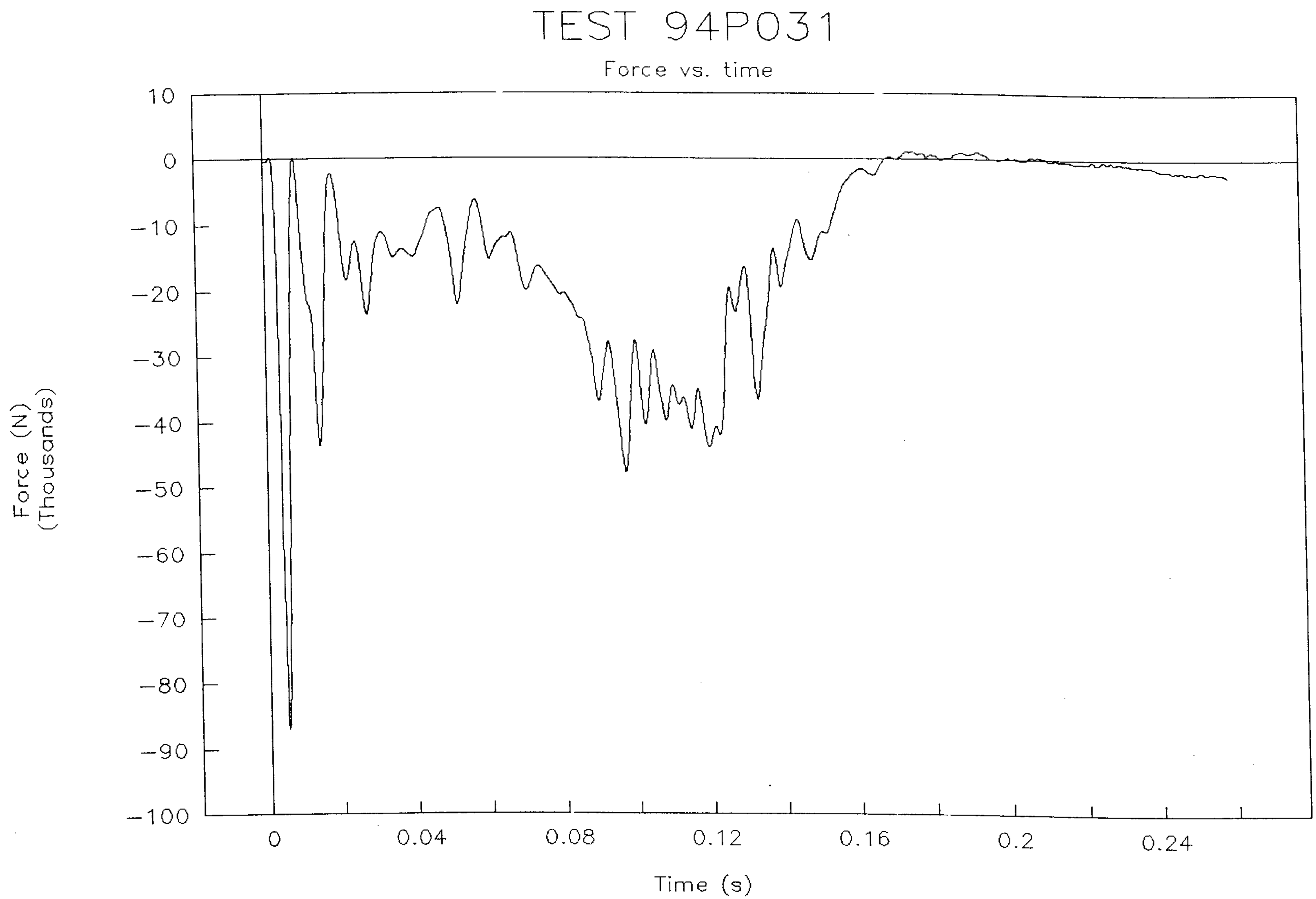


Figure 51. Acce ration data, force vs. time, test 94P031.

