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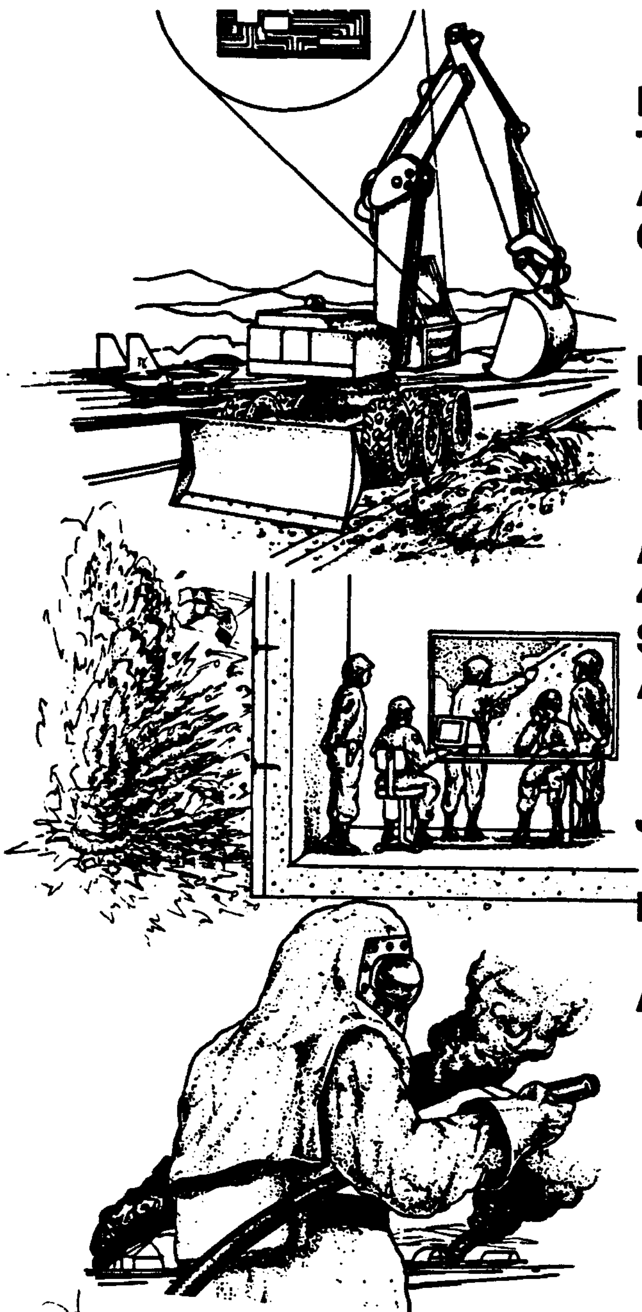

FROUDE SCALING OF BURIED STRUCTURES USING COAL AND COAL/LEAS AS SIMULANTS FOR SAND - VOLUME II OF II - STUDY RESULTS

M.A. PLAMONDON, D.E. CHITTY
R.L. GUICE

APPLIED RESEARCH ASSOCIATES, INC.
4300 SAN MATEO BLVD, N.E.,
SUITE A220
ALBUQUERQUE NM 87110

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Air Force Civil Engineering Support Agency
Civil Engineering Laboratory
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Maynard A. Plamondon, Daniel E. Cbitty, Robert L. Guice.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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13. ABSTRACT *(Maximum 200 words)*

This technical report is divided into two volumes. Volume I presents the results of the study, while Volume II contains the Appendices. This study describes the development of the Froude scaling relationships between the various parameters for the general problems of both dynamic and static loadings. The results of laboratory tests on potential simulant materials are presented. The rationale for the selection of crushed coal and a mixture of crushed coal and lead shot as simulants for sand is presented and the results of a crushed coal/cement/water mix as a simulant for concrete.

Results of proof-of-principle static tests of cone penetrometers being pushed into sand and the crushed coal and crushed coal/lead shot simulants are presented. Stress at the tip of the penetrator as a function of depth is presented for the full scale test in sand, the approximate 1/5 scale test in coal, and the approximate 1/10 scale test in the coal/lead mixture.

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Results of three tests involving a buried explosive loading on a buried cylinder are presented. A 1/10 Replica-scaled reinforced concrete cylinder located in sand was subjected to the explosive effects of a 0.39 kg sphere of C-4 explosive, buried 0.6 meters from the edge of the cylinder. Measurements of the free-field acceleration and earth stress were made at various ranges from the explosive charge. Measurements of the acceleration of the cylindrical structure were also made. A 1/5 scale test using crushed coal as the sand simulant with a 0.31 kg C-4 charge was also performed. A third test involving a testbed of a coal/lead mixture, at a scale of 1/10, using a 0.039 kg C-4 charge was conducted. The results of this study are very encouraging as to the use of coal and a coal/lead mixture as Froude simulants for sand.

EXECUTIVE SUMMARY

The response of buried structures to the explosive affects of conventional weapons is often determined by testing scale models instead of actual full size structures. The size and material properties of the scale model structures are determined based upon scaling laws. Most scale models are based upon the Replica scaling law that reduces the linear dimensions of the structure while maintaining the same material properties. This scaling law works well when the distortions resulting the non-scaled acceleration of gravity is not important. This report presents the results of scale models that use the Froude scaling law that reduces the linear dimensions of the structure and changes the material properties to avoid distortions resulting from the use of a constant acceleration of gravity. The results indicate that using coal or a mixture of coal and lead as a simulant for sand can result in model tests that properly replicate the full-scale test conditions.

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PREFACE

This report was prepared by personnel of Applied Research Associates, Inc. (ARA) of Lakewood, Colorado 80235, South Royalton, Vermont 05068, and Albuquerque, New Mexico 87110, under Contract Number F08635-89-C-0204 for the Air Force Civil Engineering Support Agency, Directorate of Research, Development and Acquisition (HQ AFCESA/RA), Tyndall Air Force Base, Florida 32403-6001.

This report summarizes work done between September 1989 and March 1991, and discusses the application of the Froude scaling technique to simulate the behavior of underground structures subjected to conventional weapons effects from a buried burst. The HQ AFCESA/RACS project officer was Capt. Rich Reid.

The authors wish to thank the efforts of Steven Quenneville of the ARA Vermont office for his efforts in performing the laboratory tests; Ed Seusy of the ARA New Mexico office for investigations into the explosive scaling and coal detonation/burning issues; Barry Bingham for test calculations of the tests, William Wood of the ARA Colorado office for field test instrumentation; Larry Smith for field construction activities; and Richard Zernow and Dr. Myron Plooster for the data reduction activities; and Don Murrell for the loan of instrumentation from the Explosive Effects Division, Structures Laboratory of the U.S. Army Waterways Experiment Station, Vicksburg, MS.

This technical report has been reviewed by the Public Affairs Office (PA) and is releasable to the National Technical Information Service, where it will be available to the general public, including foreign nationals.

This technical report has been reviewed and is approved for publication.

RICHARD A. REID, Capt, USAF
Project Officer

WILLIAM S. STRICKLAND, GM-14
Chief, Engineering Research Division

JON B. ANDERSON
Chief, Air Base Survivability Branch

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TABLE OF CONTENTS

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APPENDIX A

DESCRIPTIONS OF CANDIDATE SIMULANT MATERIALS THAT WERE NOT SELECTED

Magnetite

Description:	Particles of the natural mineral, magnetite.	
Origin:	Sharon Steel Corp. mine, Grant County, New Mexico.	
Test Specimen:	Test ID:	N3A7
	Grain Density (kg/m^3):	4700
	Dry Bulk Density (kg/m^3):	2834
	Porosity:	0.397
Test Results:	Constrained Modulus (MPa):	114
	Poisson's Ratio:	.30
Model Ratios:	Density:	1.76
	Modulus:	.305
	Length: (Scale Factor)	1/5.8

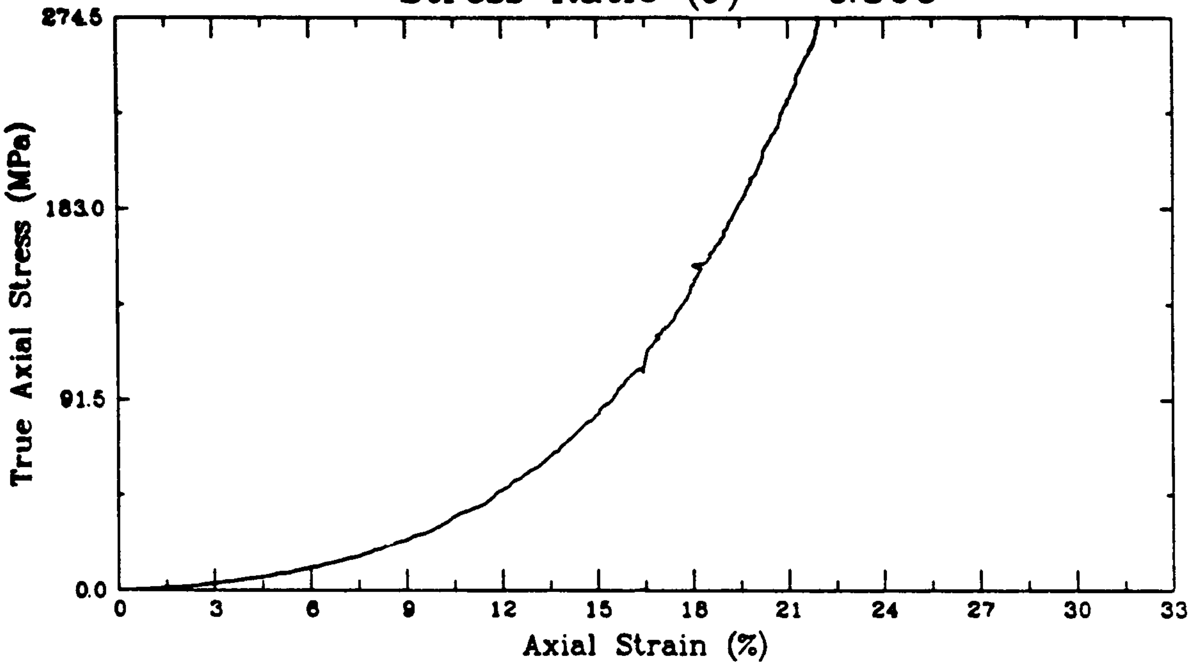
Comments: It is substantially denser than prototype sand, but almost as stiff. Therefore, the scale factor obtainable with magnetite is lower than the simulants that were selected. Lock-up occurs at a somewhat lower strain than desirable to match prototype behavior. If the low scale factor were tolerable, magnetite has the potential to serve as a Froude simulant for sand.

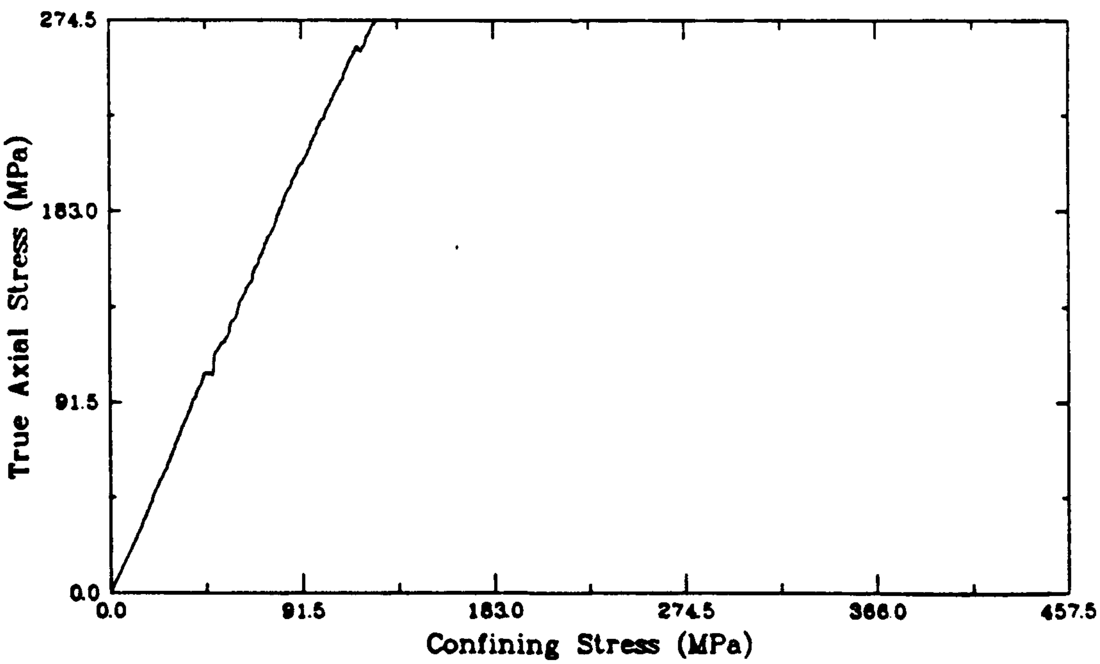
Note: Magnetite was not tested as part of this effort. File data from previous test work was used to evaluate its suitability as a simulant.

Magnetite (N3A7)

Uniaxial Strain Test

Stress Ratio (σ) = 0.305



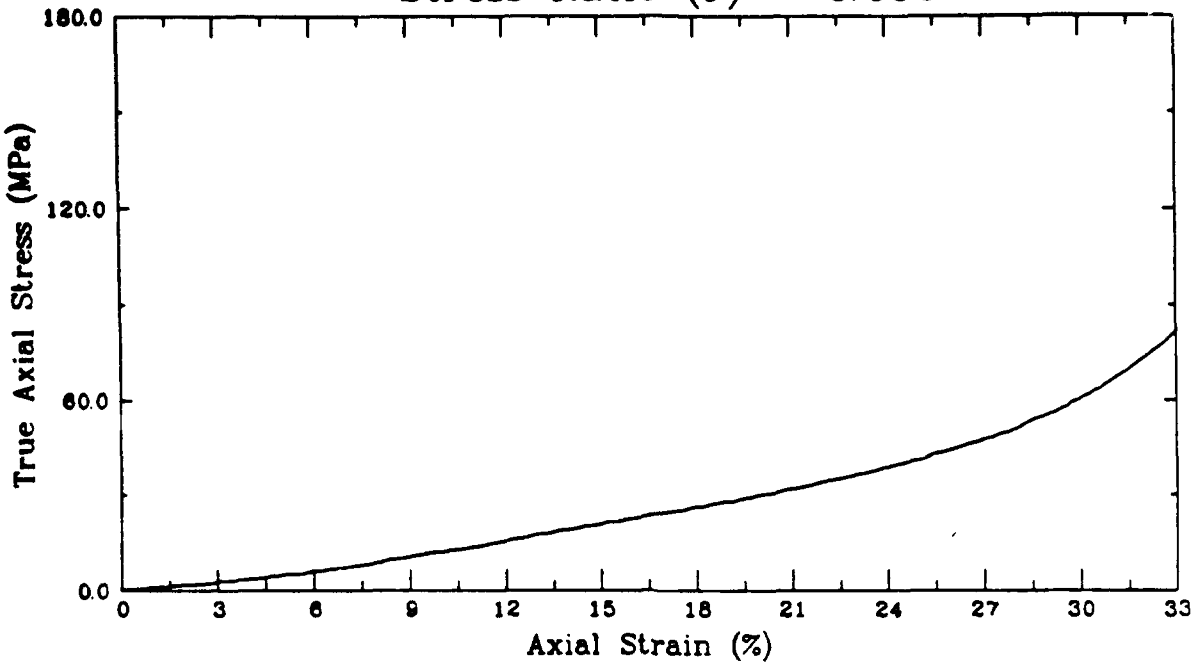


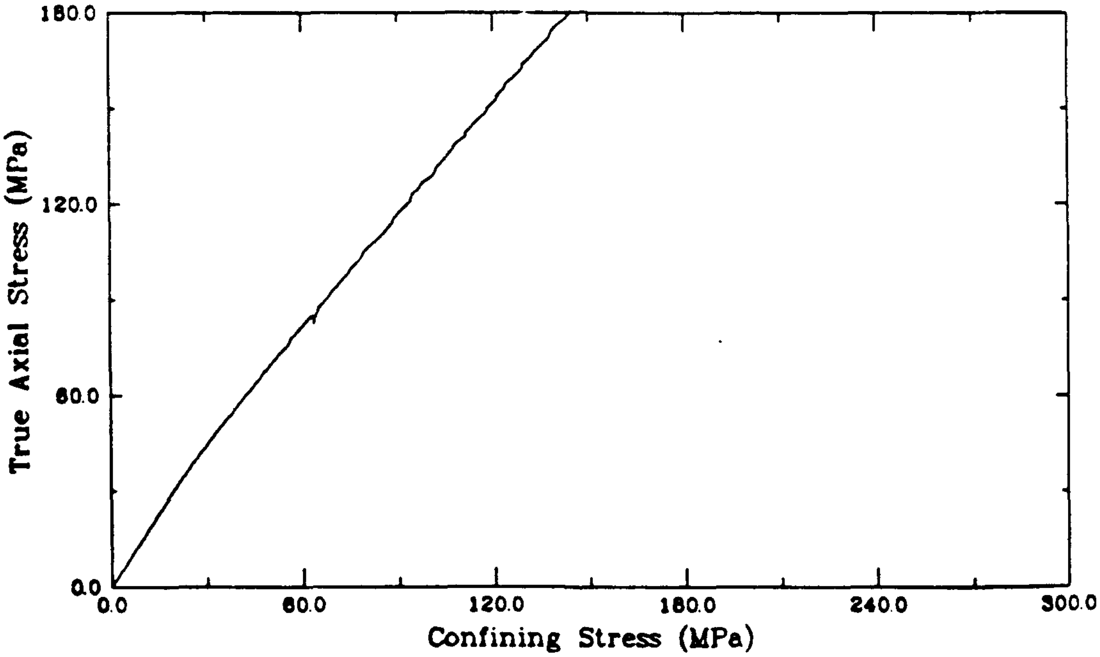
Spantex

Description:	Expandable polystyrene beads. Tested in unexpanded state. Spherical grains of approximately 0.4 mm diameter.	
Origin:	Texstyrene Plastics, Inc. 3607 North Sylvania Fort Worth, Tx 76111 (817) 831-3541	
Test Specimen:	Test ID:	D12A9
	Grain Density (kg/m^3):	940
	Dry Bulk Density (kg/m^3):	694
	Porosity:	0.262
Test Results:	Constrained Modulus (MPa):	75
	Poisson's Ratio:	0.46
Model Ratios:	Density:	.43
	Modulus:	.2
	Length: (Scale Factor)	1/2.2

Comments: This material exhibited more strain prior to lock-up than the prototype sands. Its Poisson's ratio of almost 0 5 indicates that it behaves almost like a fluid under uniaxial strain loading. While its modulus is lower than sand as required, its low density reduces the scale factor to less than 2. Since its deformation behavior does not approximate a scaled sand, and it does not have characteristics that would provide a significant scale factor, Spantex is clearly not a suitable sand simulant.

Spantex (D12A9)
Uniaxial Strain Test
Stress Ratio (σ) = 0.200





Flake 500

Description: Polytetrafluoroethylene (PTFE) powder. Manufacturer's typical grain size distribution lists 85 percent passing No. 50 and 15 percent passing No. 100 U.S. Standard sieves. Grains are much thinner in one dimension than the others, hence the name Flake. PTFE is the material commonly known by the trade name Teflon®. It has very low intergranular friction.

Origin: Custom Compounding, Inc.
8 Crozerville Road
Aston, PA 19014
(215) 358-1001

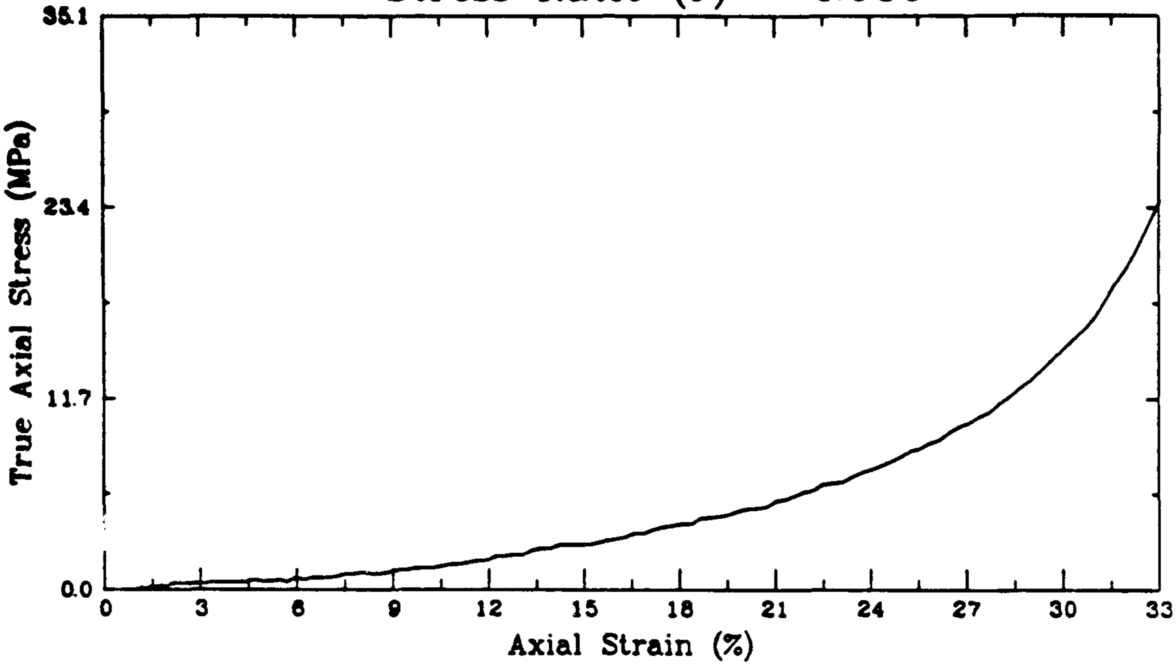
Test Specimen:	Test ID:	D13A9
	Grain Density (kg/m^3):	2160
	Dry Bulk Density (kg/m^3):	1445
	Porosity:	0.331
Test Results:	Constrained Modulus (MPa):	14
	Poisson's Ratio:	0.36
Model Ratios:	Density:	0.90
	Modulus:	0.039
	Length: (Scale Factor)	1/23

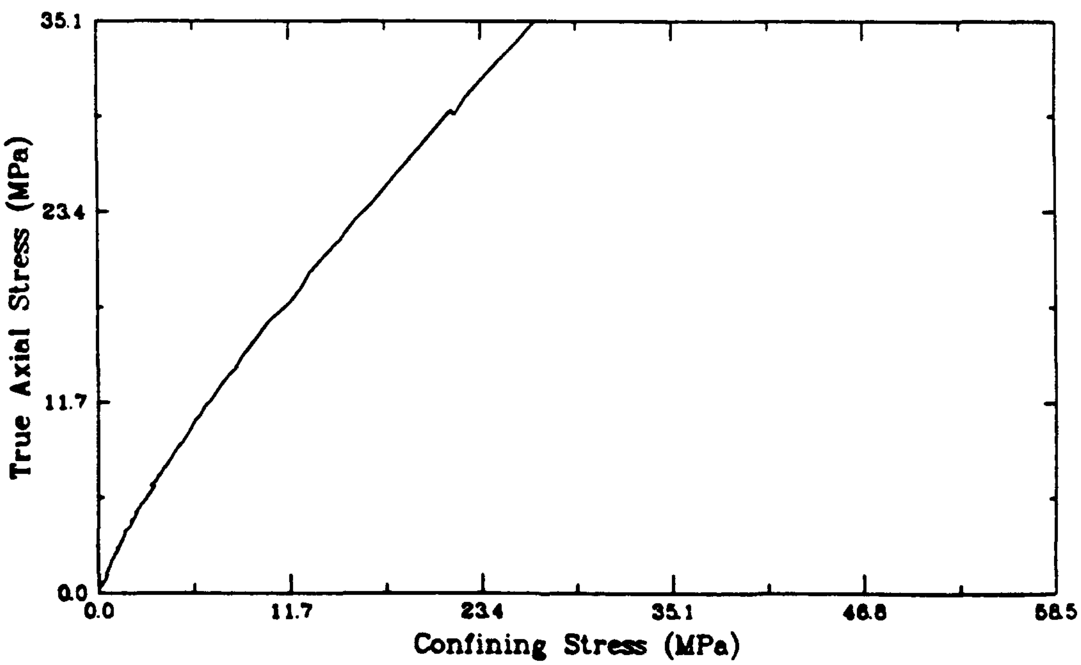
Comments: PTFE has a combination of modulus and density that result in high scale factors. Unfortunately, its stress-strain curve is not a scaled version of the sand curve and its Poisson's ratio is outside the range of prototype values. Also, at approximately $10/lb, the cost of building a test bed of the size under consideration would have been prohibitive.

Flake 500 (D13A9)

Uniaxial Strain Test

Stress Ratio (σ) = 0.039





Dicaperl CS-10-200

Description: Dicaperl is manufactured as a "lightweight filler and extender." It is composed of ceramic glass spheres, apparently hollow. The grade tested is specified to have a particle size range of 10-200 µm, with an average of 125 µm.

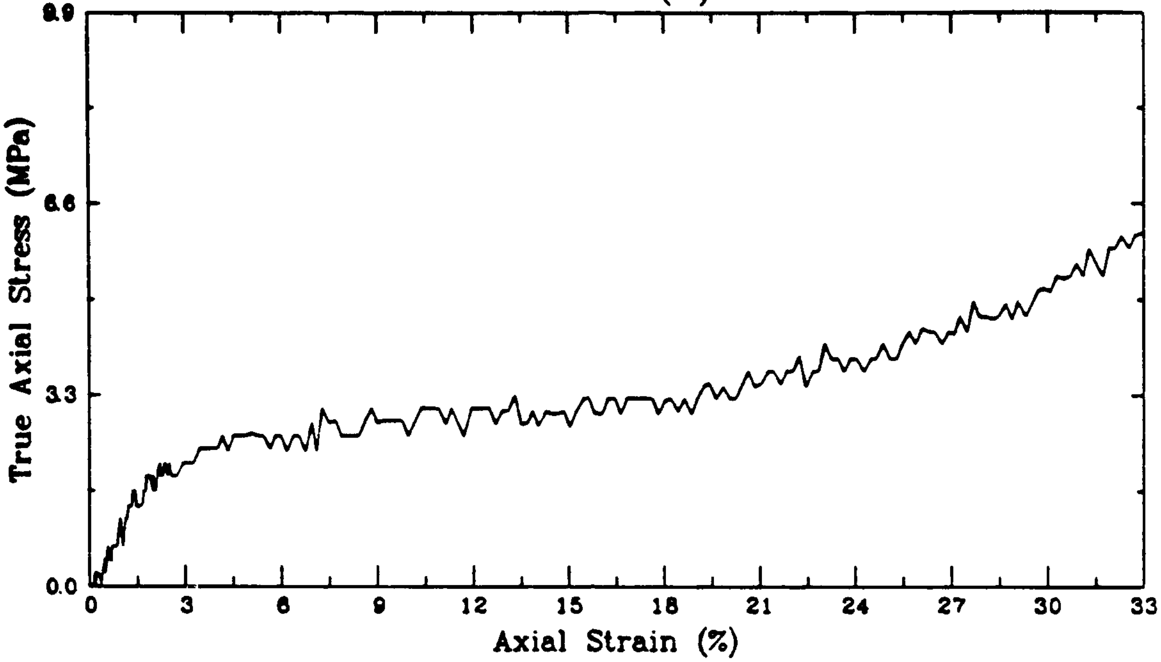
Origin: Grafco, Inc.
3435 W. Lomita Blvd.
Torrance, CA 90509
(213) 517-0700

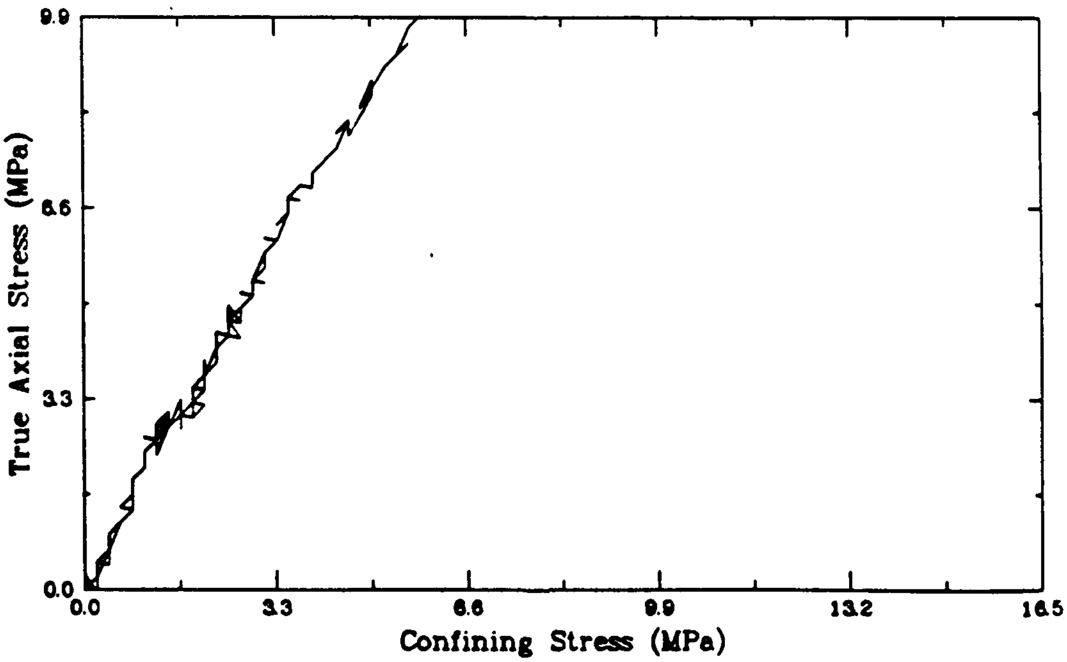
Test Specimen:	Test ID:	D14A9
	Grain Density (kg/m^3):	700
	Dry Bulk Density (kg/m^3):	482
	Porosity:	0.311
Test Results:	Constrained Modulus (MPa):	28
	Poisson's Ratio:	.39
Model Ratios:	Density:	0.3
	Modulus:	0.075
	Length: (Scale Factor)	1/4.0

Comments: The prototype sands and many of the other materials tested exhibited initial constrained moduli that were nearly constant for approximately the first 10 percent of axial strain. For most materials, the slope of that portion of the curve has been tabulated as the constrained modulus. HOwever, Dicaperl has an abrupt change in modulus at approximately 3 percent axial strain. This feature disqualifies it as a potential Froude simulant of sand. The second modulus between zero and 10 percent axial strain has been taken as the nominal value for purposes of filling out the data tables.

The grain density value of 700 kg/m^3 was provided by the manufacturer. It apparently represents the average density of an intact grain which contains some inaccessible porosity. It is hypothesized that the modulus change at 3 percent axial strain occurs as a result of crushing of the grains to expose the trapped pore space.

Dicaperl CS-10-200 (D14A9)
Uniaxial Strain Test
Stress Ratio (σ) = 0.011

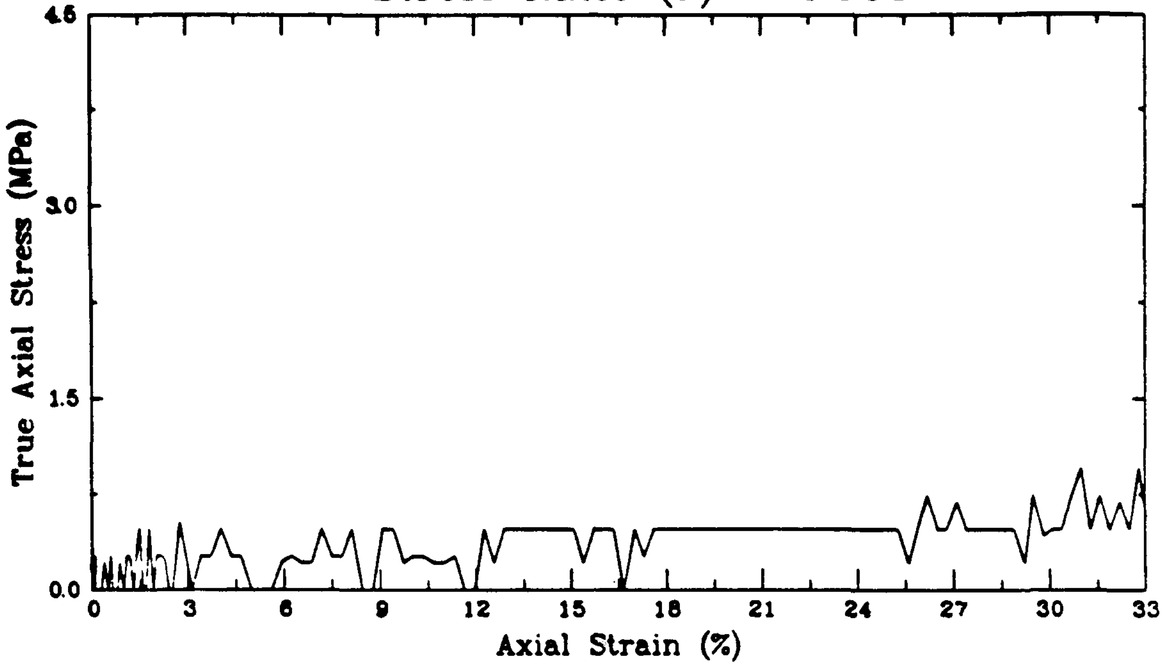


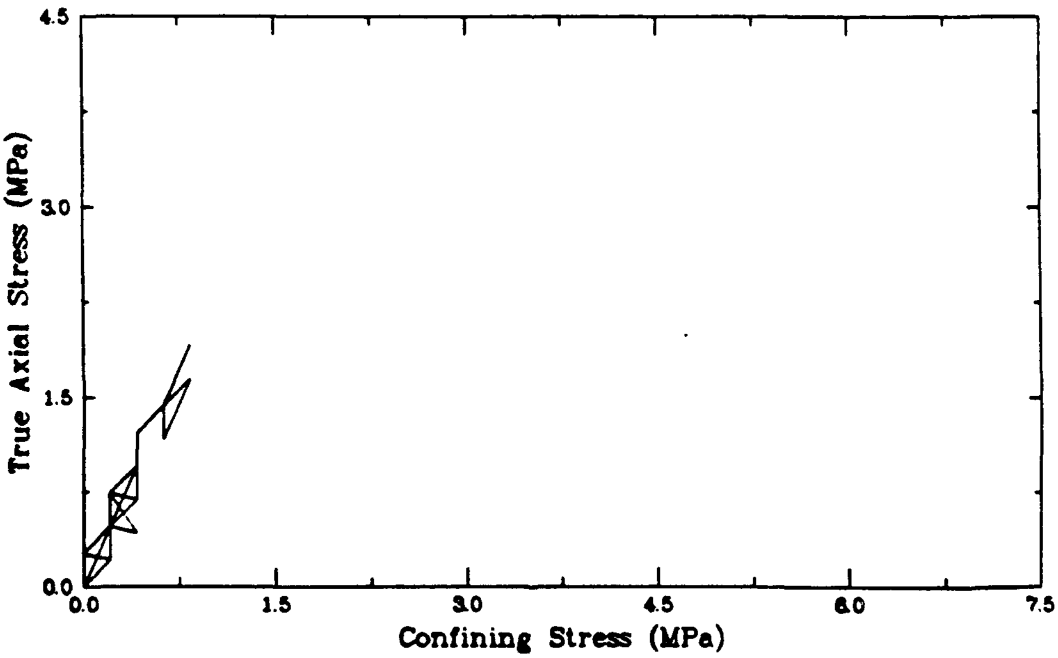


Thermo Rock

Description:	Granular material with an appearance of a mineral, rather than organic composition. The grains are irregularly shaped with the largest being approximately 1 mm. The smallest pass a U.S. Standard No. 200 sieve.
Origin:	Therm-O-Rock Industries, Inc. P.O. Box 5014 6732 W. Wills Road Chandler, AZ 85224 (602) 961-1000
Test Specimen:	Test ID: D14B9 Grain Density (kg/m^3): not measured Dry Bulk Density (kg/m^3): 199 Porosity: not available
Test Results:	Constrained Modulus (MPa): 2 Poisson's Ratio: 0.45
Model Ratios:	Density: 0.12 Modulus: 0.005 Length: 1/23 (Scale Factor)
Comments:	In the uniaxial strain test, this material was strained over 50 percent. It was beginning to stiffen at 45 percent. Thus, the stress-strain curve does not approximate a scaled sand. The solid mineral portion of this material is denser than water. However, much of the material apparently has so much entrapped air that it floats. Without substantially crushing the existing grain structure, the material is estimated to have over 50 percent porosity.

Thermo Rock (D14B9)
Uniaxial Strain Test
Stress Ratio (σ) = 0.005





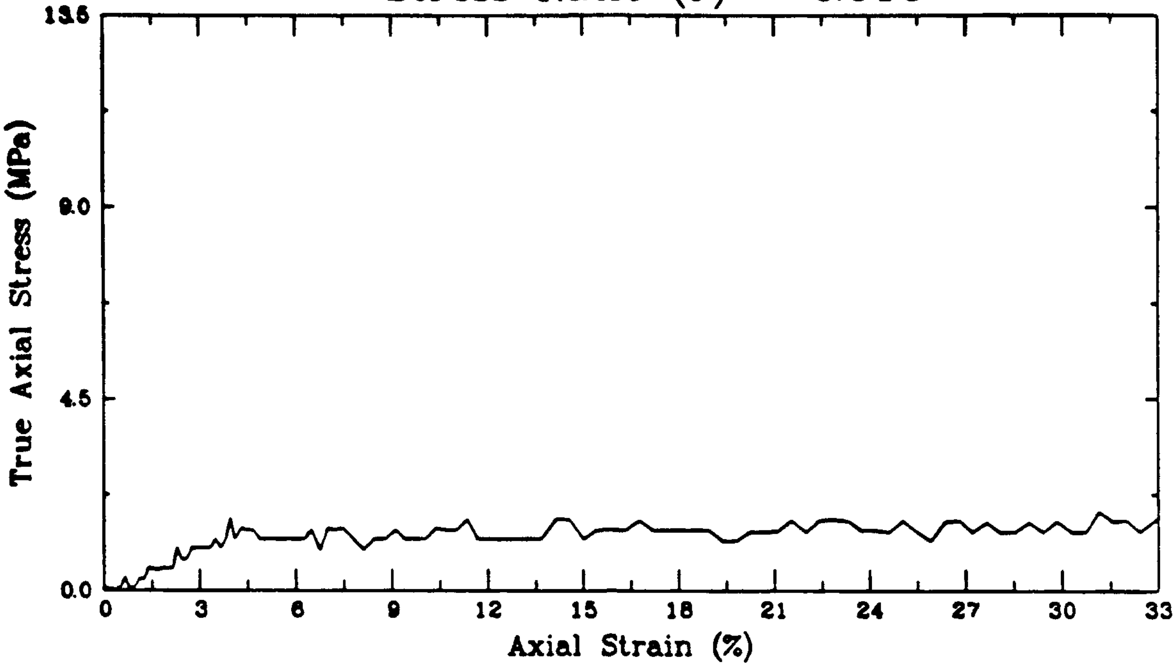
Q-Cell 600

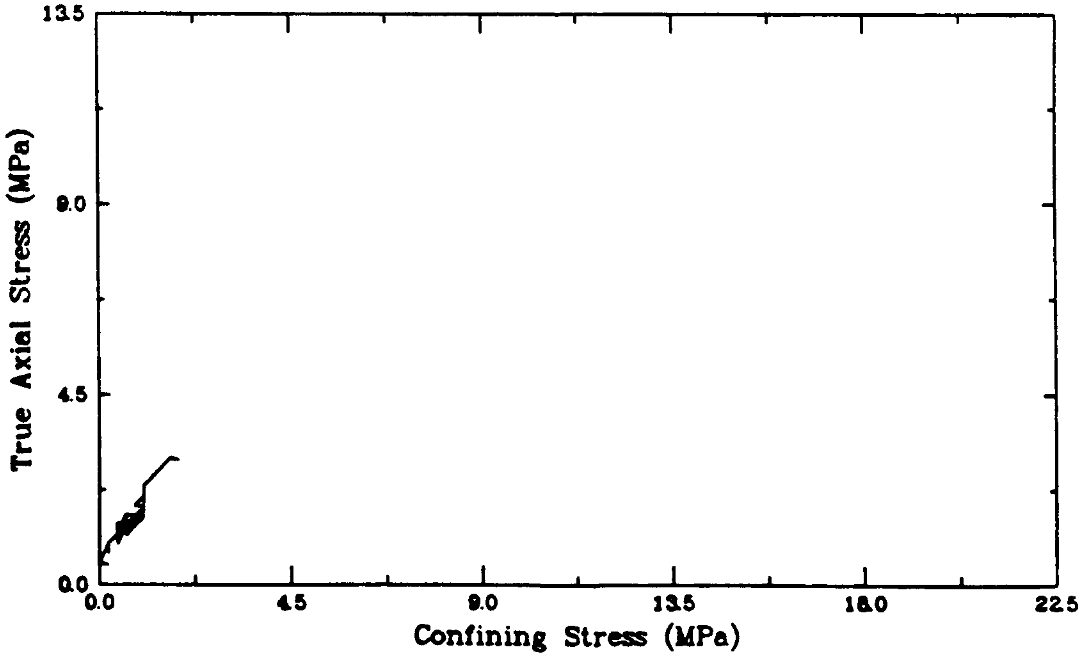
Description:	Fine inorganic microspheres. Will not pass a No. 200 U.S. Standard sieve under its own weight, but will pass if rubbed, possibly due to break-up pf particles.
Origin:	The PQ Corporation 280 Ceder Grove Road P.O. Box 258 Lafayette Hill, PA 19444-0258 (215) 941-2000

Test Specimen:	Test ID:	D15A9
	Grain Density (kg/m^3):	430
	Dry Bulk Density (kg/m^3):	298
	Porosity:	.307
Test Results:	Constrained Modulus (MPa):	6
	Poisson's Ratio:	0.41
Model Ratios:	Density:	.19
	Modulus:	.015
	Length: (Scale Factor)	1/12

Comments: This material was deformed in uniaxial strain to almost 50 percent without any significant increase in stiffness. Its Poisson's ratio is much higher than natural sands. Thus, it was not considered suitable as a sand simulant.

Q-CEL 600 (D15A9)
Uniaxial Strain Test
Stress Ratio (σ) = 0.015





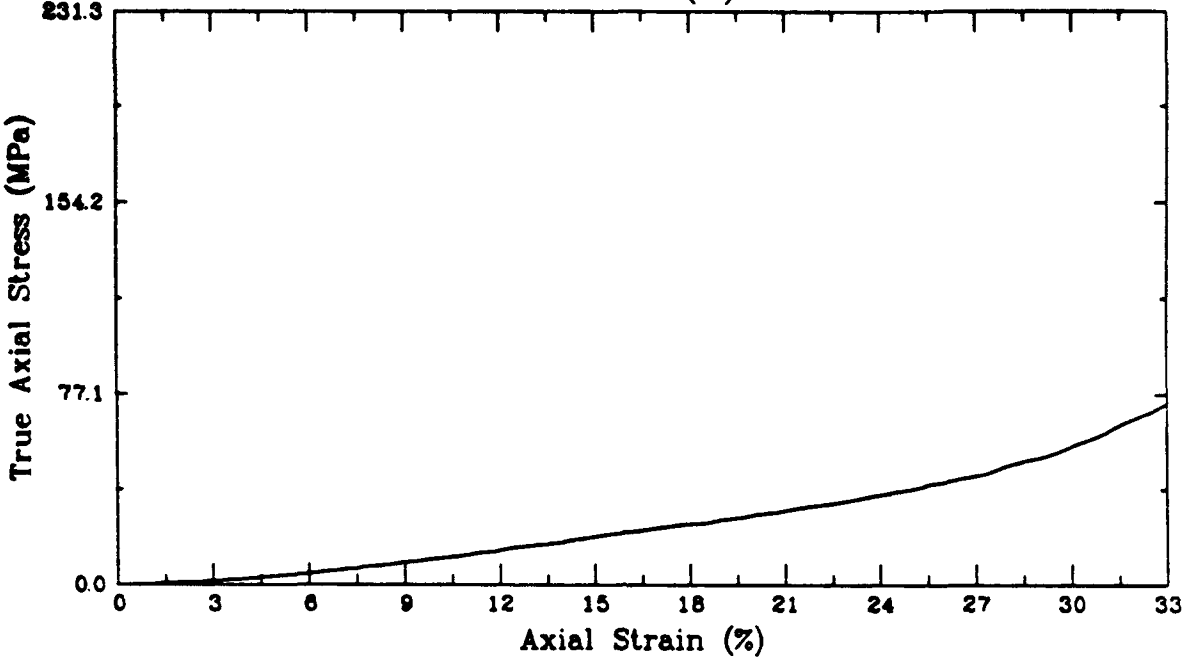
Styropor

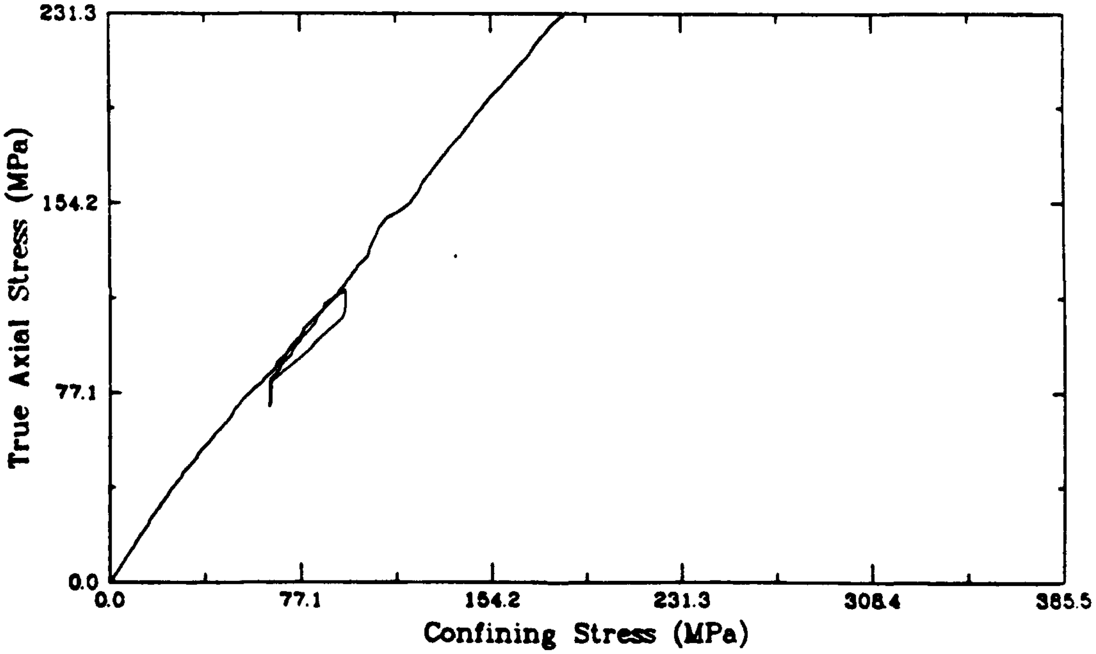
Description:	Styropor is an expandable polystyrene bead containing a volatile hydrocarbon expanding agent. Similar to Spantex.
Origin:	BASF Corporation 100 Cherry Hill Road Parsippany, NJ 07054 (201) 316-3658

Test Specimen:	Test ID:	D15B9
	Grain Density (kg/m^3):	N/A
	Dry Bulk Density (kg/m^3):	678
	Porosity:	N/A
Test Results:	Constrained Modulus (MPa):	97
	Poisson's Ratio:	0.42
Model Ratios:	Density:	0.42
	Modulus:	0.26
	Length: (Scale Factor)	1/1.6

Comments: The Poisson's ratio is very high, indicating behavior that is more fluid-like than sand. This, combined with the low scale factor makes this material unacceptable as a sand simulant.

Styropor (D15B9)
Uniaxial Strain Test
Stress Ratio (σ) = 0.257

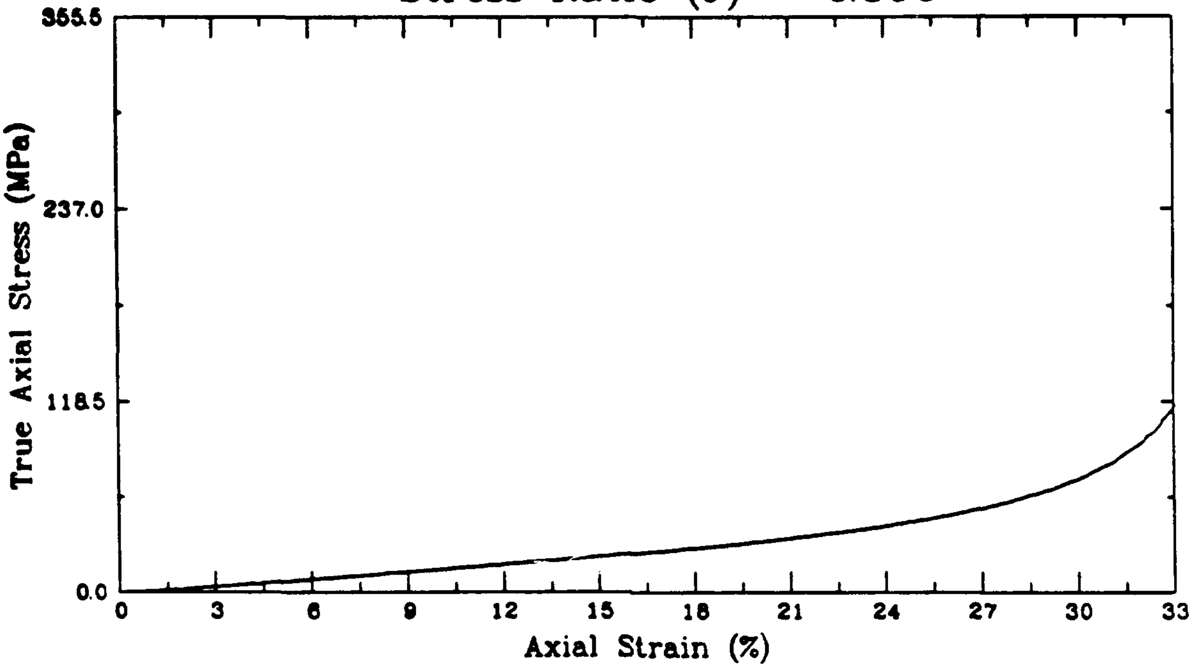


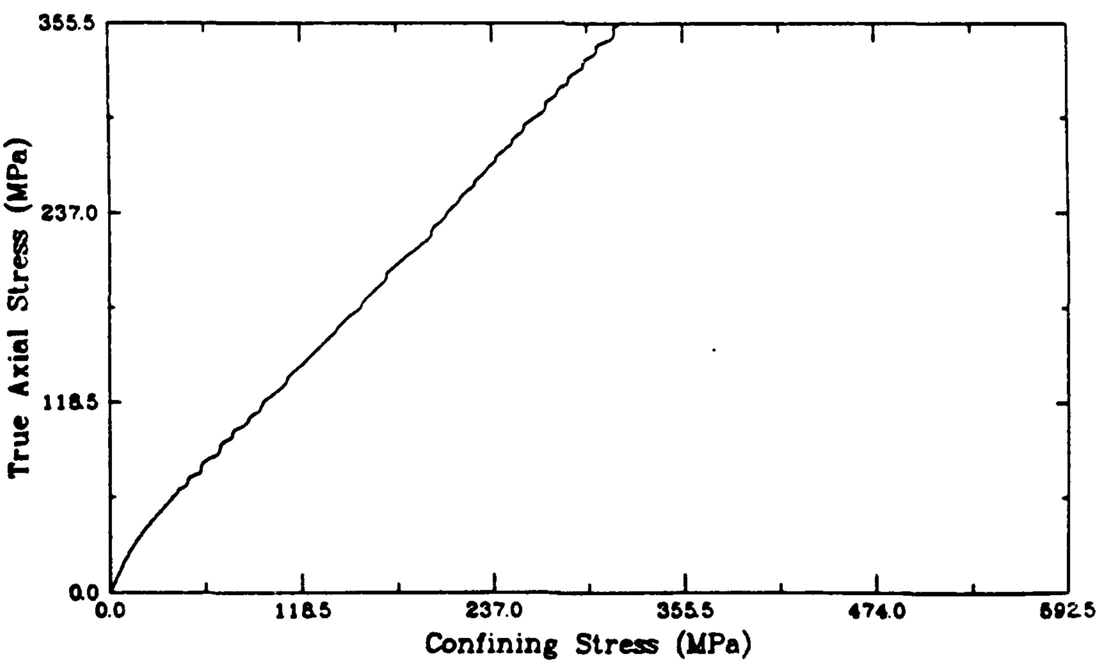


Lead Shot

Description:	Lead shot of the type used in shotgun shells. The material tested was No. 7 shot which consists of spherical particles of approximately 1.7 mm diameter.	
Origin:	A local gun supply store	
Test Specimen:	Test ID:	D18A8
	Grain Density (kg/m^3):	11,300
	Dry Bulk Density (kg/m^3):	7101
	Porosity:	0.372
Test Results:	Constrained Modulus (MPa):	148
	Poisson's Ratio:	0.43
Model Ratios:	Density:	4.4
	Modulus:	.40
	Length: (Scale Factor)	1/11
Comments:	This material has the combination of high density and low modulus required to give a scale factor of approximately 1/11. However, it has a very high Poisson's ratio, making it unacceptable as a simulant.	

Lead Shot (D18A9)
Uniaxial Strain Test
Stress Ratio (σ) = 0.395





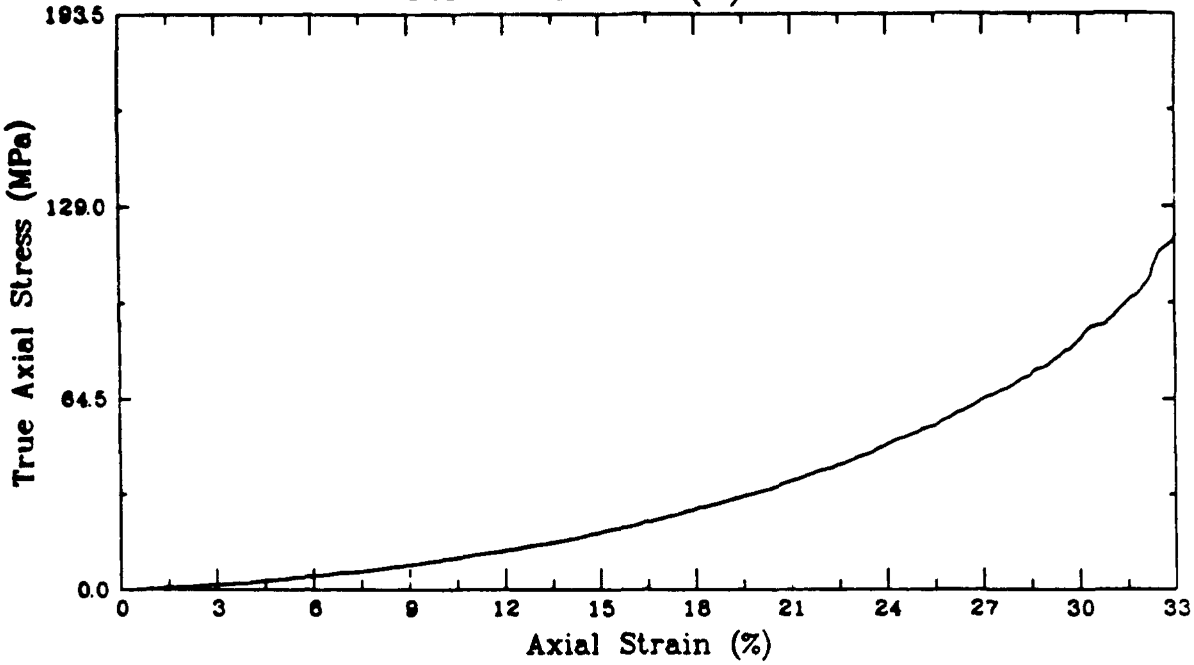
Bamberko Purge

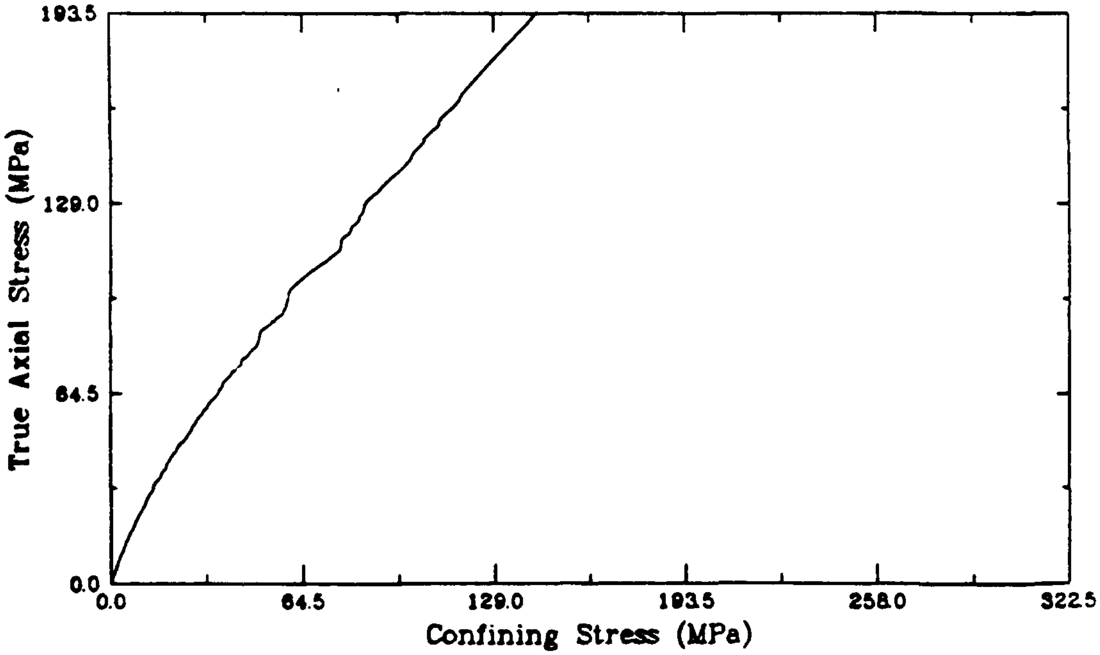
Description:	Clear granular acrylic polymer. Grains are angular, approximating the shape of natural sand grains. In the form tested, the grains were up to approximately 5 mm. This material is used to clean injection molding equipment.	
Origin:	Claude Bamberger Molding Compounds Corporation 111 Paterson Plank Road P.O. Box 67 Carlstadt, NJ 07072	
Test Specimen:	Test ID:	D2229
	Grain Density (kg/m^3):	1190
	Dry Bulk Density (kg/m^3):	715
	Porosity:	0.399
Test Results:	Constrained Modulus (MPa):	81
	Poisson's Ratio:	.31
Model Ratios:	Density:	0.44
	Modulus:	0.22
	Length: (Scale Factor)	1/2.1
Comments:	Based on the limited testing prformed, this material could be an acceptable sand simulant. However, the meager scale factor removes it from consideration for this effort.	

Bamberko Purge (D22Z9)

Uniaxial Strain Test

Stress Ratio (σ) = 0.215

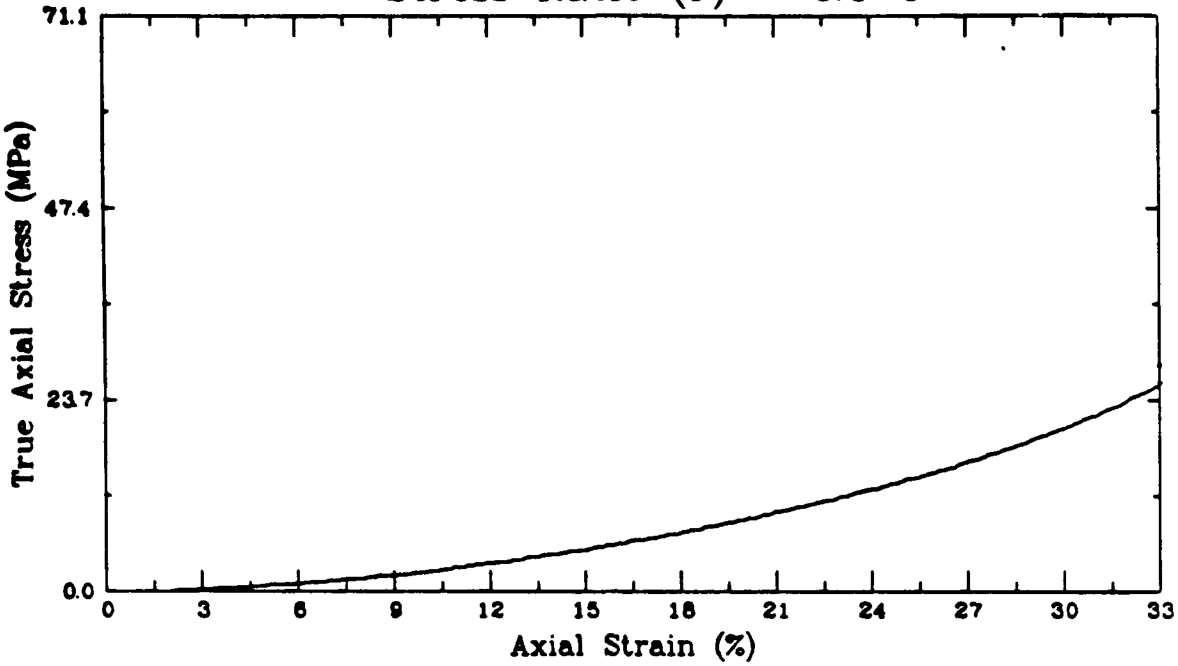


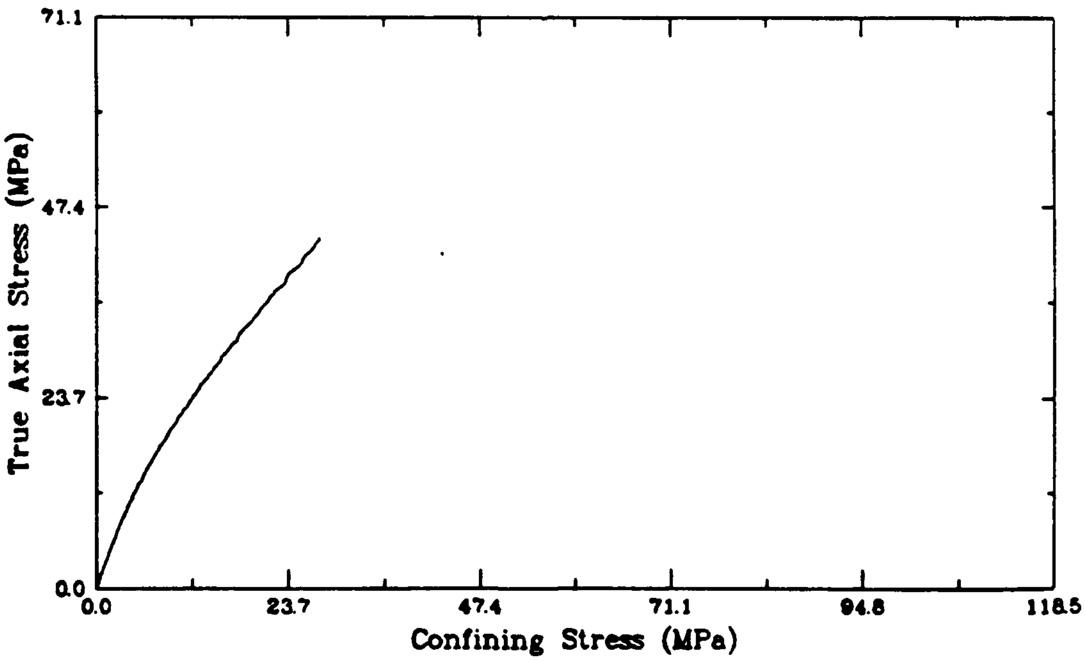


Alcon PCTFE

Description:	Polychloro-Trifluoroethylene Copolymer, white powder. Similar to PTFE, except more frictional.	
Origin:	Allied Signal, Inc. P.O. Box 2332R Morristown, NJ 07960	
Test Specimen:	Test ID:	J2A0
	Grain Density (kg/m^3):	2130
	Dry Bulk Density (kg/m^3):	1177
	Porosity:	0.447
Test Results:	Constrained Modulus (MPa):	30
	Poisson's Ratio:	0.32
Model Ratios:	Density:	0.73
	Modulus:	0.079
	Length: (Scale Factor)	1/9.2
Comments:	Based on the limited testing performed, this material appears to have the potential to serve as a Froude-scale simulant for sand. The specimen was tested at a rather high porosity and consequently, it underwent almost 40 percent strain without the lock-up that is present on the sand stress-strain curves. However, this could probably be adjusted by increasing the initial density of the specimen. A major drawback of this material is its cost of $40-60 per kg. Since a coal/lead mixture provides at least as favorable simulant properties at a much lower cost, PCTFE was dropped from consideration as a simulant.	

Aclon CTFE (J2A0)
Uniaxial Strain Test
Stress Ratio (σ) = 0.079





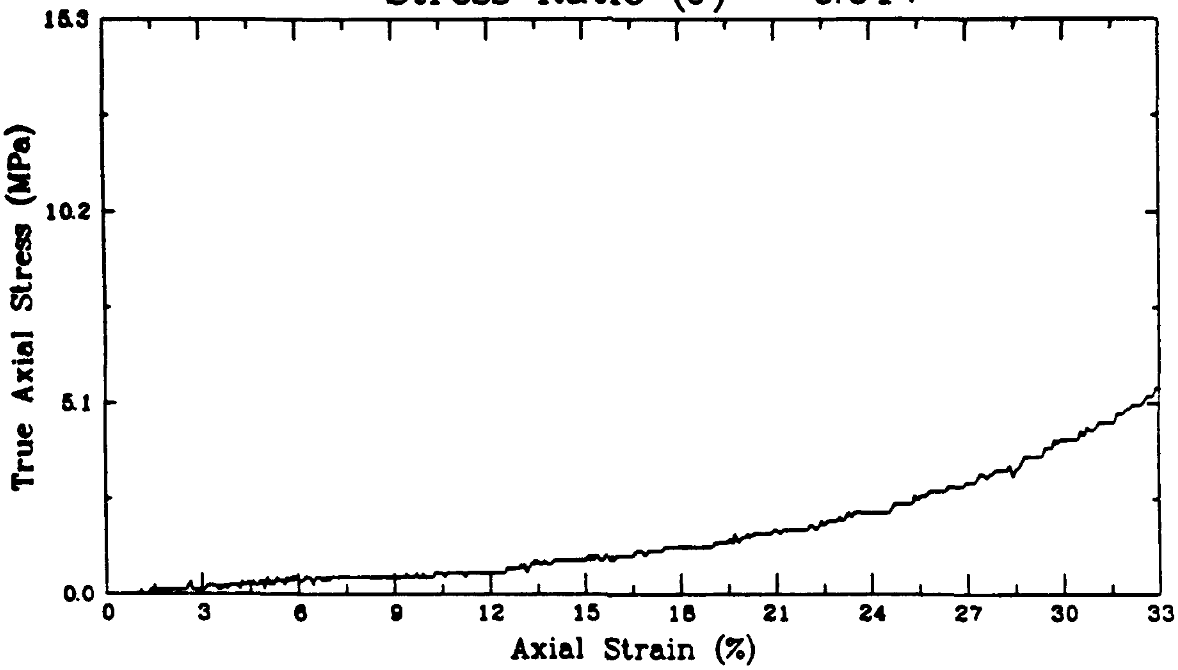
PTFE 50 Inox

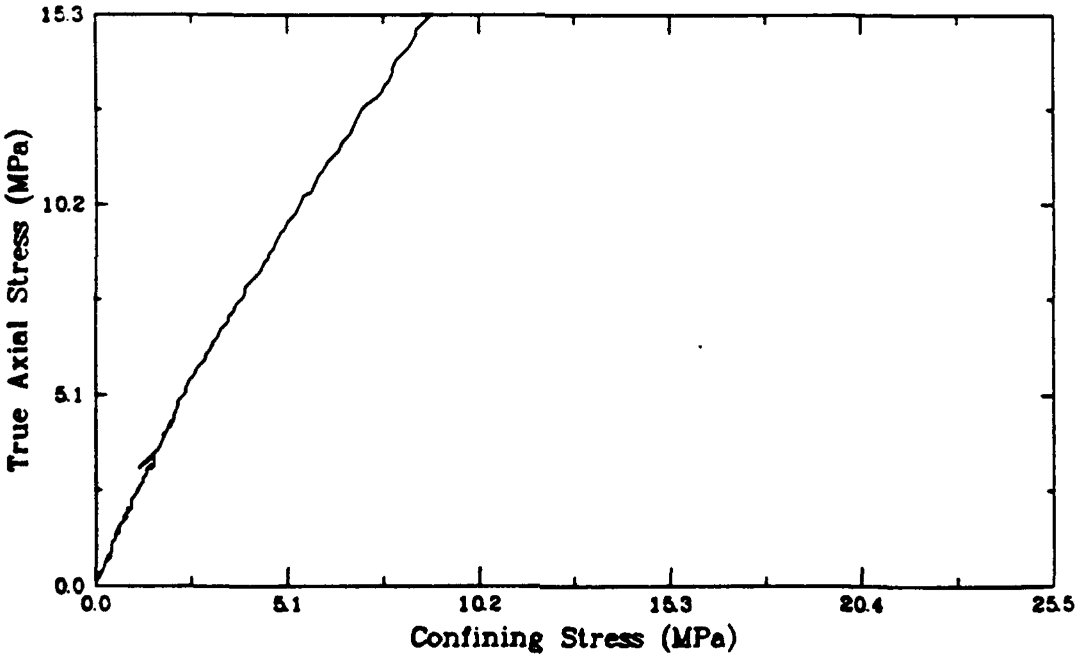
Description:	PTFE that is filled with 50% by weight stainless steel. This substantially increases the density of the material over plain PTFE and, because the filler interferes with the TFE-TFE bonding, it actually lowers the modulus.	
Origin:	Ausimont 44 Whippany Road Morristown NJ, 07960-1838	
Test Specimen:	Test ID:	J3B0
	Grain Density (kg/m^3):	3250
	Dry Bulk Density (kg/m^3):	1815
	Porosity:	0.442
Test Results:	Constrained Modulus (MPa):	6
	Poisson's Ratio:	0.38
Model Ratios:	Density:	1.13
	Modulus:	0.017
	Length: (Scale Factor)	1/66
Comments:	Based solely on initial constrained modulus and density, the filled PTFEs have the largest scale factors of the materials tested for this effort. Owing to the high initial porosity of the specimen tested, its strain to lock-up was excessive in comparison to the prototype sands, and the Poisson's ratio is too high. At over $30/kg, this is also a very expensive material.	

PTFE 50 INOX (J3B0)

Uniaxial Strain Test

Stress Ratio (σ) = 0.017

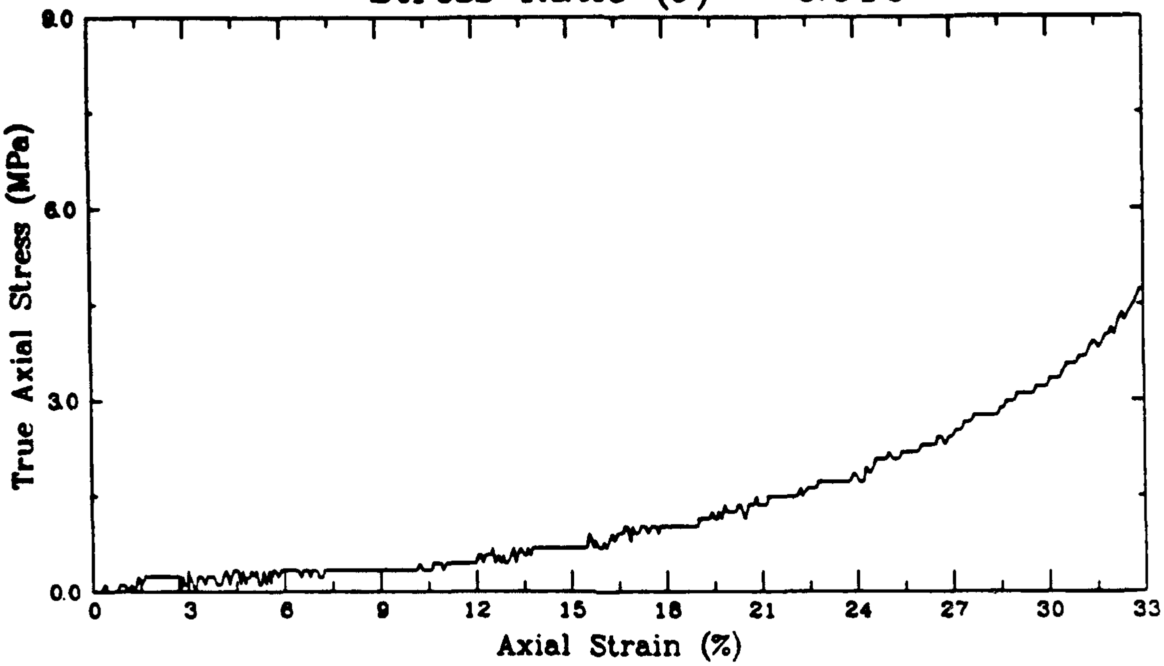


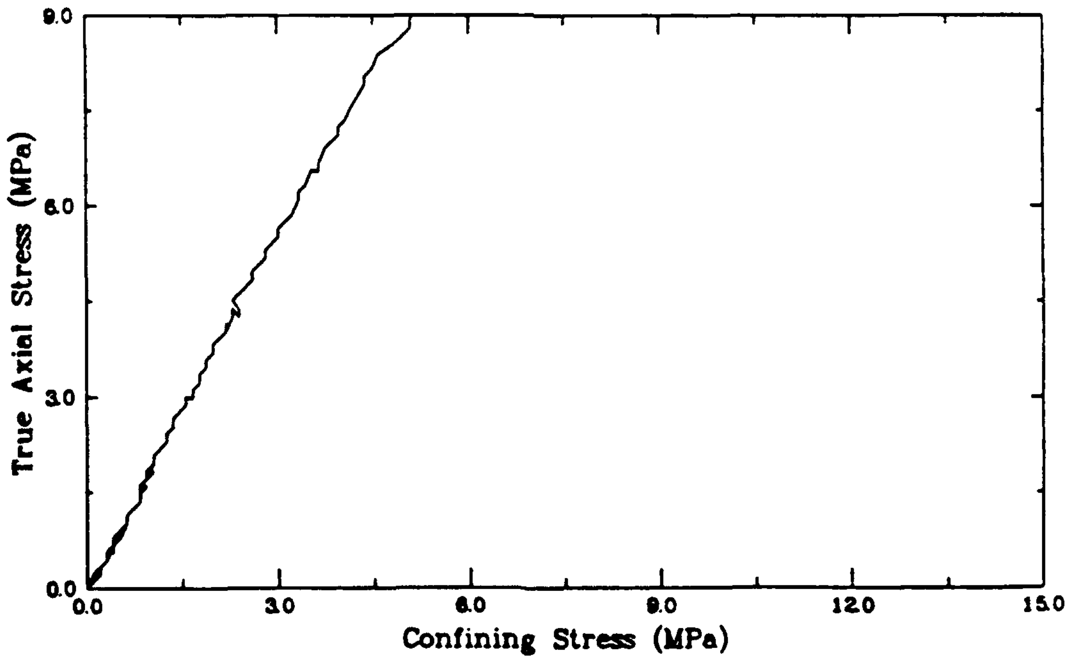


PTFE 25 Glass

Description:	Similar to PTFE 50 Inox, except that the filling is 25% ground glass by weight.	
Origin:	Ausimont 44 Whippany Road Morristown NJ, 07960-1838	
Test Specimen:	Test ID:	J4A0
	Grain Density (kg/m^3):	2220
	Dry Bulk Density (kg/m^3):	1165
	Porosity:	0.475
Test Results:	Constrained Modulus (MPa):	5
	Poisson's Ratio:	0.38
Model Ratios:	Density:	0.72
	Modulus:	0.010
	Length: (Scale Factor)	1/76
Comments:	Based solely on initial constrained modulus and density, the filled PTFEs have the largest scale factors of the materials tested for this effort. Owing to the high initial porosity of the specimen tested, its strain to lock-up was excessive in comparison to the prototype sands, and the Poisson's ratio is too high. At over $30/kg, this is also a very expensive material.	

PTFE 25 Glass (J4A0)
Uniaxial Strain Test
Stress Ratio (σ) = 0.010





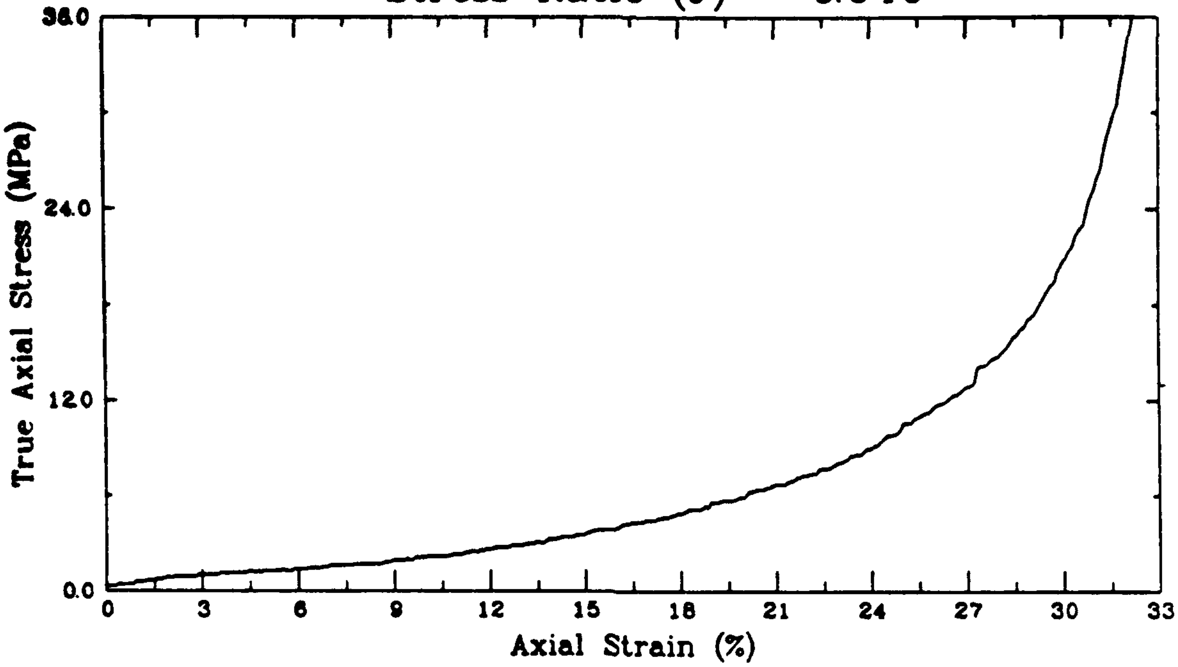
Flake 500 with Fiber

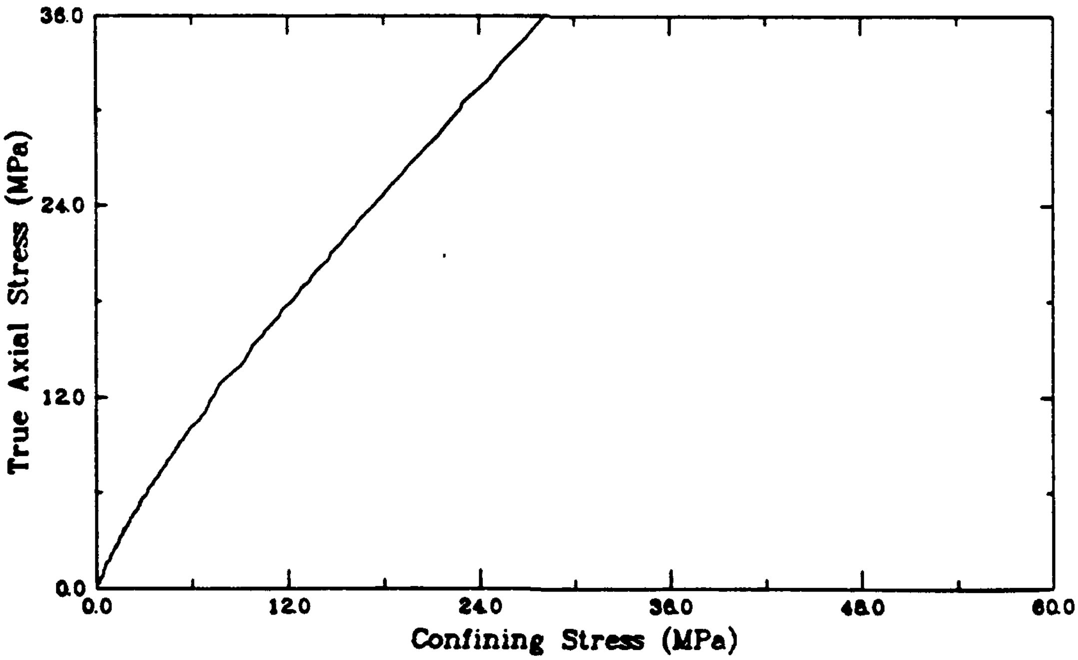
Description:	In an effort to raise the friction of PTFE, a mix was made of Flake 500 and polymer fibers (exact composition unknown) of the type that are use to make fiber reinforced concrete.
Origin:	See Flake 500 and a local concrete batch plant.

Test Specimen:	Test ID:	J4B0
	Grain Density(kg/m^3):	Fiber density not known
	Dry Bulk Density (kg/m^3):	1400
	Porosity:	Not known
Test Results:	Constrained Modulus (MPa):	15
	Poisson's Ratio:	0.41
Model Ratios:	Density:	0.41
	Modulus:	0.87
	Length: (Scale Factor)	1/21

Comments: The addition of fiber to the Flake 500 did not substantially modify its properties. The measured Poisson's ratio is actually higher, opposite the desired trend.

Flake w/Fiber (J4B0)
Uniaxial Strain Test
Stress Ratio (σ) = 0.040





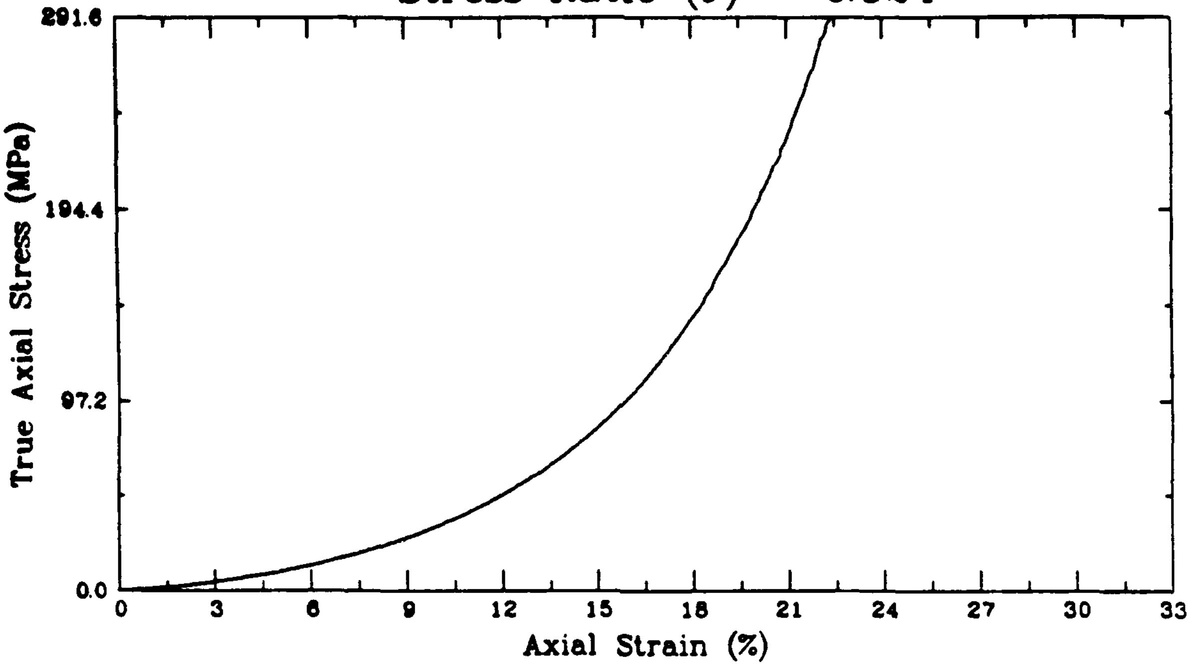
Barite

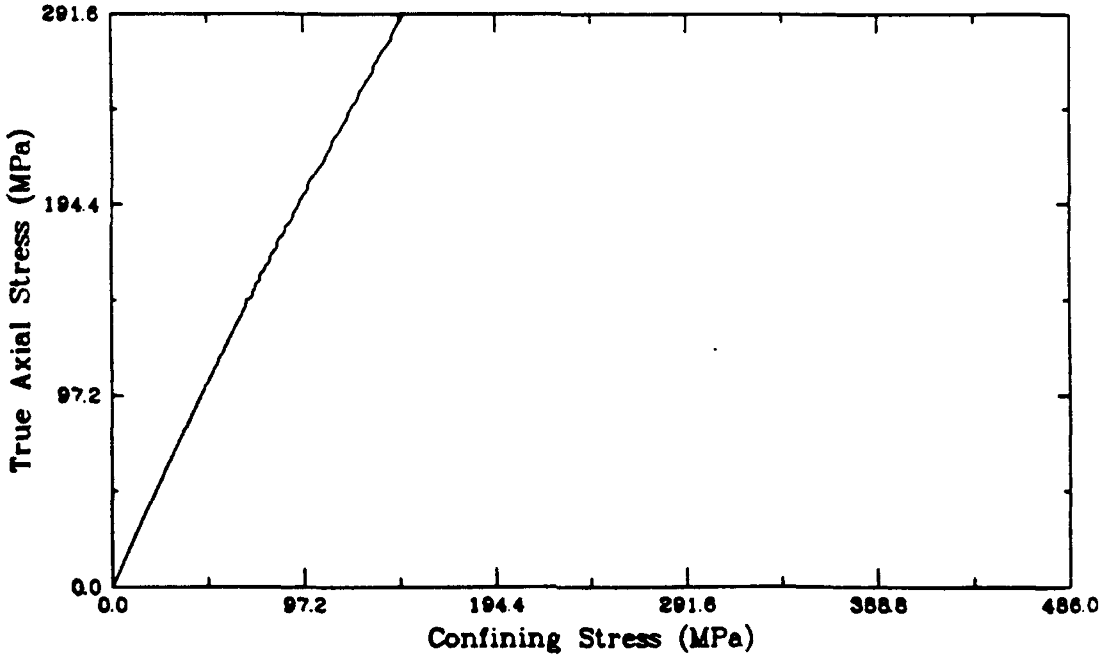
Description:	Barite (barium sulfate) is a yellowish brown mineral. Because of its high grain density, finely powdered barite is used in suspension with water to form a high density fluid for well drilling operations.
Origin:	NL Baroid Division NL Petroleum Services Houston, TX

Test Specimen:	Test ID:	J25A0
	Grain Density (kg/m^3):	4480
	Dry Bulk Density (kg/m^3):	2842
	Porosity:	0.366
Test Results:	Constrained Modulus (MPa):	121
	Poisson's Ratio:	0.31
Model Ratios:	Density:	1.76
	Modulus:	.324
	Length: (Scale Factor)	1/5.5

Comments: Based on the tests performed, this material could possibly be used as a Froude scale simulant for sand. It has a rather modest scale factor, and is substantially more expensive than coal for the same scale factor.

Barite (J25A0)
Uniaxial Strain Test
Stress Ratio (σ) = 0.324

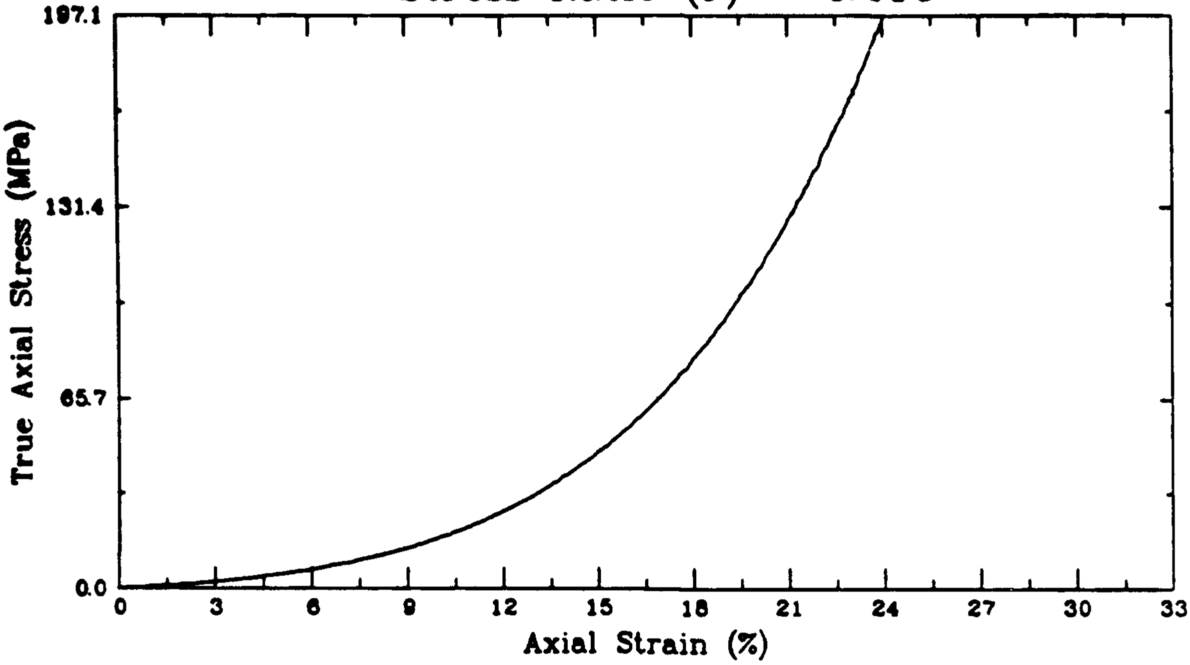


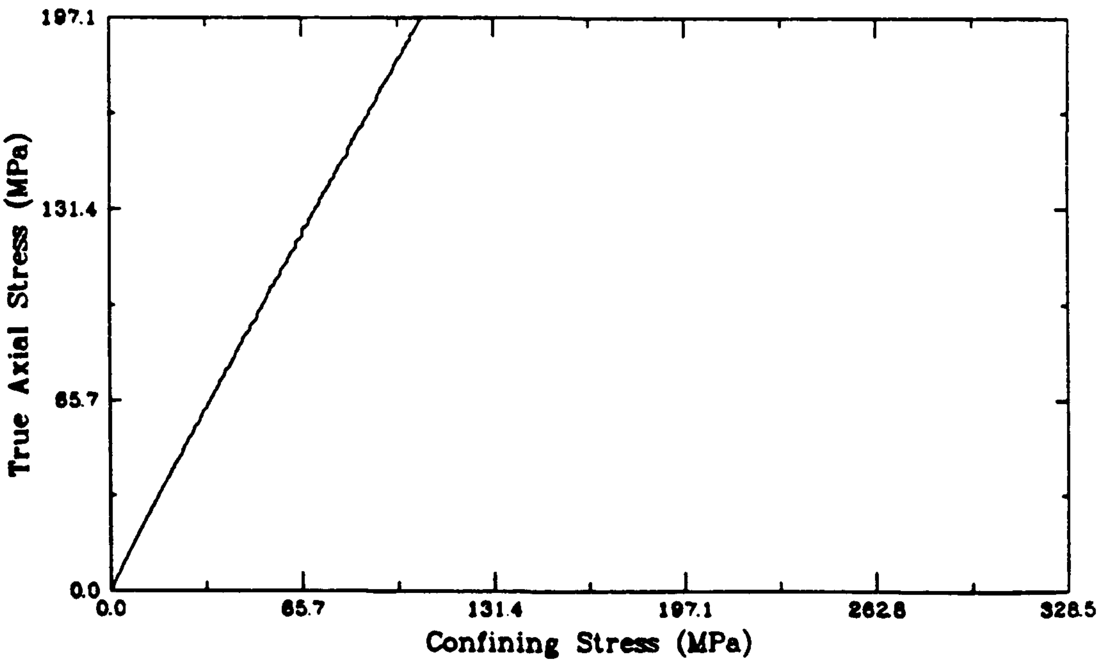


Fly Ash

Description:	Fly ash is produced from the partiulate material that is trapped in the smoke stack scrubbers of coal burning power plants. It is a light gray powder. It can be used in place of a fraction of the portland cement in concrete.	
Origin:	Pozzolanic International Suite 401, 107 Commons West Ithaca, NY 14805 (607) 272-3257	
Test Specimen:	Test ID:	J26A0
	Grain Density (kg/m^3):	Not known
	Dry Bulk Density (kg/m^3):	1356
	Porosity:	Not known
Test Results:	Constrained Modulus (MPa):	82
	Poisson's Ratio:	0.36
Model Ratios:	Density:	0.84
	Modulus:	0.219
	Length: (Scale Factor)	1/3.9
Comments:	Based on the measured modulus and density, this material would give a scale factor of only about 1/4. Since other better materials were discovered, it was not considered further.	

Fly Ash (J26A0)
Uniaxial Strain Test
Stress Ratio (σ) = 0.219





APPENDIX B

DESCRIPTION OF VARIOUS COAL AND COAL/LEAD MIXTURES

COAL

Three different types of coal were tested in the course of the search for suitable simulants. Of those, two, Anthracite coal and so-called Denver coal were tested and eliminated. Specific information concerning the origin of these materials is not known.

The bituminous coal that was selected for use as a Froude scale sand simulant was purchased from a coal broker in New Jersey:

Kennedy and Decker
(201) 635-0731

The shipping labels on the barrels of coal indicate that it came from:

Bradford Coal Co., Inc.
P.O. Box 368
Bigler, Pennsylvania 16825

The three different coals have different grain densities, as follows:

Material	Grain Density (kg/m^3)
Anthracite Coal	1650
Bituminous Coal	1330
"Denver" Coal	1460

LEAD

Lead in two different forms was used in various phases of the simulant selection laboratory testing.

No. 7 Lead Shot. This material, which was intended for use in shotgun shells, was obtained from a local sporting goods store. It is designated No. 7 and consists of nominally uniform spherical particles of 1.7 mm diameter.

Free Flow Lead Shot. This material consists of particles with a range of sizes, all smaller than the No. 7 shot. Its specifications list the following grain size characteristics:

0.41 - 1.14 mm	90 percent
0.23 - 0.41 mm	10 percent

A grain size analysis of a small sample of free flow shot produced results essentially confirming that specification. This material was supplied as Product Code 20900 by:

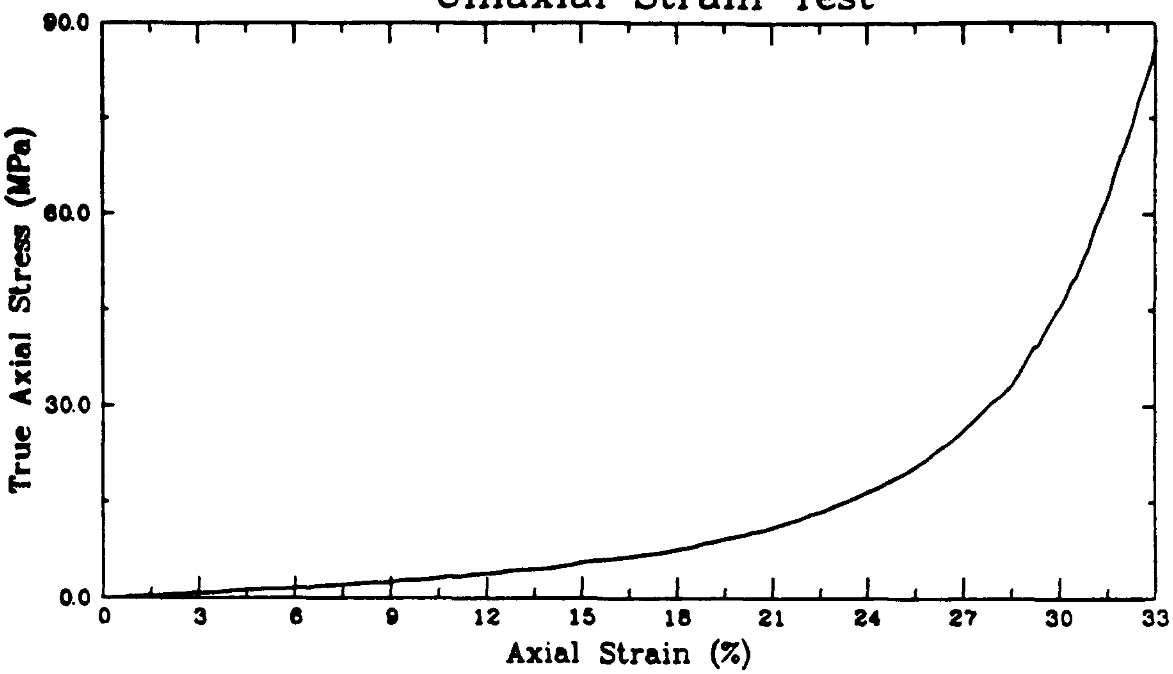
Taracorp Industries, Inc.
16th and Cleveland Boulevard
Granite City, Illinois 62040
(618) 451-4400

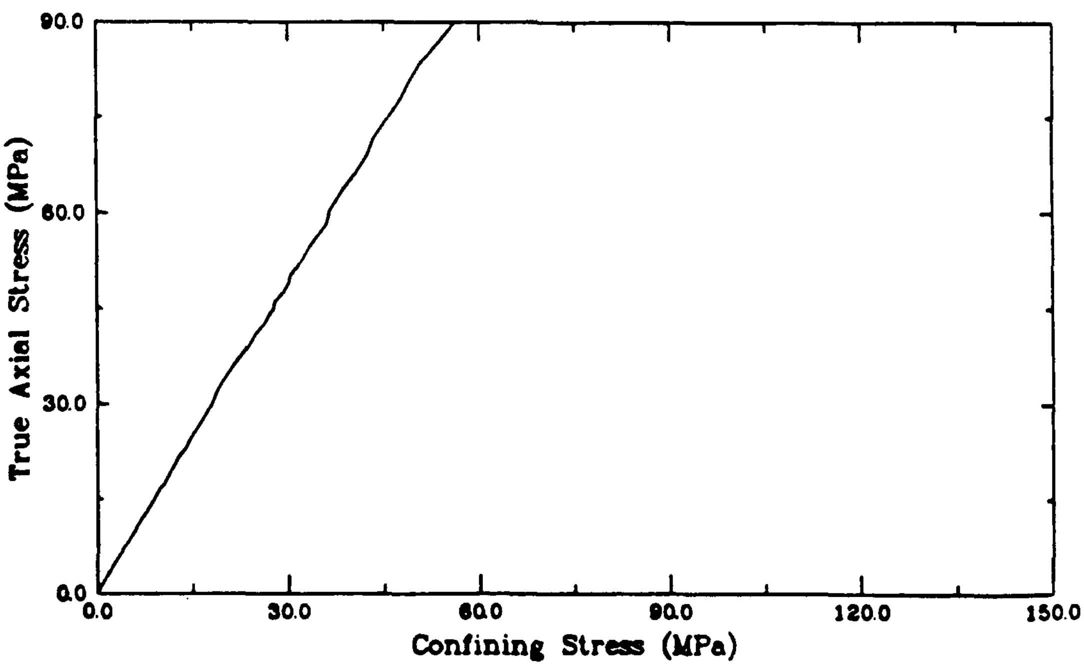
The density of solid lead grains is 11,300 kg/m^3.

Anthracite Coal (D20A9)

Description:	This hard coal was manually crushed and only material that passed a No. 10 sieve was used. In addition, approximately half of the portion passing a No. 50 sieve was removed.	
Test Specimen:	Dry Bulk Density (kg/m^3):	956
	Porosity:	.420
Test Results:	Constrained Modulus (MPa):	43
	Poisson's Ratio:	0.38
Model Ratios:	Density:	0.59
	Modulus:	0.114
	Length: (Scale Factor)	1/5.2
Comments:	This material shows promise as a simulant, but a larger scale factor is desired.	

Anthracite Coal (D20A9)
Uniaxial Strain Test

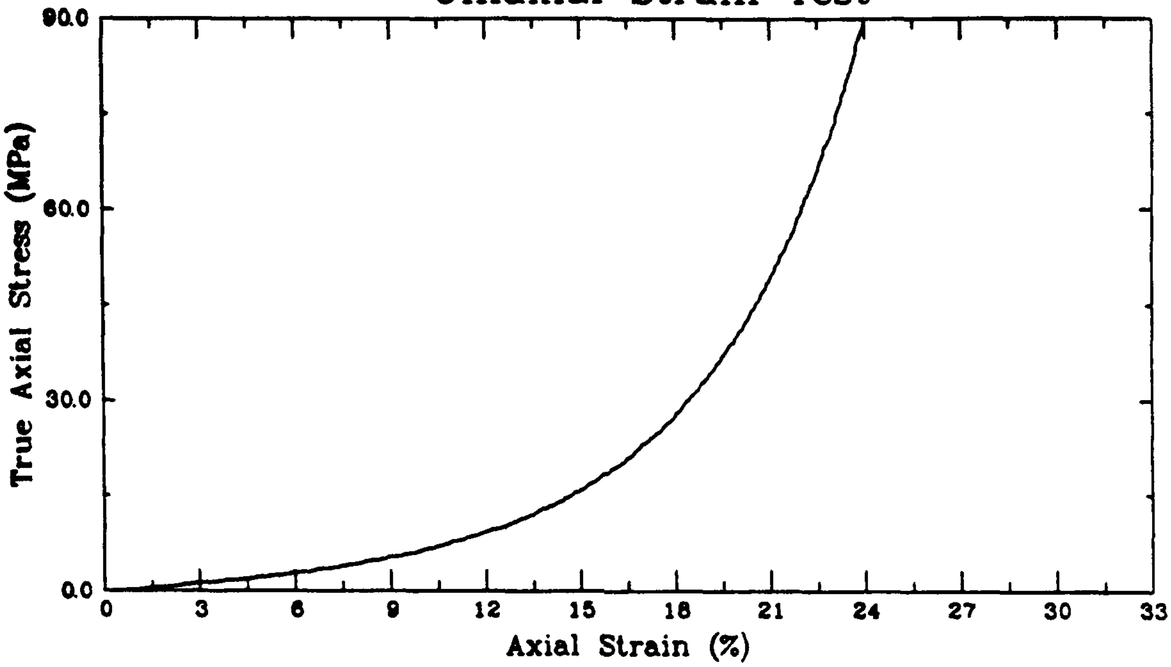


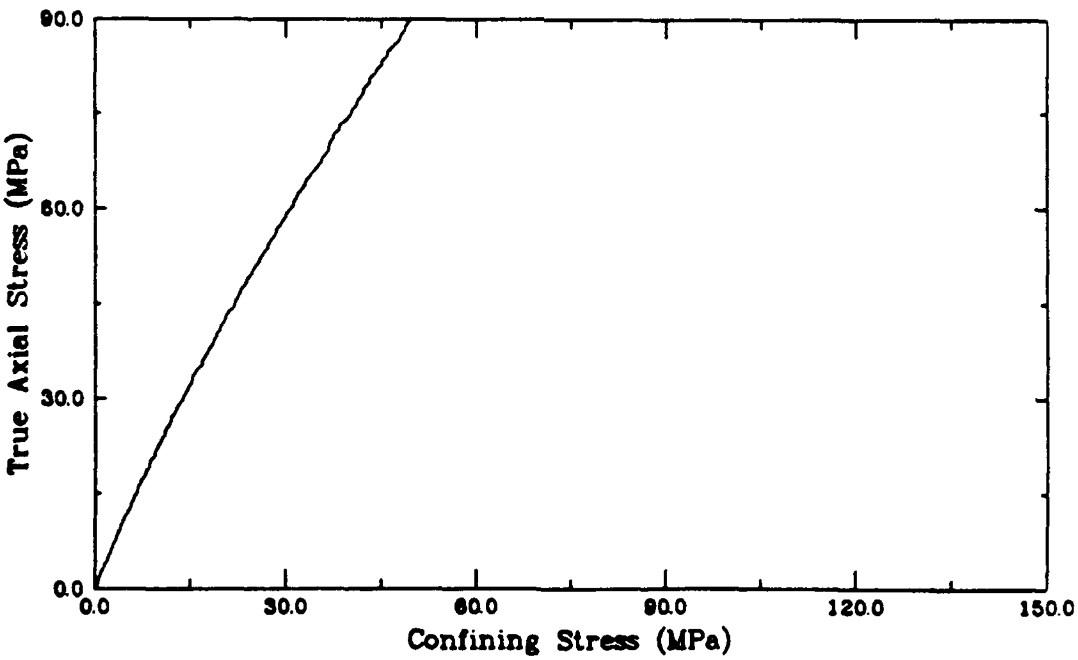


Bituminous Coal (J2B0)

Description:	As with the anthracite, this soft coal was manually crushed and only material that passed a No. 10 sieve was used for preparation of the specimen.	
Test Specimen:	Dry Bulk Density (kg/m^3):	988
	Porosity:	.257
Test Results:	Constrained Modulus (MPa):	53
	Poisson's Ratio:	0.34
Model Ratios:	Density:	0.61
	Modulus:	0.141
	Length: (Scale Factor)	1/4.4
Comments:	Due to the softness of bituminous coal, some of the grains were apparently crushed during sample preparation, as evidenced by the very low porosity. As a result, the modulus measured in this test was higher than the previous anthracite coal test (D20A9).	