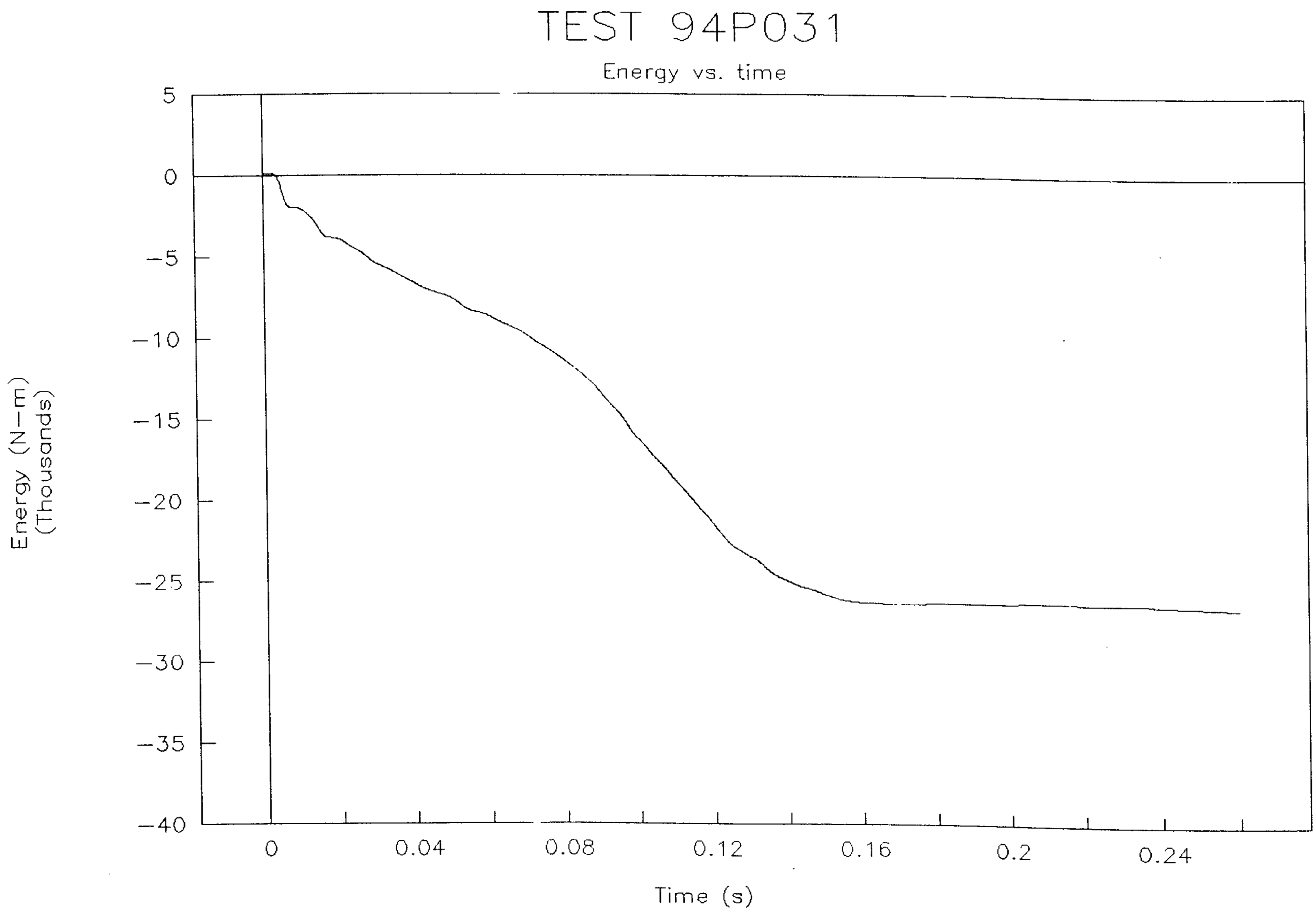


Figure 52. Accelerometer data, energy vs. time, test 94P031.

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