Bituminous Coal (J2B0)
Uniaxial Strain Test





Bituminous Coal (J3A0)

Description: The material tested here was similar to the previous bituminous coal test (J2B0), except that an effort was made to keep the porosity up. All material passing a No. 50 sieve was removed before packing the specimen, and care was taken not to over compact it.

Test Specimen:

	Dry Bulk Density (kg/m^3):	857
	Porosity:	.356

Test Results:

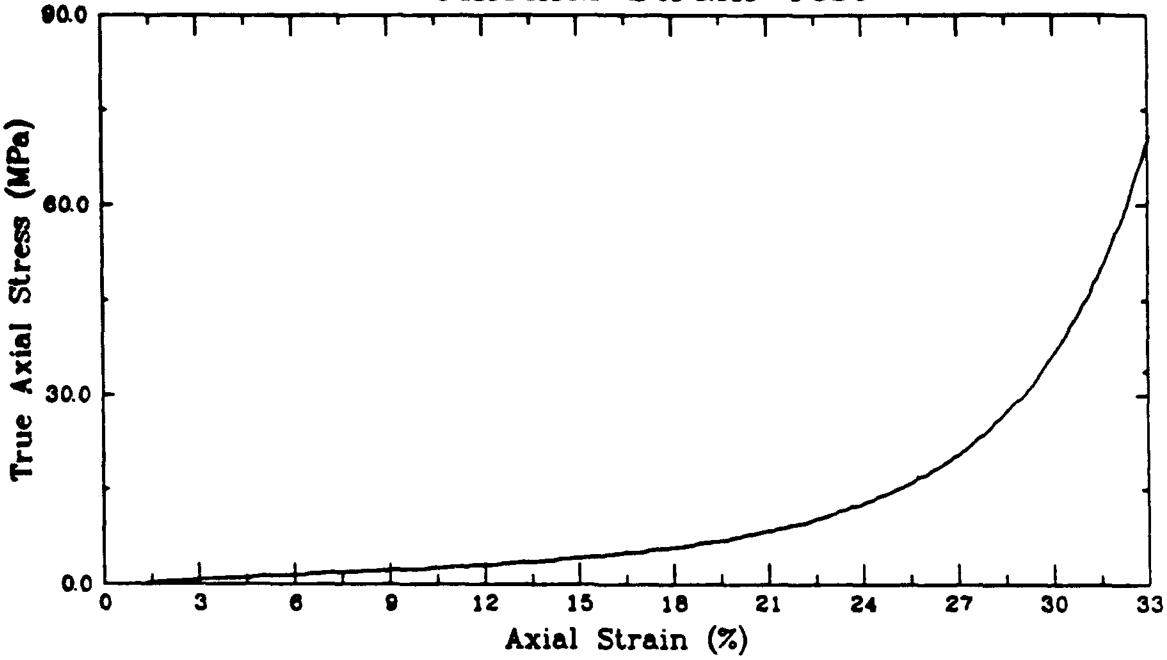
	Constrained Modulus (MPa):	24
	Poisson's Ratio:	0.33

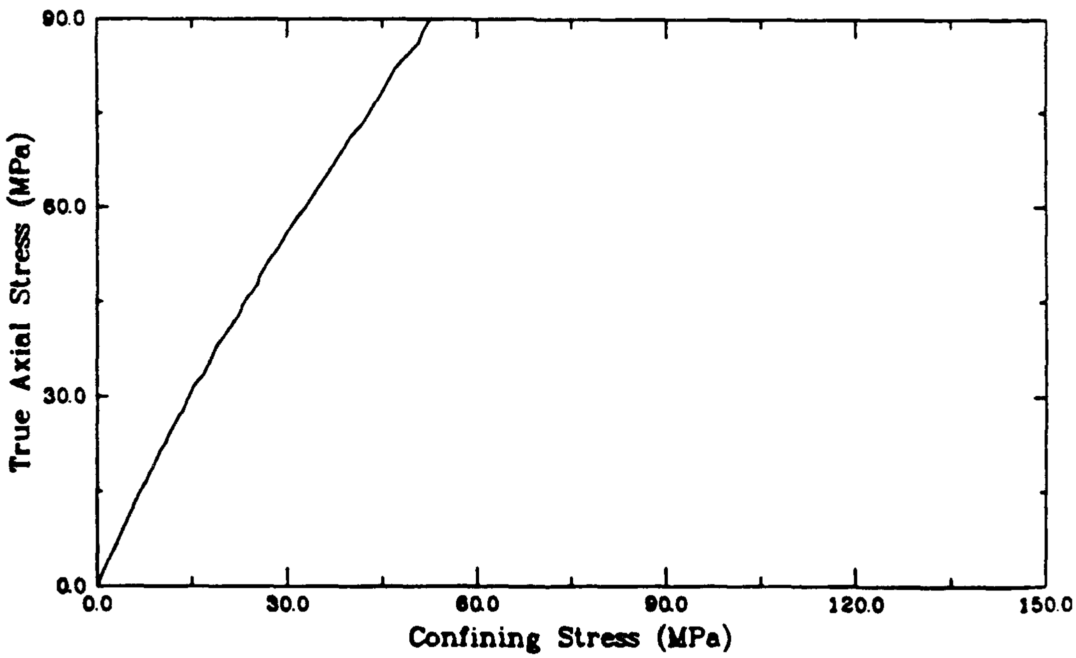
Model Ratios:

	Density:	0.53
	Modulus:	0.064
	Length: (Scale Factor)	1/8.3

Comments: This test produced a significantly lower modulus than the other bituminous coal test, apparently as a result of the lower density.

Bituminous Coal (J3A0)
Uniaxial Strain Test





Anthracite Coal and Lead (J5A0)

Description: In an attempt to increase the scale factor, lead was added to this specimen to increase the density. The specimen was composed of 50 percent anthracite coal and 50 percent lead by weight. Since the grain density of lead is almost seven times that of the coal, the volume of lead in the specimen was only about 13% of the total solid volume. The lead was No. 7 shot and the coal had the following sieve analysis:

Sieve Size	Percent Passed
5	100
8	61
20	17
50	0

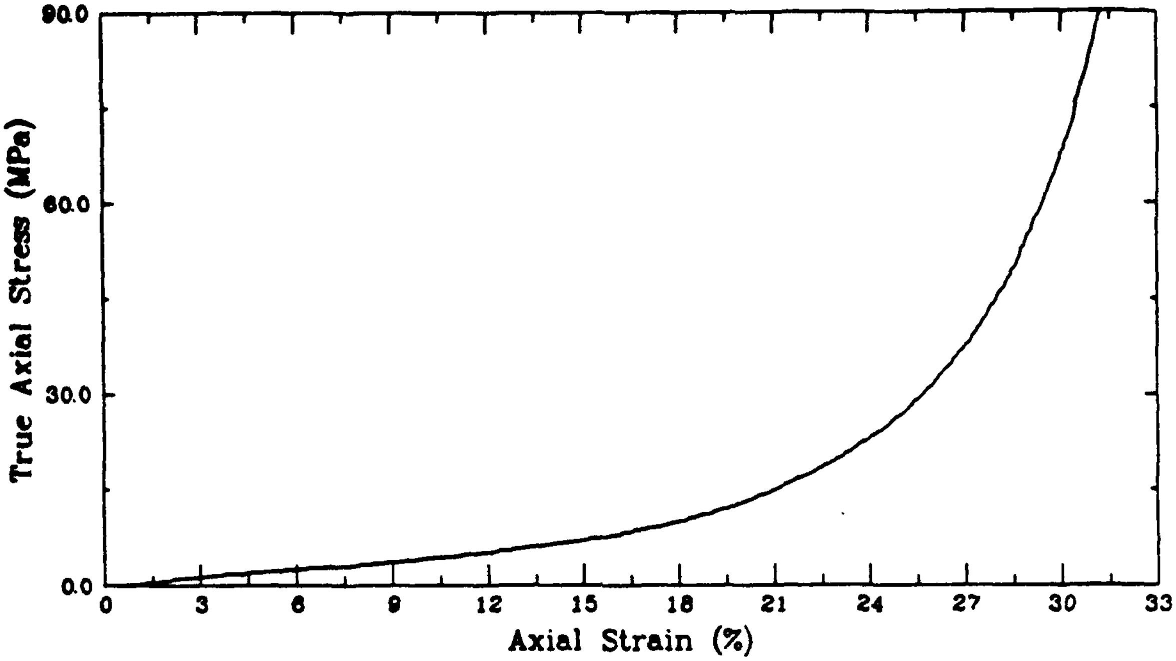
Test Specimen: Dry Bulk Density (kg/m^3): 1946
Porosity: .326

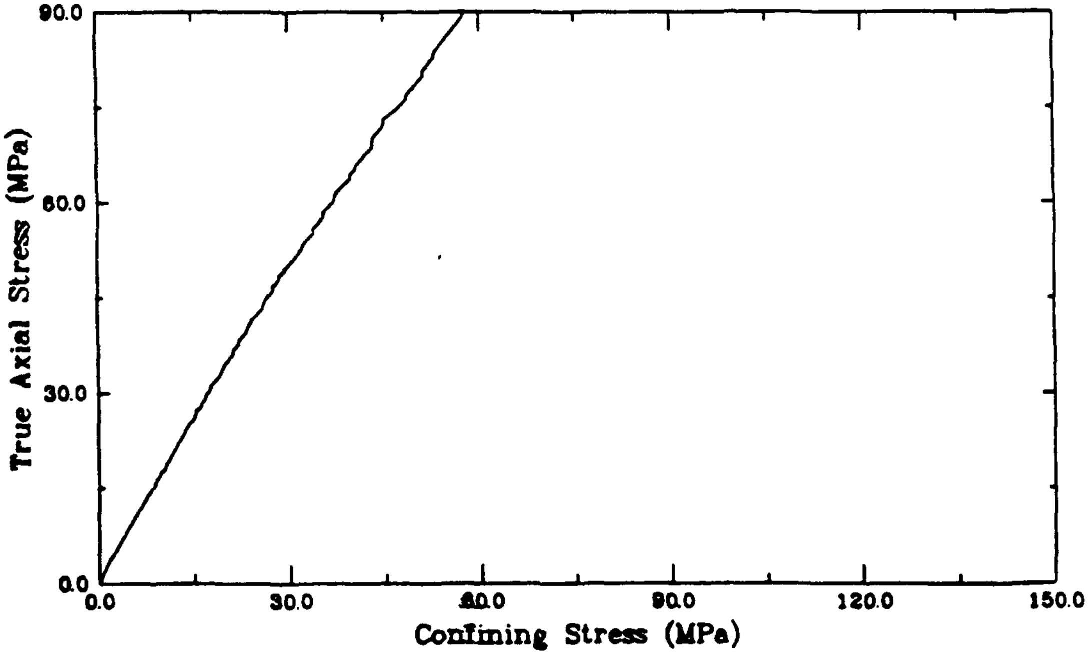
Test Results: Constrained Modulus (MPa): 39
Poisson's Ratio: 0.35

Model Ratios: Density: 1.21
Modulus: 0.105
Length: 1/11.5
(Scale Factor)

Comments: The addition of lead had the desired effect. The density increased with the modulus remaining in the range of moduli measured for pure coal.

Anthracite Coal and Lead (J5A0)
Uniaxial Strain Test





40% Bituminous Coal - 60% Lead (J5B0)

Description: The constituents were proportioned 40% bituminous coal and 60% lead, by weight. The lead was No.7 shot and the coal had the following sieve analysis:

Sieve Size	Percent Passed
5	100
8	57
20	18
50	0

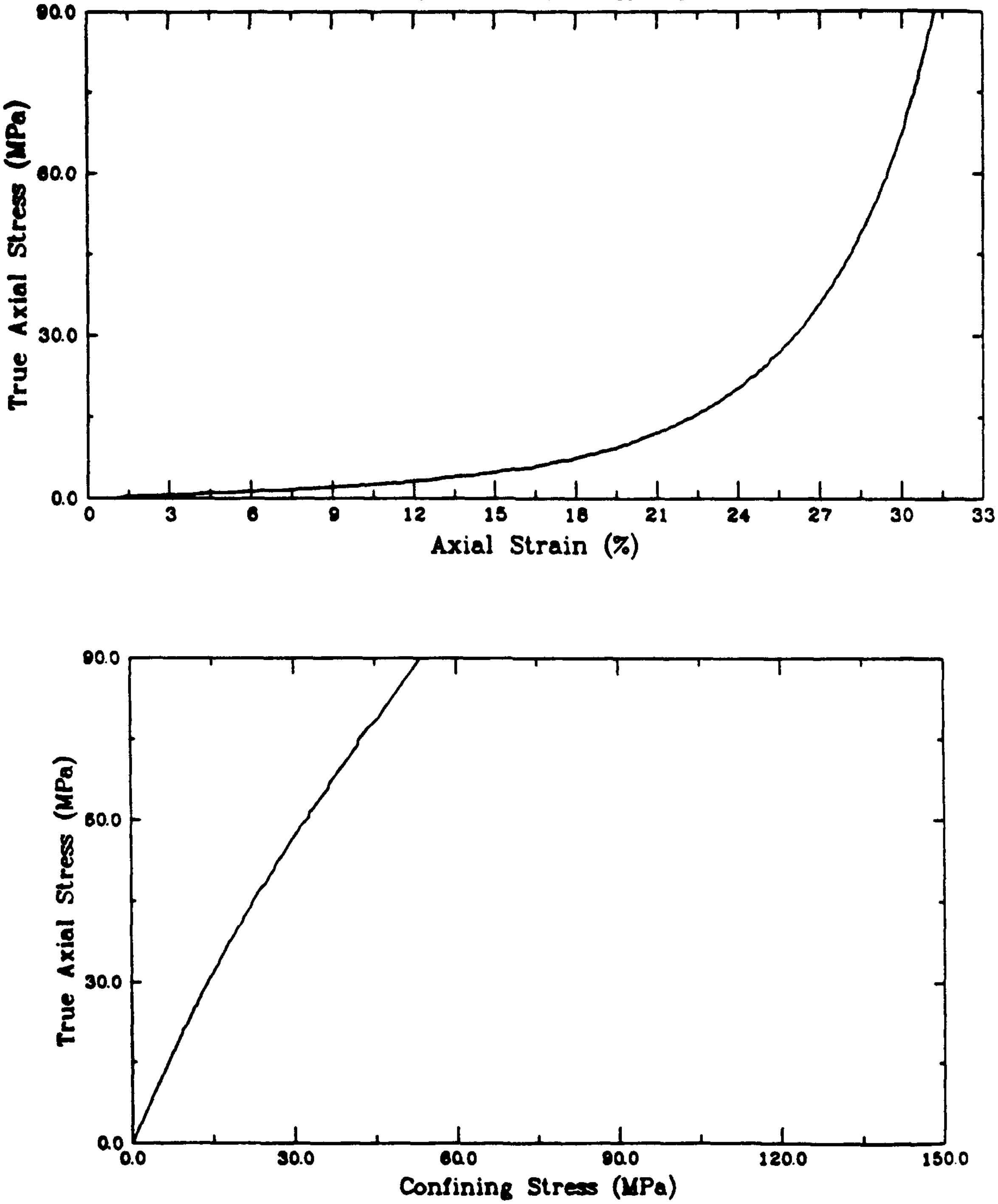
Test Specimen: Dry Bulk Density (kg/m^3): 1810
Porosity: .360

Test Results: Constrained Modulus (MPa): 23
Poisson's Ratio: 0.30

Model Ratios: Density: 1.12
Modulus: 0.061
Length: 1/18.5
(Scale Factor)

Comments: This is the lowest modulus recorded in any of the coal and coal/lead tests. This scale factor approaches 20, but it was not possible to reproduce these results in subsequent tests.

40% Bituminous Coal - 60% Lead (J5B0)
Uniaxial Strain Test



50% Bituminous Coal - 50% Lead (J9A0)

Description: Similar to specimen J5B0, this had a lower lead content as indicated by the title. The lead was No.7 shot and the coal had the following sieve analysis:

Sieve Size	Percent Passed
5	100
8	60
20	20
50	0

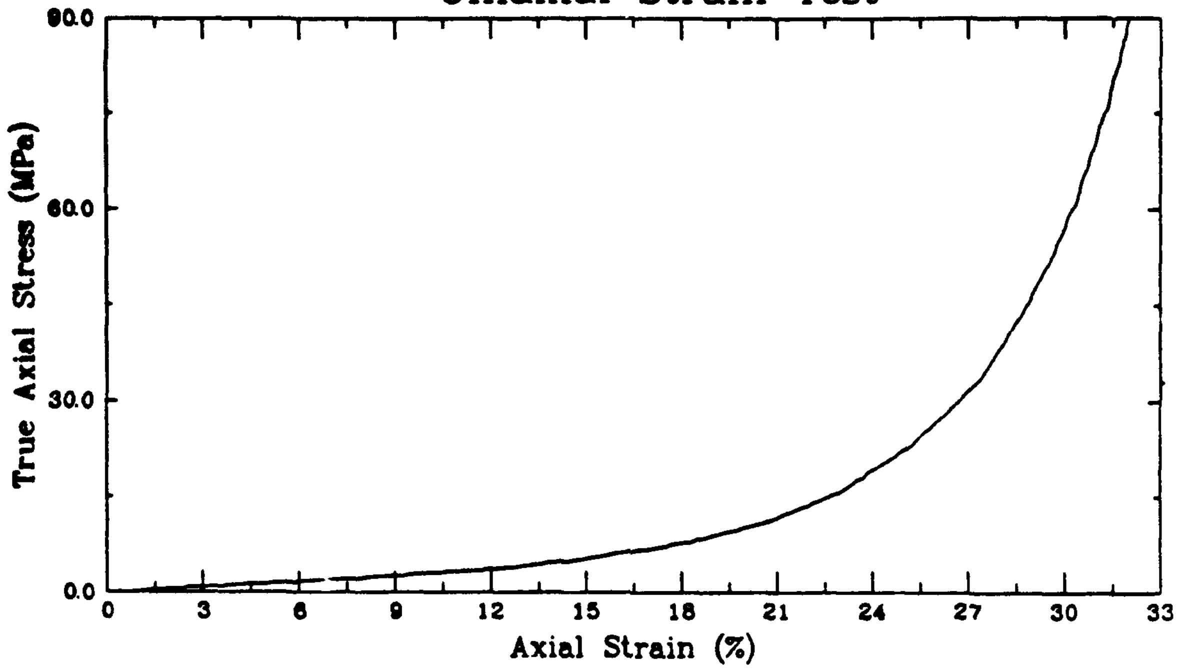
Test Specimen: Dry Bulk Density (kg/m^3): 1514
Porosity: .364

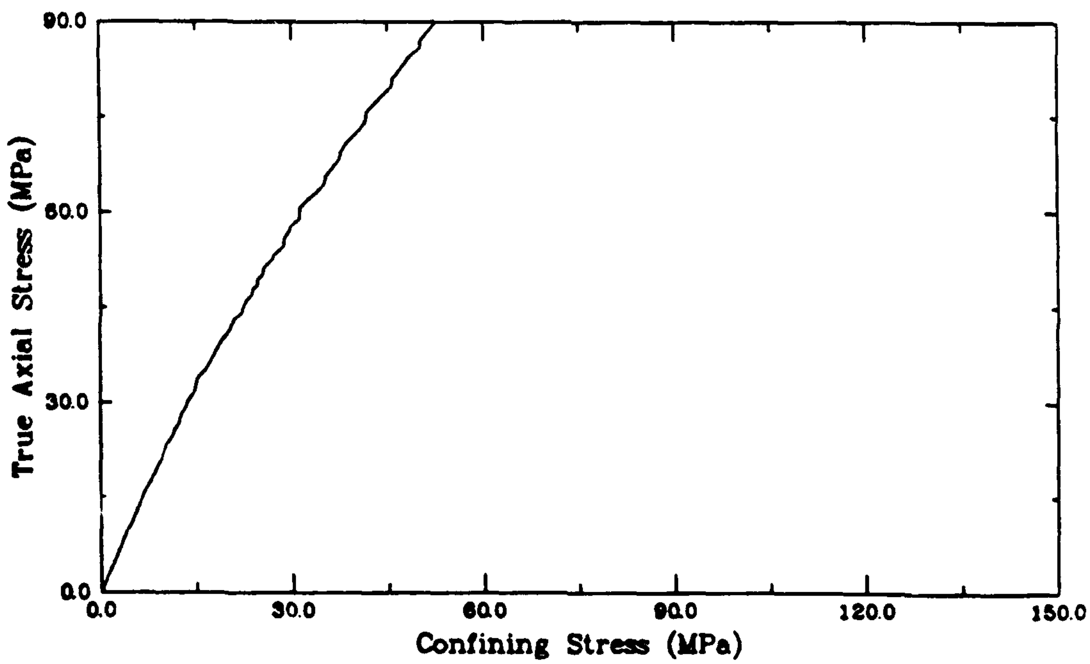
Test Results: Constrained Modulus (MPa): 31
Poisson's Ratio: 0.30

Model Ratios: Density: 0.94
Modulus: 0.082
Length: 1/11.5
(Scale Factor)

Comments: The reduced density due to the lower lead content and the higher modulus resulted in significantly less of a scale factor than in the first bituminous coal/lead test (J5B0).

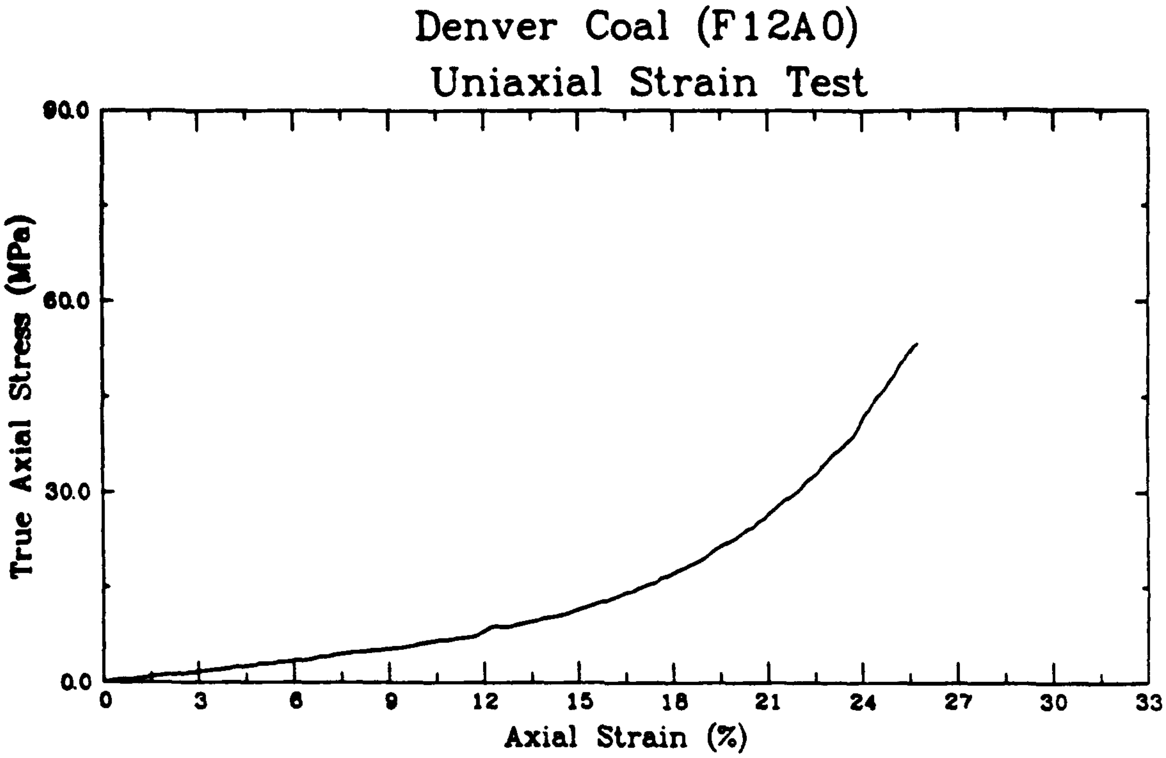
50% Bituminous Coal – 50% Lead (J9A0)
Uniaxial Strain Test

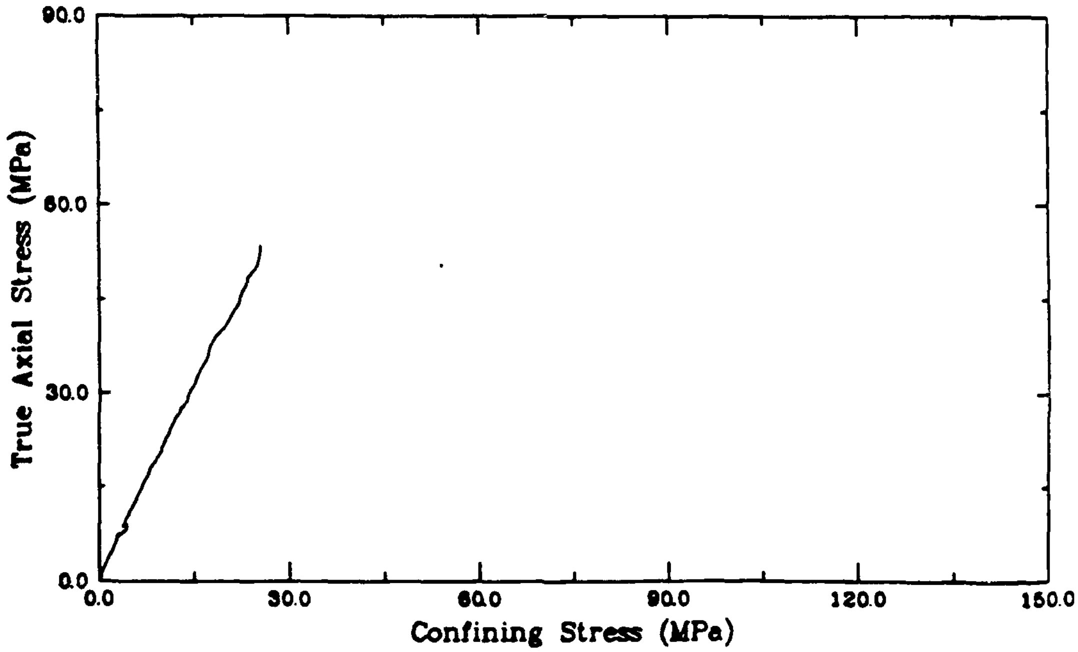




Denver Coal (F12A0)

Description:	This was the first test on coal obtained from the Denver area. The specimen was constructed to have the same sieve analysis as J9A0.	
Test Specimen:	Dry Bulk Density (kg/m^3):	828
	Porosity:	0.433
Test Results:	Constrained Modulus (MPa):	57
	Poisson's Ratio:	0.33
Model Ratios:	Density:	0.51
	Modulus:	0.152
	Length: (Scale Factor)	1/3.4
Comments:	The stiffness of this material was substantially higher than the bituminous coal.	

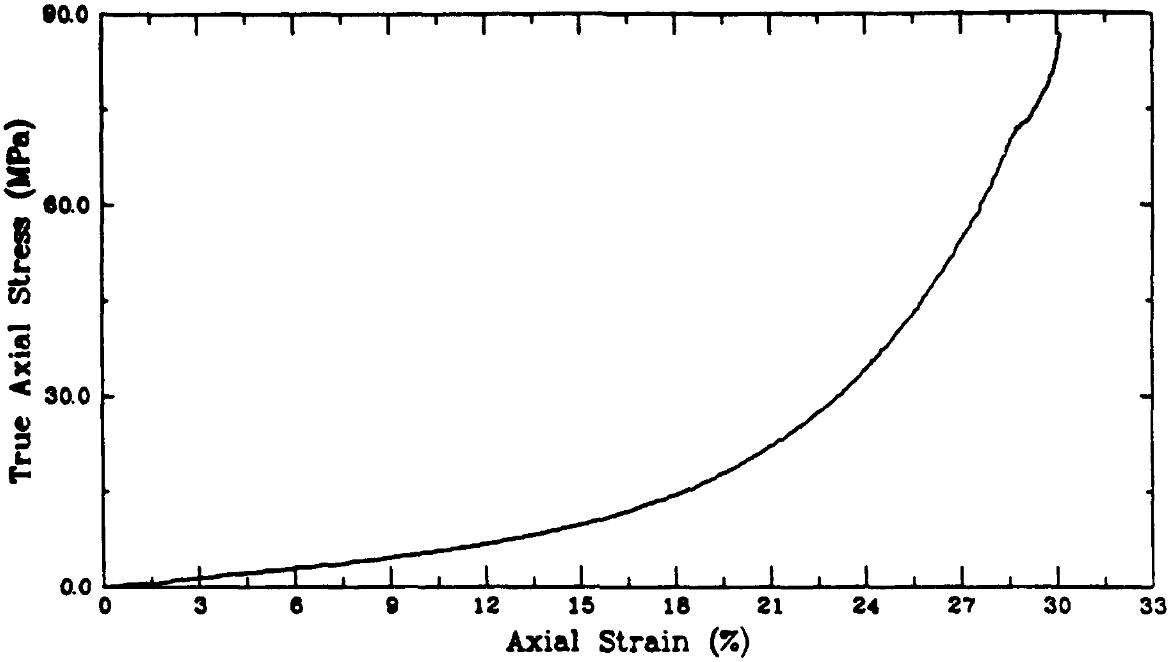

Denver Coal (F12A0)
Uniaxial Strain Test
True Axial Stress (MPa)
90.0
60.0
30.0
0.0
0
3
6
9
12
15
18
21
24
27
30
33
Axial Strain (%)

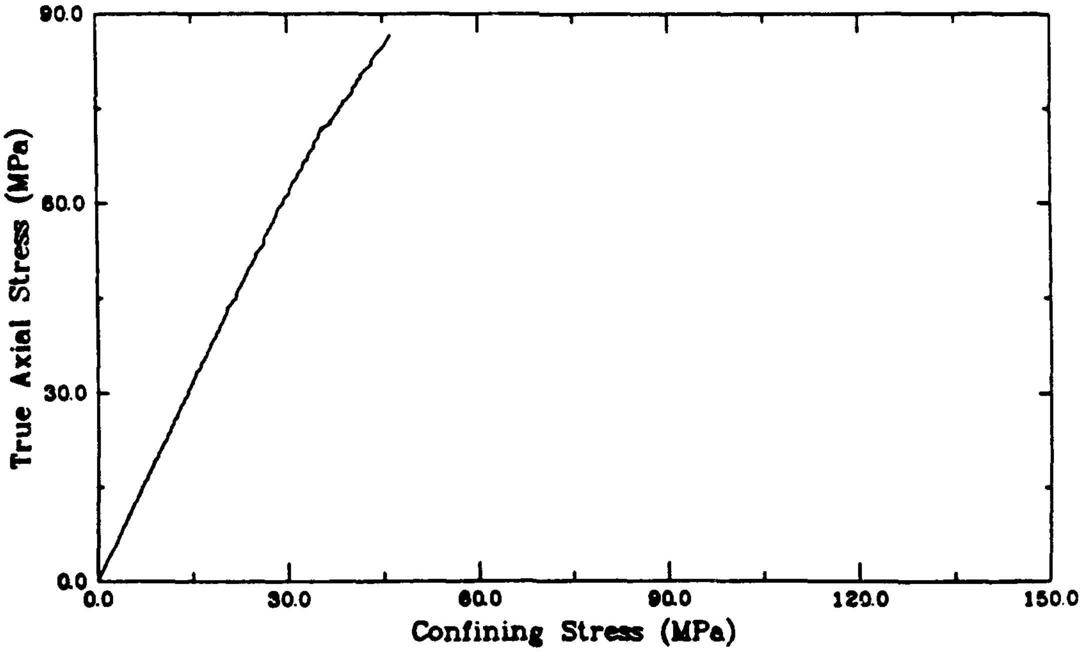

True Axial Stress (MPa)
90.0
60.0
30.0
0.0
0.0
30.0
60.0
90.0
120.0
150.0
Confining Stress (MPa)

Denver Coal (F13A0)

Description:	This is essentially a retest of F12A0 to see if a lower modulus might be obtained. Except for a slight difference in density, the specimen was identical to the F12A0 specimen.	
Test Specimen:	Dry Bulk Density (kg/m^3):	820
	Porosity:	.438
Test Results:	Constrained Modulus (MPa):	53
	Poisson's Ratio:	0.32
Model Ratios:	Density:	0.51
	Modulus:	0.141
	Length: (Scale Factor)	1/3.6
Comments:	The results were essentially the same as test F12A0.	

Denver Coal (F13A0)
Uniaxial Strain Test





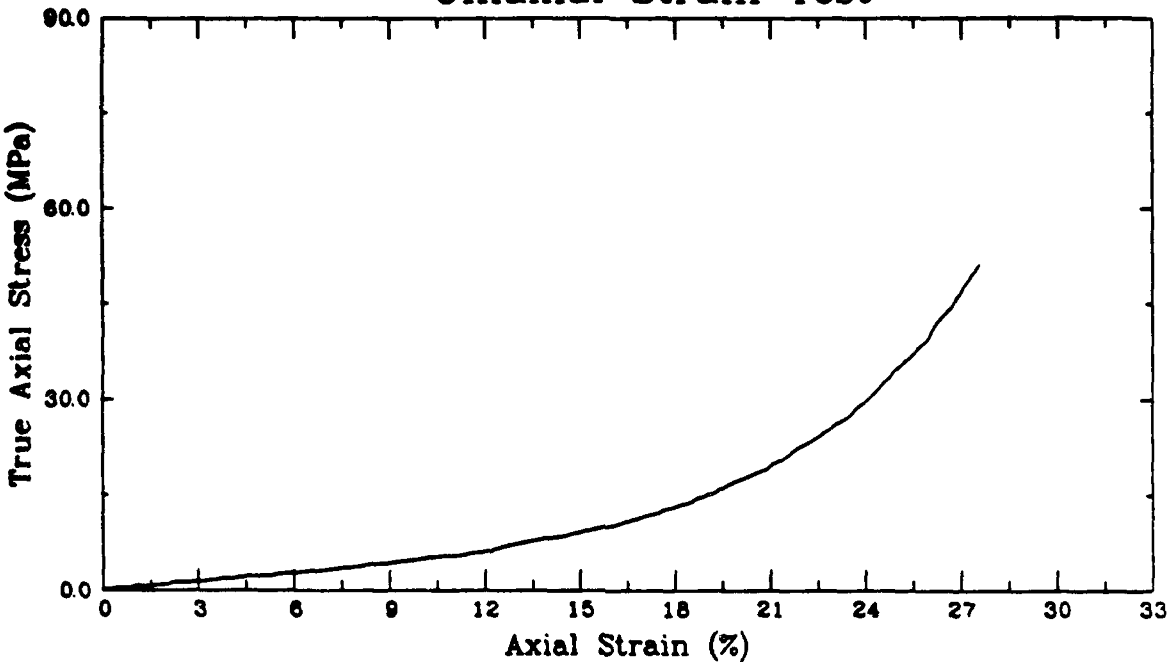
40% Denver Coal - 60% Lead (F14A0)

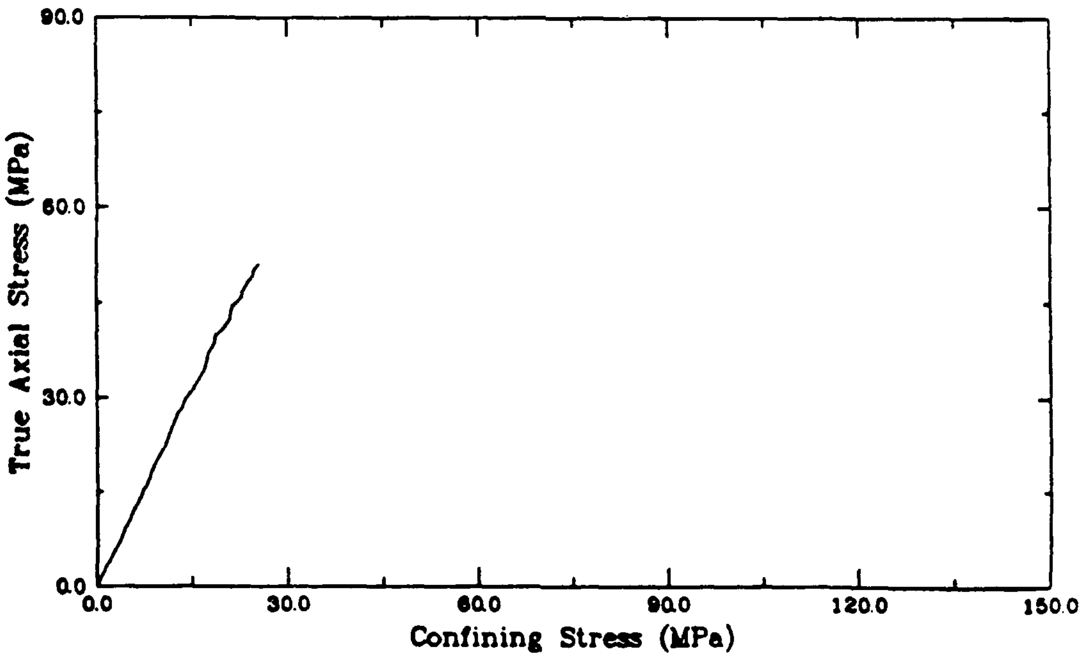
Description: The coal had the same sieve analysis as J9A0 and No. 7 lead shot was included in the indicated proportions.

Test Specimen:	Dry Bulk Density (kg/m^3):	1756
	Porosity:	0.426
Test Results:	Constrained Modulus (MPa):	47
	Poisson's Ratio:	0.32
Model Ratios:	Density:	1.09
	Modulus:	0.126
	Length: (Scale Factor)	1/8.7

Comments: The modulus was somewhat lower than the previous two tests on Denver coal, but still higher than that of bituminous coal. Thus, it was concluded that scale factors for Denver coal and its mixtures would not be as desirable as the bituminous coal.

40% Denver Coal - 60% Lead (F14A0)
Uniaxial Strain Test

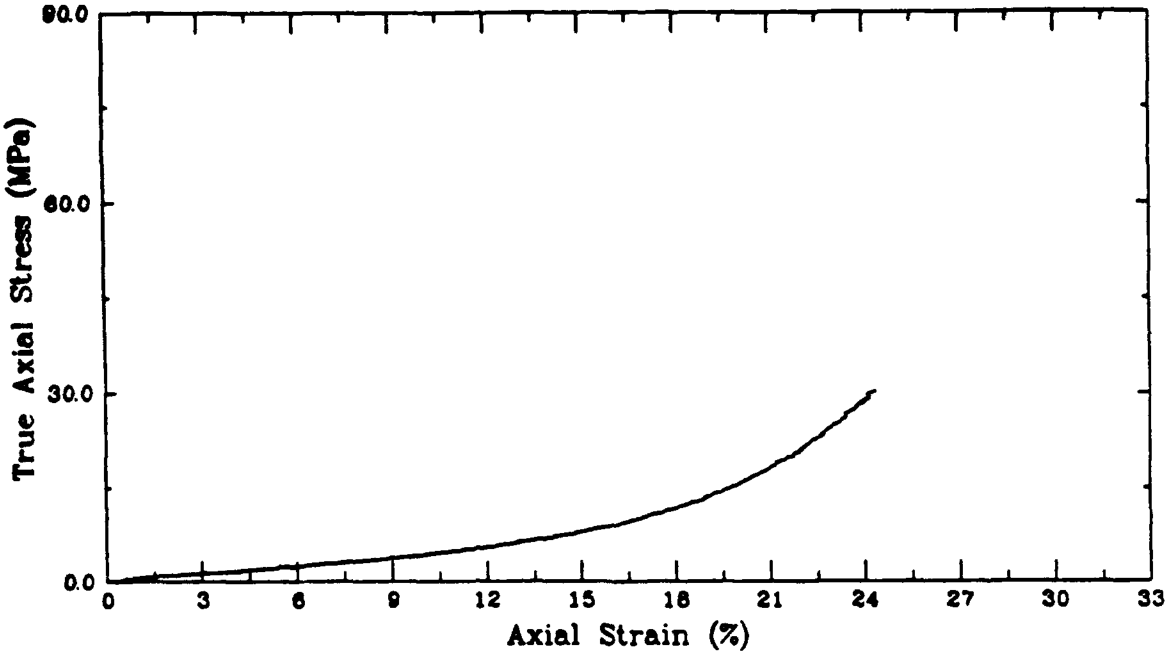


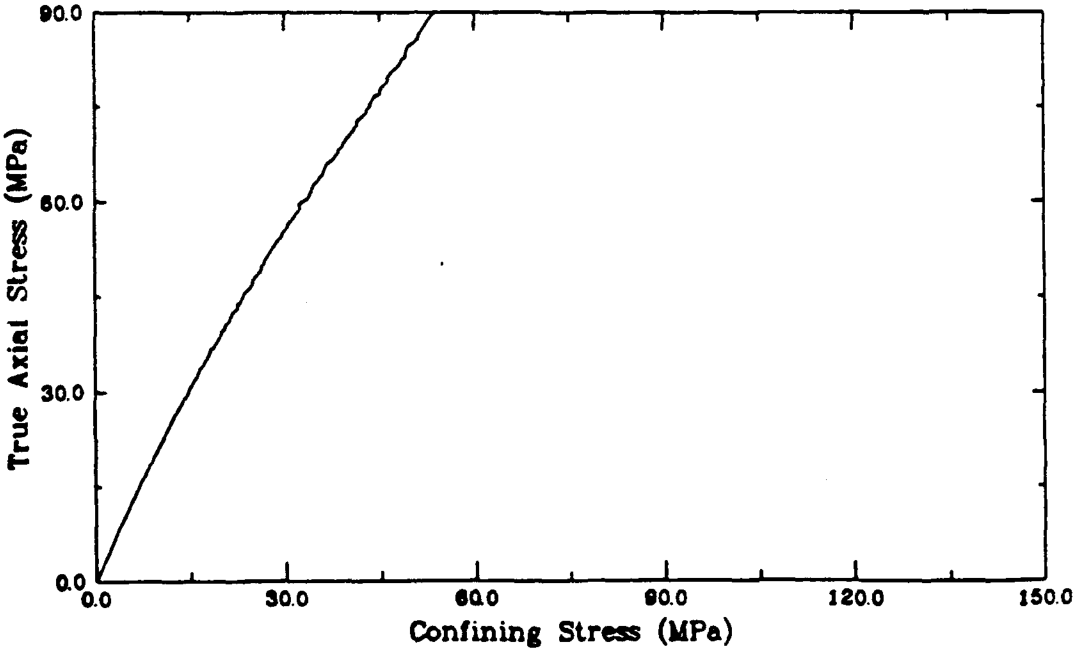


40% Bituminous Coal - 60% Lead (A12A0)

Description:	The coal used to construct this specimen was from the batch purchased for the first round of static POP tests, and free flow lead shot was used. The sieve analysis of the coal was the same as J9A0.	
Test Specimen:	Dry Bulk Density (kg/m^3):	1858
	Porosity:	0.343
Test Results:	Constrained Modulus (MPa):	38
	Poisson's Ratio:	0.31
Model Ratios:	Density:	1.15
	Modulus:	0.102
	Length: (Scale Factor)	1/11.3
Comments:	It was anticipated that the modulus would be closer to the value of 23-24 MPa measured in tests J3A0 and J5B0. It was judged that the higher modulus measured in this test was related to the lower porosity of this specimen relative to the earlier bituminous coal tests.	

40% Bituminous Coal - 60% Lead (A12A0)
Uniaxial Strain Test





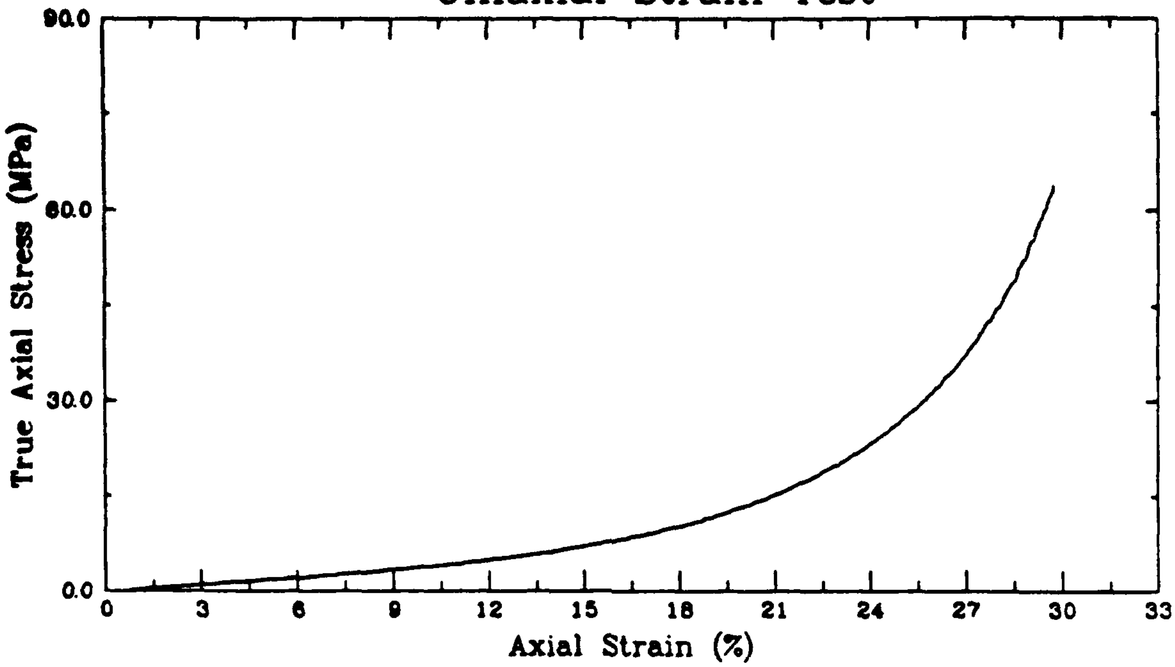
40% Bituminous Coal - 60% Lead (A16A0)

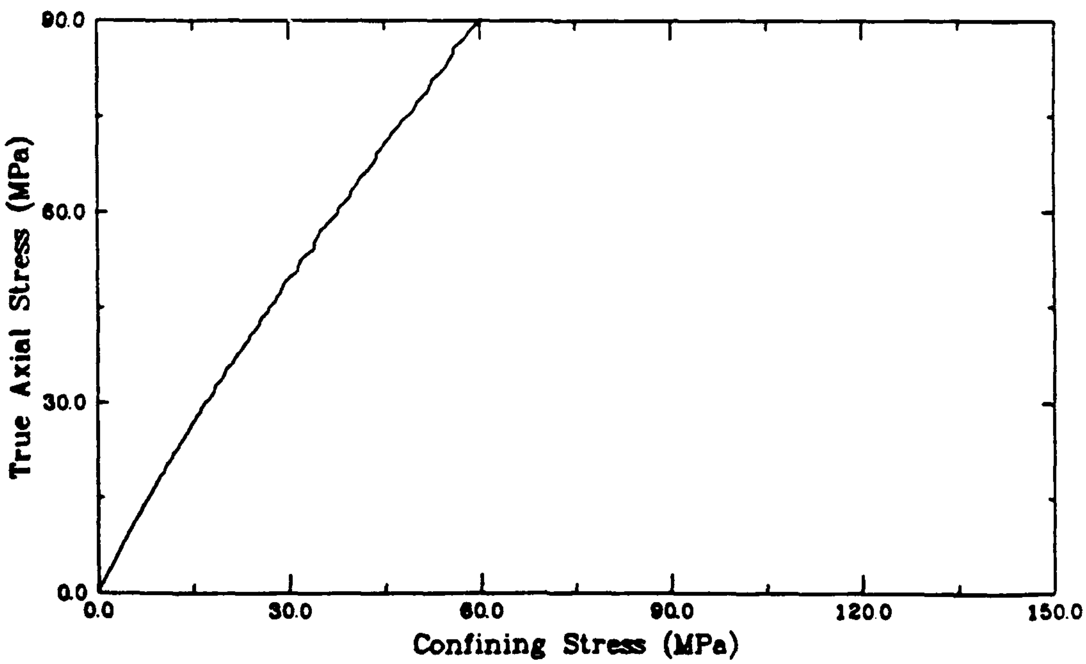
Description: In an effort to raise the porosity, and, it was hoped, lower the modulus, this specimen was prepared with coal having appoxoimately uniform grain sizes. All coal passed a No. 20 and was retained on a No. 50 sieve. The lead was free flow lead shot.

Test Specimen:	Dry Bulk Density (kg/m^3):	1786
	Porosity:	.368
Test Results:	Constrained Modulus (MPa):	39
	Poisson's Ratio:	0.35
Model Ratios:	Density:	1.11
	Modulus:	0.105
	Length: (Scale Factor)	1/10.6

Comments: The desired higher porosity was obtained, but it did not result in the lower modulus. The initial modulus was essentially the same as that measured in test A12A0. This, combined with the lower density, resulted in a slightly less desirable scale factor.

40% Bituminous Coal (20-50 Sieve Only) - 60% Lead (A16A0)
Uniaxial Strain Test

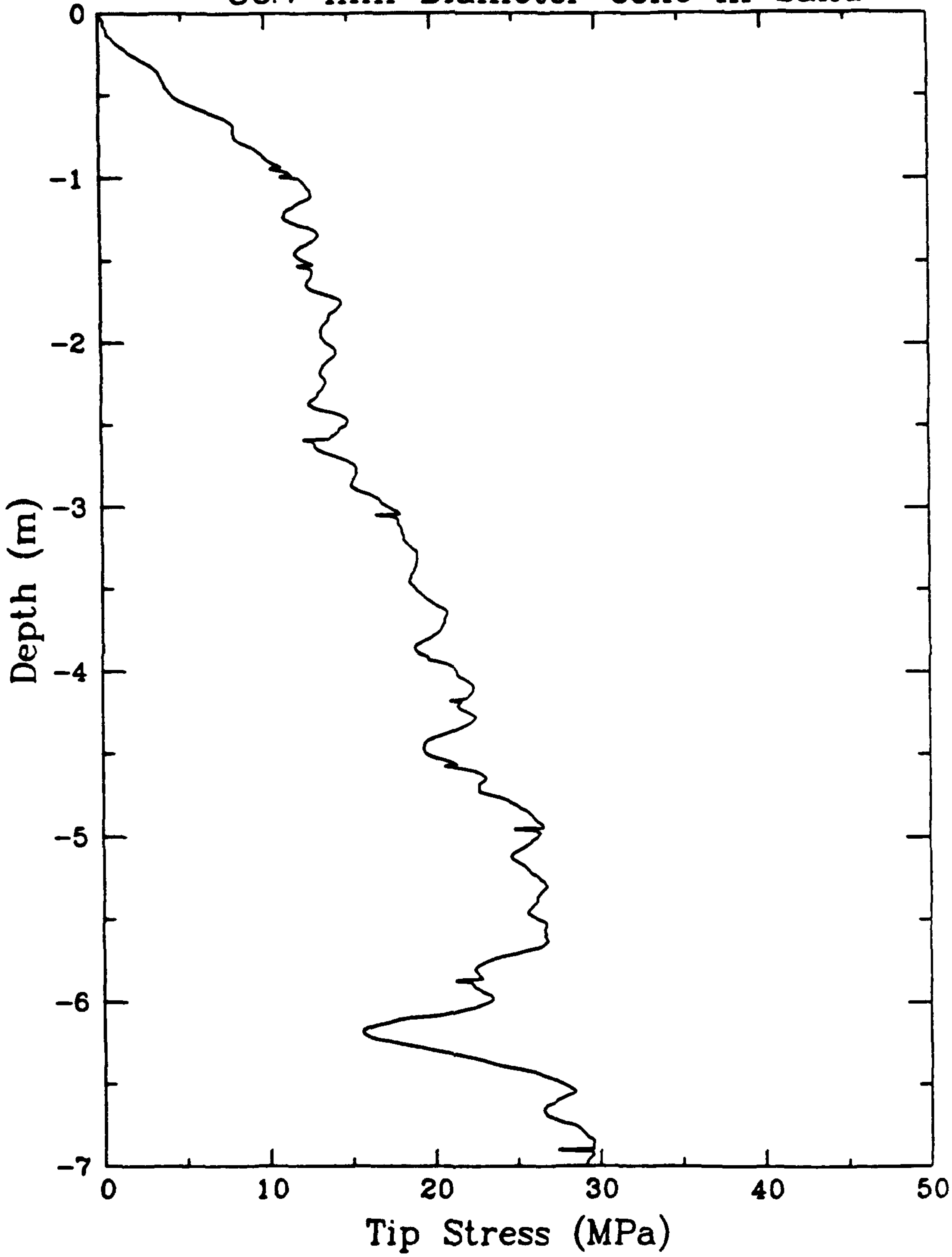


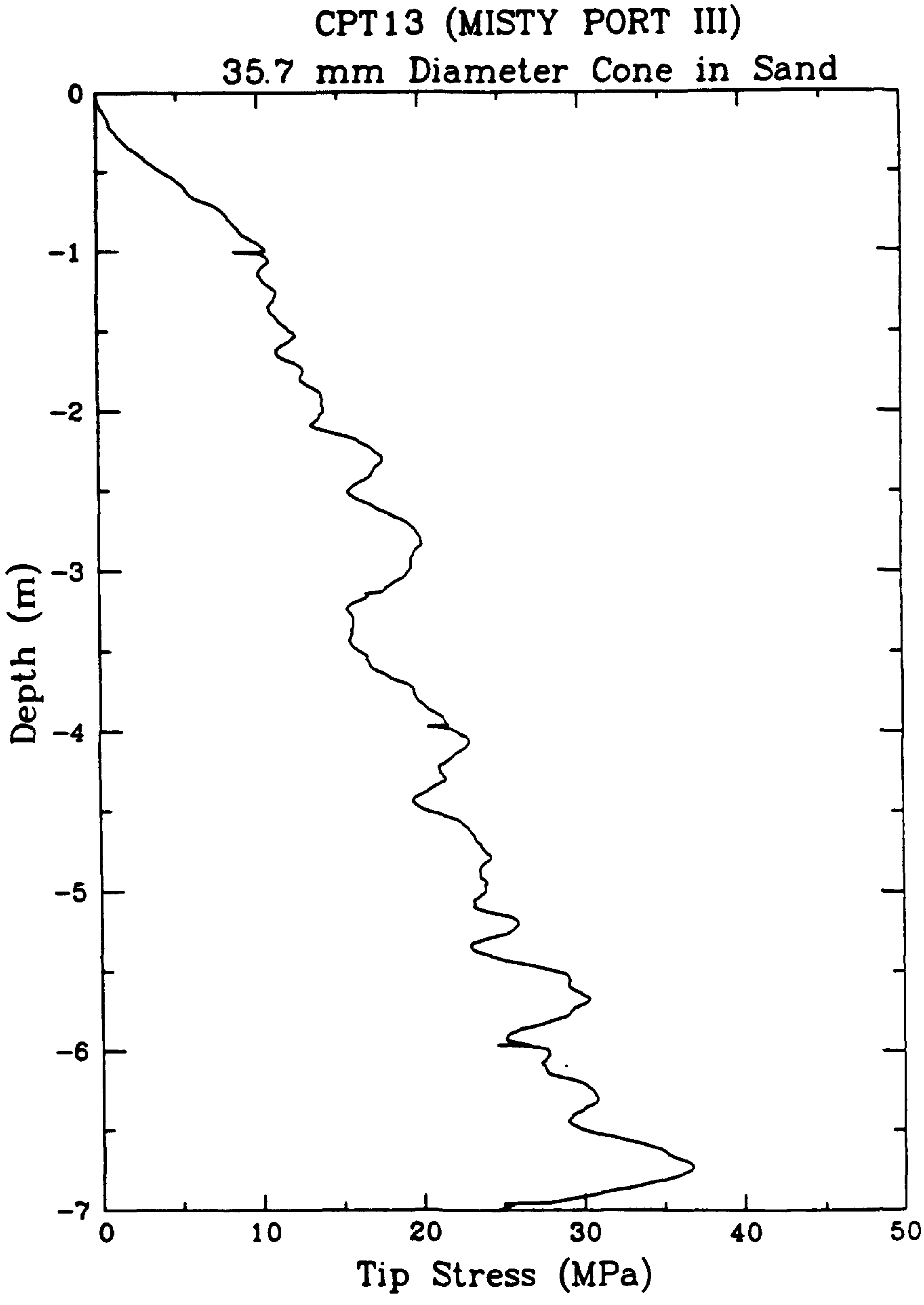


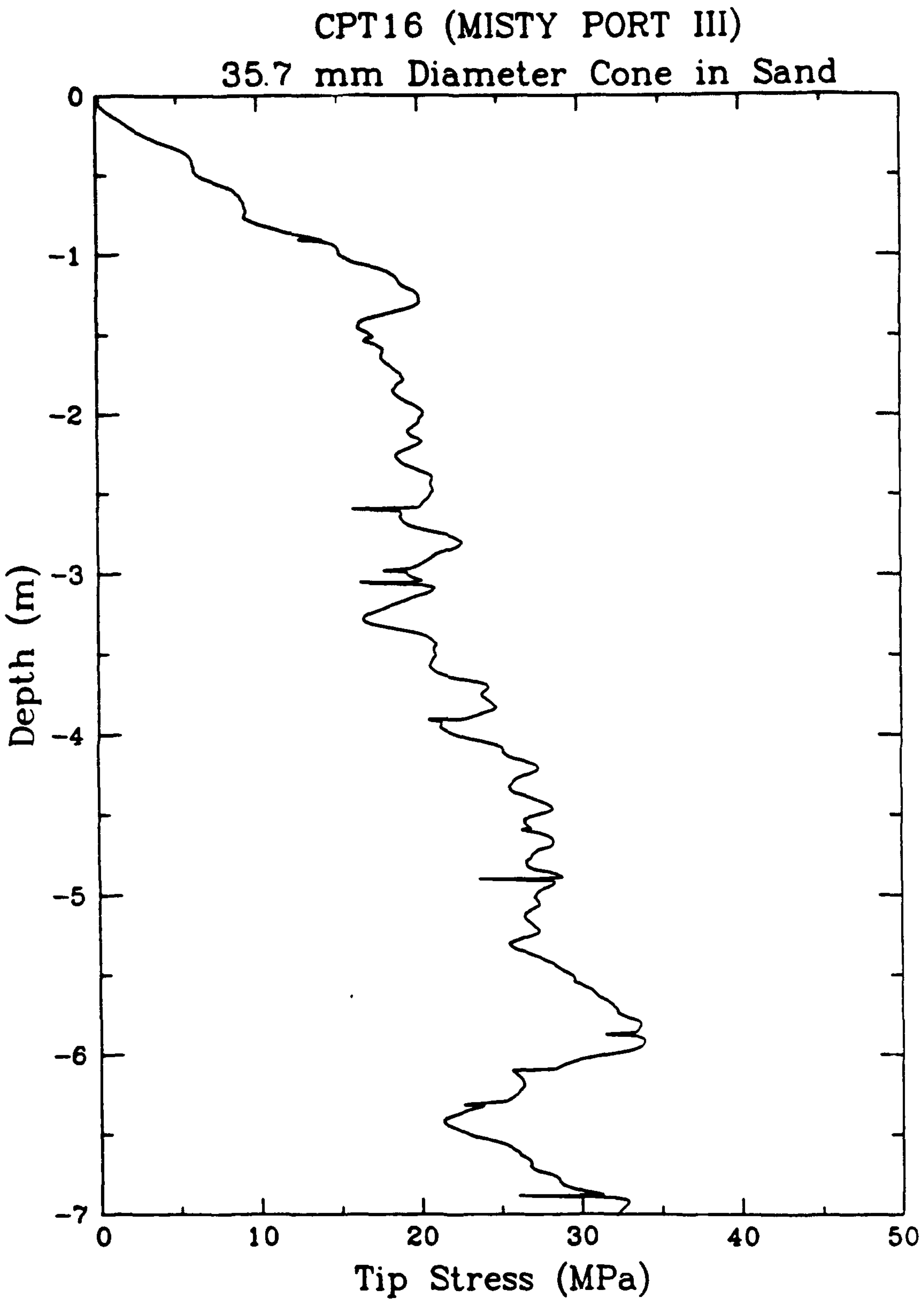
APPENDIX C

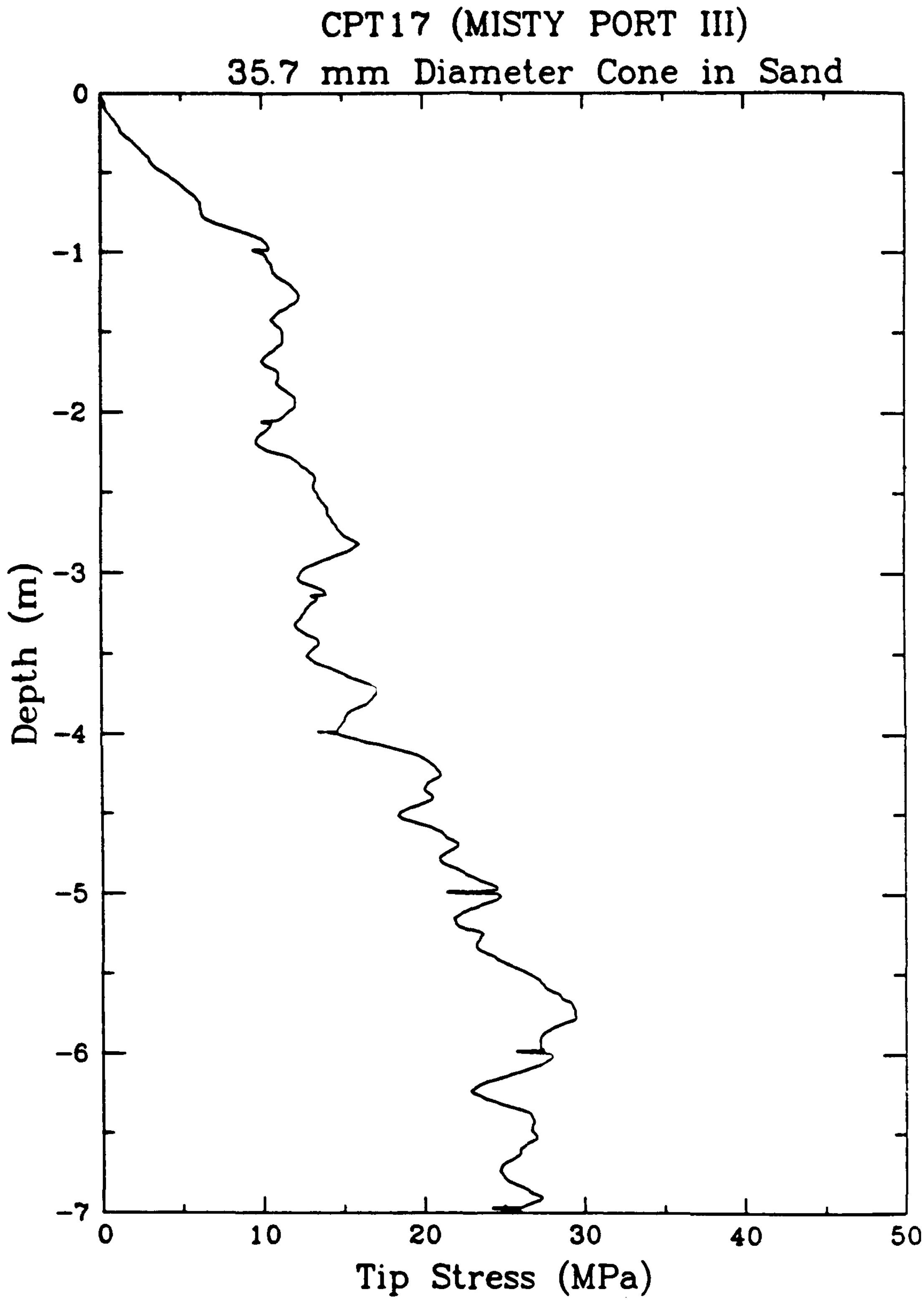
DATA FROM THE STATIC PROOF-OF-PRINCIPLE CONE PENETRATION TESTS

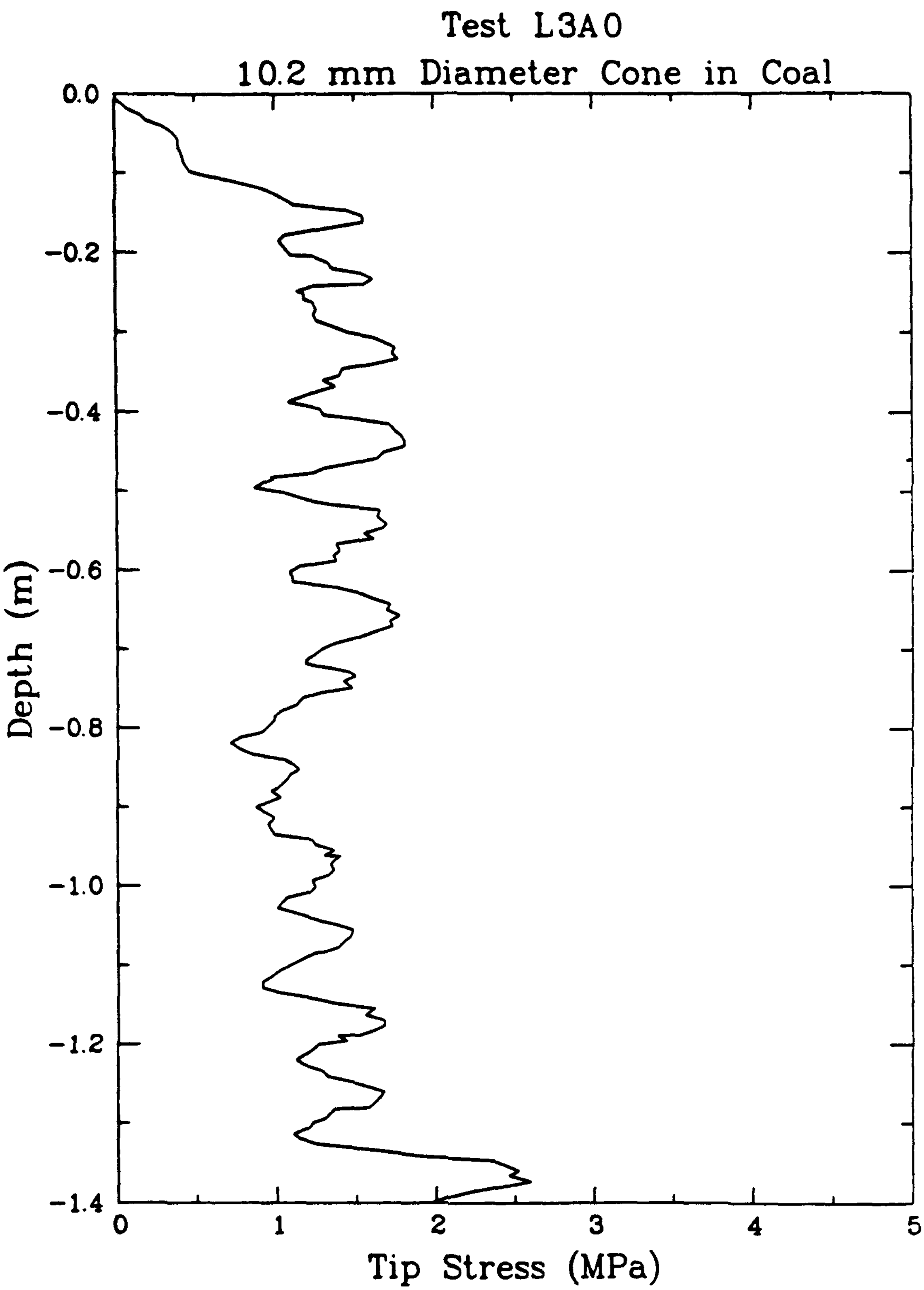
CPT03 (MISTY PORT III)
35.7 mm Diameter Cone in Sand




CPT13 (MISTY PORT III)
35.7 mm Diameter Cone in Sand
Depth (m)
0
-1
-2
-3
-4
-5
-6
-7
0
10
20
30
40
50
Tip Stress (MPa)


CPT16 (MISTY PORT III)
35.7 mm Diameter Cone in Sand
Depth (m)
0
-1
-2
-3
-4
-5
-6
-7
0
10
20
30
40
50
Tip Stress (MPa)

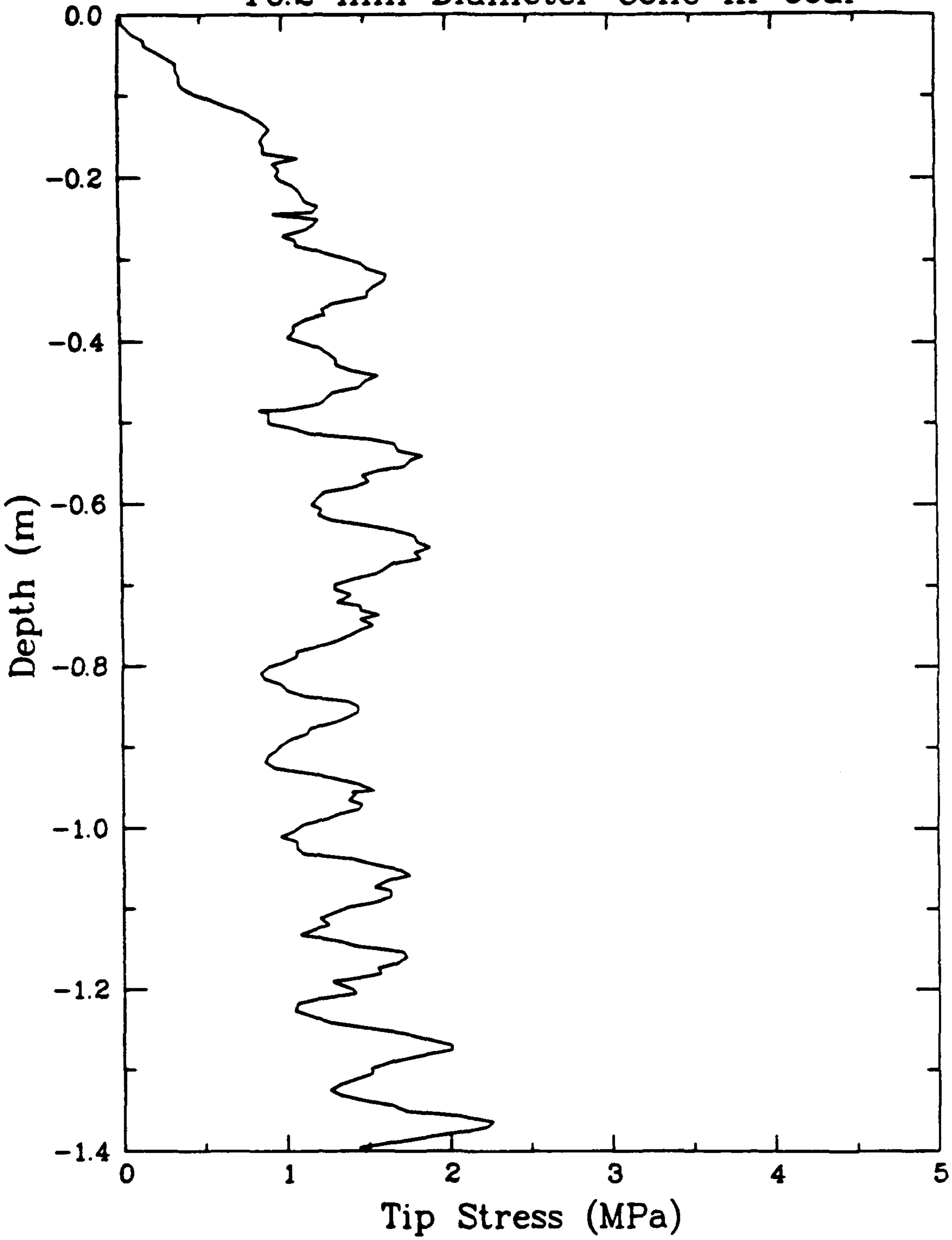

CPT17 (MISTY PORT III)
35.7 mm Diameter Cone in Sand
Depth (m)
0
-1
-2
-3
-4
-5
-6
-7
0
10
20
30
40
50
Tip Stress (MPa)

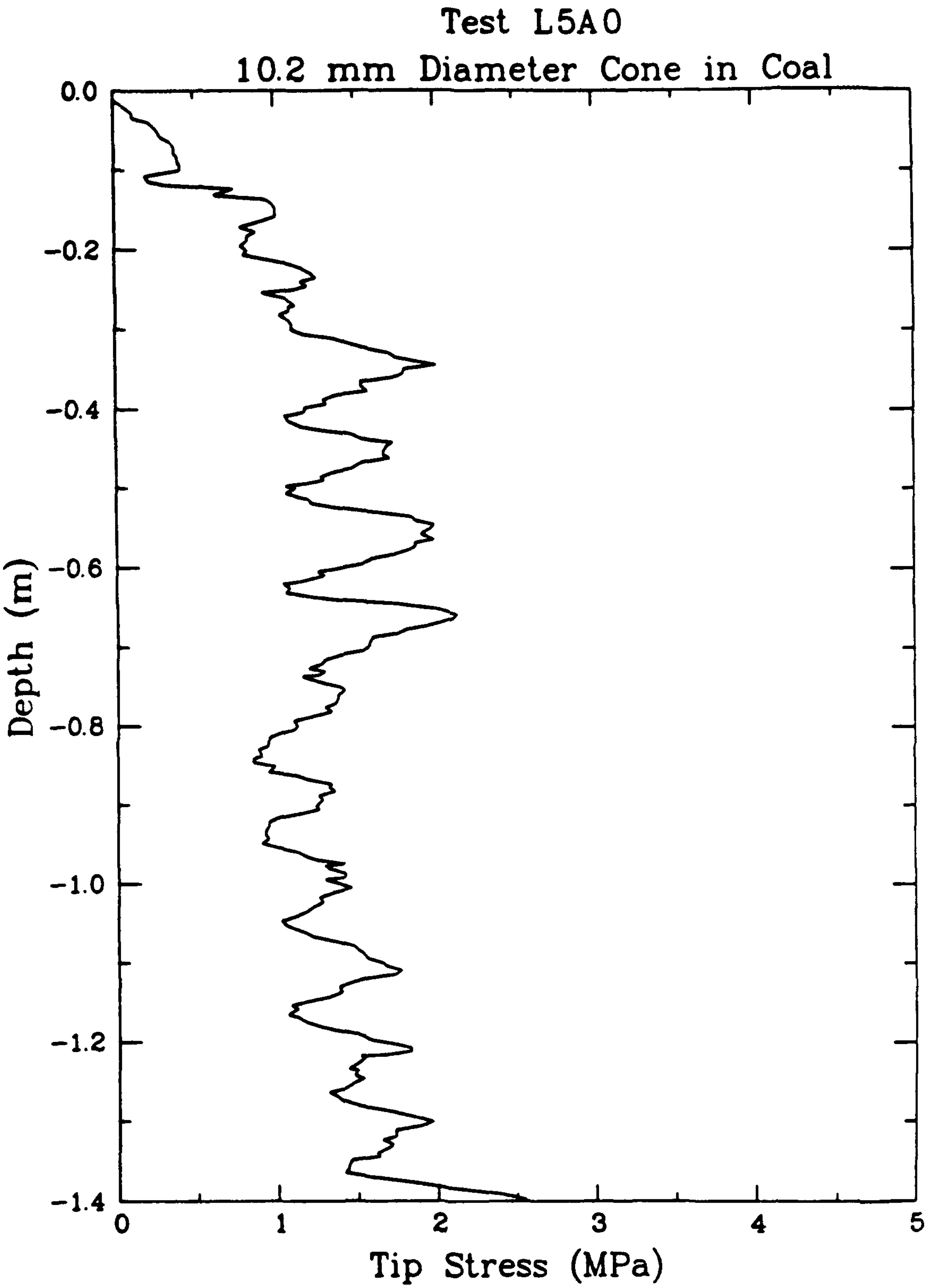


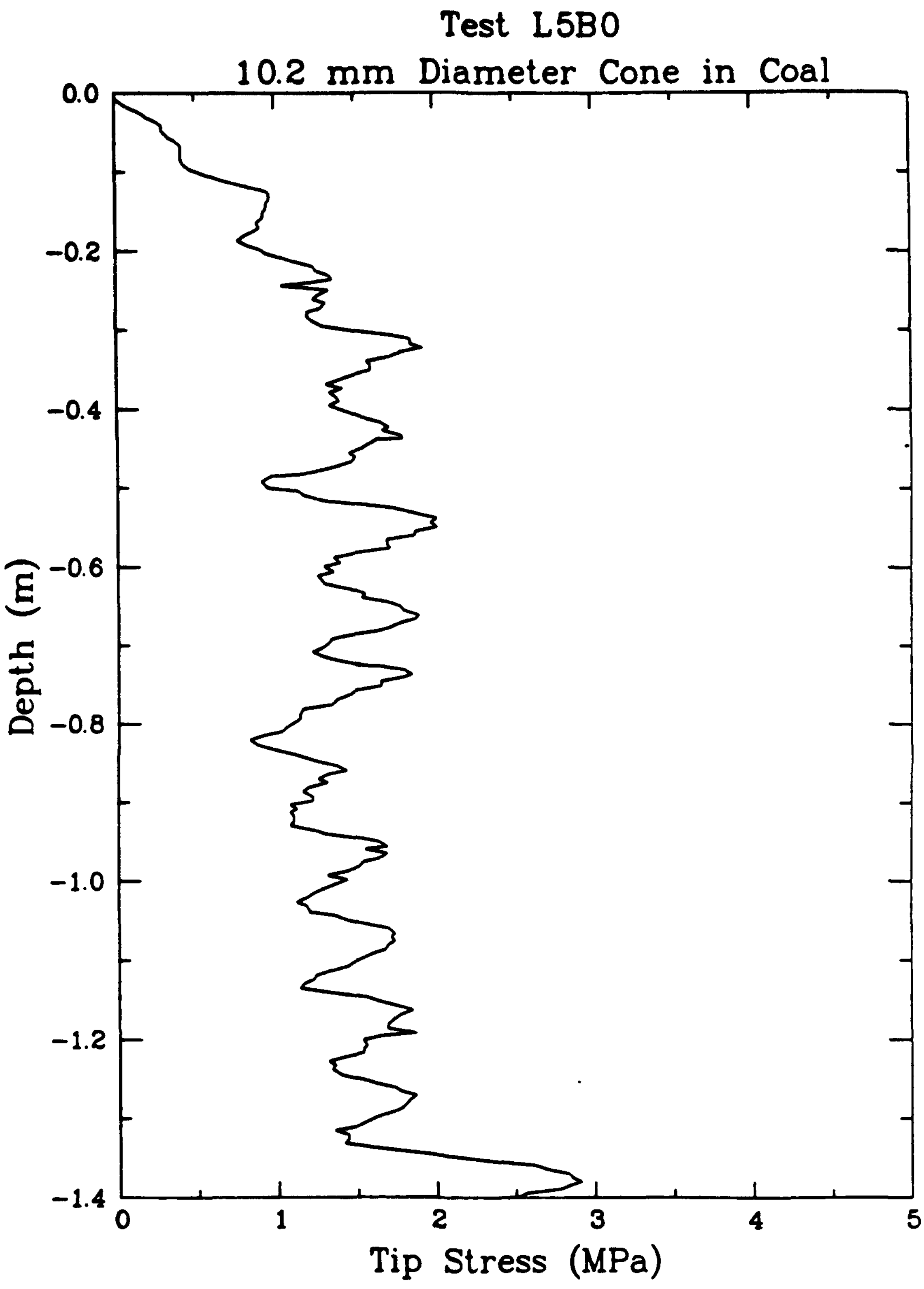
Test L3A0
10.2 mm Diameter Cone in Coal
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-1.2
-1.4
Depth (m)
0
1
2
3
4
5
Tip Stress (MPa)

Test L3B0

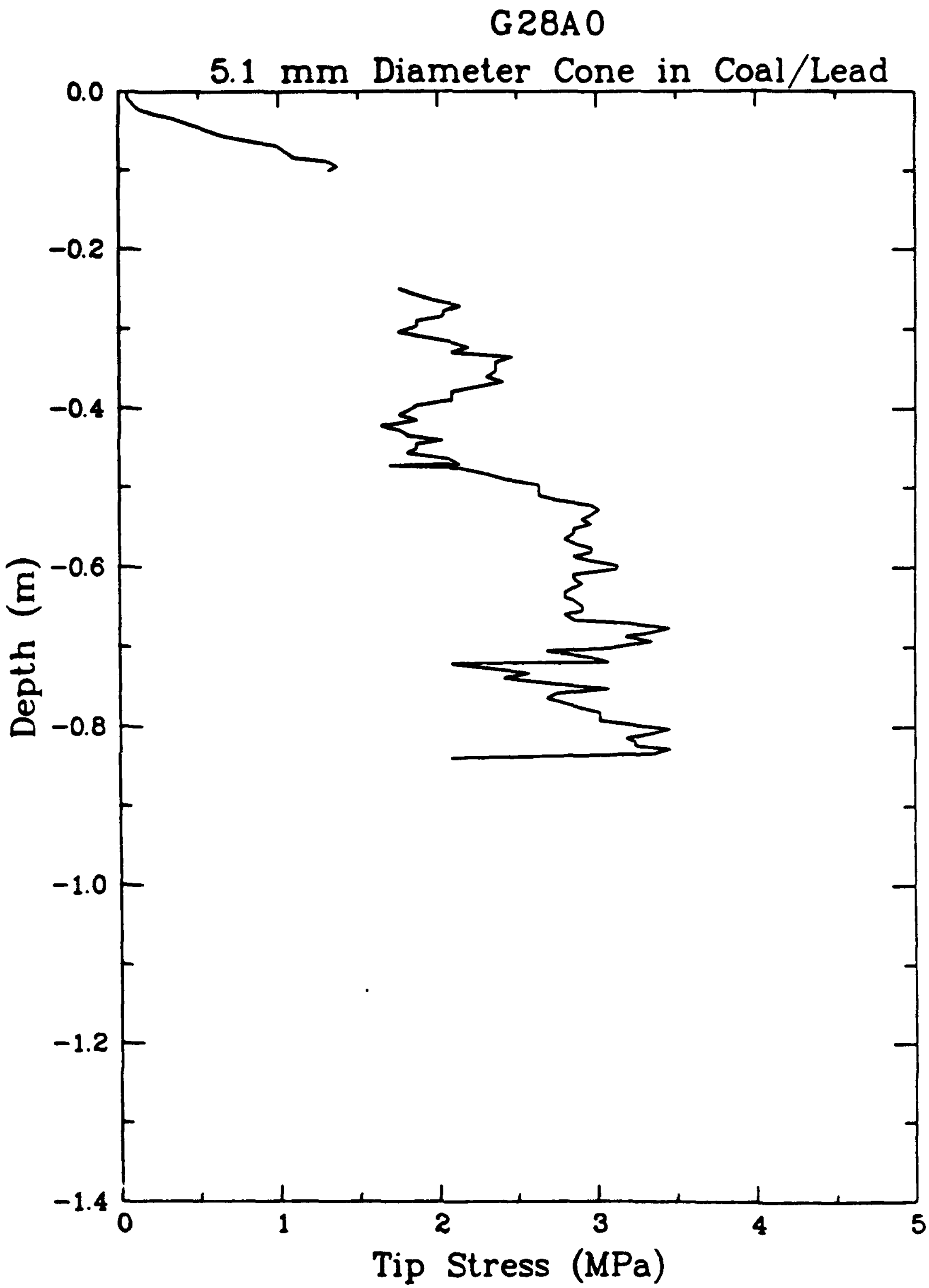
10.2 mm Diameter Cone in Coal

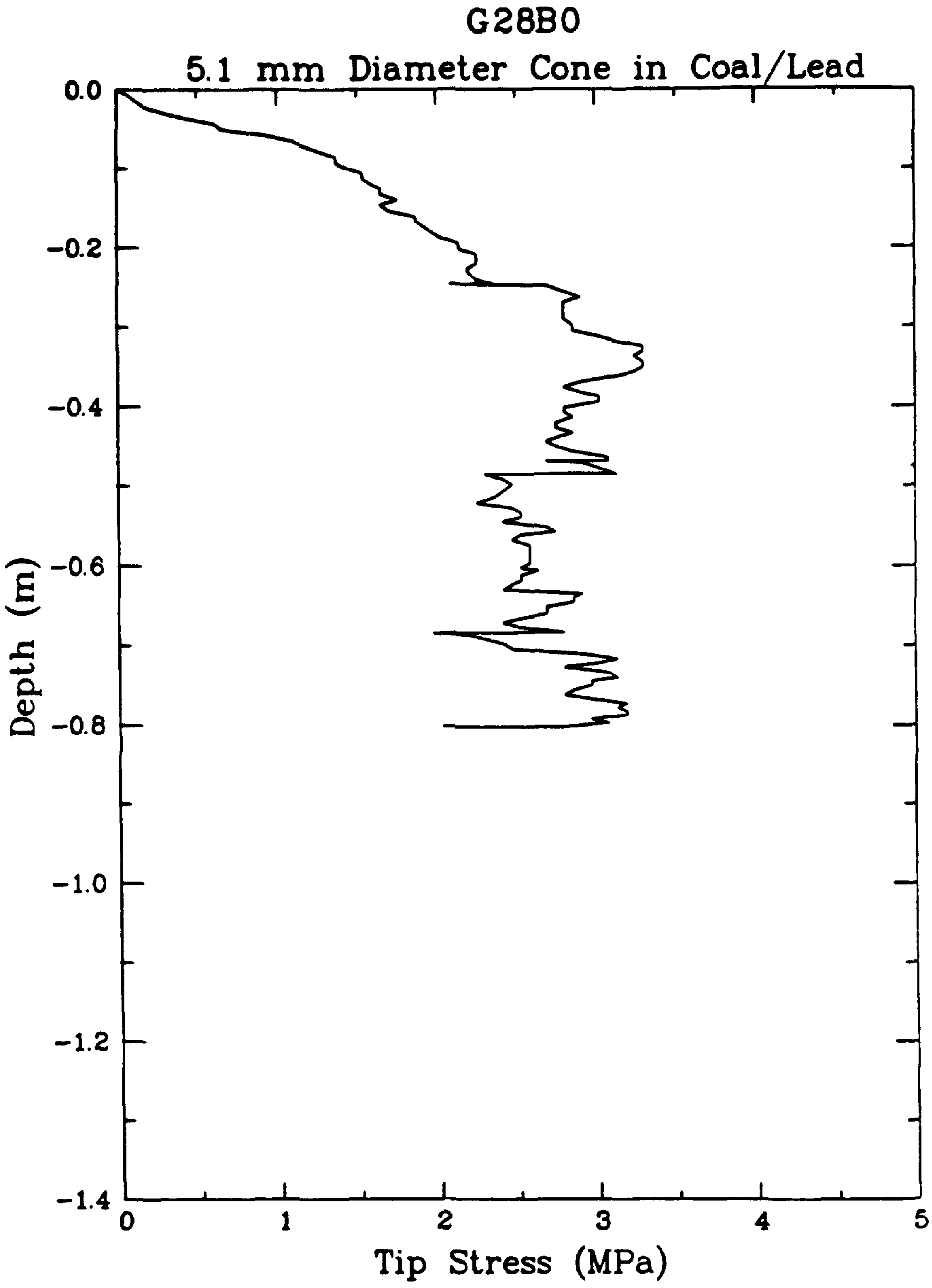


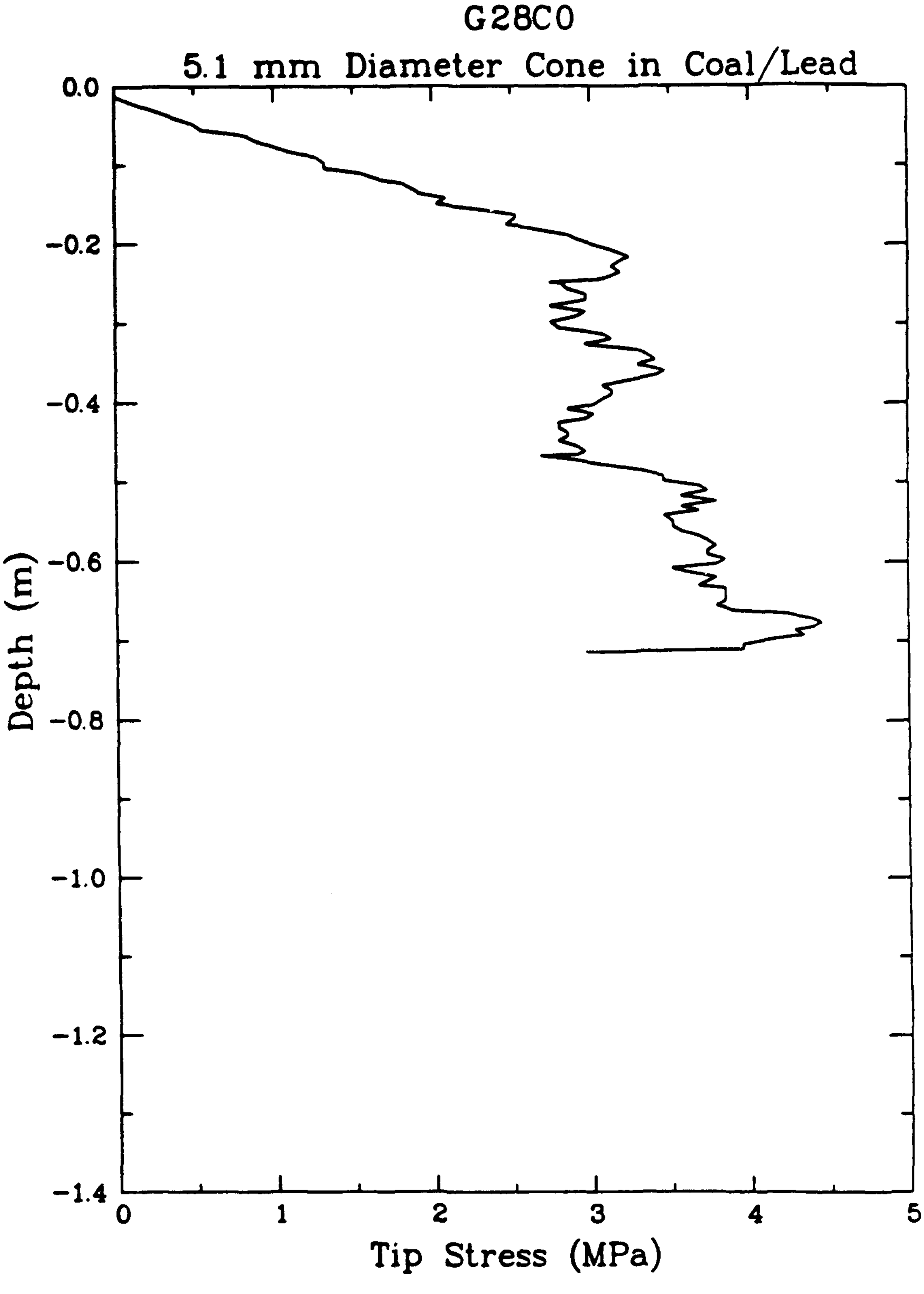

Test L5A0
10.2 mm Diameter Cone in Coal
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-1.2
-1.4
Depth (m)
0
1
2
3
4
5
Tip Stress (MPa)

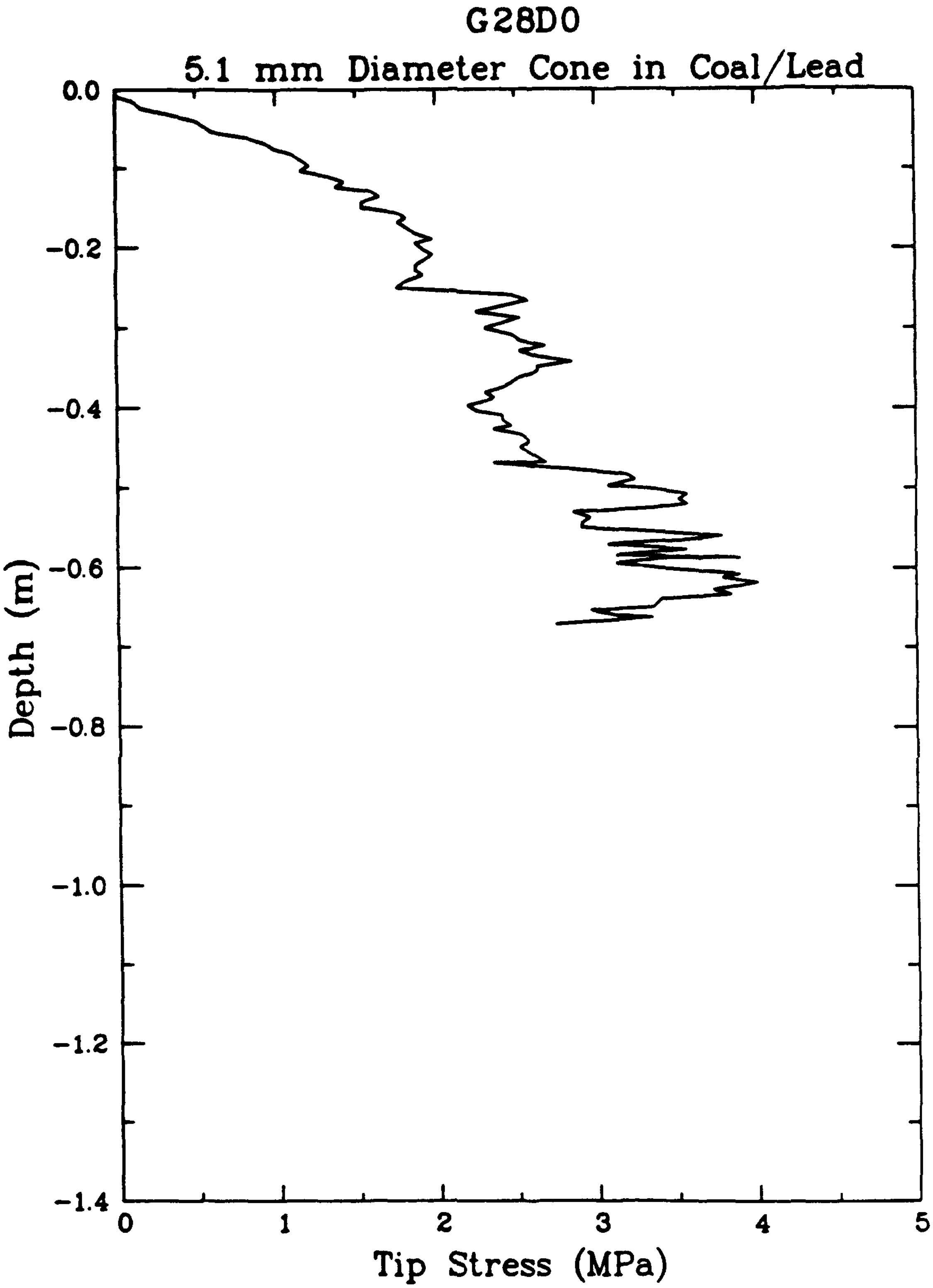


Test L5B0
10.2 mm Diameter Cone in Coal
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-1.2
-1.4
Depth (m)
0
1
2
3
4
5
Tip Stress (MPa)


G28A0
5.1 mm Diameter Cone in Coal/Lead
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-1.2
-1.4
Depth (m)
0
1
2
3
4
5
Tip Stress (MPa)


G28B0
5.1 mm Diameter Cone in Coal/Lead
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-1.2
-1.4
Depth (m)
0
1
2
3
4
5
Tip Stress (MPa)


G28C0
5.1 mm Diameter Cone in Coal/Lead
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-1.2
-1.4
Depth (m)
0
1
2
3
4
5
Tip Stress (MPa)


G28D0
5.1 mm Diameter Cone in Coal/Lead
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-1.2
-1.4
Depth (m)
0
1
2
3
4
5
Tip Stress (MPa)

APPENDIX D

DYNAMIC CYLINDER TESTS

MEASUREMENT LISTS
TEST LAYOUTS
PREDICTED VALUES
TEST BED DENSITY MEASUREMENTS

Measurement List

1/10 Replica Scale (Free Field)

Meas. No.	Gen.	x**	y	z	Sens Axis	Pred Peak	Make	Model	Range
3301	ff	.29	.06	0	r	70kg	Endevco	7270A*	140k
3302	ff	.44	.09	0	r	11kg	Endevco	7270A	50k
3303	ff	0	.3	0	+y	70kg	Endevco	7270A	140k
3304	ff	0	-.3	0	-y	70kg	Endevco	7270A	100k
3305	ff	.585	0	0	x	7.0kg	Endevco	7270A	50k
3502	ff	.32	-.19	0	r	17.4MPa	Kulite	LQV-080-UH	27M
3503	ff	.45	-.26	0	r	7.4MPa	Kulite	LQV-080-UH	27M
3504	ff	.585	-.34	0	r	4.1MPa	Kulite	LQV-080-UH	27M

1/10 Replica Scale (Structure)

Meas. No.	Gen.	r**	d	z	Sens Axis	Pred Peak	Make	Model	Range
3401	s	.125	349	0	r	3.6kg	Endevco	2262C	5k
3402	s	.125	349	0	t	3.6kg	Endevco	2262C	5k
3403	s	.125	79	0	t	3.6kg	Endevco	2262C	5k
3404	s	.125	79	0	r	3.6kg	Endevco	2262C	10k
3405	s	.125	169	0	t	3.6kg	Endevco	2262C	10k
3406	s	.125	169	0	r	3.6kg	Endevco	2262C	10k
3407	s	.125	259	0	r	7.0kg	Endevco	2262C	10k
3408	s	.125	259	0	t	7.0kg	Endevco	2262C	10k

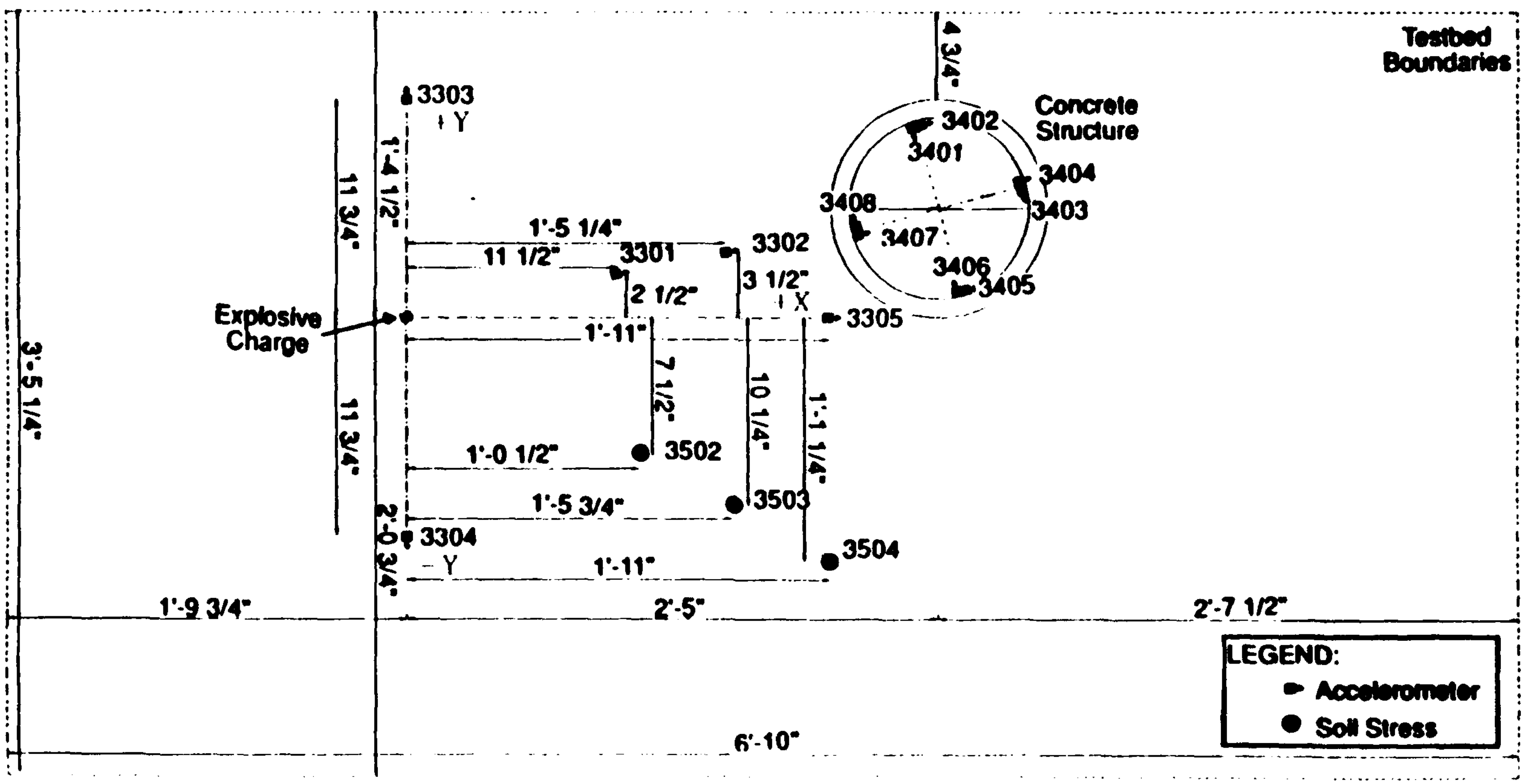
Legend

x = meters
y = meters
z = meters
r = meters or radial
d = degrees
s = structural
ff = free field
t = tangential

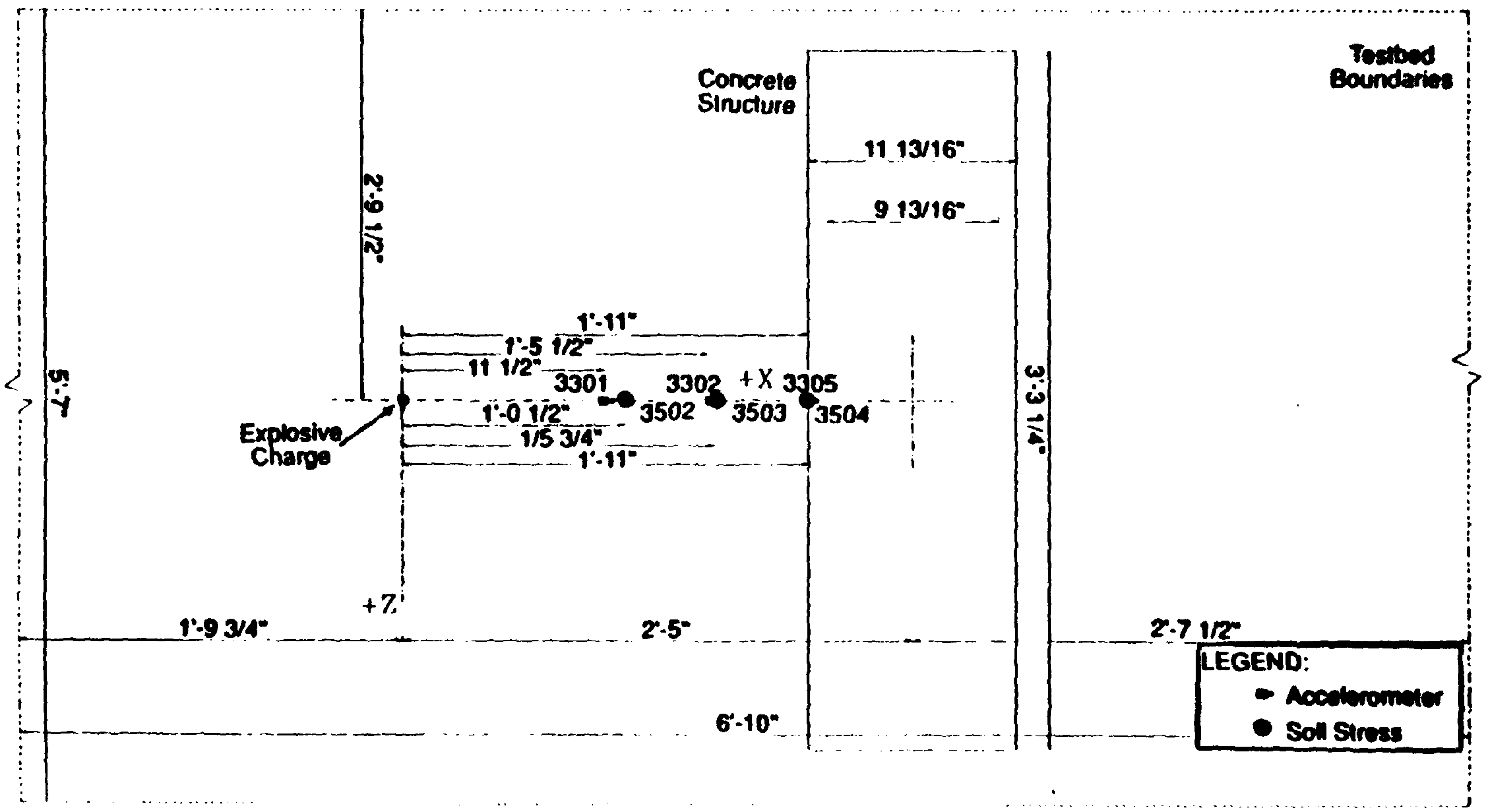
* Note: The 7270A may be substituted with the 7270 or 2264A as available.

** Note: Coordinate system originates at center of charge for free field gages and at center point of structure for structure gages.

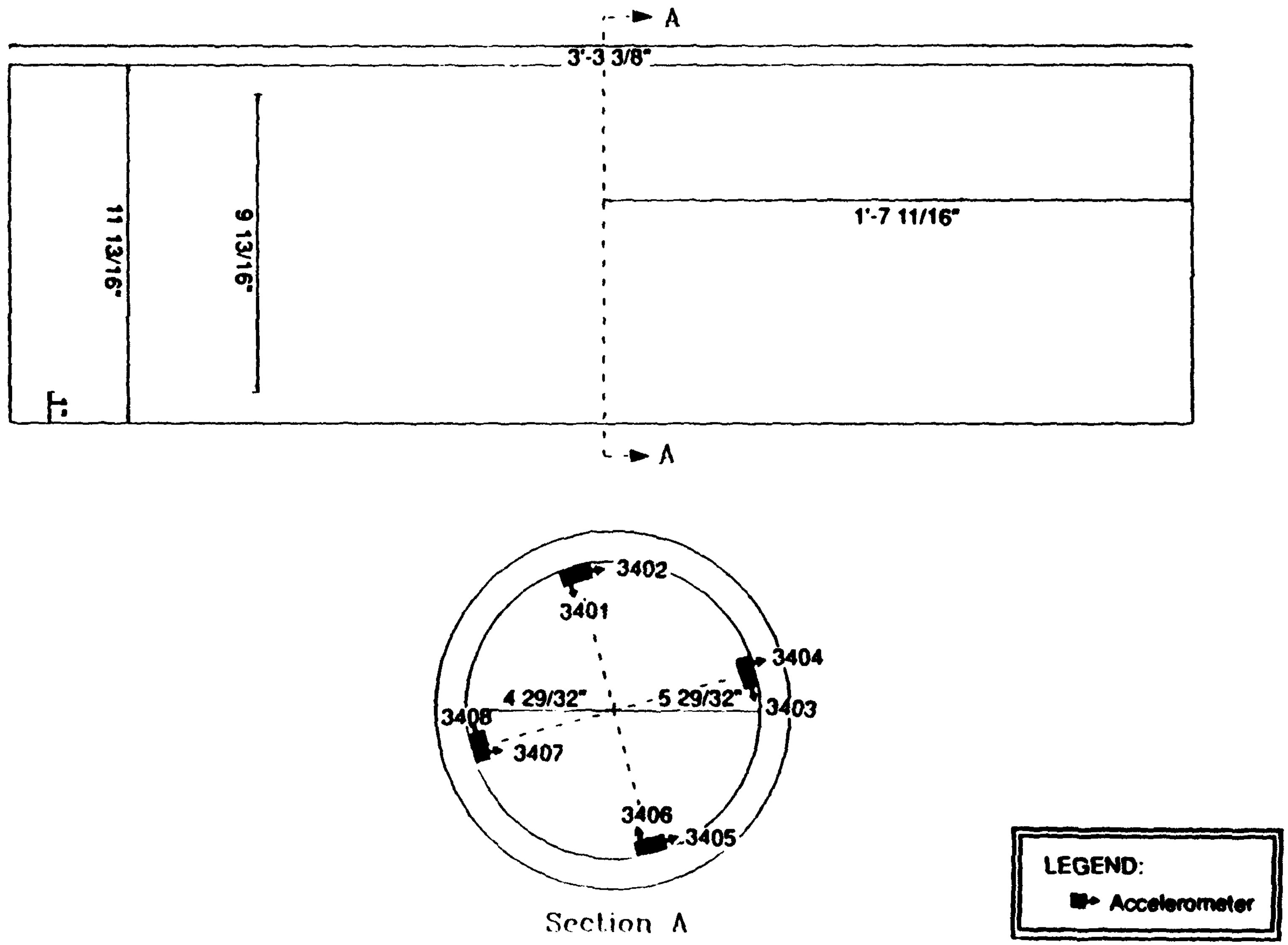
1/10 Replica Scale Testbed (elevation view)



1/10 Replica Scale Testbed (plan view)



1/10 Scale Replica Structure



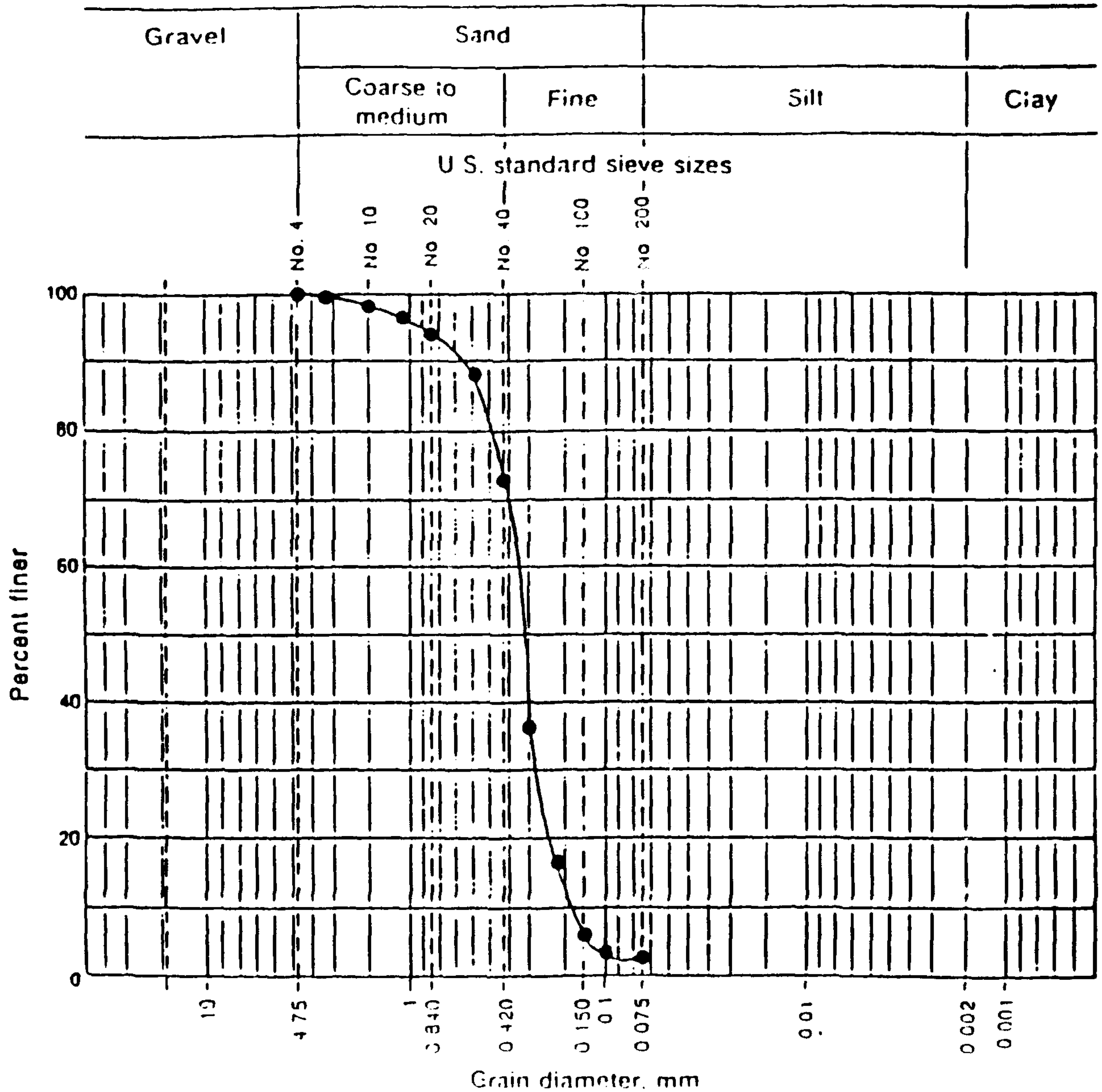
Pretest Predictions

1/10th Replica Scale Experiment

	LUGS METHODOLOGY				SAMSON2 FE CALCULATION		
Range (m)	v_p (m/s)	A_p* (g's)	A_p** (g's)	σ_p (MPa)	v_p (m/s)	A_p (g's)	σ_p (MPa)
.225	87.2	586,000	58,600	85.5	67.5	244,000	121.0
.3	54.5	265,000	26,500	44.2	34.9	69,800	31.9
.375	37.6	147,000	14,700	27.2	20.8	25,200	17.4
.45	27.6	92,200	9,220	18.6	14.0	11,100	10.8
.525	21.1	62,700	6,270	13.5	9.61	5,250	7.40
.60	16.7	45,500	4,550	10.3	7.24	3,530	5.38
.675	--	--	--	--	--	--	4.10
.75	11.2	27,000	2,700	6.6	4.42	1,790	3.17

* Assumes accelerometer canister length of .01 m. Longer canister length reduces peak estimate proportionately.

** Assumes accelerometer canister of 0.1m length.



Target Sand Grain Size Distribution.

Sand Densities for 1/10th Replica-Scale Tests

Measurements in Pounds Per Cubic Foot

	Top middle	Top Left	Top Right	Bottom Left	Bottom Right
Bottom	103.				99.9
Middle	93.9	98.7	95.9	95.96	100.0
Top		97.5	100.0	97.5	96.3

Me asurement List

1/5 Froude Scale (Free Field)

Meas. No.	Gen.	x**	y	z	Sens Axis	Pred Peak	Make	Model	Range
2301	ff	.59	.12	0	r	6.9kg	Endevco	7270A*	10k
2302	ff	.88	.18	0	r	1.1kg	Endevco	7270A	2k
2303	ff	0	.6	0	+y	6.9kg	Endevco	7270A	10k
2304	ff	0	-.6	0	-y	6.9kg	Endevco	7270A	10k
2305	ff	1.17	0	0	x	706g	Endevco	7270A	5k
2501	ff	.39	-.23	0	r	12.1MPa	Kulite	LQV-080-UH	27M
2502	ff	.65	-.38	0	r	1.74MPa	Kulite	LQV-080-UH	27M
2503	ff	.91	-.53	0	r	0.74MPa	Kulite	LQV-080-UH	1.4M

1/5 Froude Scale (Structure)

No.	Gen.	r**	d	z	Axis	Peak	Make	Model	Range
2401	s	.25	349	0	r	360g	Endevco	2262C	1k
2402	s	.25	349	0	t	360g	Endevco	2262C	1k
2403	s	.25	79	0	t	360g	Endevco	2262C	1k
2404	s	.25	79	0	r	360g	Endevco	2262C	1k
2405	s	.25	169	0	t	360g	Endevco	2262C	1k
2406	s	.25	169	0	r	360g	Endevco	2262C	1k
2407	s	.25	259	0	r	706g	Endevco	2262C	1k
2408	s	.25	259	0	t	706g	Endevco	2262C	1k

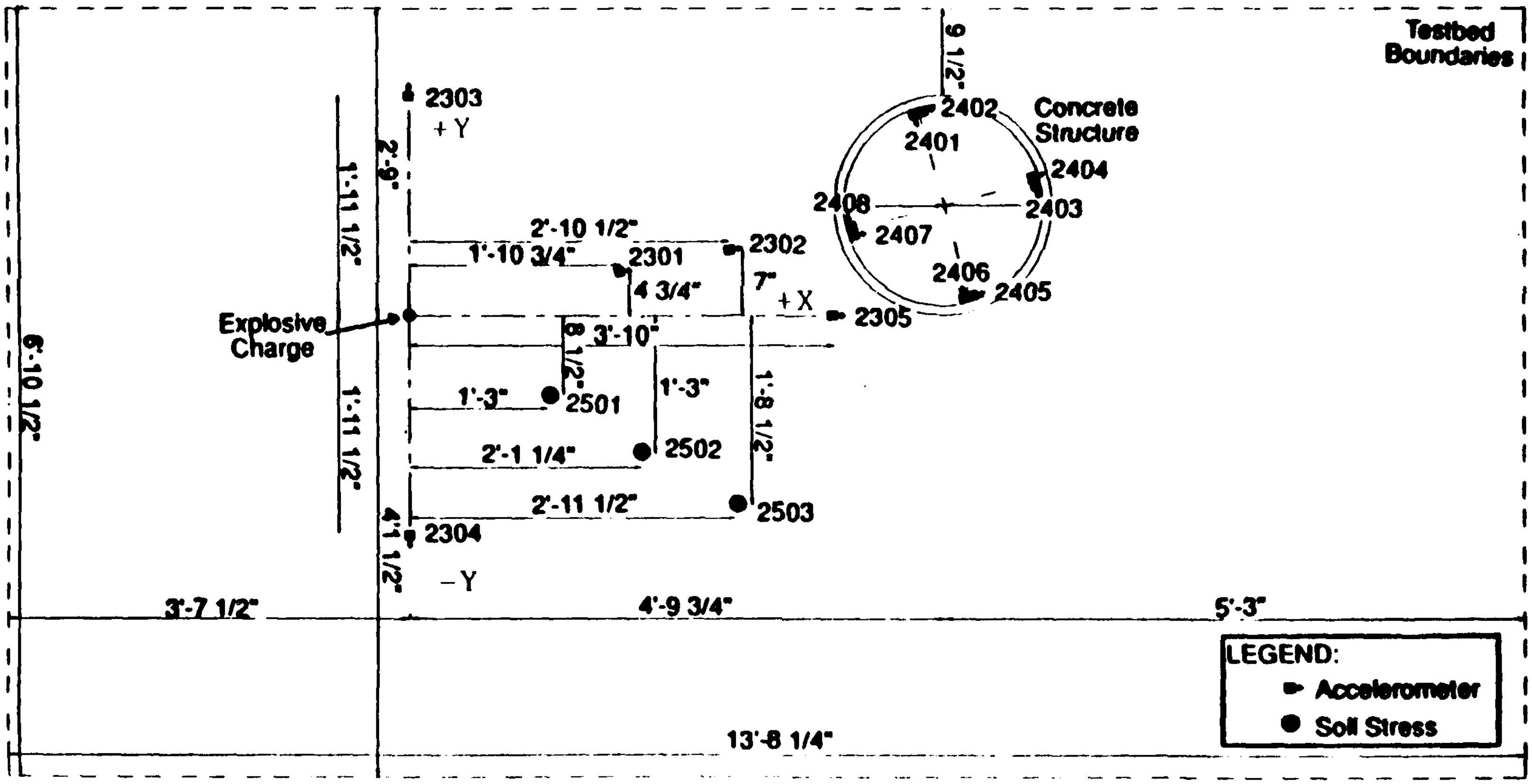
Legend

x = meters
y = meters
z = meters
r = meters or radial
d = degrees
s = structural
ff = free field
t = tangential

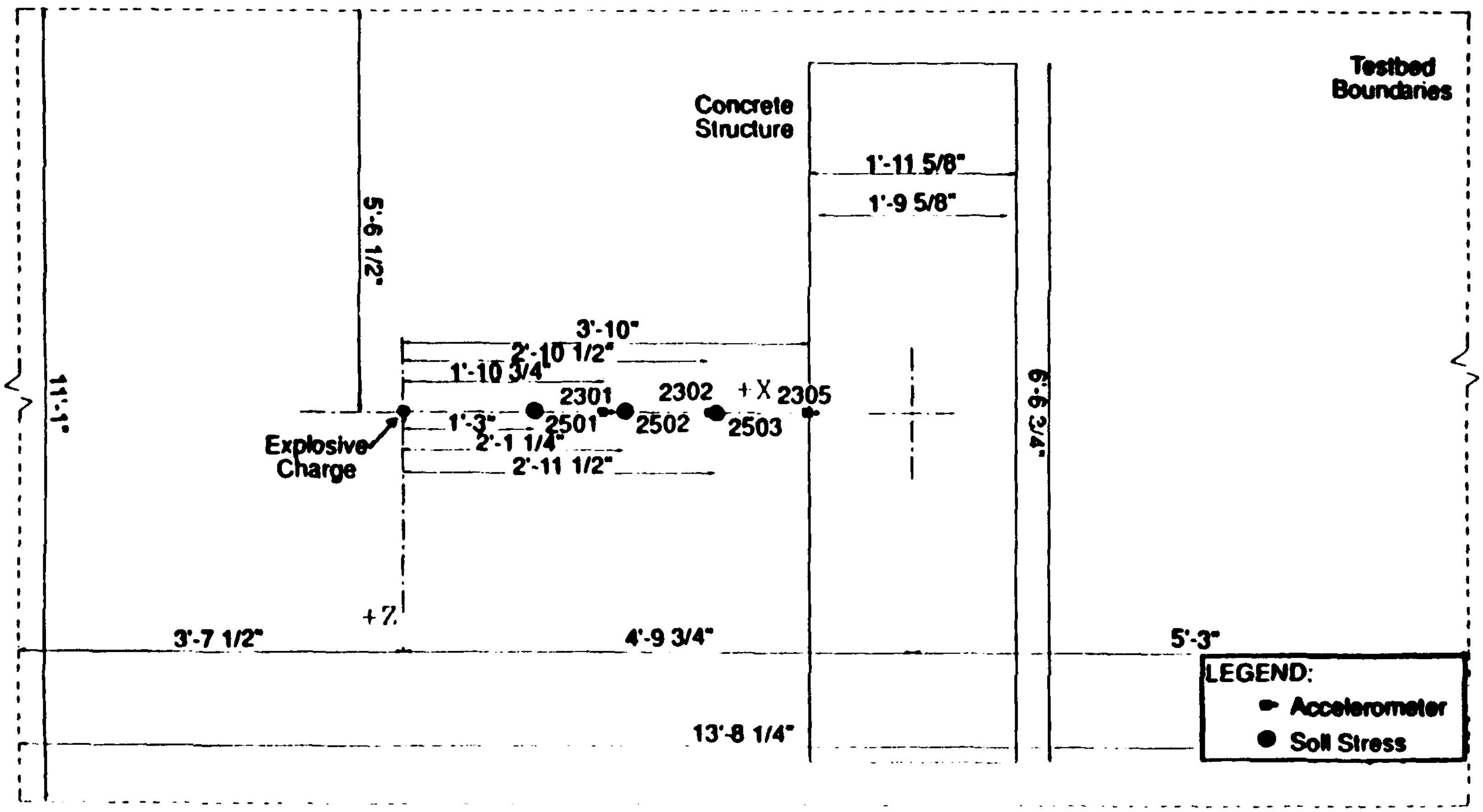
* Note: The 7270A may be substituted with the 7270 or 2264A as available.

** Note: Coordinate system originates at center of charge for free field gages and at center point of structure for structure gages.

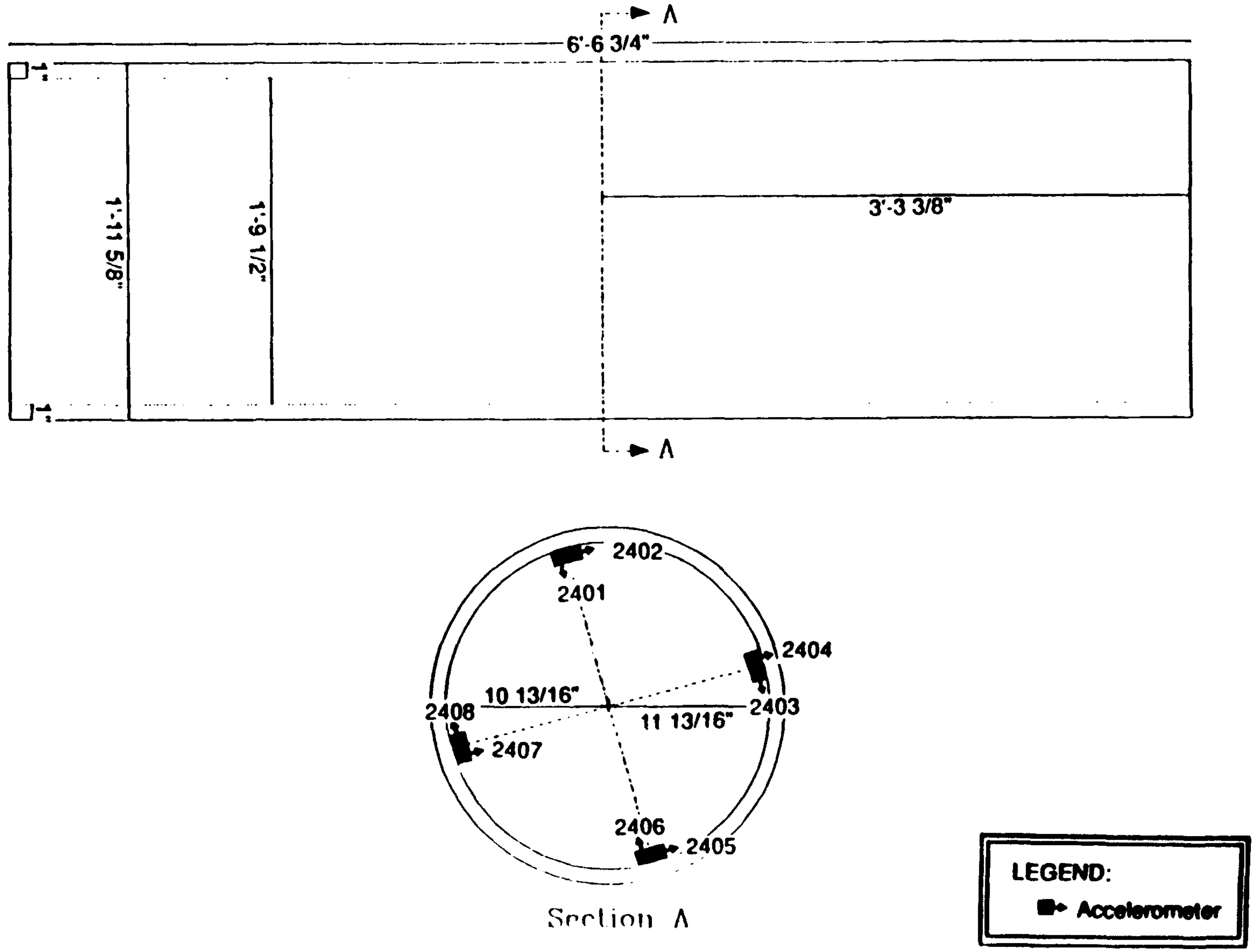
1/5 Froude Scale Testbed (elevation view)



1/5 Froude Scale Testbed (plan view)



1/5 Scale Froude Structure



Section A

Pretest Predictions

1/5th Froude Scale Experiment

	LUGS METHODOLOGY				SAMSON2 FE CALCULATION		
Range (m)	V_p (m/s)	A_p* (g's)	A_p** (g's)	σ_p (MPa)	V_p (m/s)	A_p (g's)	σ_p (MPa)
.45	39.0	58,600	11,000	8.55	30.2	24,400	12.1
.60	24.4	26,500	5,200	4.42	15.6	6,980	3.19
.75	16.8	14,700	3,000	2.72	9.30	2,520	1.74
.90	12.3	9,220	2,000	1.86	6.26	1,110	1.08
1.05	9.44	6,270	1,200	1.35	4.30	525	.74
1.20	7.47	4,550	900	1.03	3.24	353	.54
1.50	5.01	2,700	500	.66	1.98	179	.32

* Assumes accelerometer canister length of .02 m. Longer canister length reduces peak estimate proportionately.

** Assumes accelerometer canister of 0.1m length and somewhat less dense (≈ 1/2) than "standard".

Coal Densities In 1/5 Froude Test

These are the coal density measurements (lb/cuft) recorded by Larry Smith for the 1/5th scale Froude test.

DEPTH (in)	NW Corner	NE Corner	SE Corner	SW Corner	CENTER (1)
9	55.4(2)	–	–	51.4(2)	
12	52.6	51.2	51.0	50.8	52.8
26	50.7	54.9	54.9	53.5	55.9
33	53.4	54.8	52.4	54.1	56.9
48	53.9	51.9	52.7	54.2	53.8

33 50.4 at edge of structure where coal was compacted by hand using a rolling pin.

Note 1: The measurements in the CENTER column were taken at the center of the pit at the 48" depth. Samples at the other depths were taken 6' from the east wall of the pit to keep clear of the structure. All samples were taken at a point 4' from the north pit wall.

Note 2: The density measurements at 9" depth were in the coarser coal used to fill in at the edges of the pit.

All corner measurements were taken 30" from each wall, except for those at 9" which were taken at 20" from the west wall so as to remain clear of the fine coal in the center of the pit.

Measurement List

1/10 Froude Scale (Free Field)

Meas. No.	Gen.	x**	y	z	Sens Axis	Pred Peak	Make	Model	Range
1301	ff	.29	.06	0	r	6.9kg	Endevco	7270A*	10k
1302	ff	.44	.09	0	r	1.1kg	Endevco	7270A	2k
1303	ff	0	.3	0	+y	6.9kg	Endevco	7270A	10k
1304	ff	0	-.3	0	-y	6.9kg	Endevco	7270A	10k
1305	ff	.585	0	0	x	706g	Endevco	7270A	5k
1501	ff	.19	-.11	0	r	12.1MPa	Kulite	LQV-080-UH	27M
1502	ff	.32	-.19	0	r	1.74MPa	Kulite	LQV-080-UH	27M
1503	ff	.45	-.26	0	r	0.74MPa	Kulite	LQV-080-UH	1.4M

1/10 Froude Scale (Structure)

Meas. No.	Gen.	r**	d	z	Sens Axis	Pred Peak	Make	Model	Range
1401	s	.125	349	0	r	360g	Endevco	2262A	1k
1402	s	.125	349	0	t	360g	Endevco	2262A	1k
1403	s	.125	79	0	t	360g	Endevco	2262A	1k
1404	s	.125	79	0	r	360g	Endevco	2262A	1k
1405	s	.125	169	0	t	360g	Endevco	2262A	1k
1406	s	.125	169	0	r	360g	Endevco	2262A	1k
1407	s	.125	259	0	r	706g	Endevco	2262A	1k
1408	s	.125	259	0	t	706g	Endevco	2262A	1k

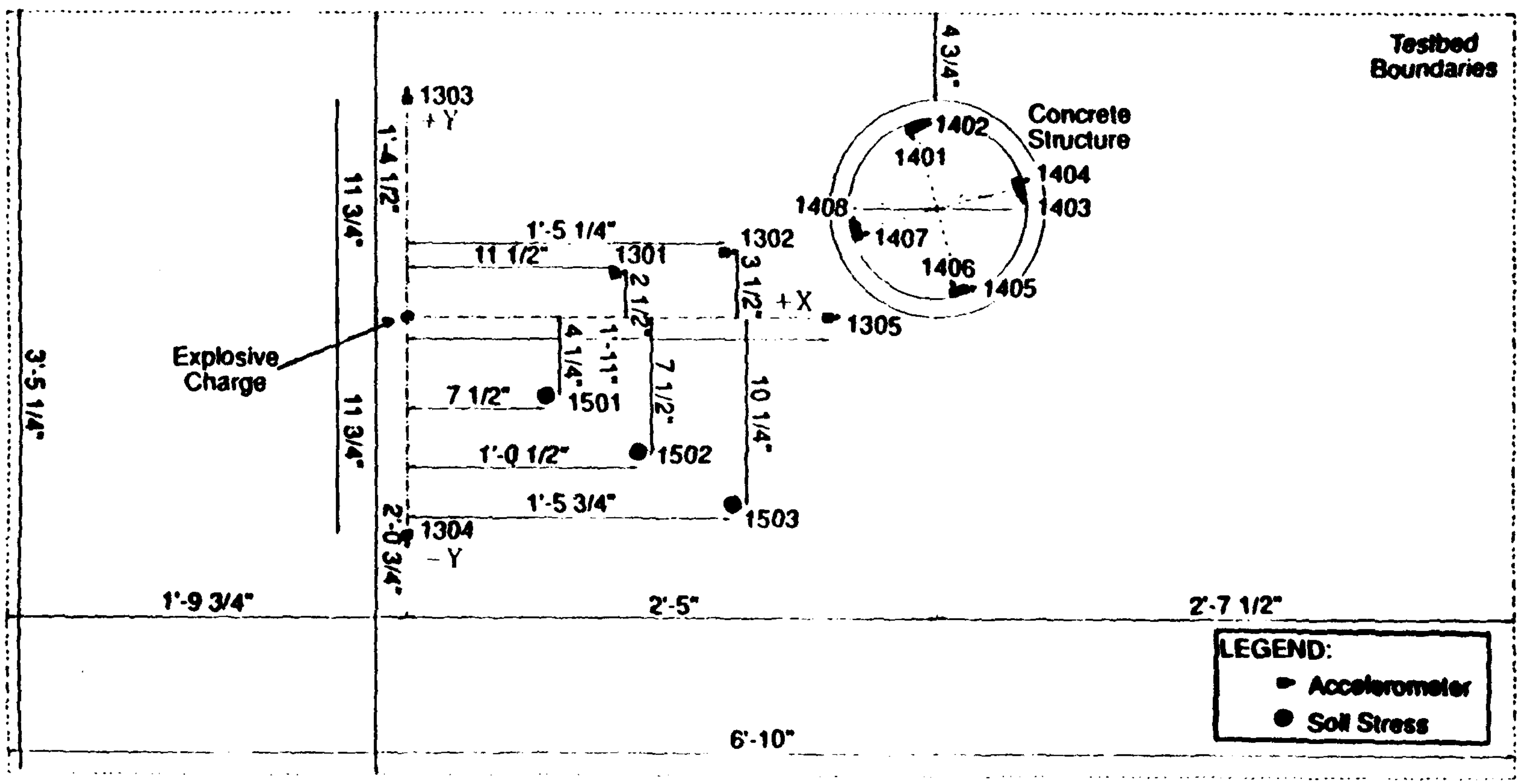
Legend

x = meters
y = meters
z = meters
r = meters or radial
d = degrees
s = structural
ff = free field
t = tangential

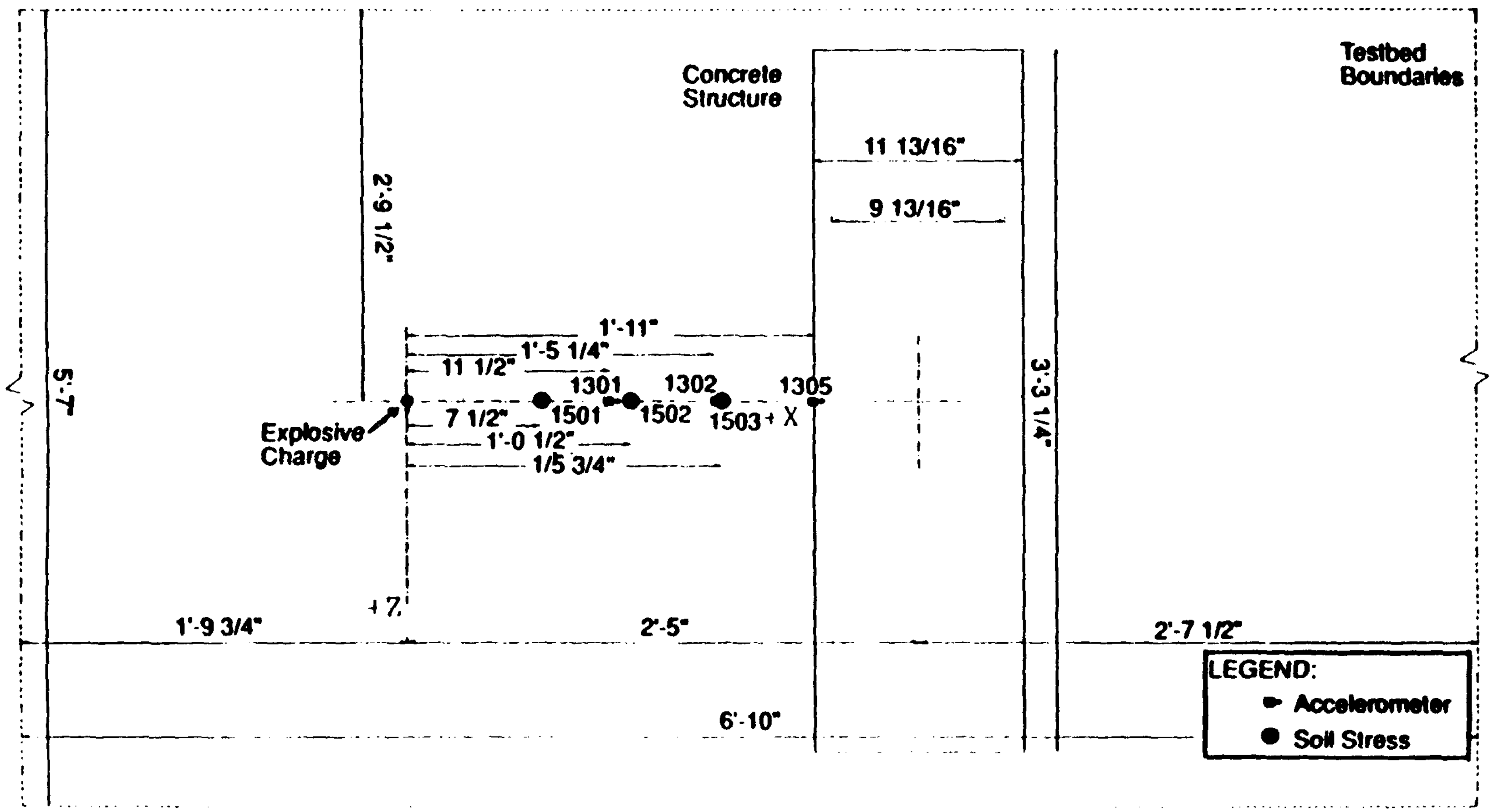
* Note: The 7270A may be substituted with the 7270 or 2264A as available.

** Note: Coordinate system originates at center of charge for free field gages and at center point of structure for structure gages.

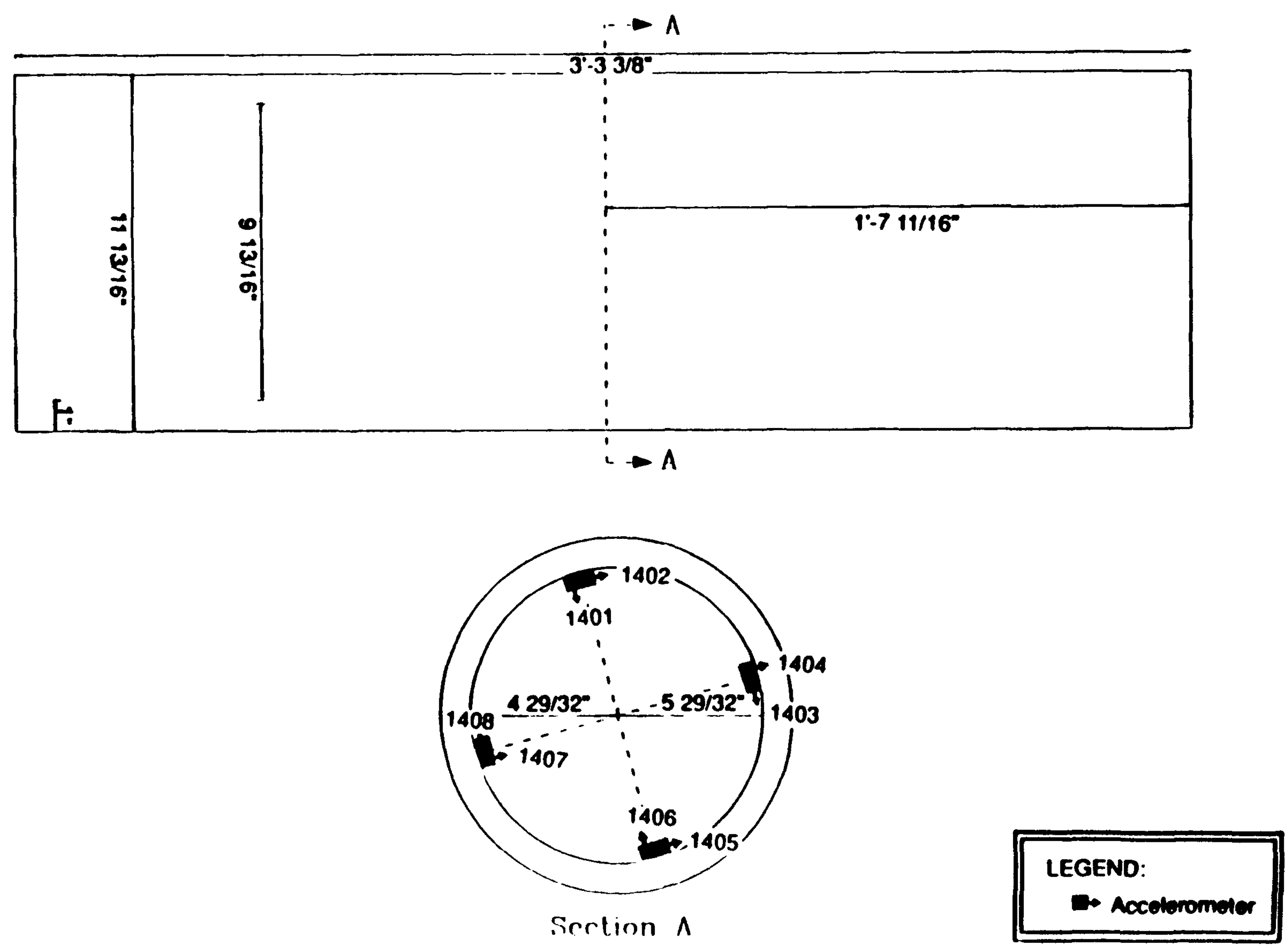
1/10 Froude Scale Testbed (elevation view)



1/10 Froude Scale Testbed (plan view)



1/10 Scale Replica Structure



Pretest Predictions

1/10th Froude Scale Experiment

	LUGS METHODOLOGY				SAMSON2 FE CALCULATION		
Range (m)	V_p (m/s)	A_p* (g's)	A_p** (g's)	σ_p (MPa)	V_p (m/s)	A_p (g's)	σ_p (MPa)
.225	27.6	58,600	5,860	8.55	21.3	24,400	12.1
.3	17.2	26,500	2,650	4.42	11.0	6,980	3.19
.375	11.9	14,700	1,470	2.72	6.58	2,520	1.74
.45	8.73	9,220	920	1.86	4.43	1,110	1.08
.525	6.67	6,270	620	1.35	3.04	525	.74
.60	5.28	4,550	455	1.03	2.29	353	.54
.75	3.54	2,700	270	.66	1.40	179	.32

* Assumes accelerometer canister length of .01 m. Longer canister length reduces peak estimate proportionately.

** Assumes accelerometer canister of 0.1m length.

Coal/Lead Densities in 1/10 Froude-Scale Test

These are the coal/lead mixture density measurements (lb/cuft) recorded by Larry Smith for the 1/10th scale Froude test. All corner measurements were taken 18" from each wall.

DEPTH (in)	SW Corner	NW Corner	NE Corner	SE Corner	CENTER (1)
8	160***	110	—	108	100
16	100	130*	107	105	—
20	137**	134**	142**	137**	—
28	131	109	116	126	114
33	115	—	107	—	114
4 (from bottom)	—	82	120	—	—

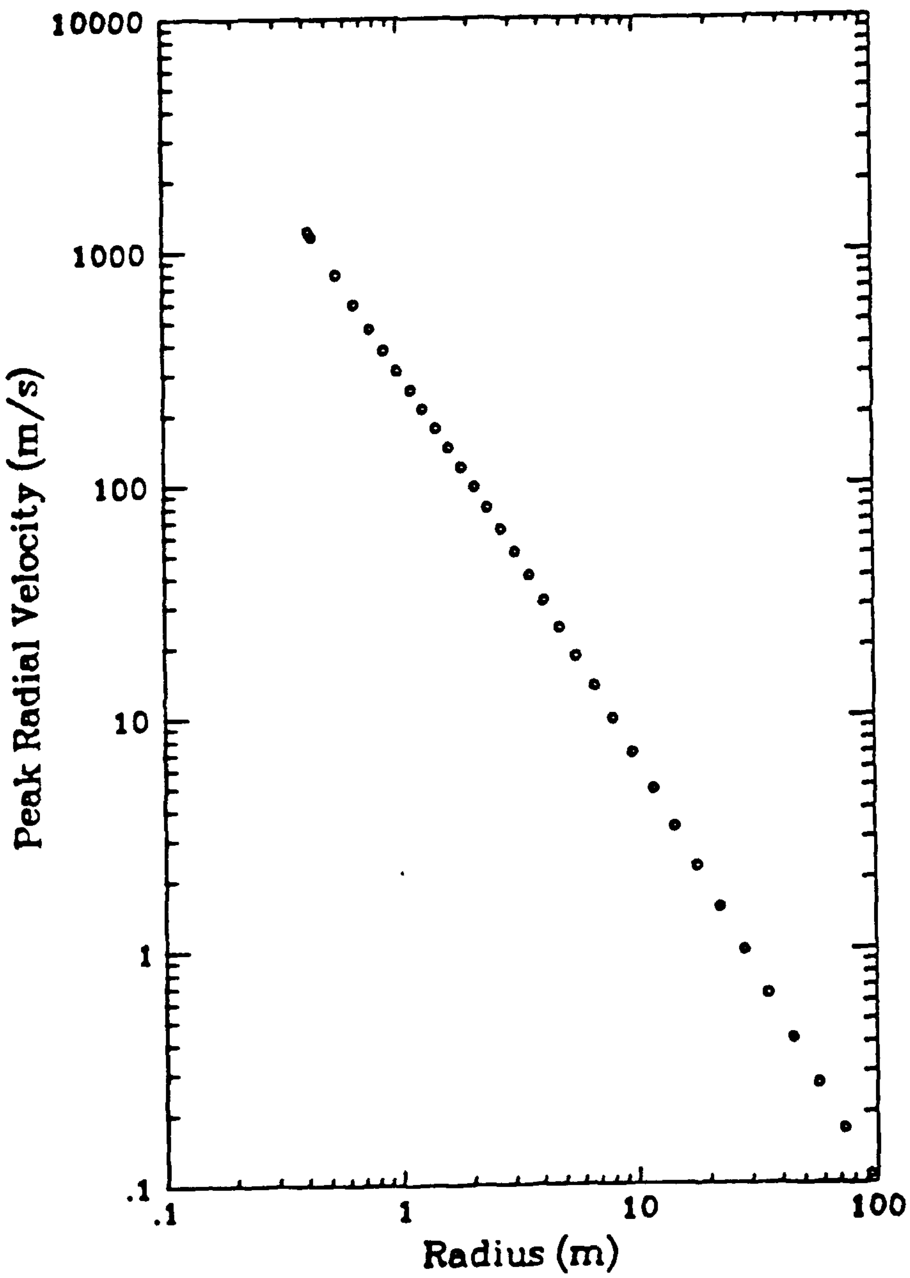
* Coal/lead mixture was dumped from the mixer into this corner of the pit, and considerable weight accumulated above this sample before the mixture was spread out to the rest of the pit.

** There was a great deal of foot traffic in the pit corners prior to removing these samples, which seems to have compacted the mixture in these samples. After these high readings were taken, foot traffic in the pit was avoided as much as possible to prevent such compaction. The crew always avoided walking in the center of the pit (between charge and structure) so the mixture was probable not compacted as much in this area.

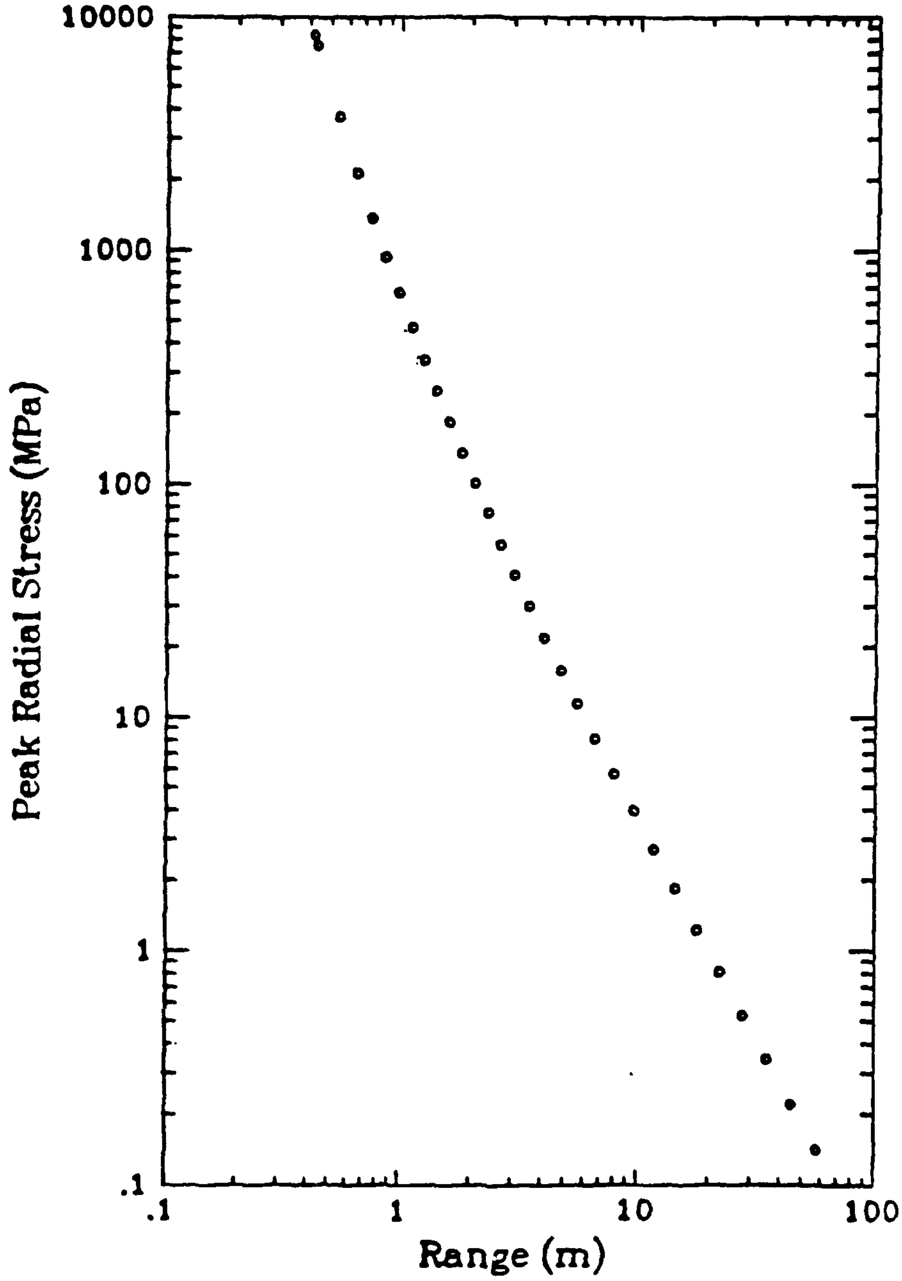
*** No explanation for this high reading.

The coal/lead mixture tended to separate whenever it was disturbed, with lead going to the bottom. This was observed when it was poured from the mixer into the pit, or when it was shoveled from one point to another. Whether this could account for some of the variation in the readings is not clear.

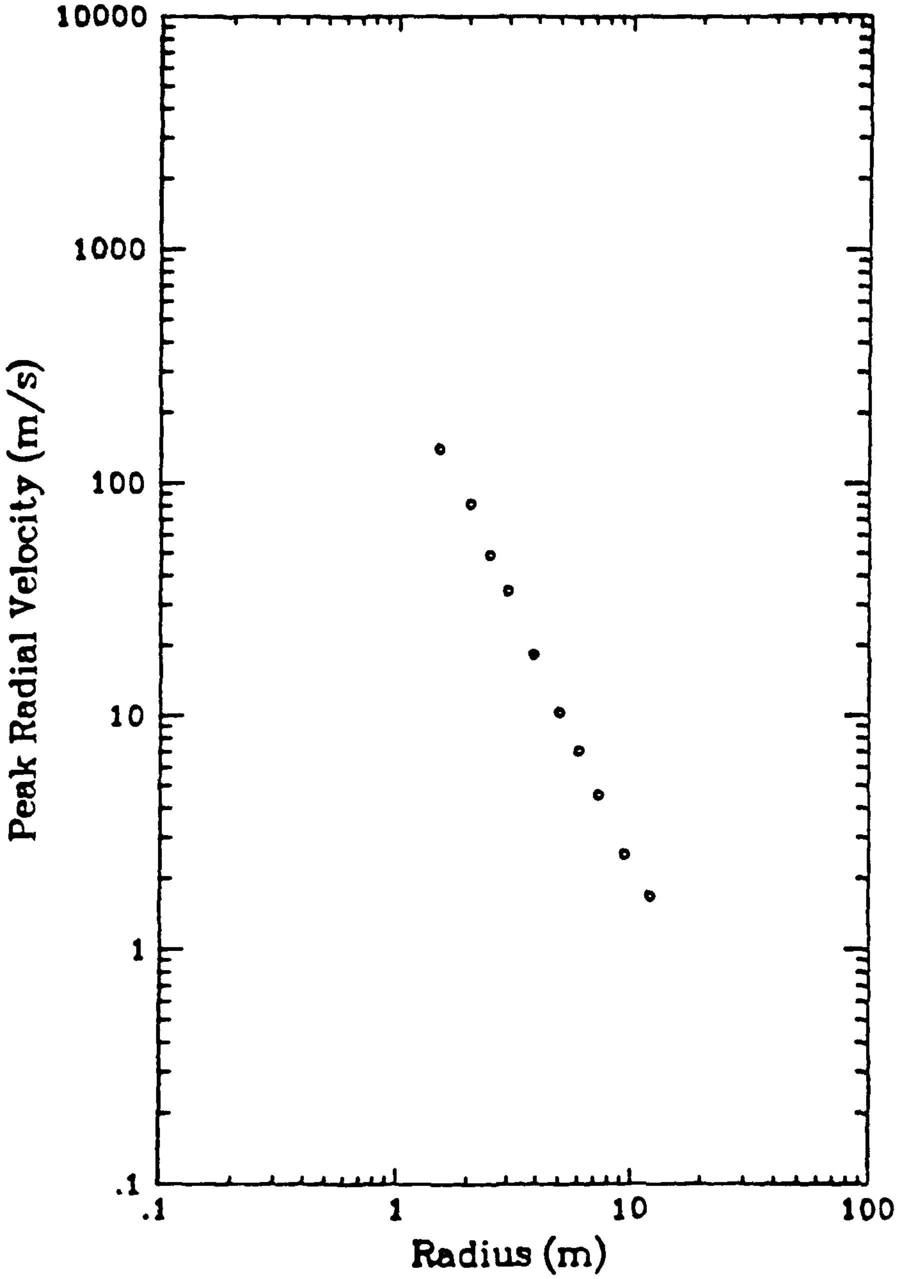
500 kg TNT in Randolph Sand (LUGS Methodology)



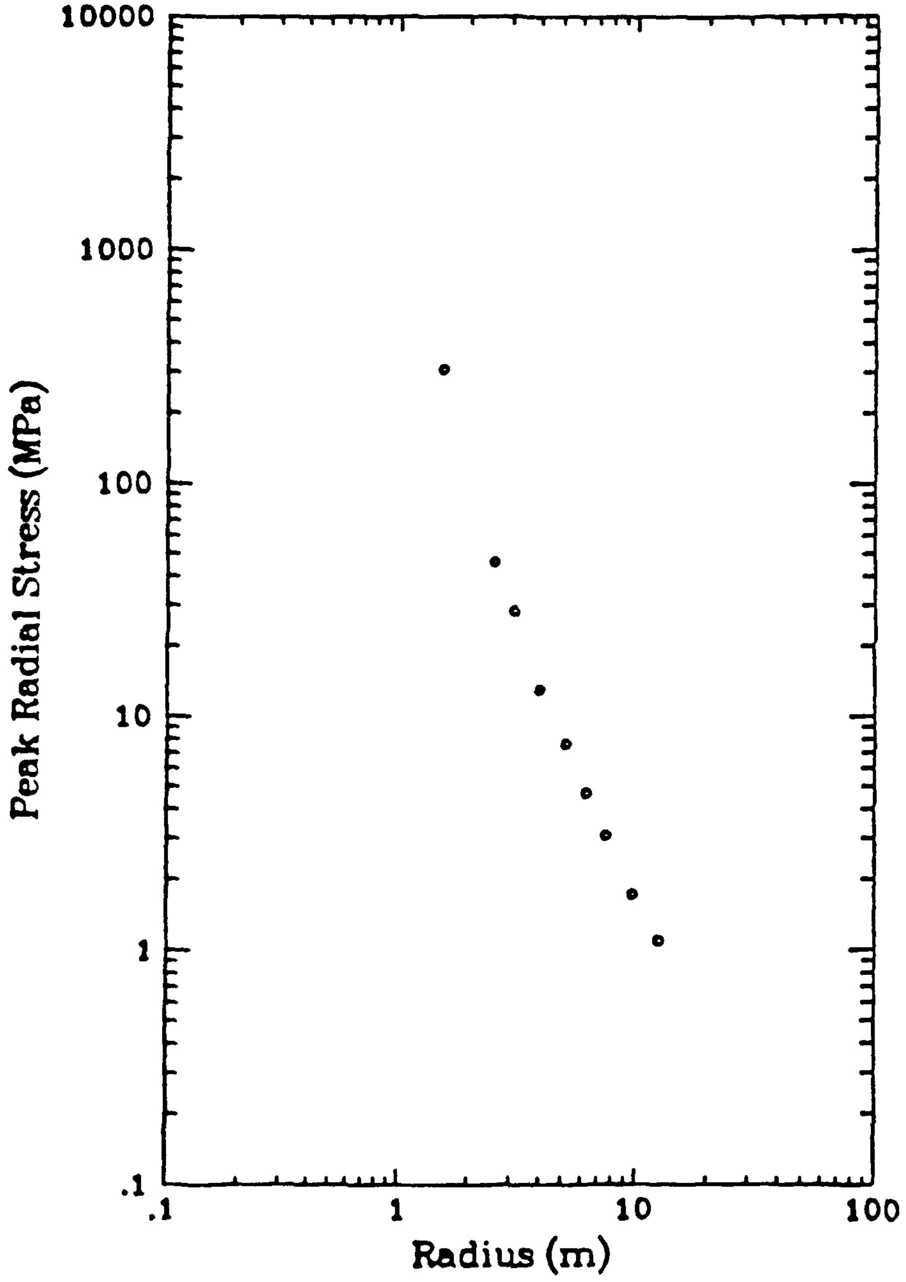
500 kg TNT in Randolph Sand (LUGS Methodology)



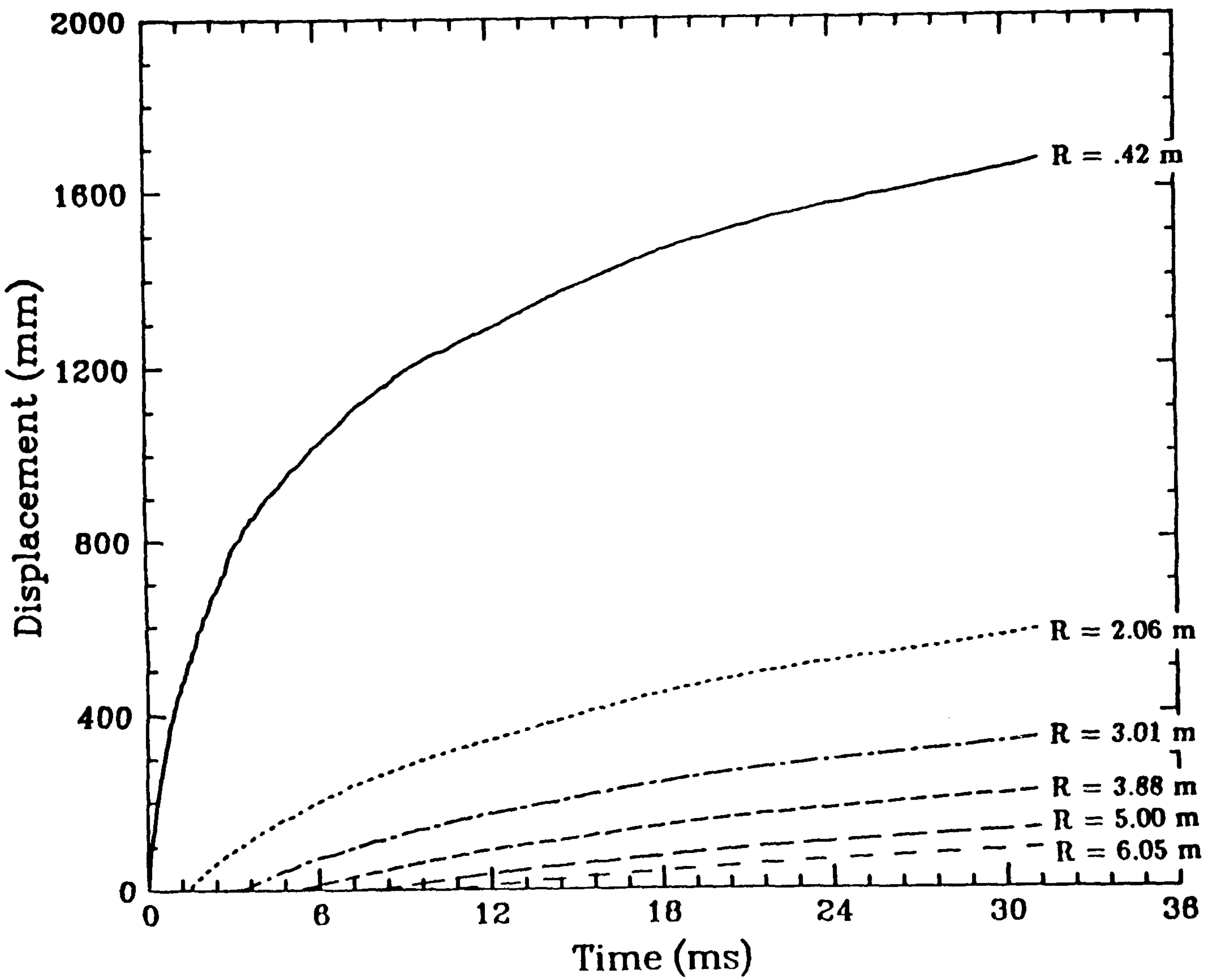
500 kg TNT in Randolph Sand
(Finite Element Method)



500 kg TNT in Randolph Sand
(Finite Element Method)



500 kg TNT In Randolph Sand (Finite Element Method)



Prediction for 500 kg TNT in Randolph Sand

	LUGS METHODOLOGY			SAMSON2 FE CALCULATION		
Range (m)	V_p (m/s)	A_p* (g's)	σ_p (MPa)	V_p (m/s)	A_p (g's)	σ_p (MPa)
2.25	87.2	58,600	85.5	67.5	24,400	121.0
3.0	54.5	26,500	44.2	34.9	6,980	31.9
3.75	37.6	14,700	27.2	20.8	2,520	17.4
4.5	27.6	9,220	18.6	14.0	1,110	10.8
5.25	21.1	6,270	13.5	9.61	525	7.40
6.0	16.7	4,550	10.3	7.24	353	5.38
7.5	11.2	2,700	6.6	4.42	179	3.17

* Assumes accelerometer canister length of 0.1 m

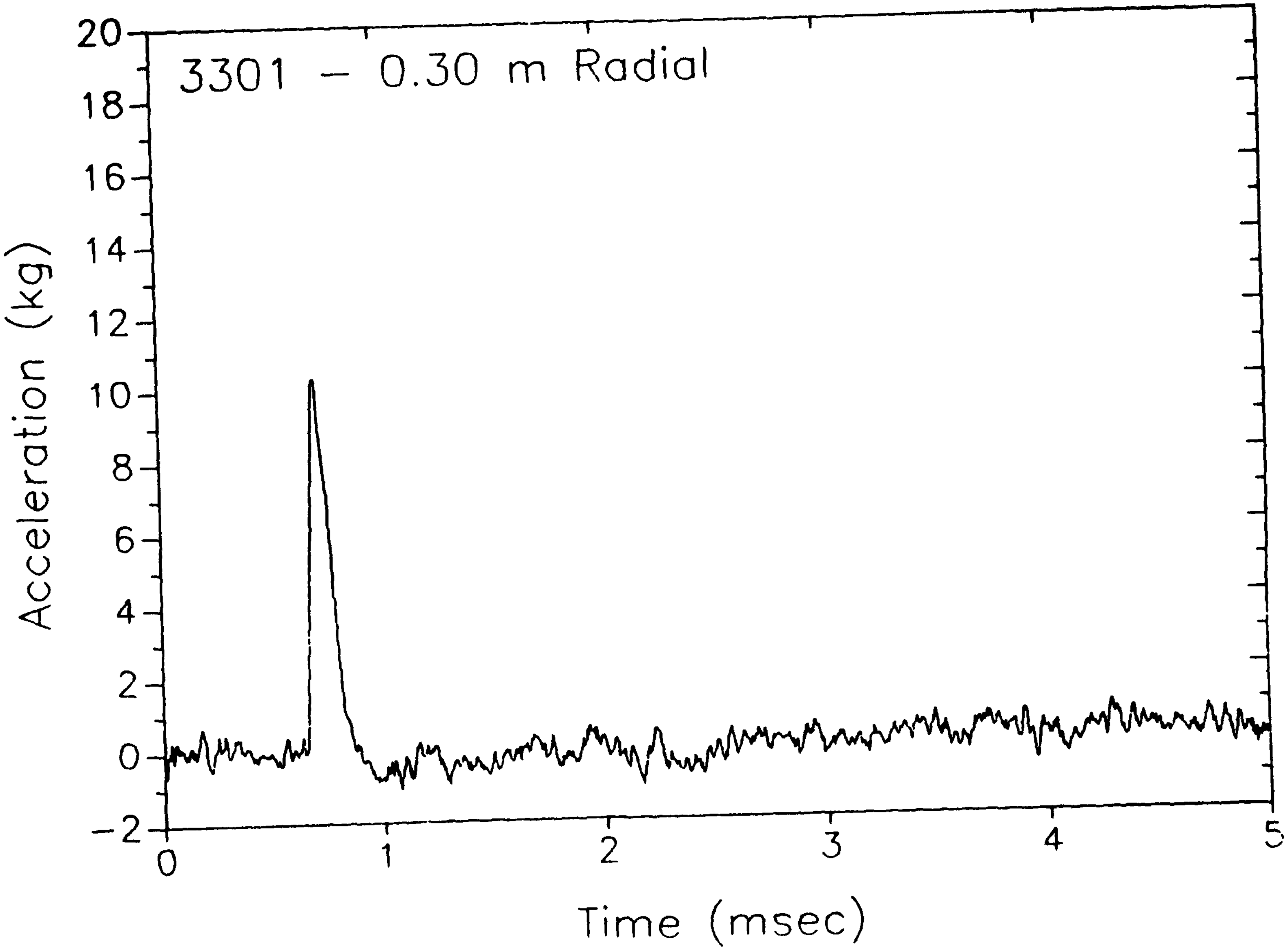
APPENDIX E

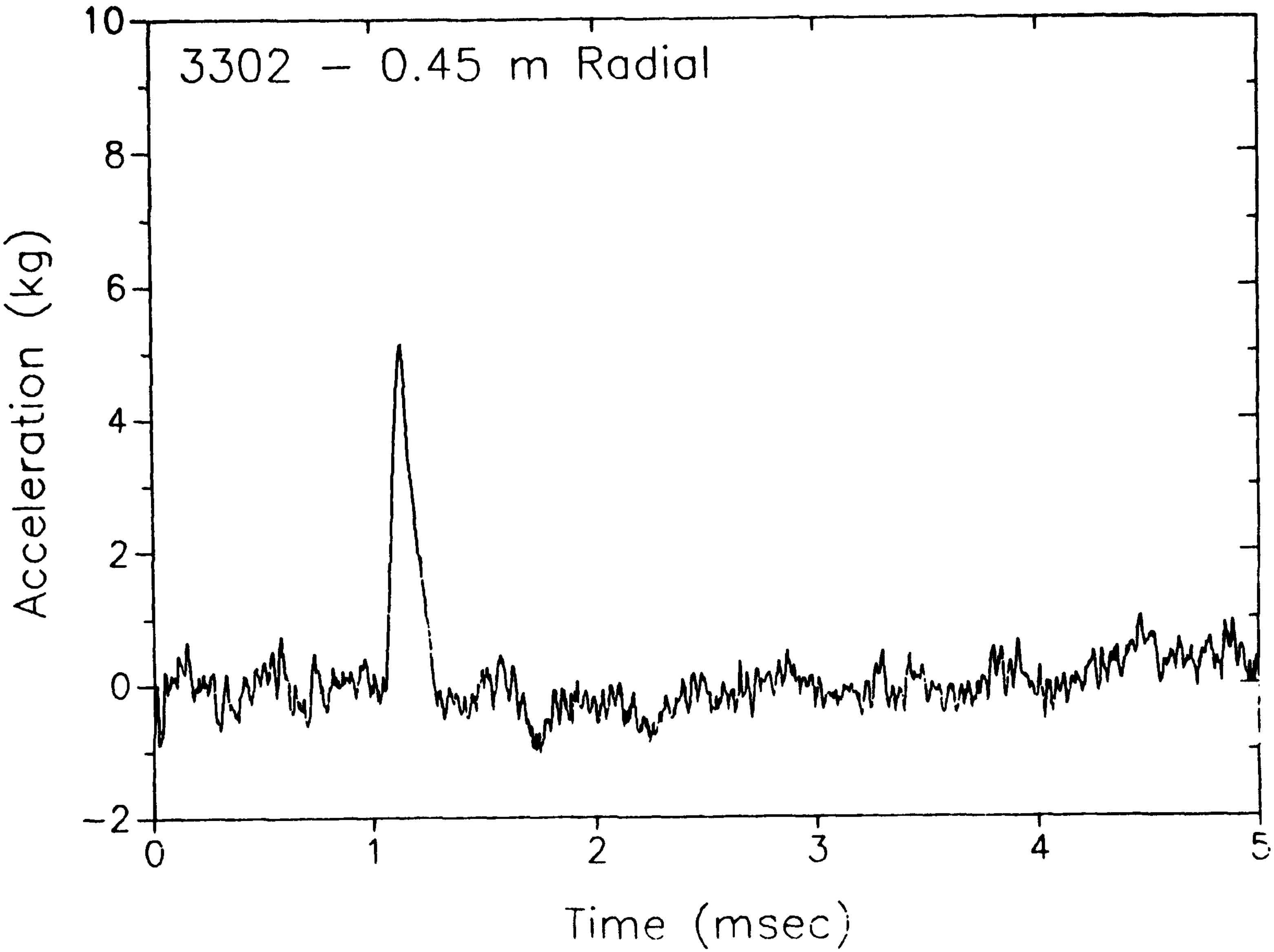
DATA PLOTS FROM DYNAMIC TESTS

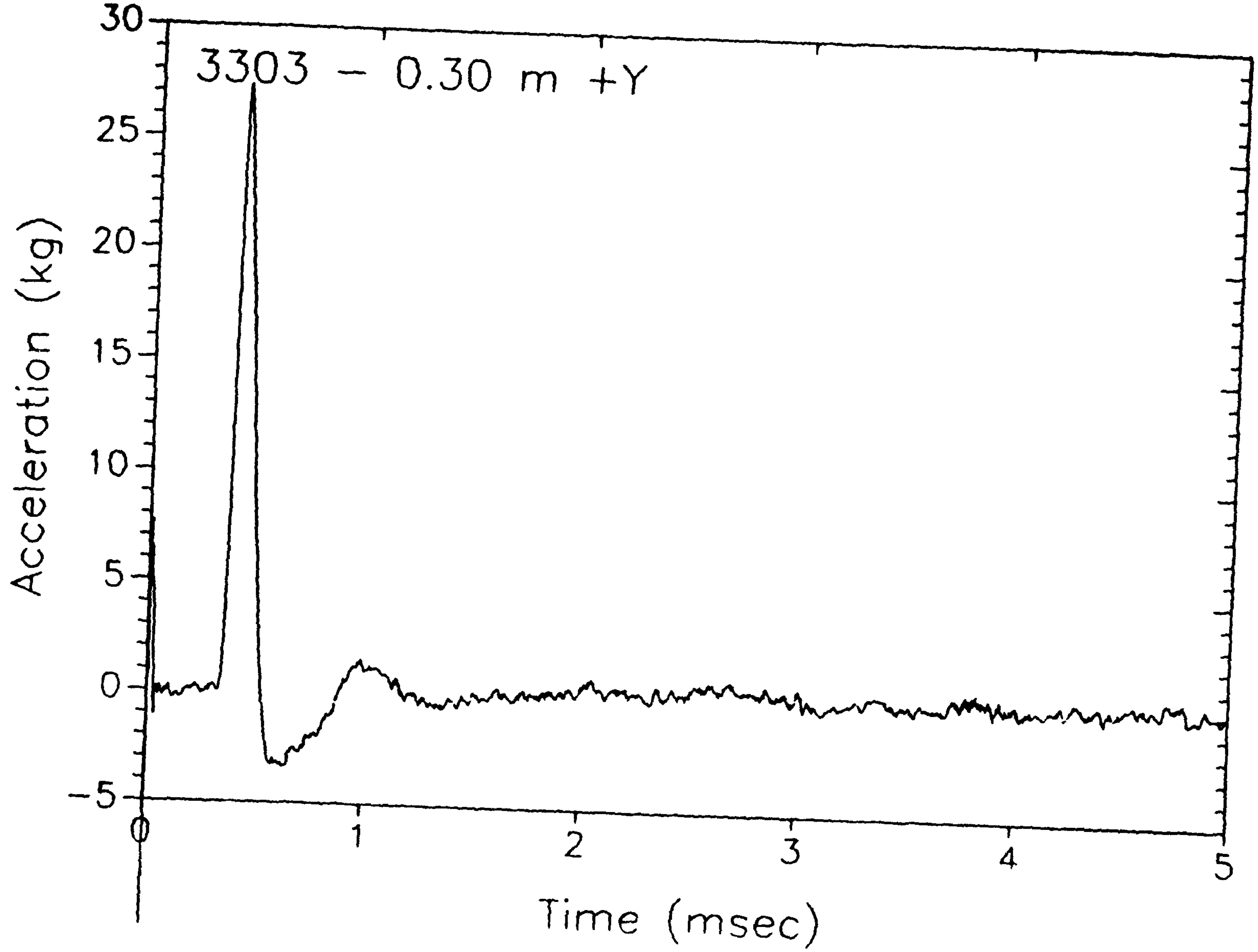
On the plots of accelerations and velocities on the structure, the radial values (with respect to the structure) are plotted with solid lines, and the transverse values with dashed lines.

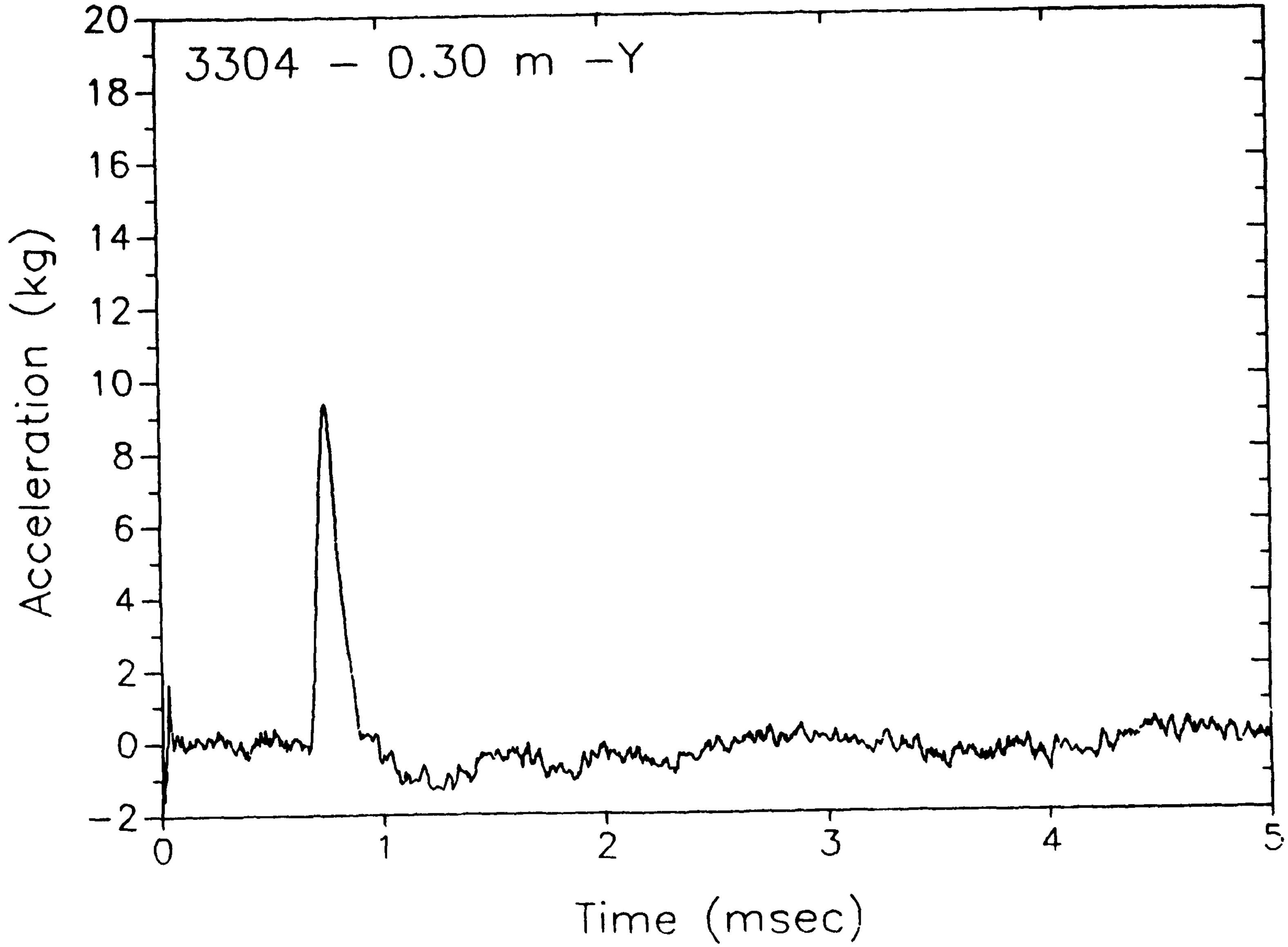
1/10 REPLICA SCALED TEST

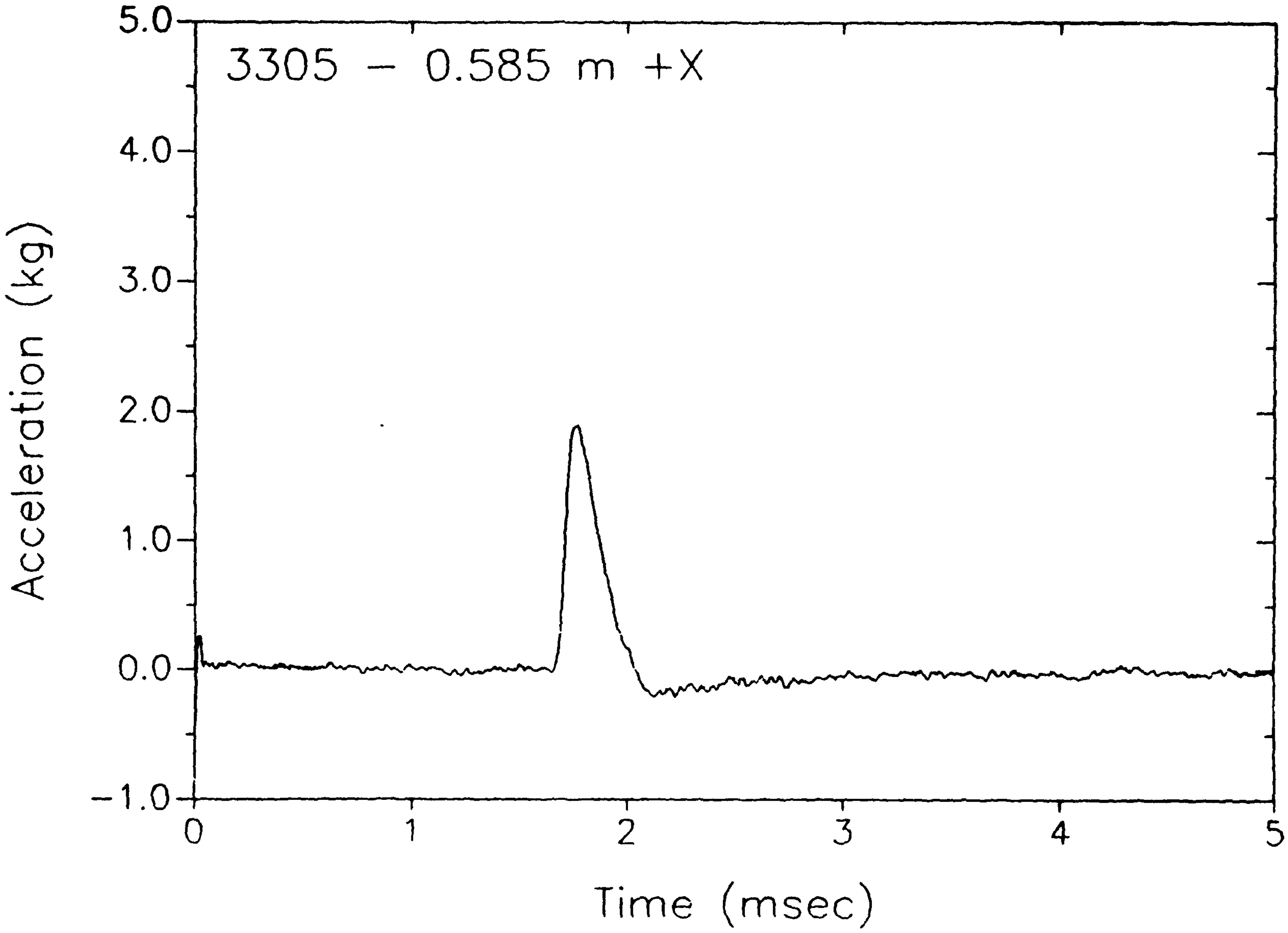
"SAND"

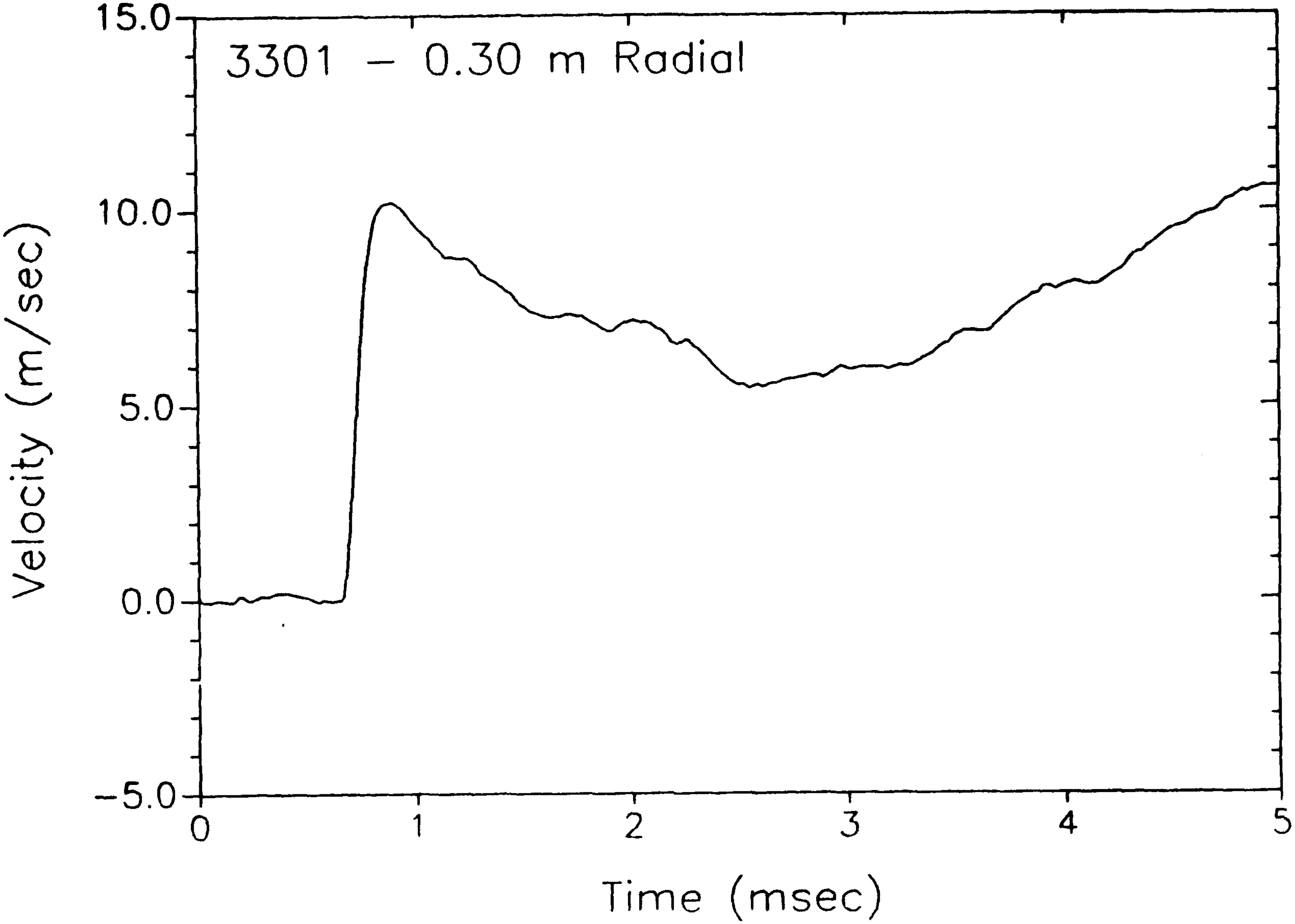

3301 – 0.30 m Radial
Acceleration (kg)
Time (msec)
20
18
16
14
12
10
8
6
4
2
0
–2
0
1
2
3
4
5

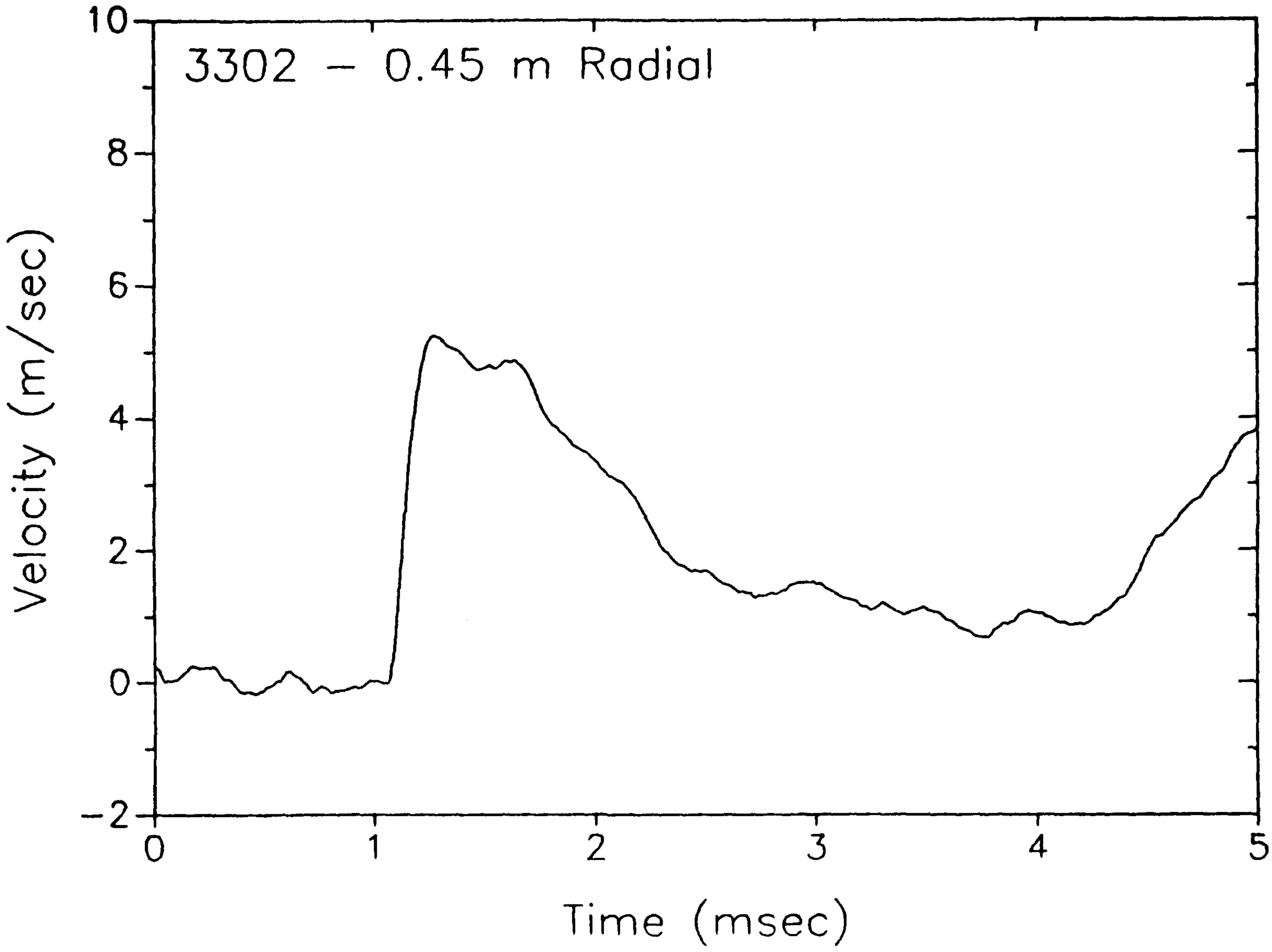

3302 – 0.45 m Radial
Acceleration (kg)
Time (msec)
10
8
6
4
2
0
–2
0
1
2
3
4
5

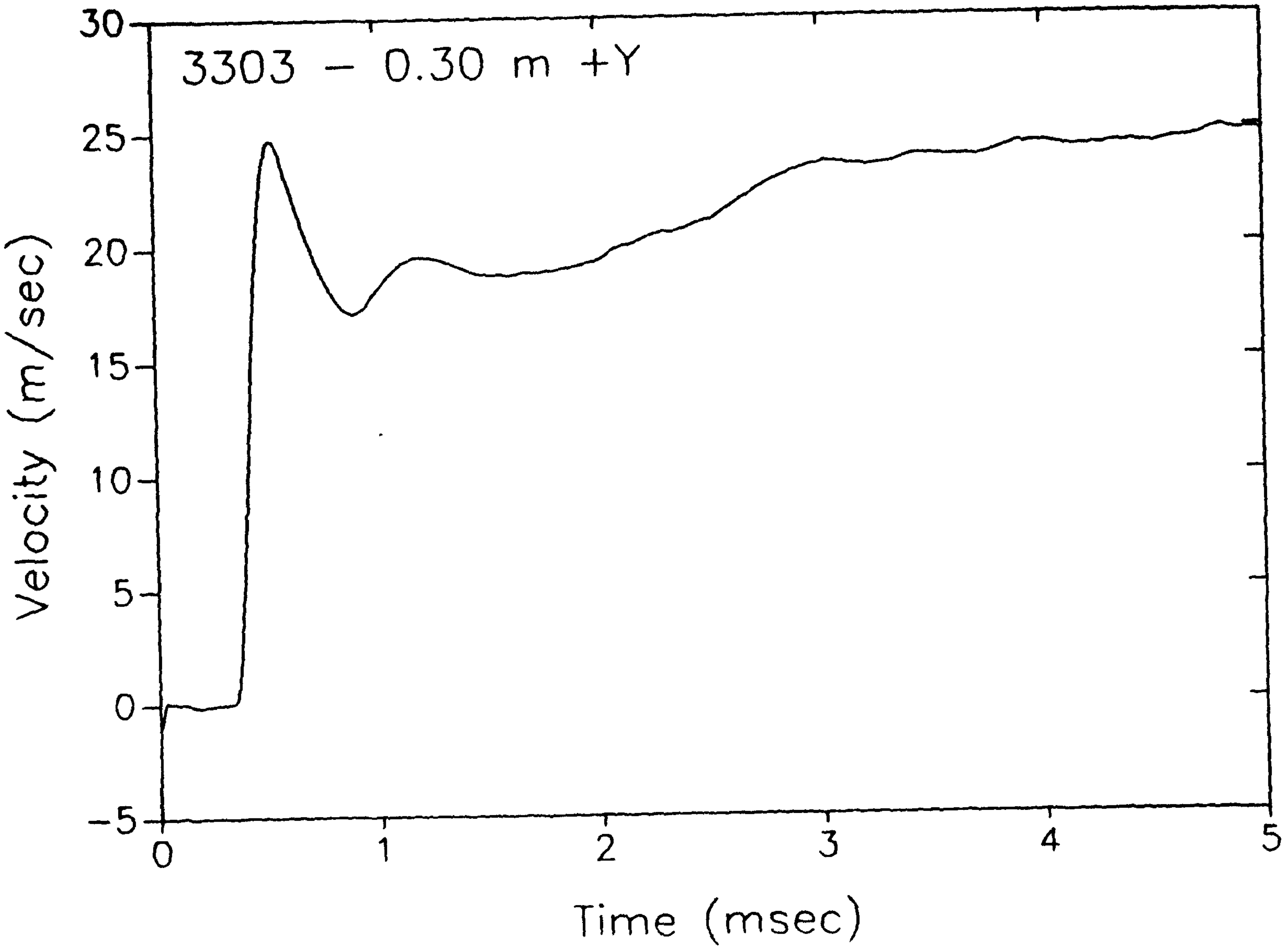

3303 - 0.30 m +Y
Acceleration (kg)
30
25
20
15
10
5
0
-5
0
1
2
3
4
5
Time (msec)

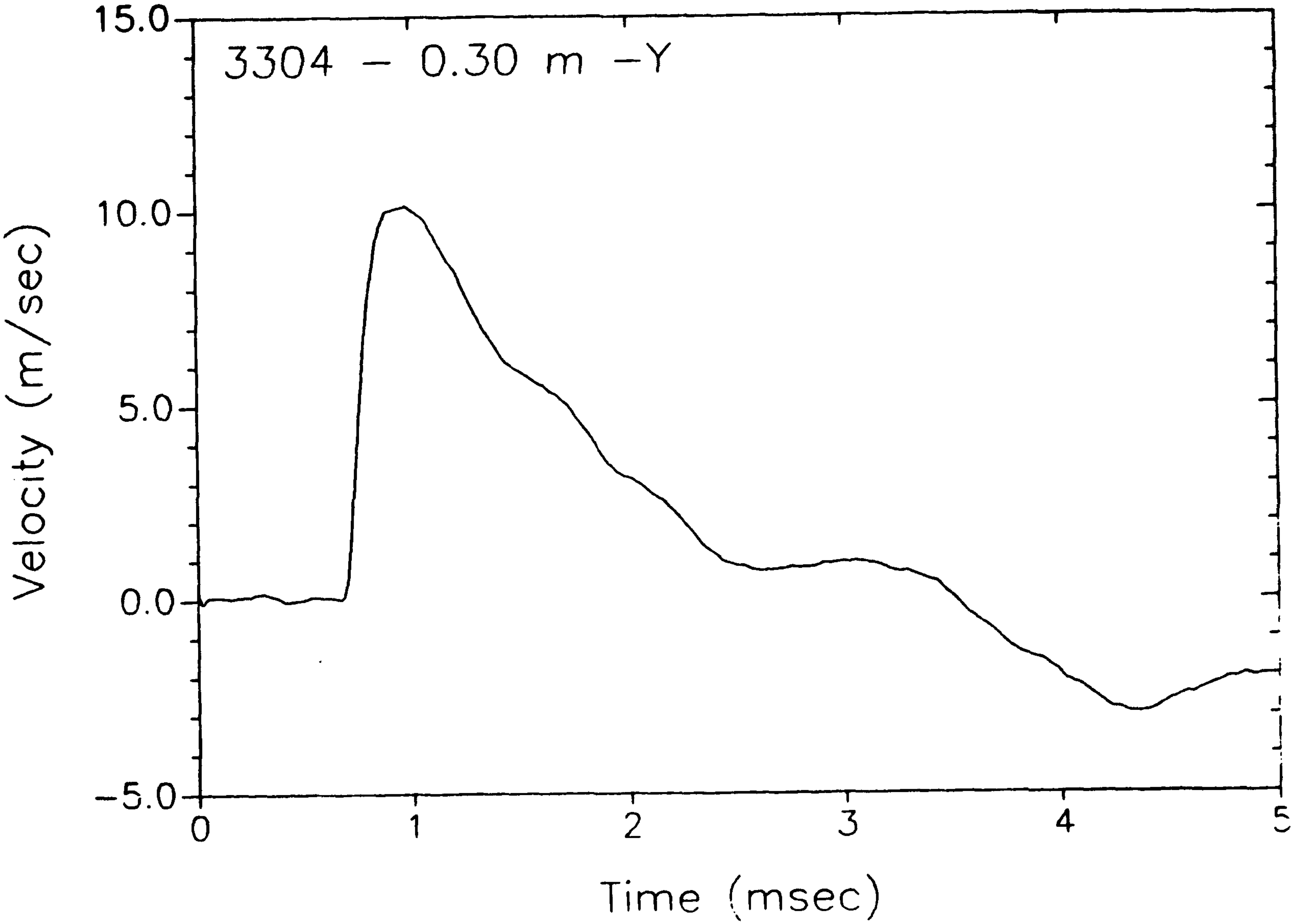

3304 – 0.30 m –Y
Acceleration (kg)
20
18
16
14
12
10
8
6
4
2
0
–2
0
1
2
3
4
5
Time (msec)

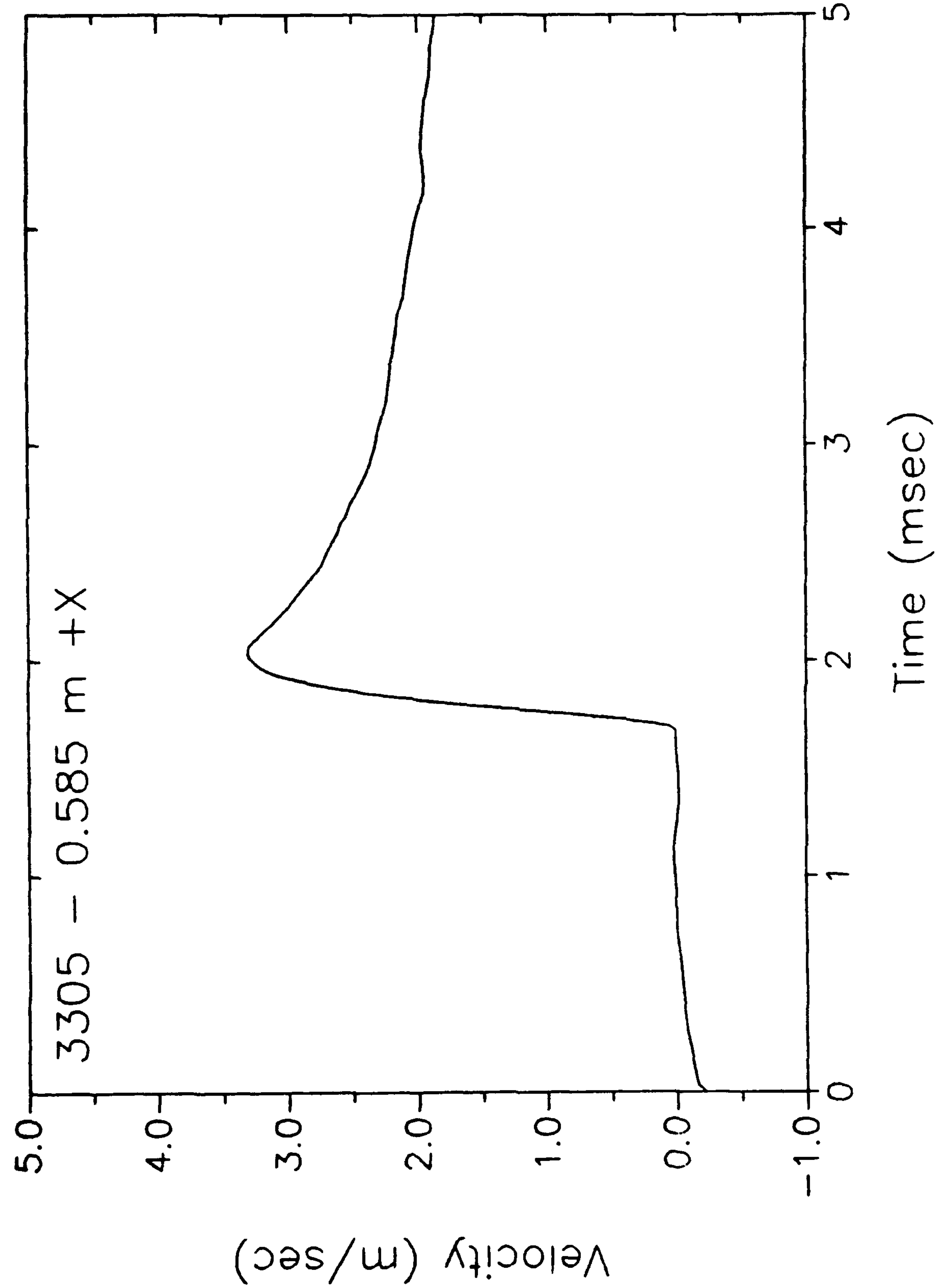

3305 – 0.585 m +X
Acceleration (kg)
5.0
4.0
3.0
2.0
1.0
0.0
–1.0
0
1
2
3
4
5
Time (msec)


3301 – 0.30 m Radial
15.0
10.0
5.0
0.0
–5.0
Velocity (m/sec)
0
1
2
3
4
5
Time (msec)

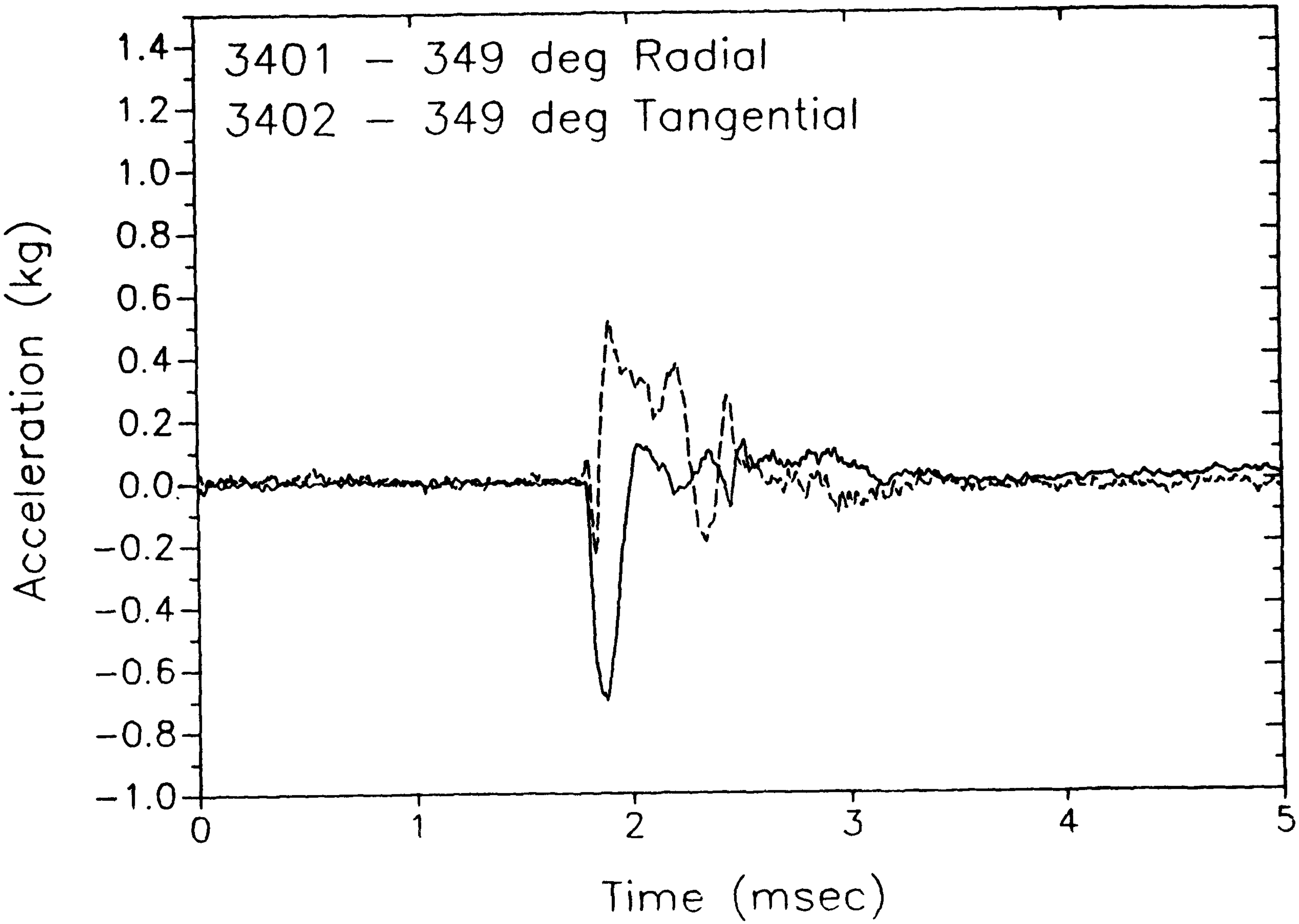

3302 – 0.45 m Radial
Velocity (m/sec)
Time (msec)
10
8
6
4
2
0
−2
0
1
2
3
4
5

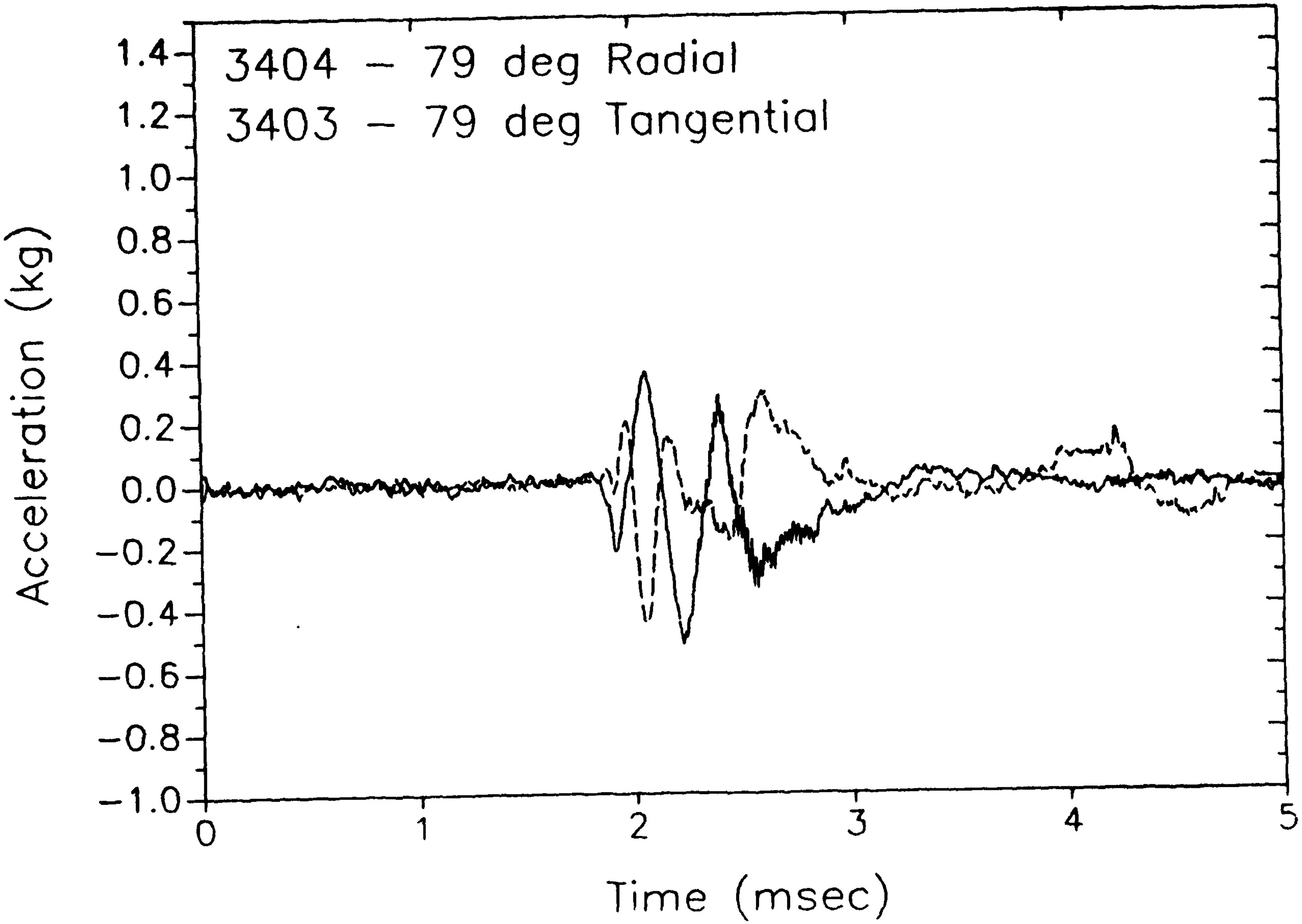

3303 – 0.30 m +Y
Velocity (m/sec)
Time (msec)
30
25
20
15
10
5
0
–5
0
1
2
3
4
5

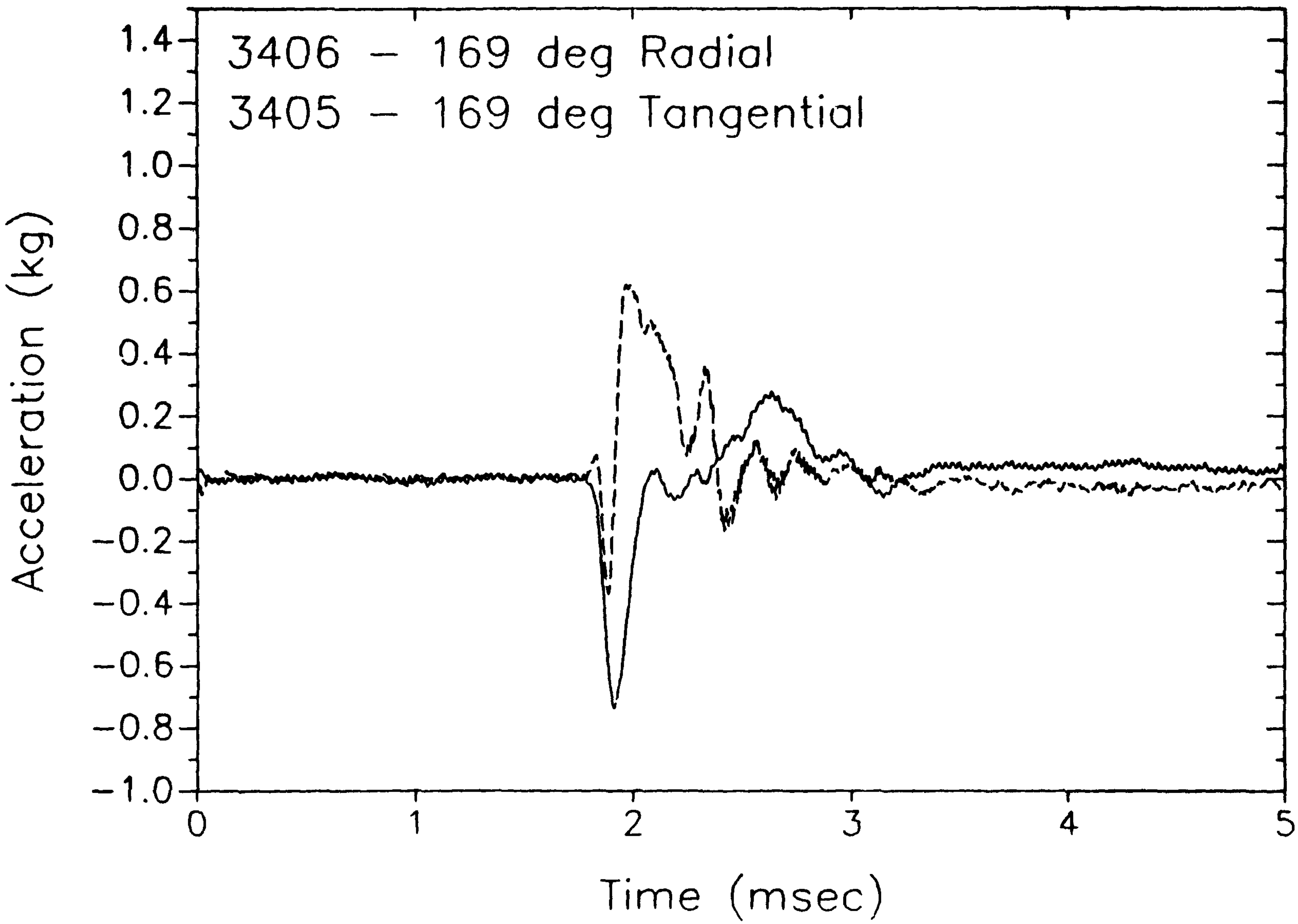

3304 – 0.30 m –Y
Velocity (m/sec)
15.0
10.0
5.0
0.0
–5.0
0
1
2
3
4
5
Time (msec)

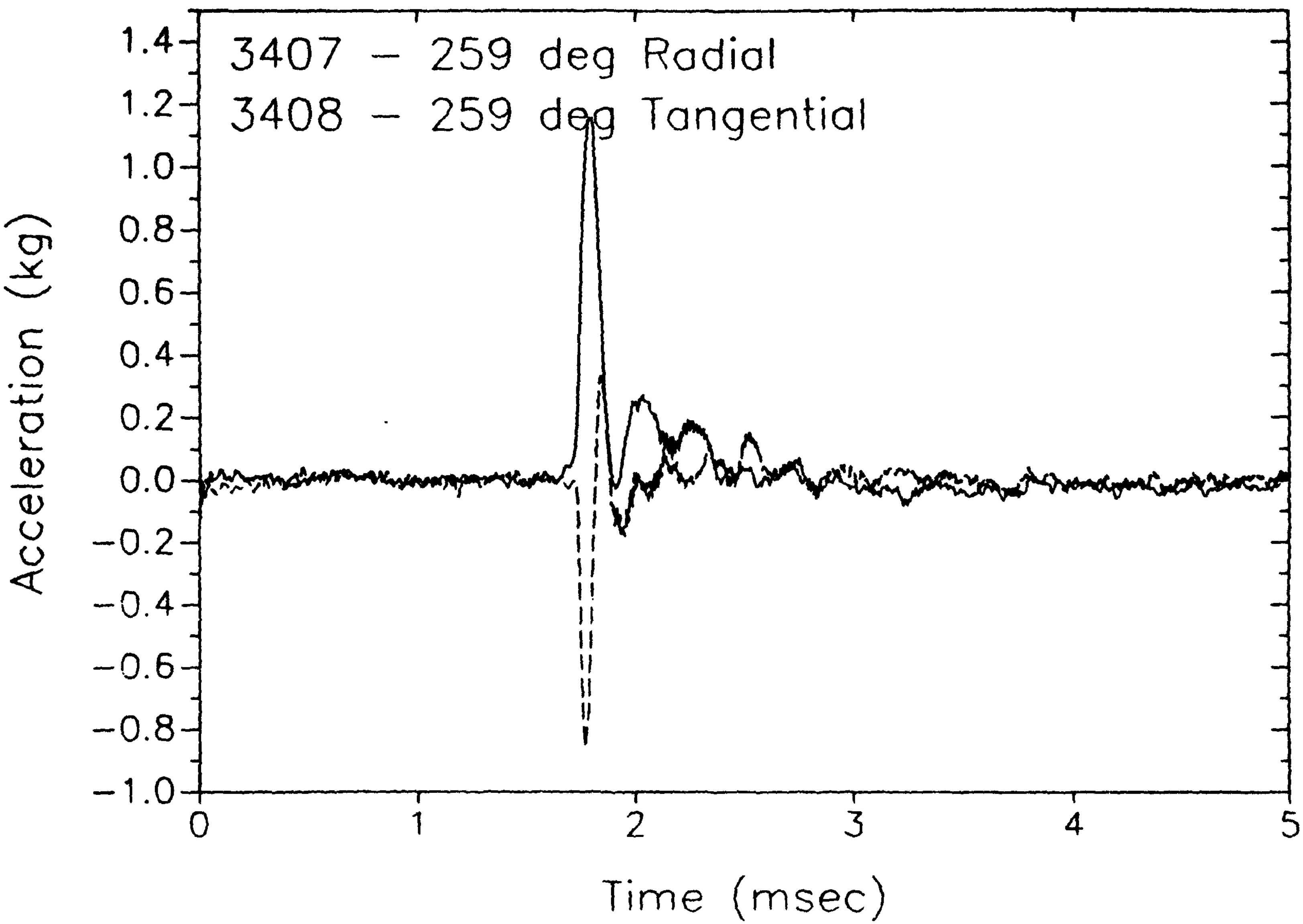


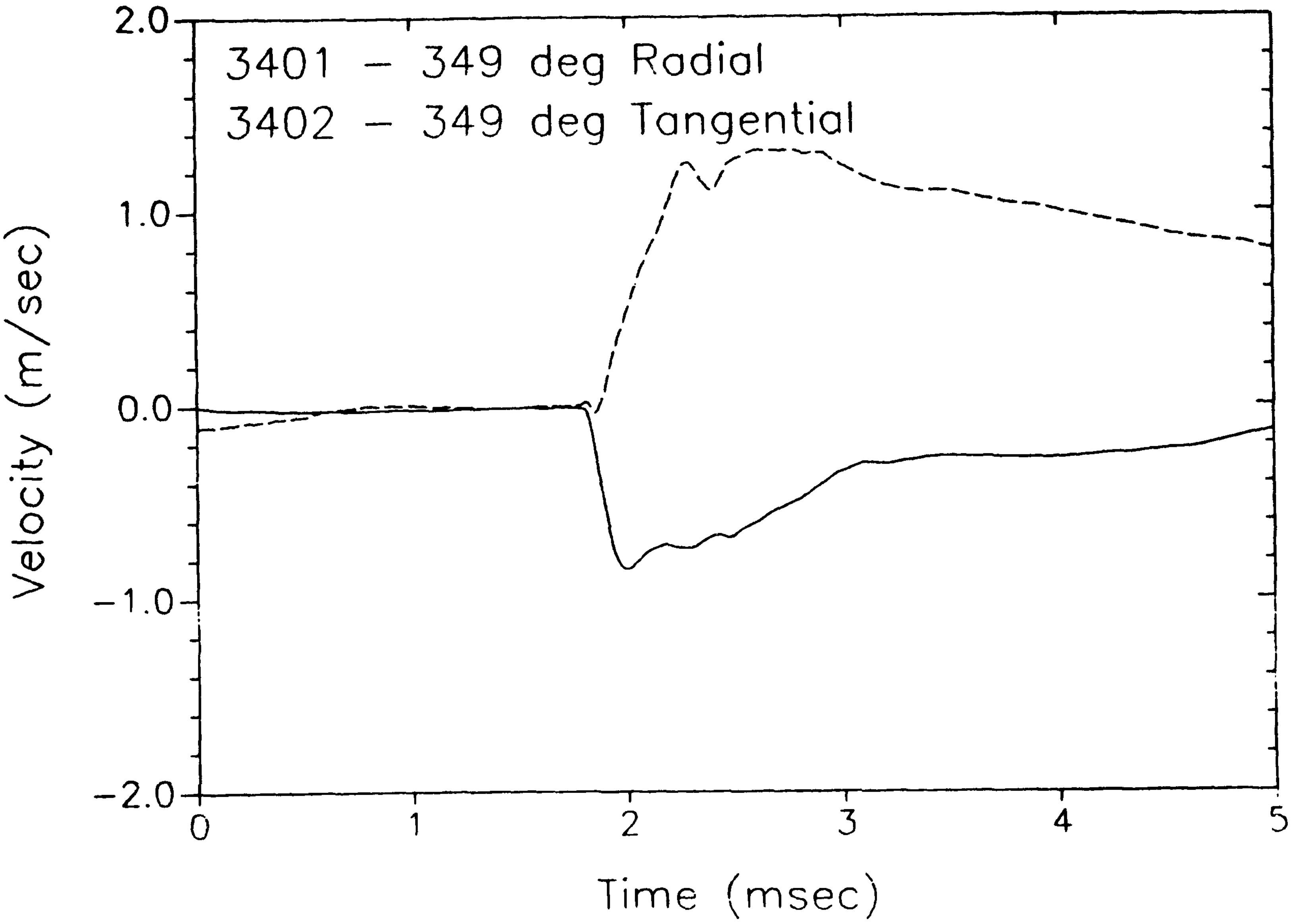
3305 – 0.585 m +X
Velocity (m/sec)
Time (msec)
5.0
4.0
3.0
2.0
1.0
0.0
–1.0
0
1
2
3
4
5

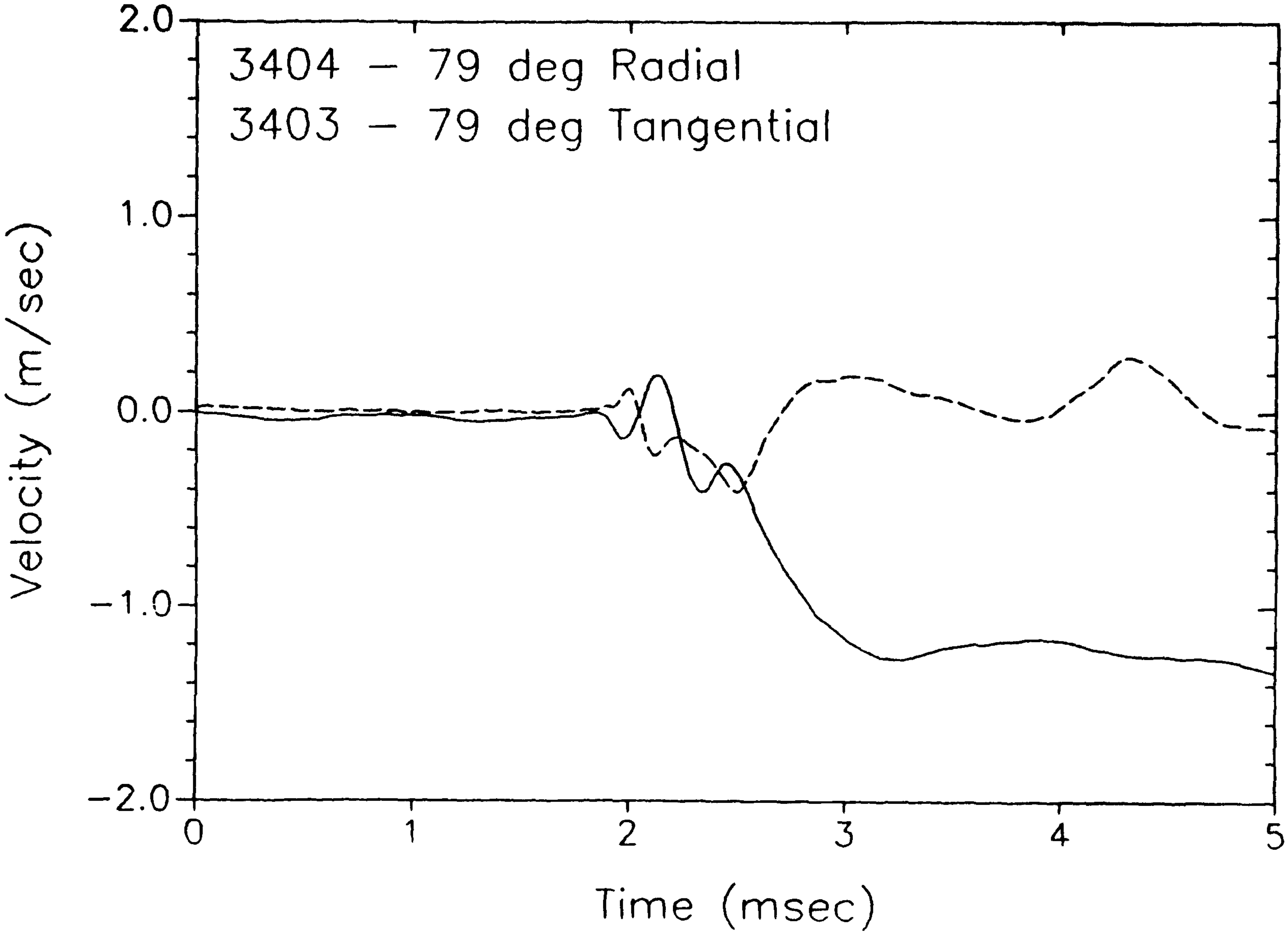

3401 – 349 deg Radial
3402 – 349 deg Tangential
Acceleration (kg)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
−1.0
0
1
2
3
4
5
Time (msec)

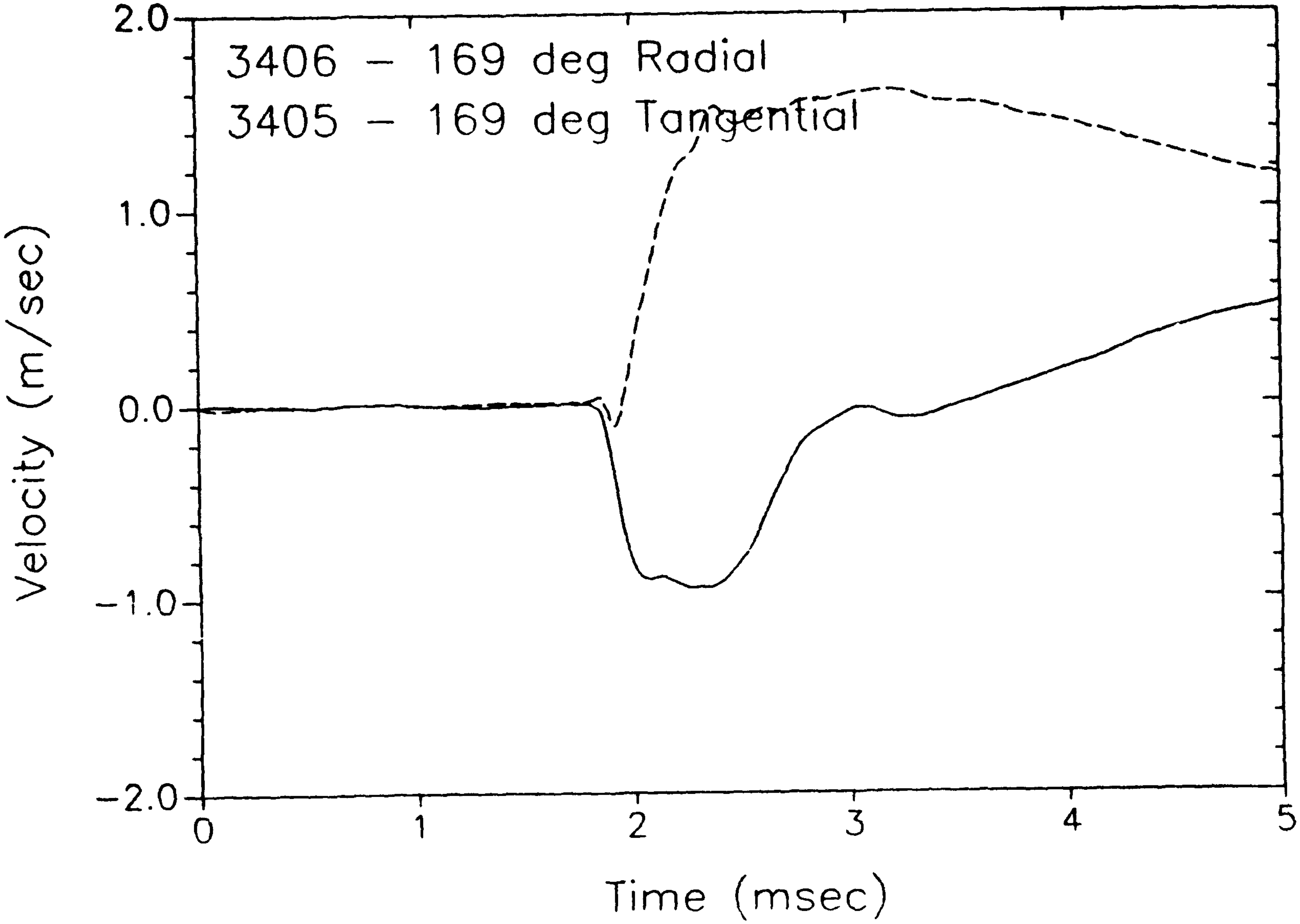

3404 – 79 deg Radial
3403 – 79 deg Tangential
Acceleration (kg)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
−1.0
0
1
2
3
4
5
Time (msec)

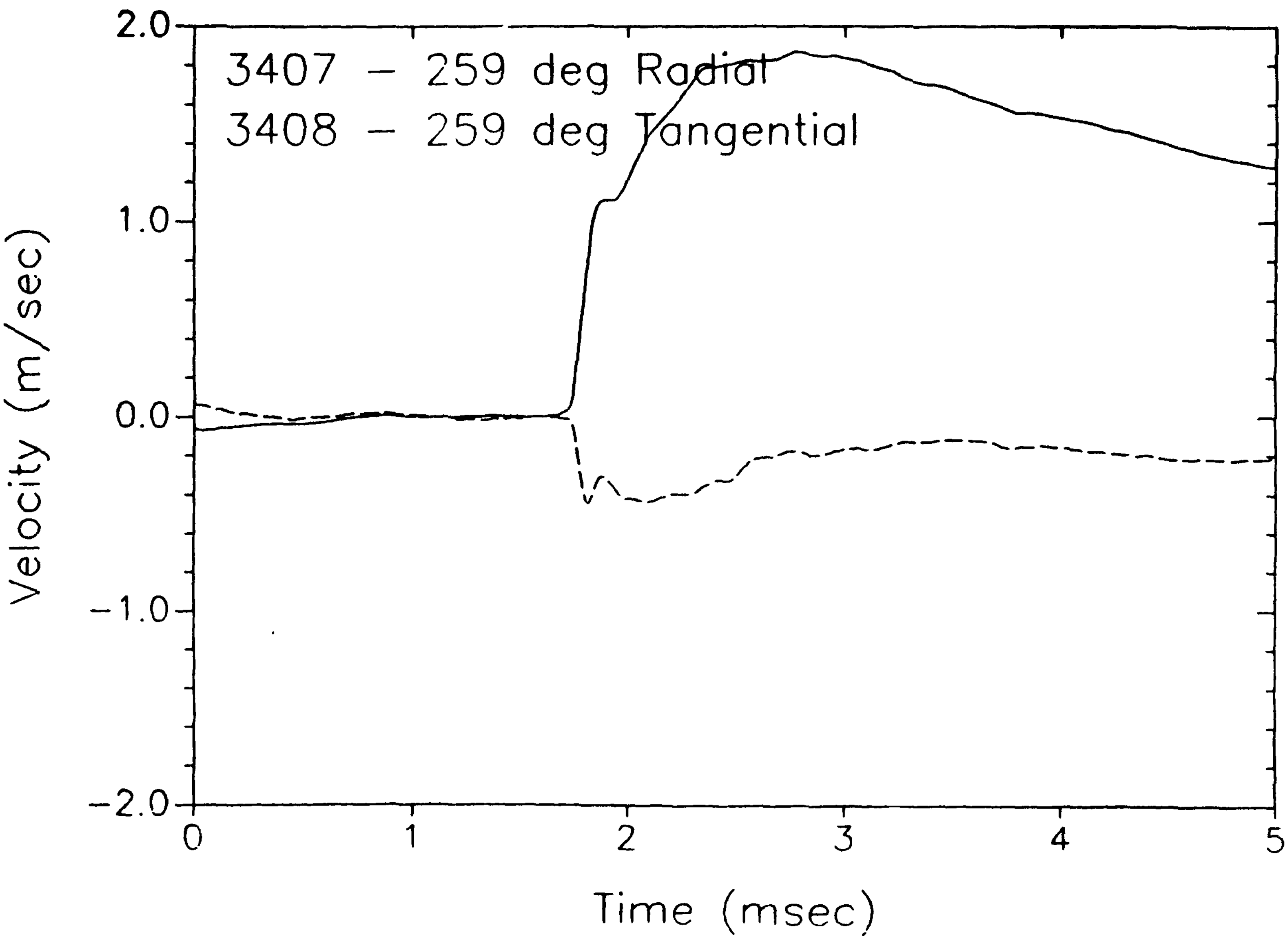

3406 – 169 deg Radial
3405 – 169 deg Tangential
Acceleration (kg)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
−1.0
0
1
2
3
4
5
Time (msec)

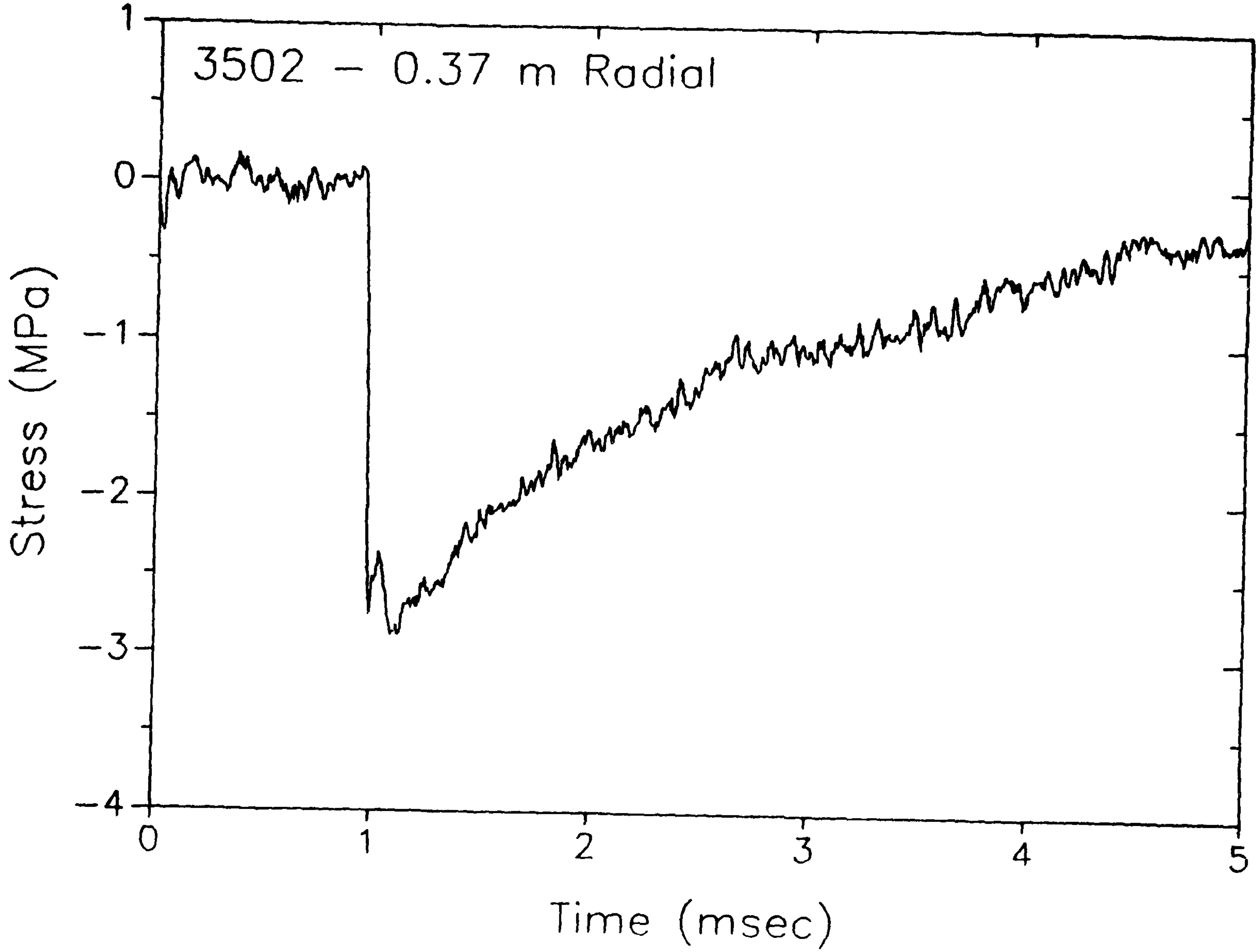

3407 — 259 deg Radial
3408 — 259 deg Tangential
Acceleration (kg)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
−1.0
0
1
2
3
4
5
Time (msec)

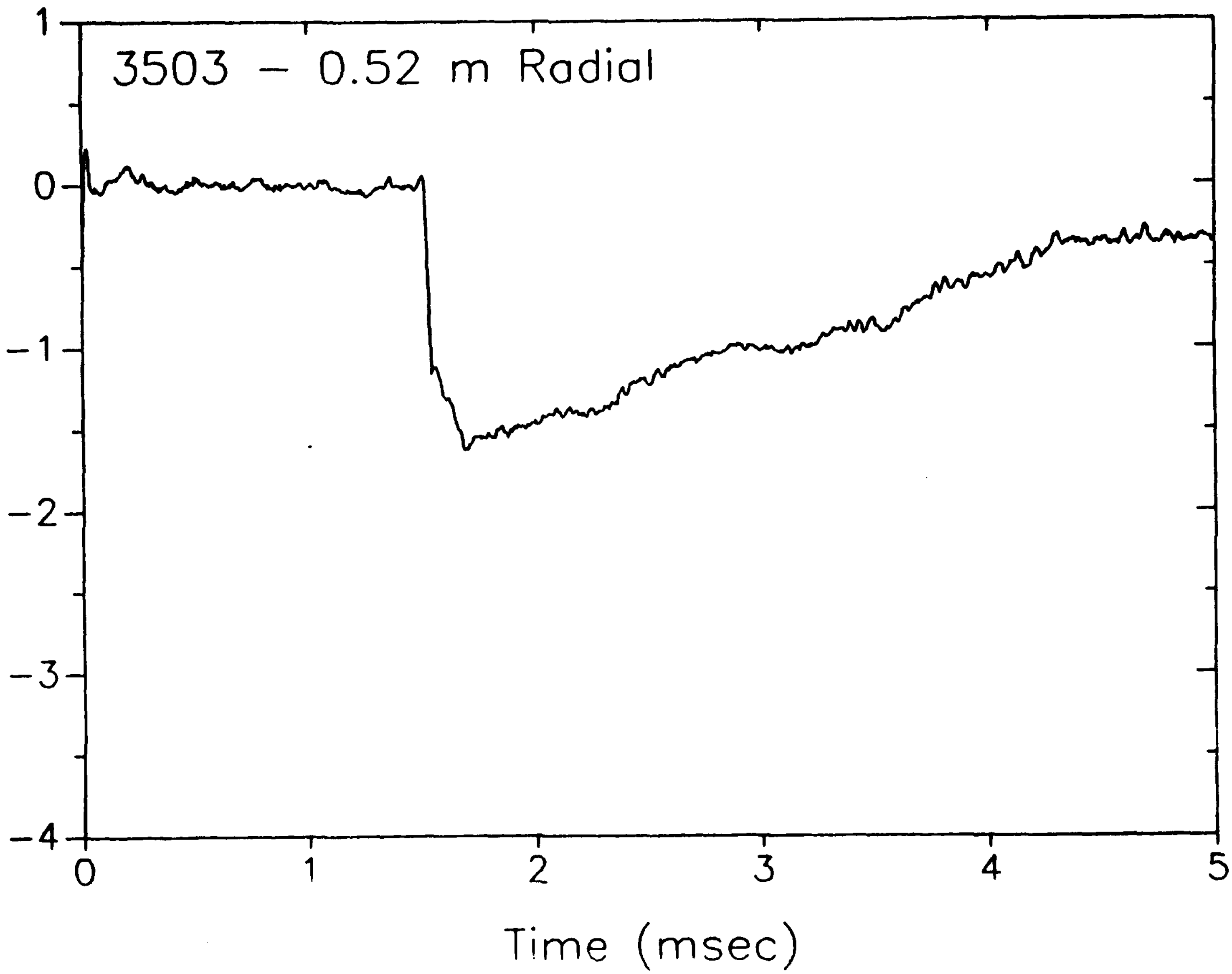

3401 – 349 deg Radial
3402 – 349 deg Tangential
2.0
1.0
0.0
−1.0
−2.0
Velocity (m/sec)
0
1
2
3
4
5
Time (msec)

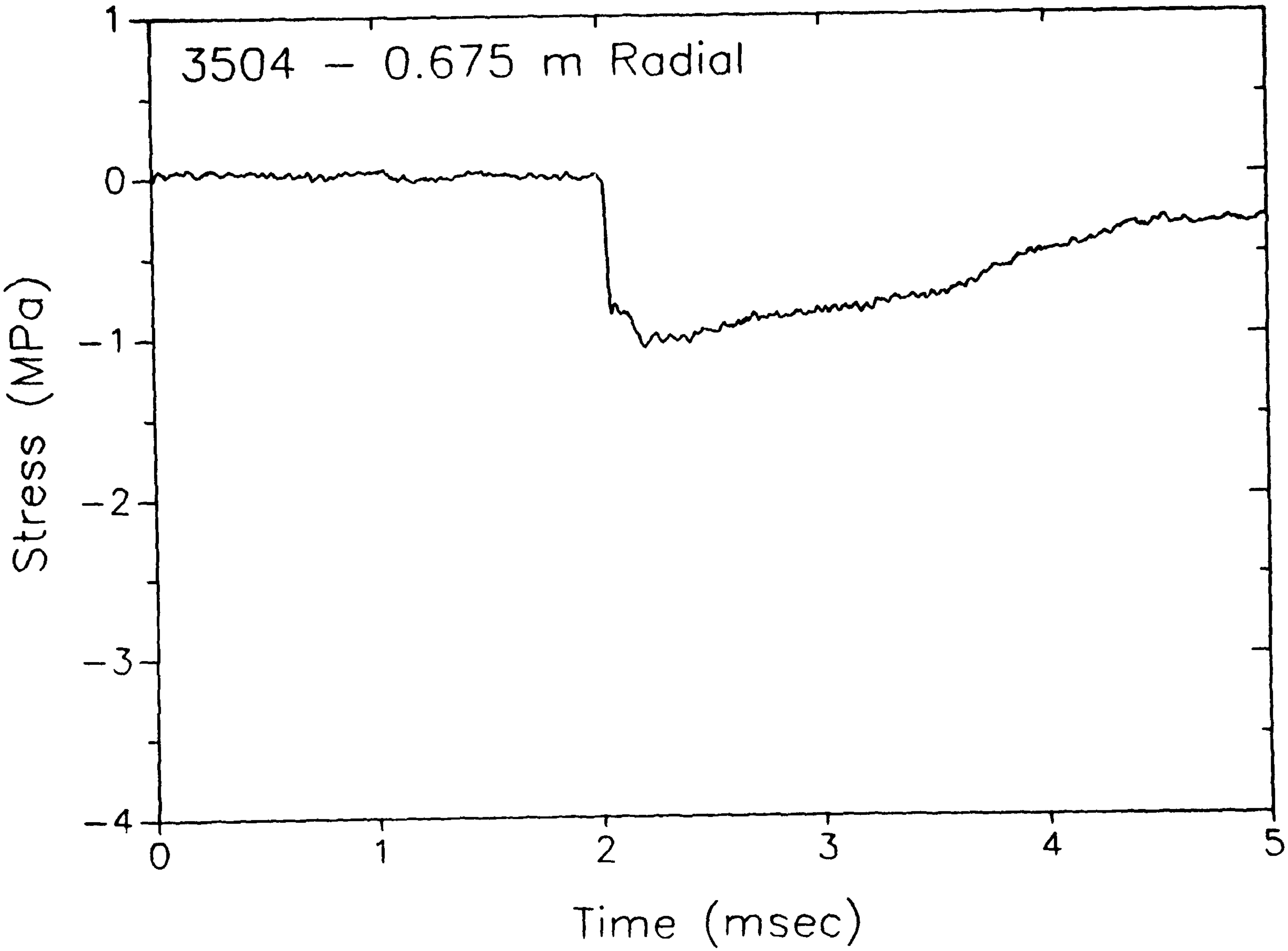

3404 – 79 deg Radial
3403 – 79 deg Tangential
2.0
1.0
0.0
-1.0
-2.0
Velocity (m/sec)
0
1
2
3
4
5
Time (msec)


3406 – 169 deg Radial
3405 – 169 deg Tangential
2.0
1.0
0.0
−1.0
−2.0
Velocity (m/sec)
0
1
2
3
4
5
Time (msec)


3407 – 259 deg Radial
3408 – 259 deg Tangential
Velocity (m/sec)
Time (msec)
2.0
1.0
0.0
-1.0
-2.0
0
1
2
3
4
5

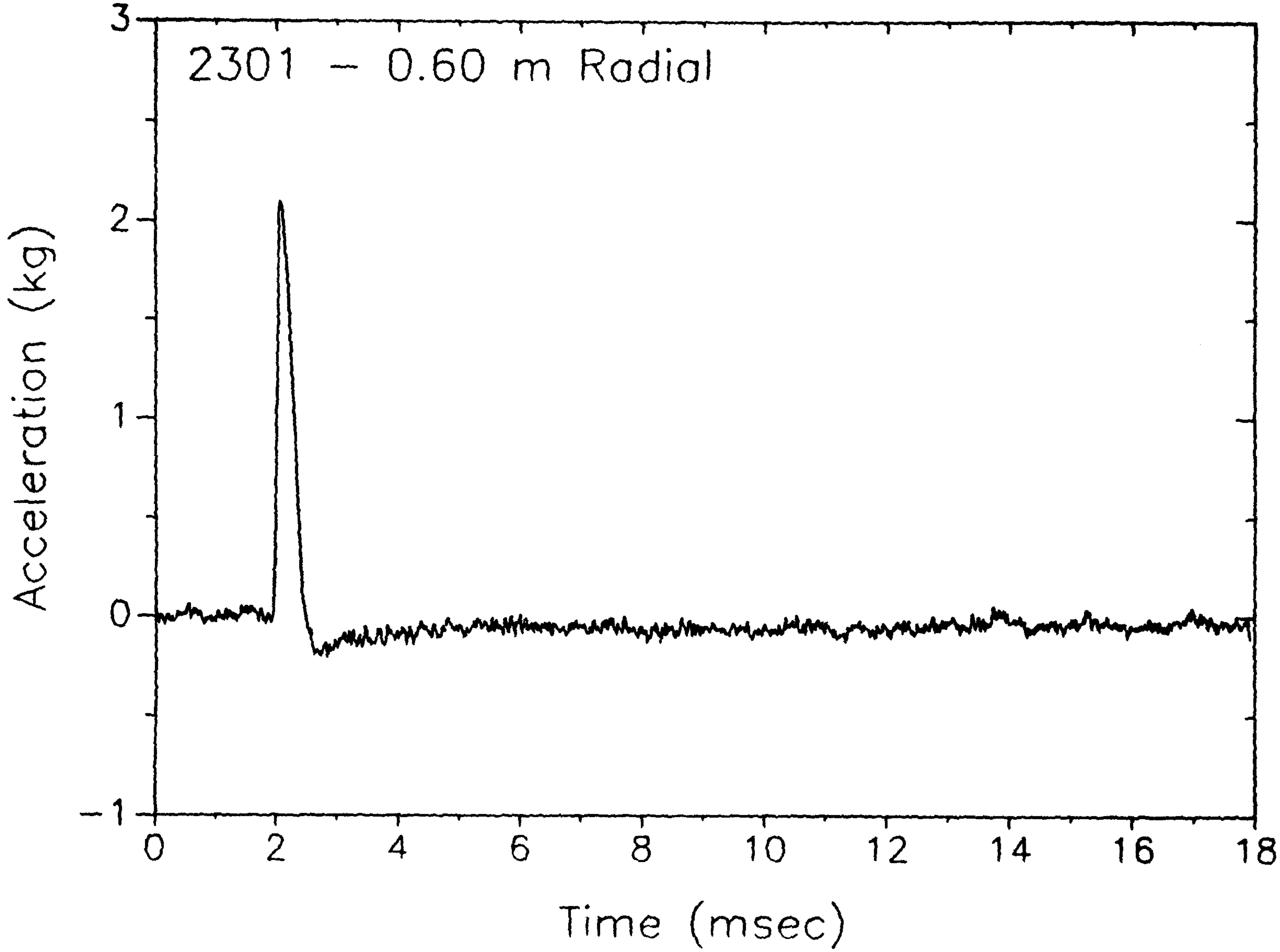

3502 – 0.37 m Radial
Stress (MPa)
1
0
−1
−2
−3
−4
0
1
2
3
4
5
Time (msec)

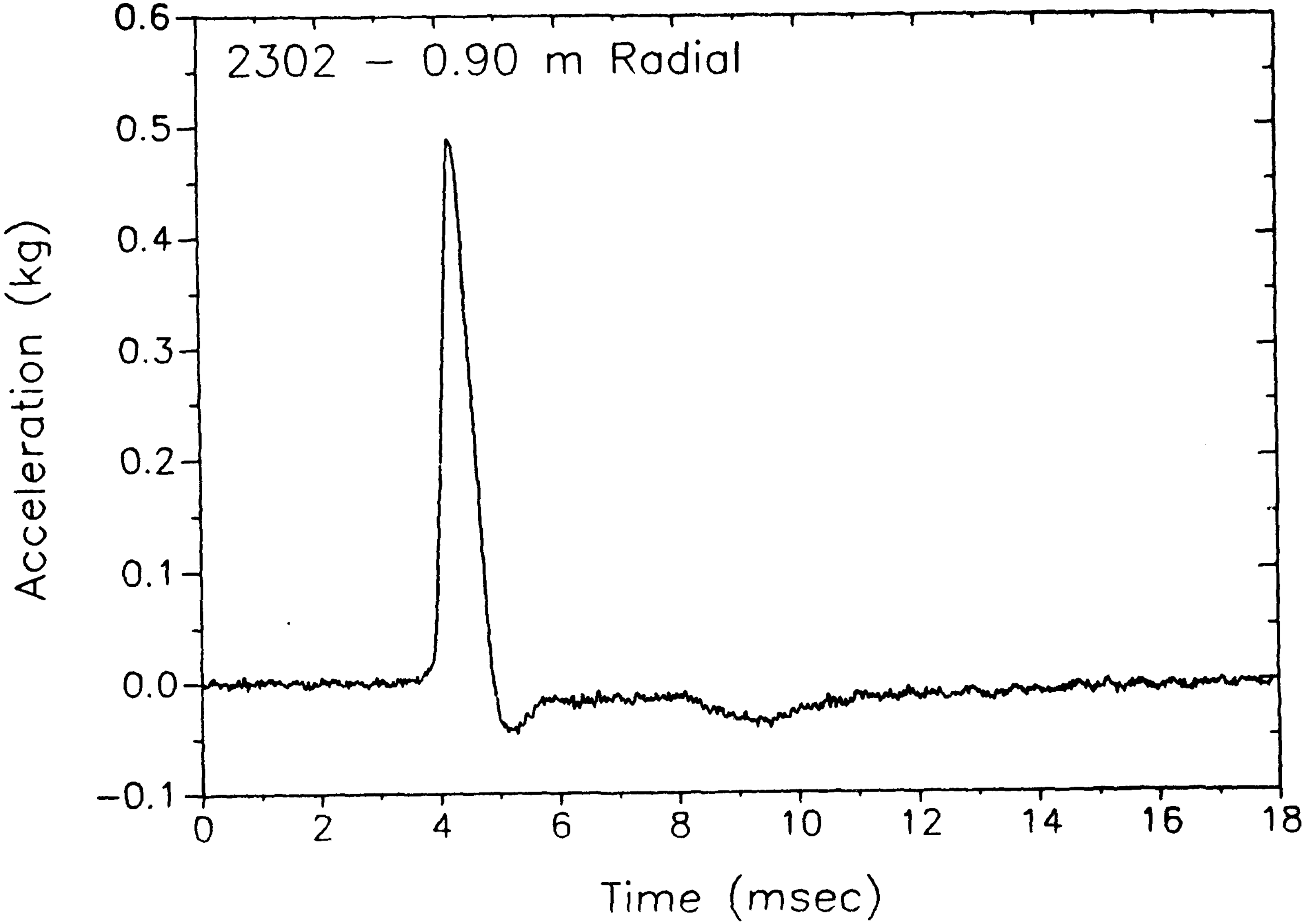

3503 – 0.52 m Radial
Stress (MPa)
Time (msec)
1
0
−1
−2
−3
−4
0
1
2
3
4
5

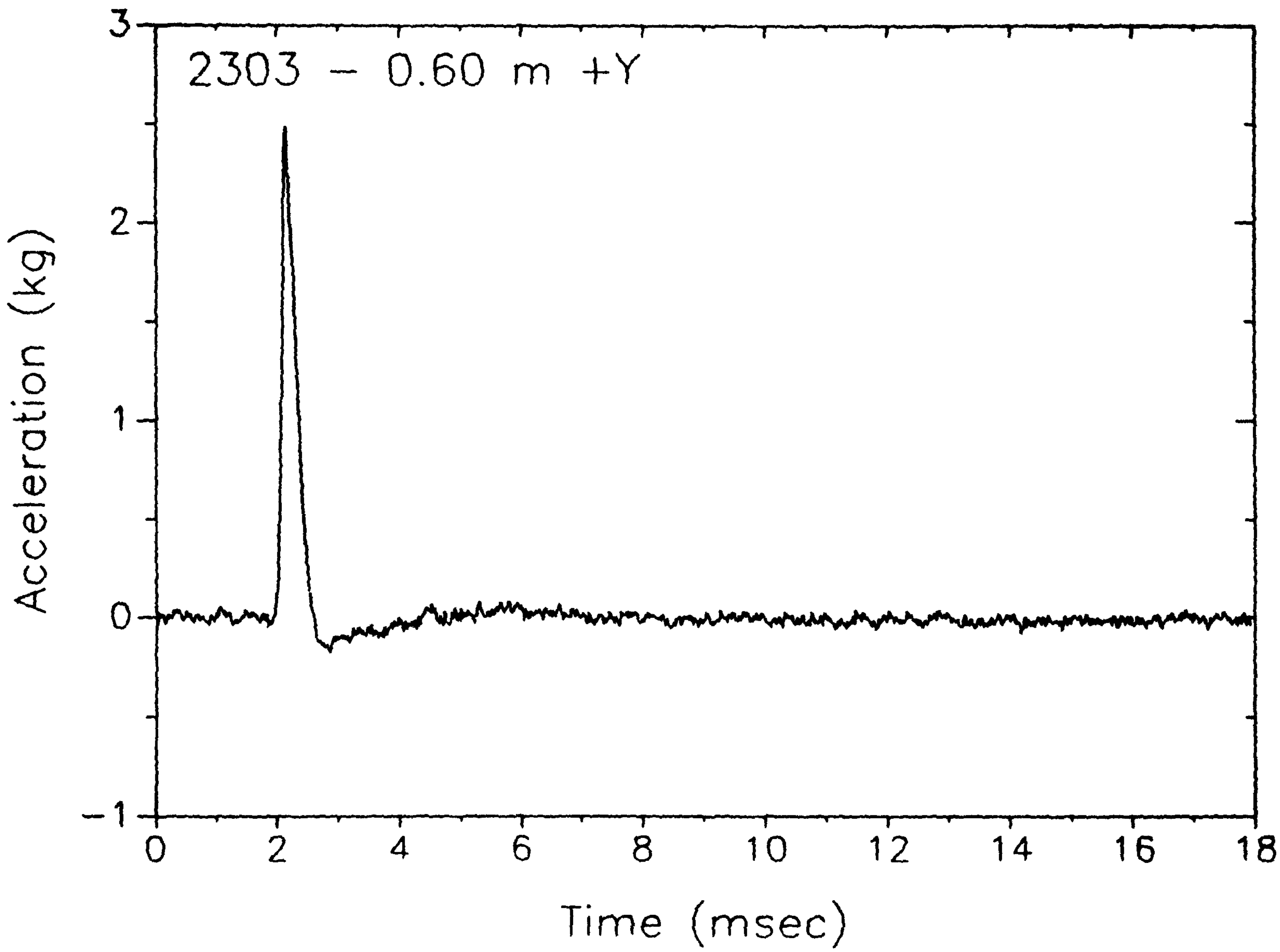

3504 – 0.675 m Radial
Stress (MPa)
Time (msec)
1
0
–1
–2
–3
–4
0
1
2
3
4
5

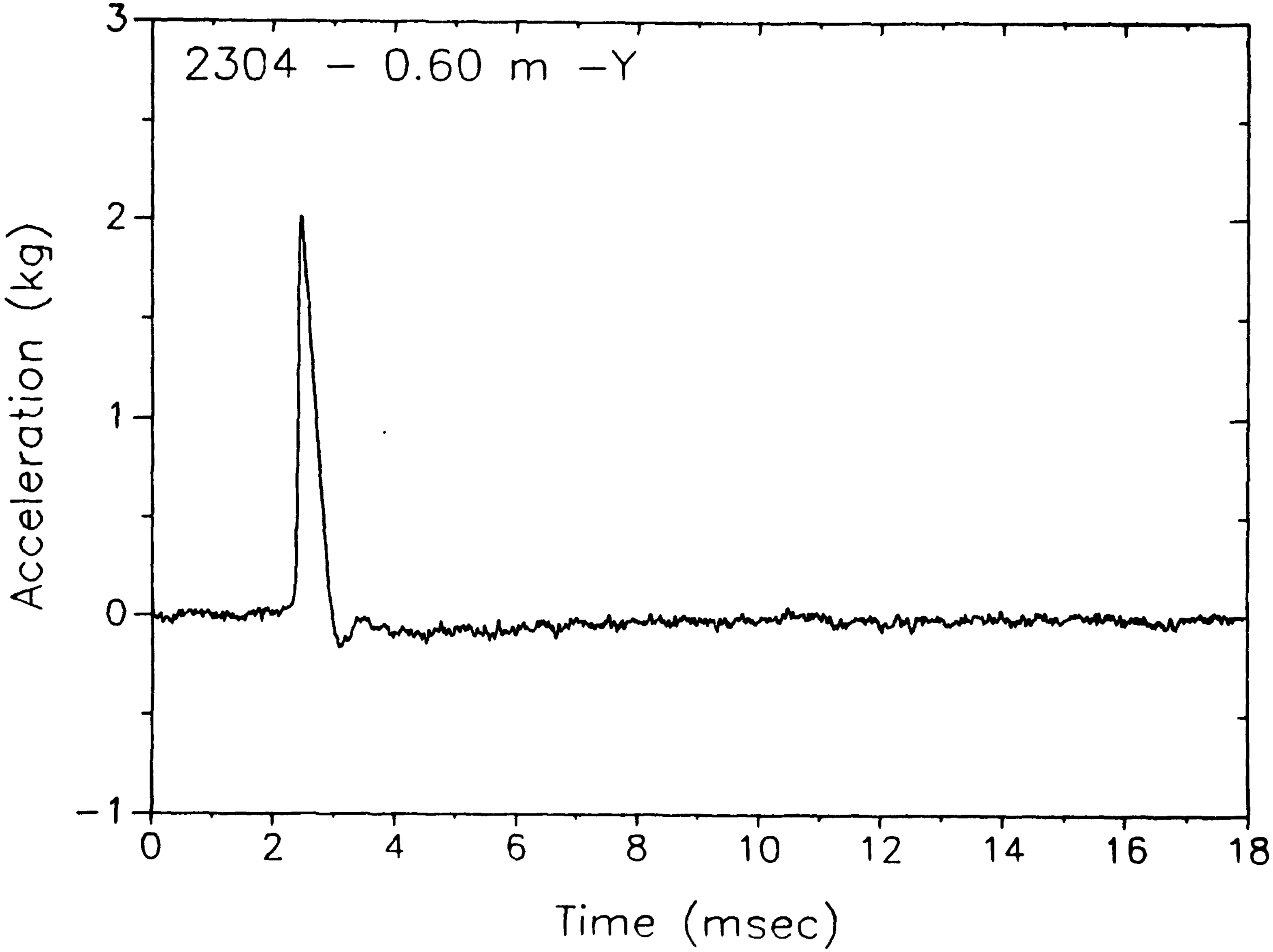
1/5 FROUDE SCALED TEST

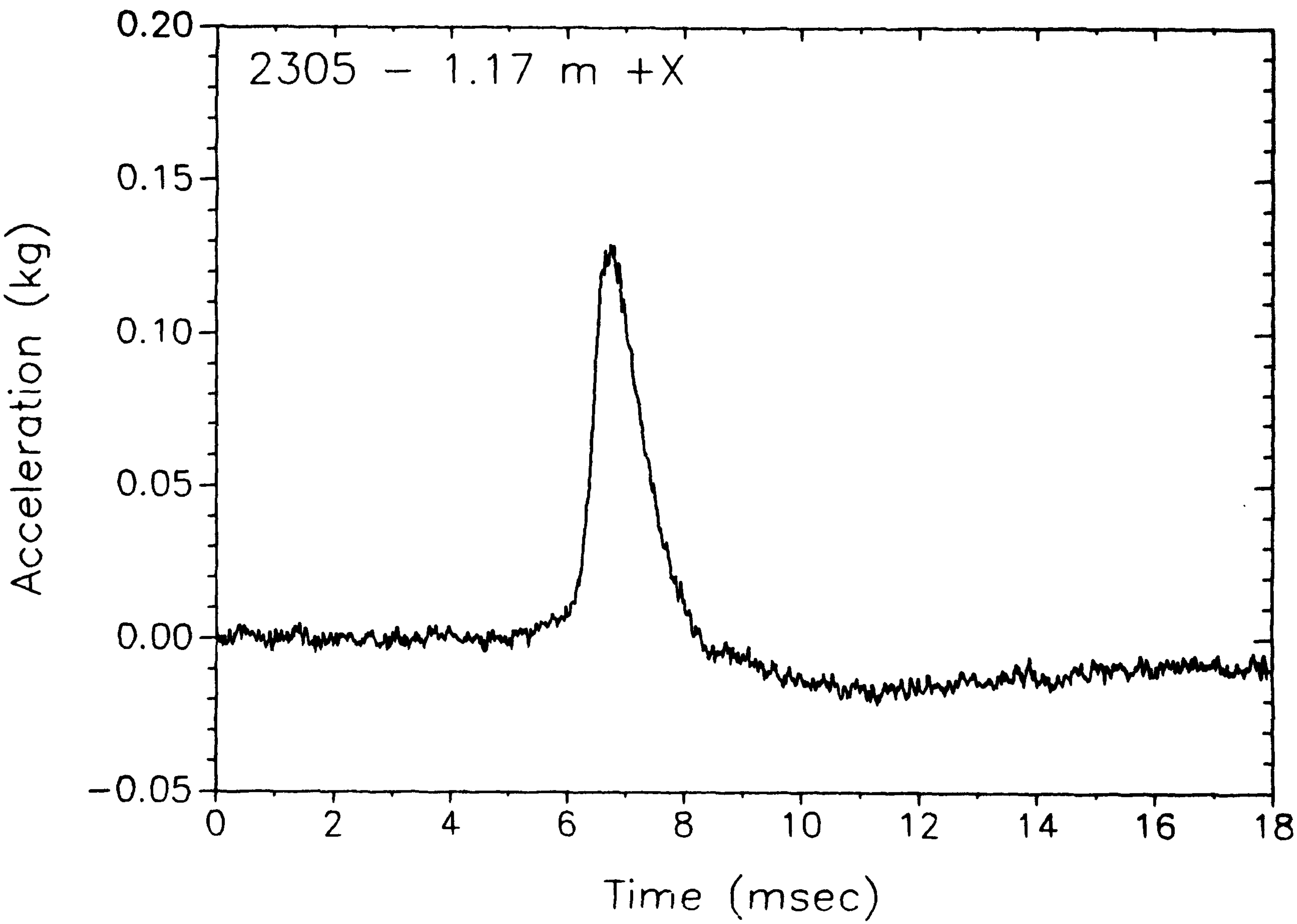
"COAL"

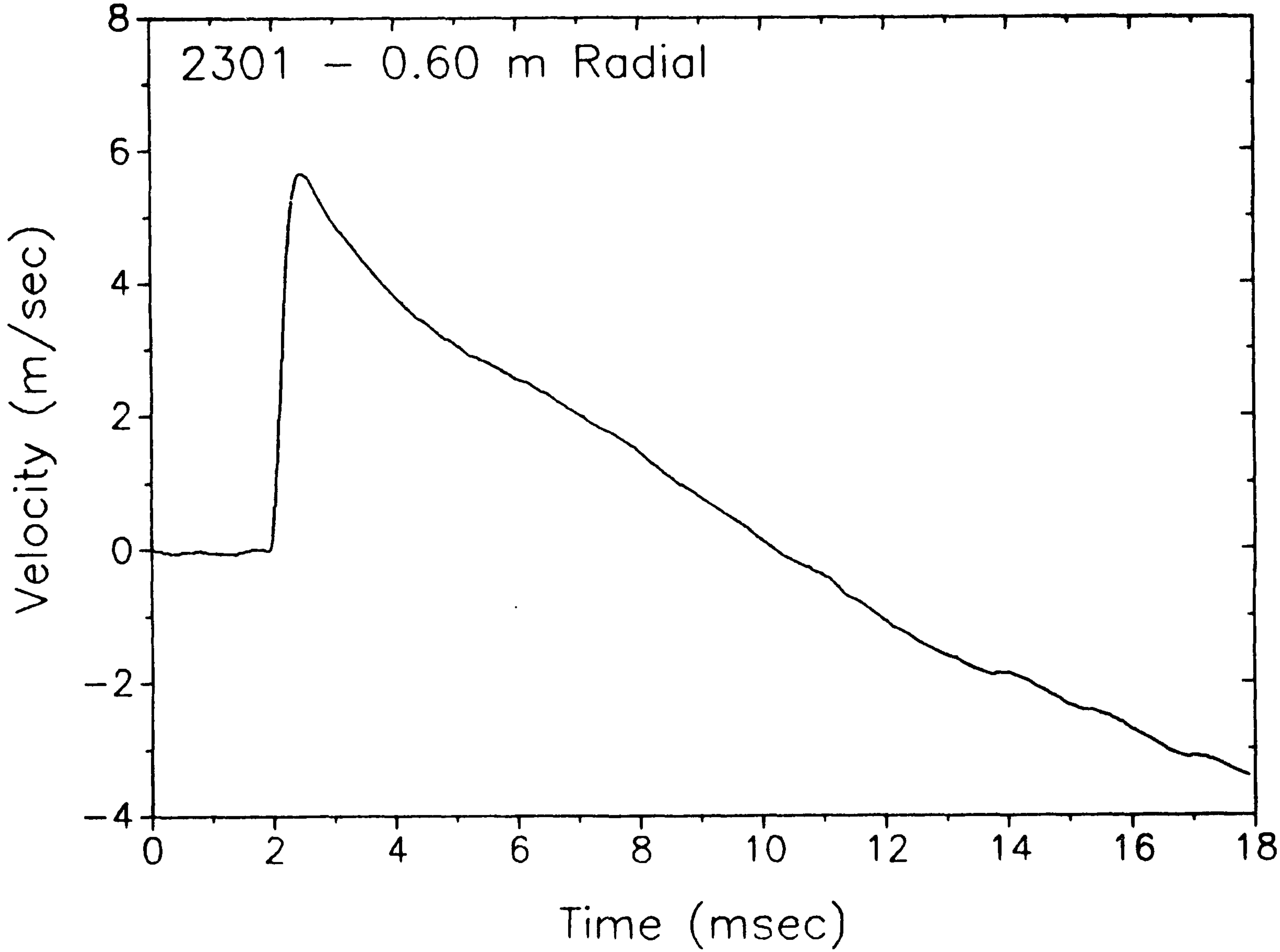

2301 – 0.60 m Radial
Acceleration (kg)
3
2
1
0
–1
0
2
4
6
8
10
12
14
16
18
Time (msec)

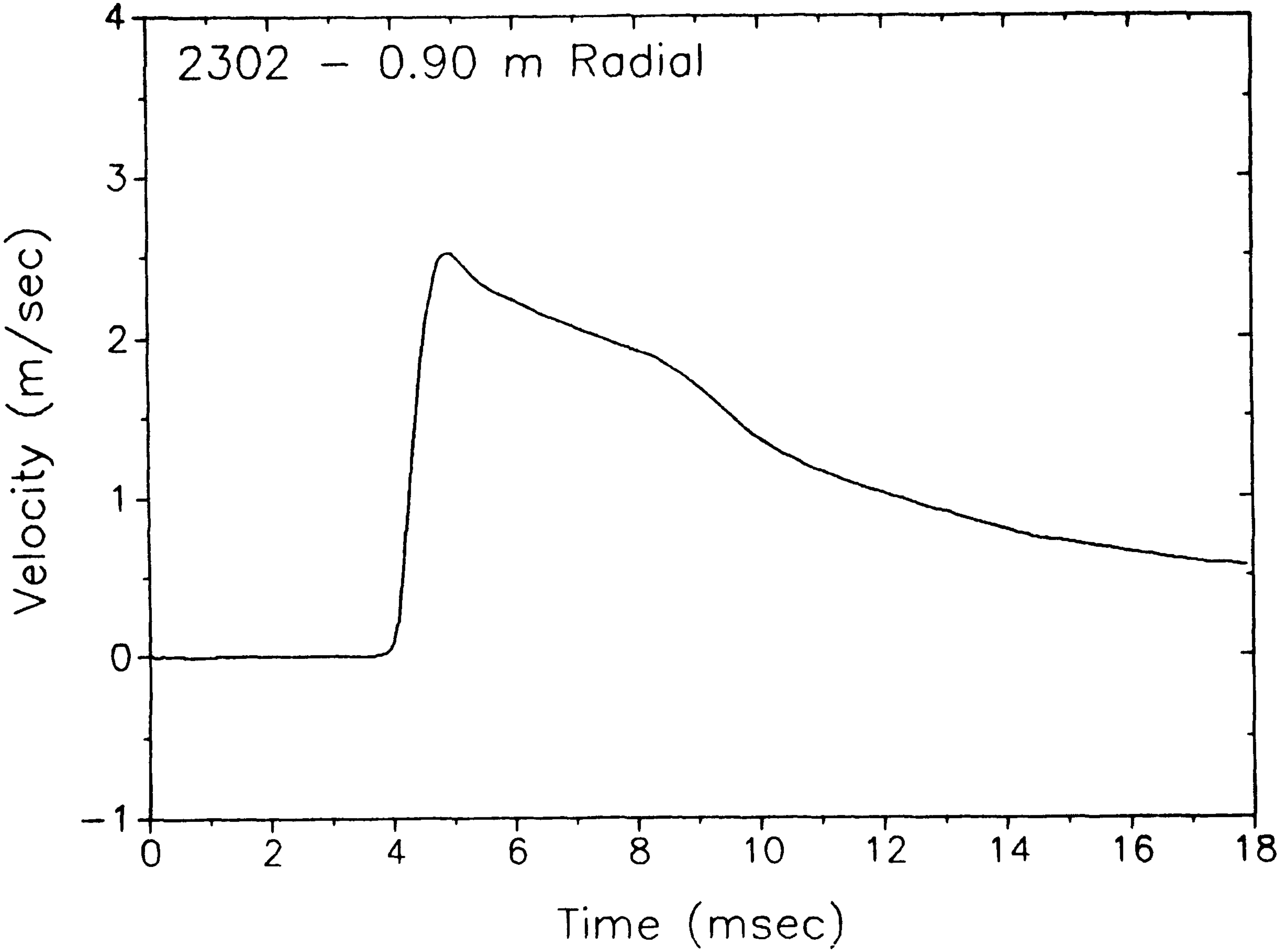

2302 – 0.90 m Radial
Acceleration (kg)
0.6
0.5
0.4
0.3
0.2
0.1
0.0
–0.1
0
2
4
6
8
10
12
14
16
18
Time (msec)

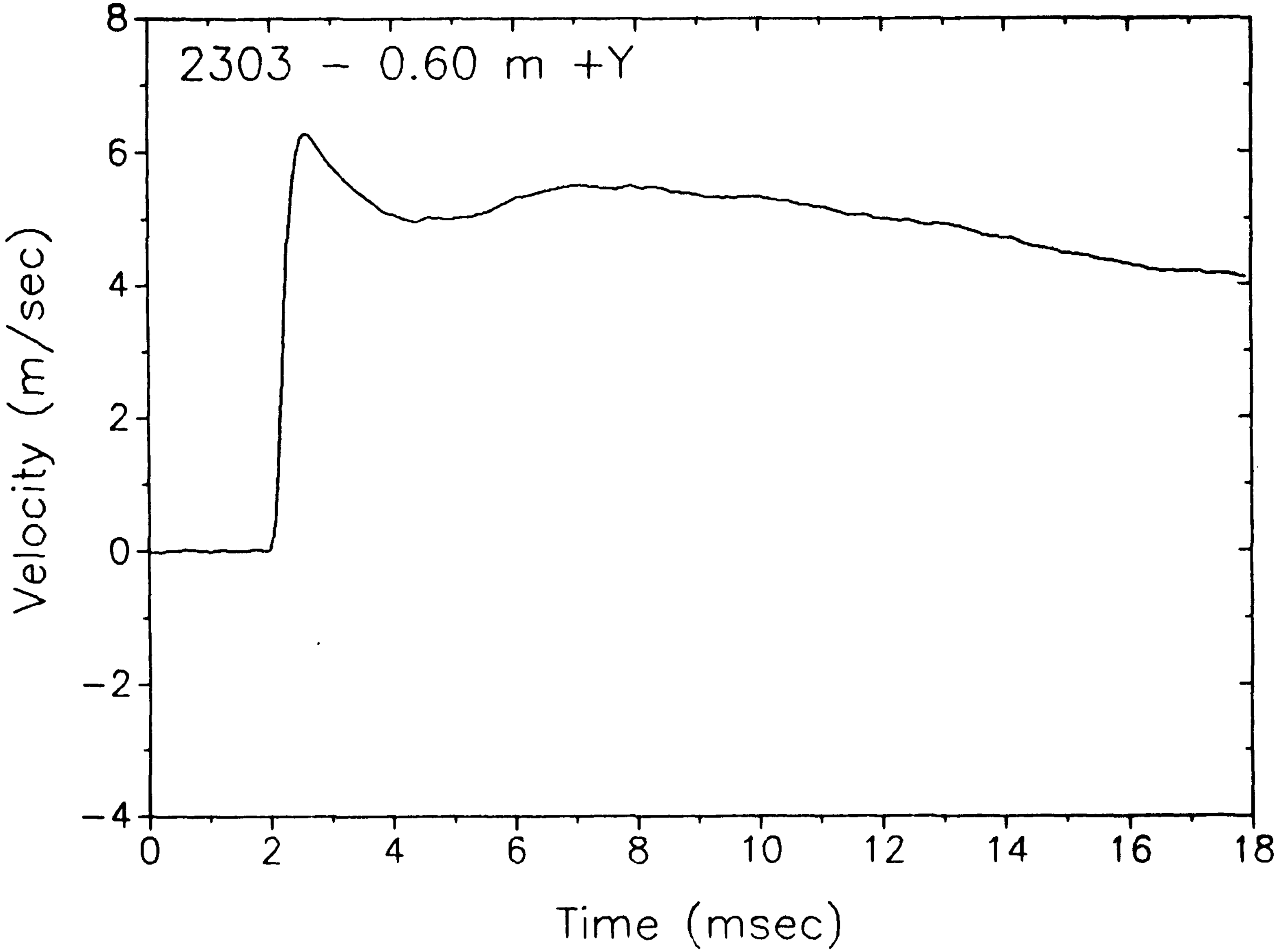

2303 – 0.60 m +Y
Acceleration (kg)
3
2
1
0
–1
0
2
4
6
8
10
12
14
16
18
Time (msec)

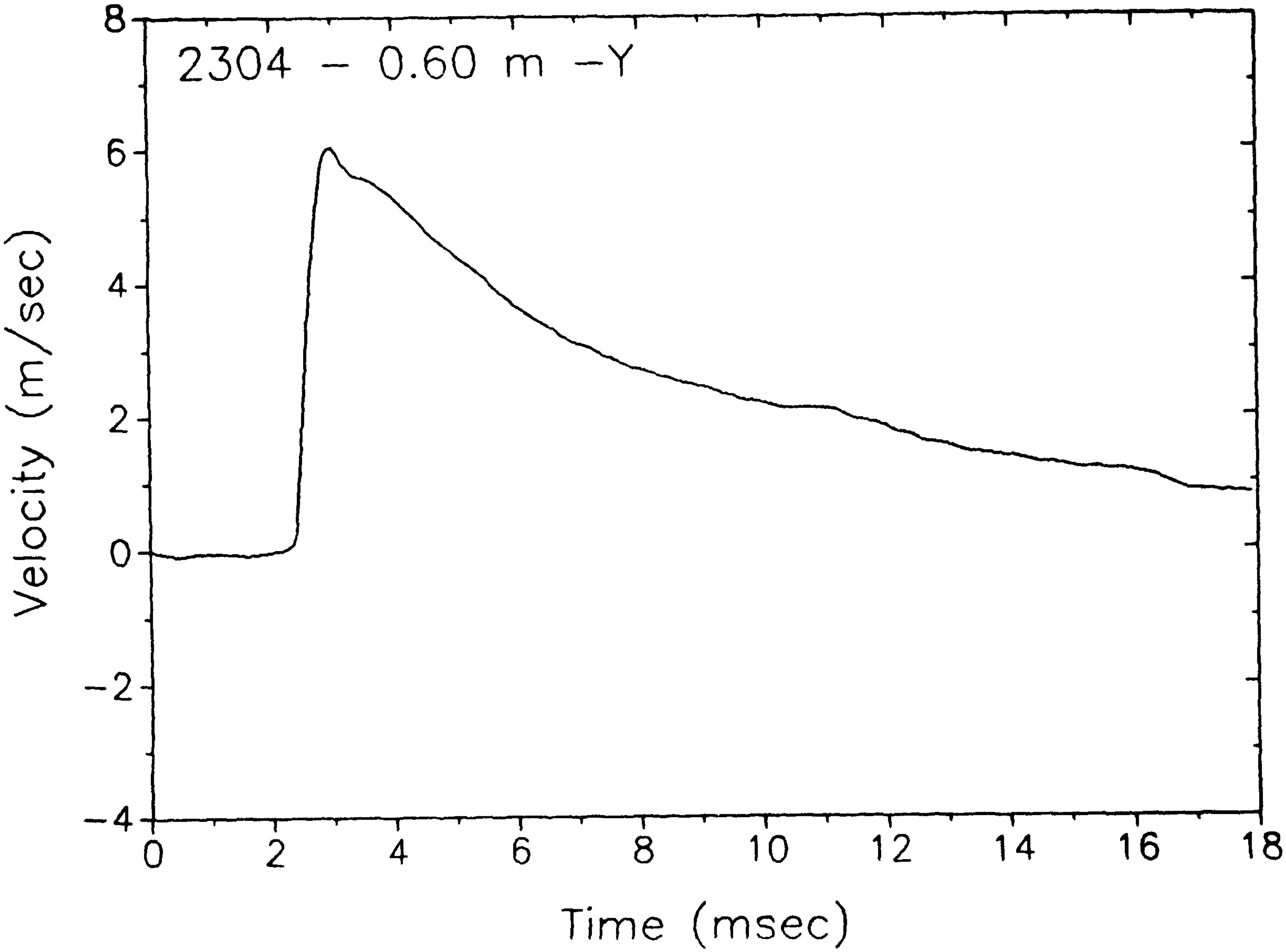

2304 – 0.60 m –Y
Acceleration (kg)
3
2
1
0
–1
0
2
4
6
8
10
12
14
16
18
Time (msec)

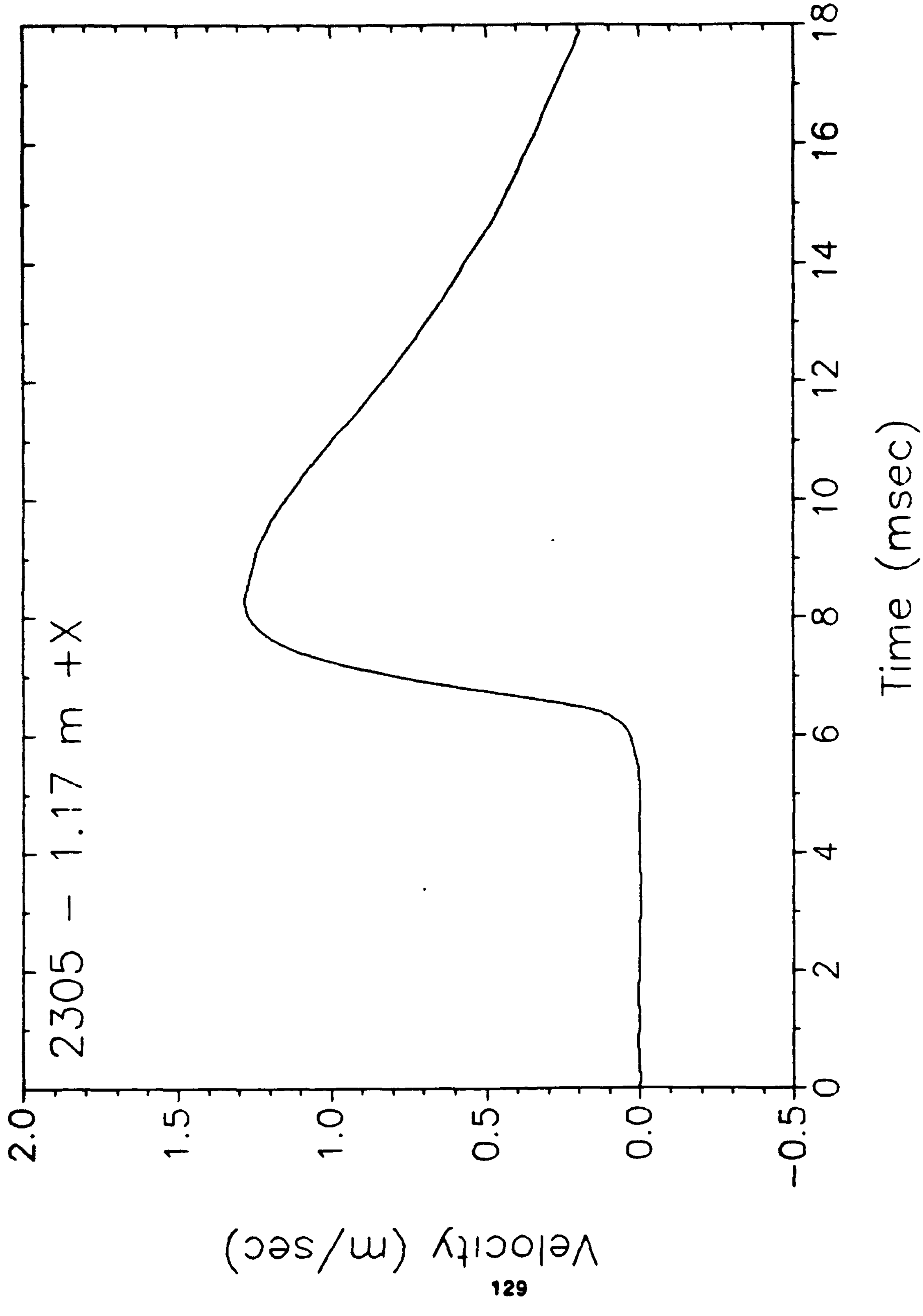

2305 – 1.17 m +X
Acceleration (kg)
0.20
0.15
0.10
0.05
0.00
−0.05
0
2
4
6
8
10
12
14
16
18
Time (msec)

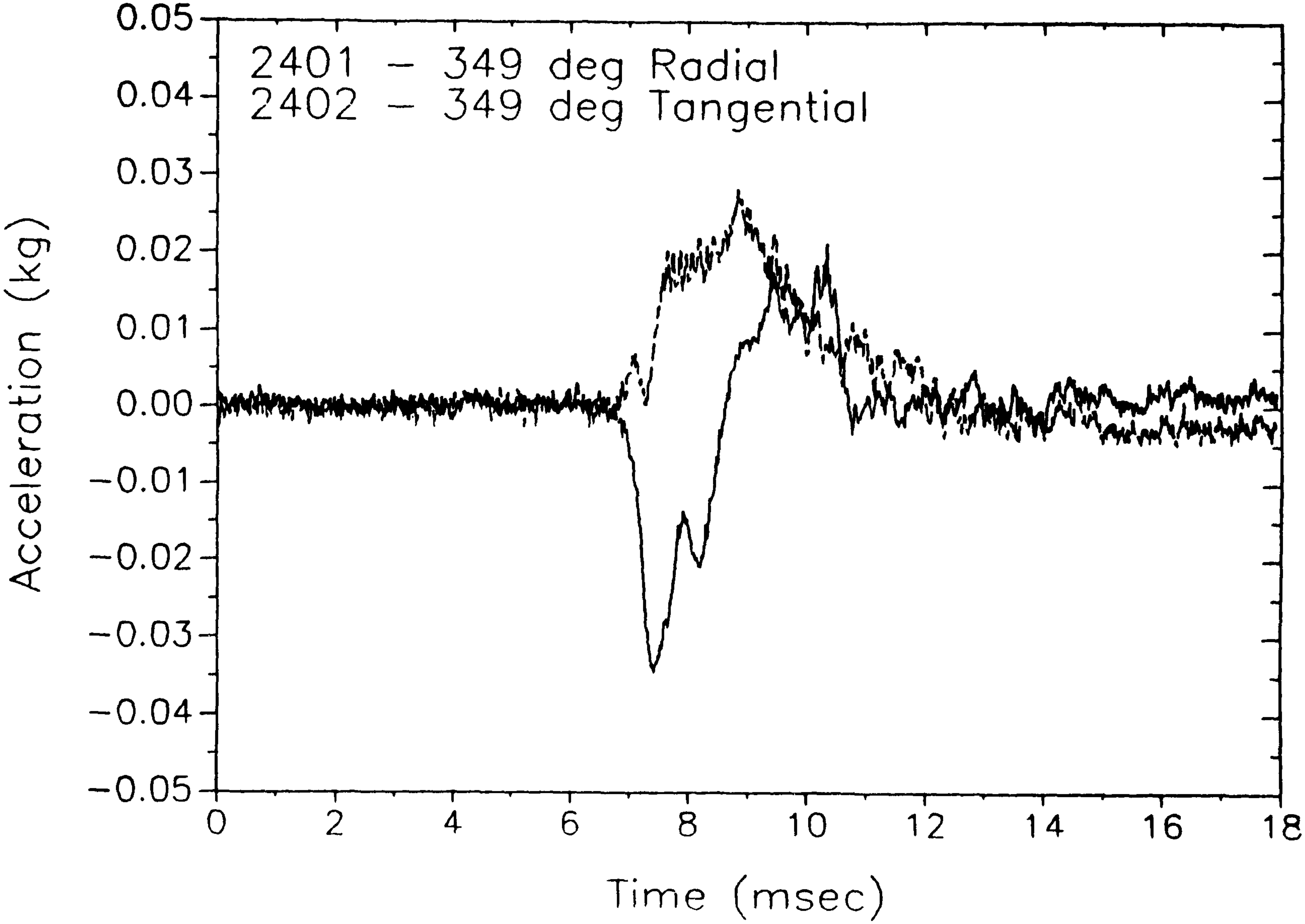

2301 – 0.60 m Radial
Velocity (m/sec)
Time (msec)
8
6
4
2
0
−2
−4
0
2
4
6
8
10
12
14
16
18


2302 – 0.90 m Radial
Velocity (m/sec)
Time (msec)
4
3
2
1
0
−1
0
2
4
6
8
10
12
14
16
18

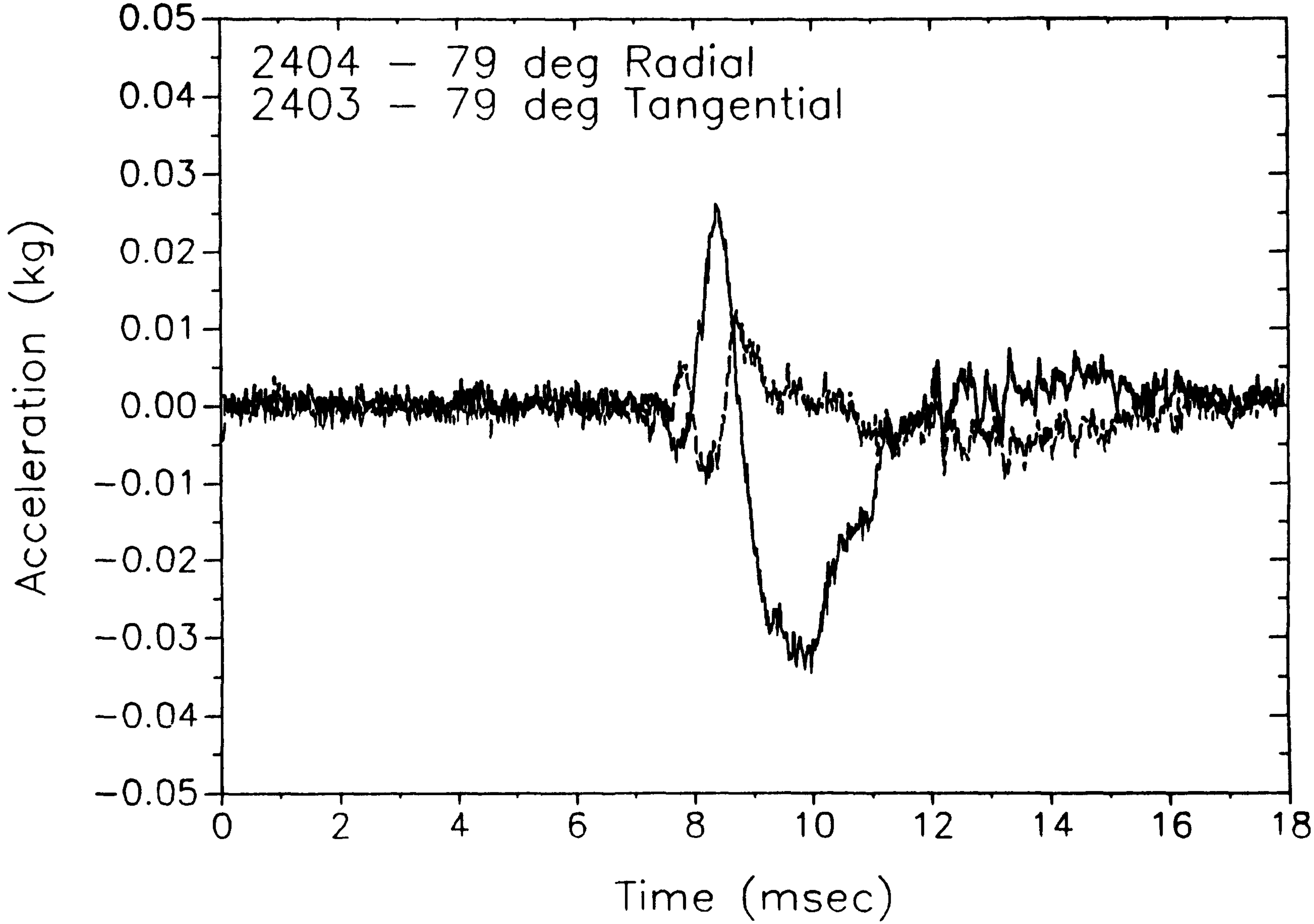

2303 – 0.60 m +Y
Velocity (m/sec)
Time (msec)
8
6
4
2
0
−2
−4
0
2
4
6
8
10
12
14
16
18

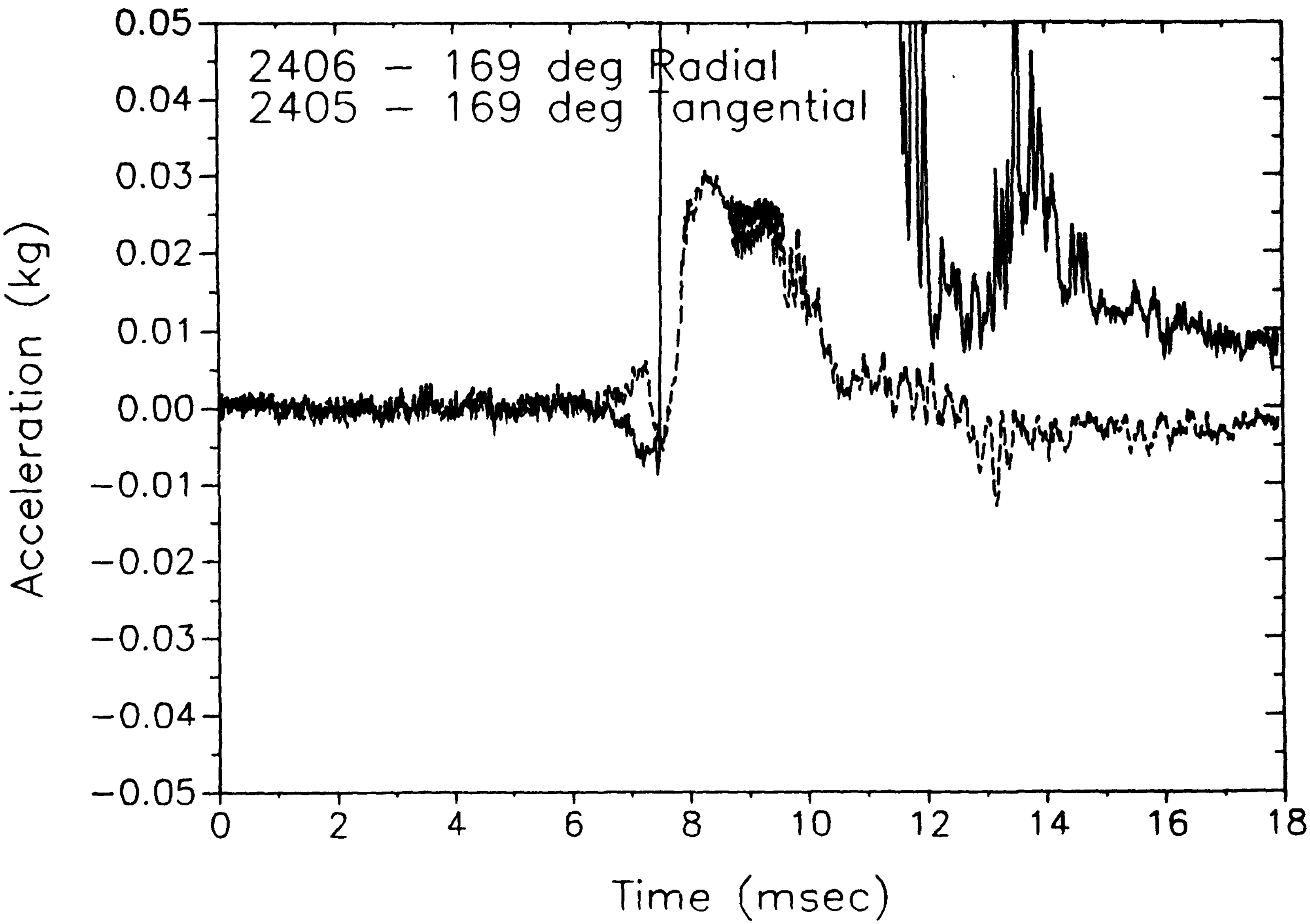

2304 – 0.60 m –Y
Velocity (m/sec)
Time (msec)
8
6
4
2
0
−2
−4
0
2
4
6
8
10
12
14
16
18

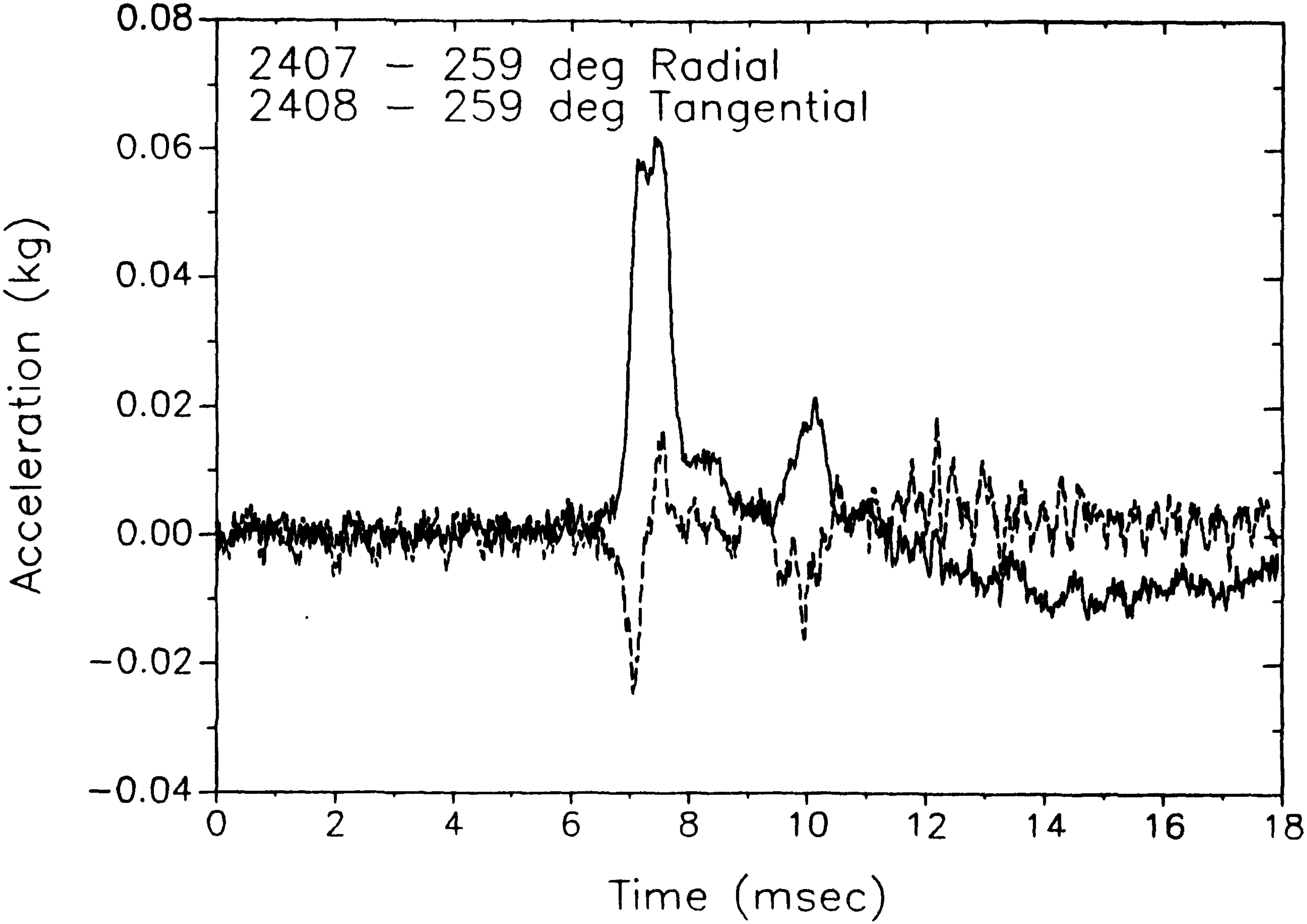

2305 – 1.17 m +X
Velocity (m/sec)
Time (msec)
2.0
1.5
1.0
0.5
0.0
−0.5
0
2
4
6
8
10
12
14
16
18

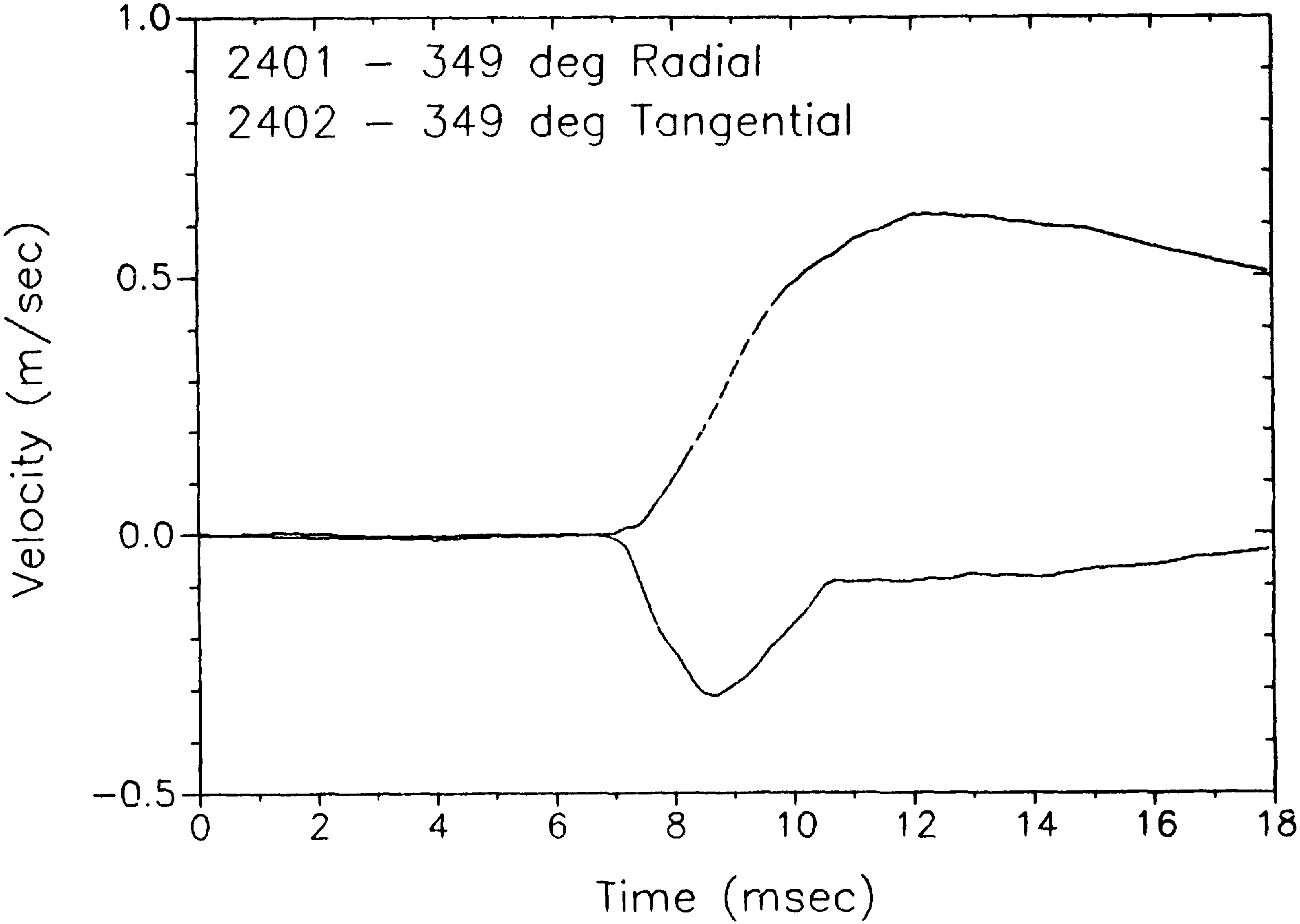


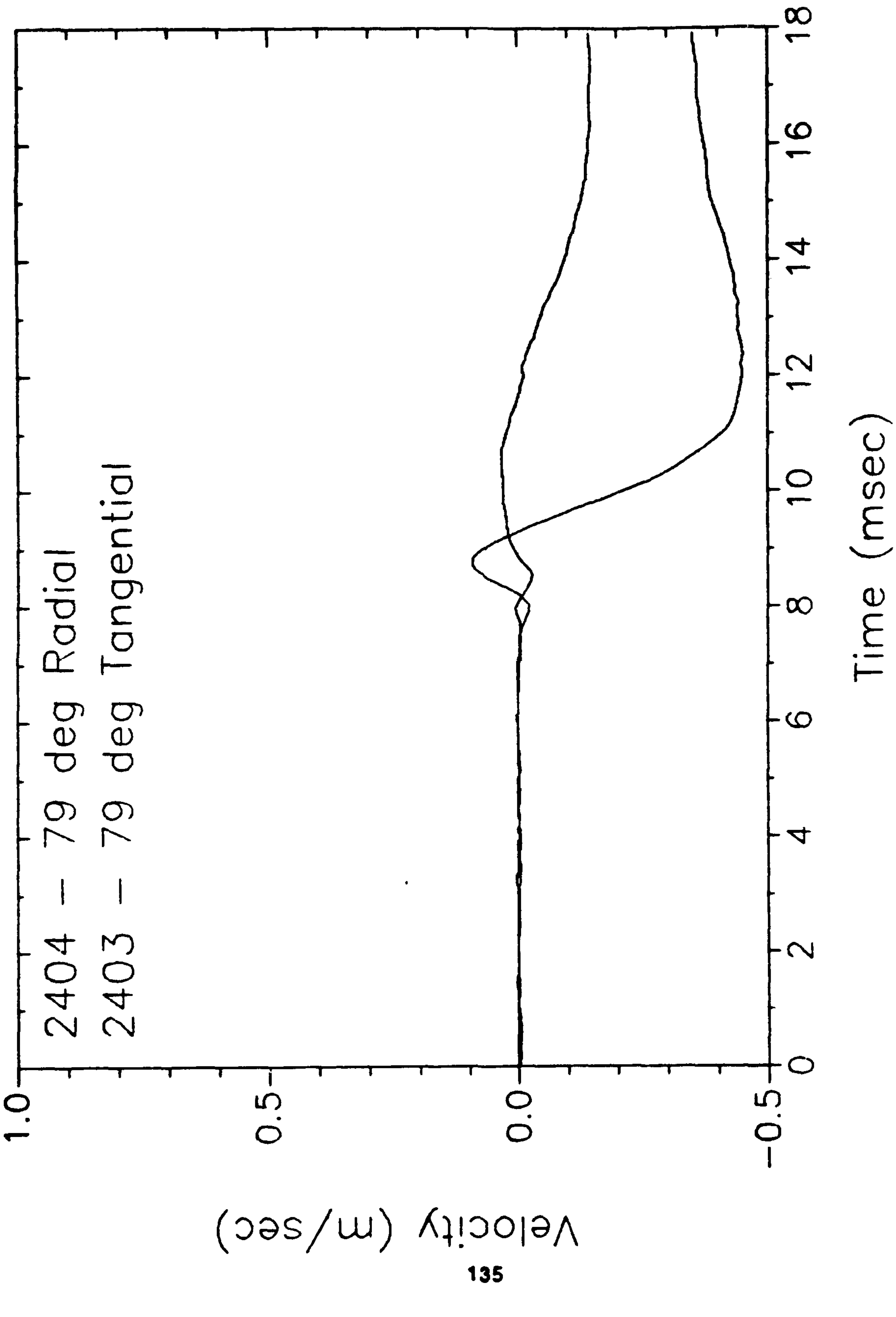
2401 – 349 deg Radial
2402 – 349 deg Tangential
0.05
0.04
0.03
0.02
0.01
0.00
−0.01
−0.02
−0.03
−0.04
−0.05
Acceleration (kg)
0
2
4
6
8
10
12
14
16
18
Time (msec)

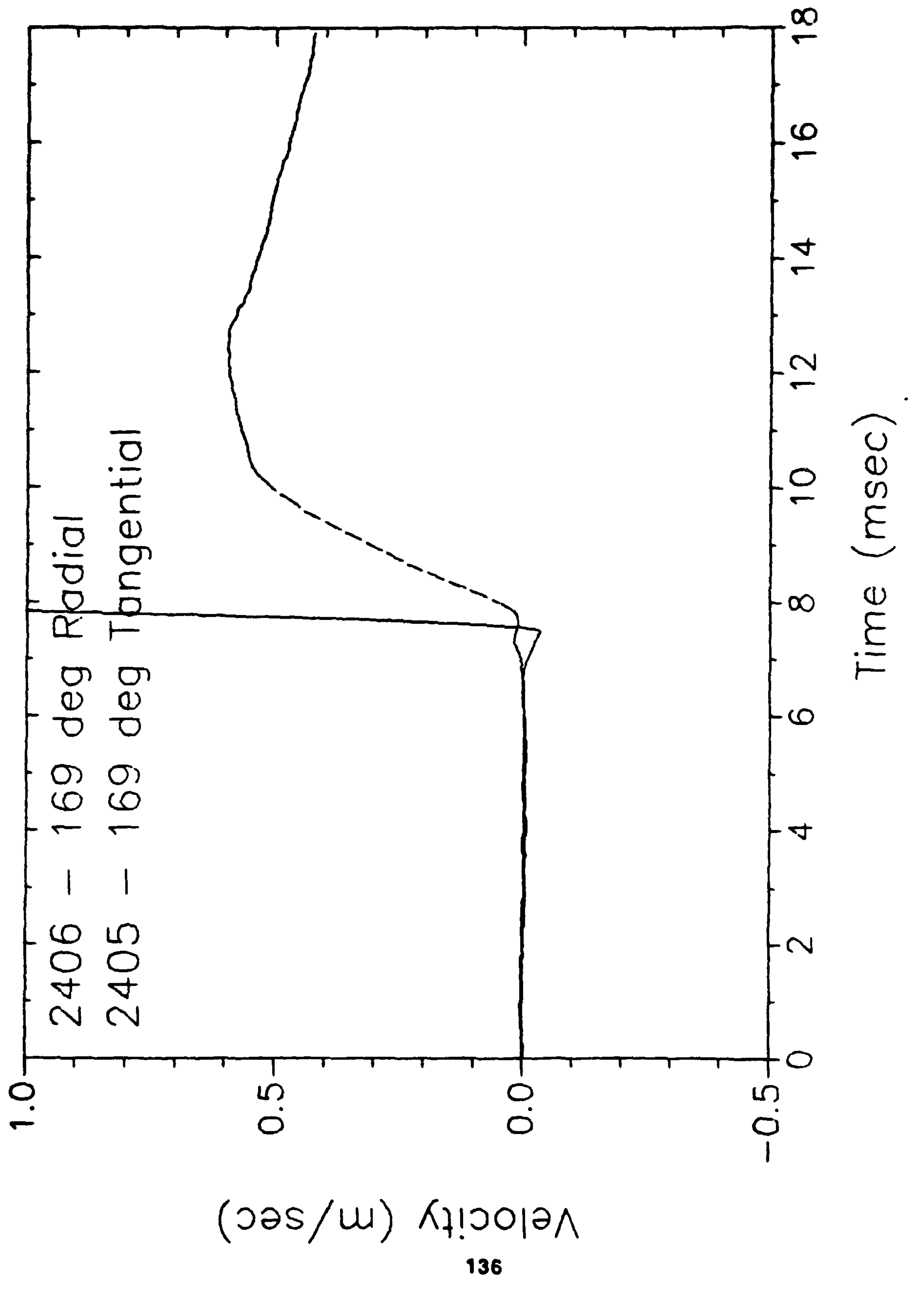

2404 – 79 deg Radial
2403 – 79 deg Tangential
Acceleration (kg)
0.05
0.04
0.03
0.02
0.01
0.00
−0.01
−0.02
−0.03
−0.04
−0.05
0
2
4
6
8
10
12
14
16
18
Time (msec)


2406 – 169 deg Radial
2405 – 169 deg Tangential
Acceleration (kg)
0.05
0.04
0.03
0.02
0.01
0.00
–0.01
–0.02
–0.03
–0.04
–0.05
0
2
4
6
8
10
12
14
16
18
Time (msec)

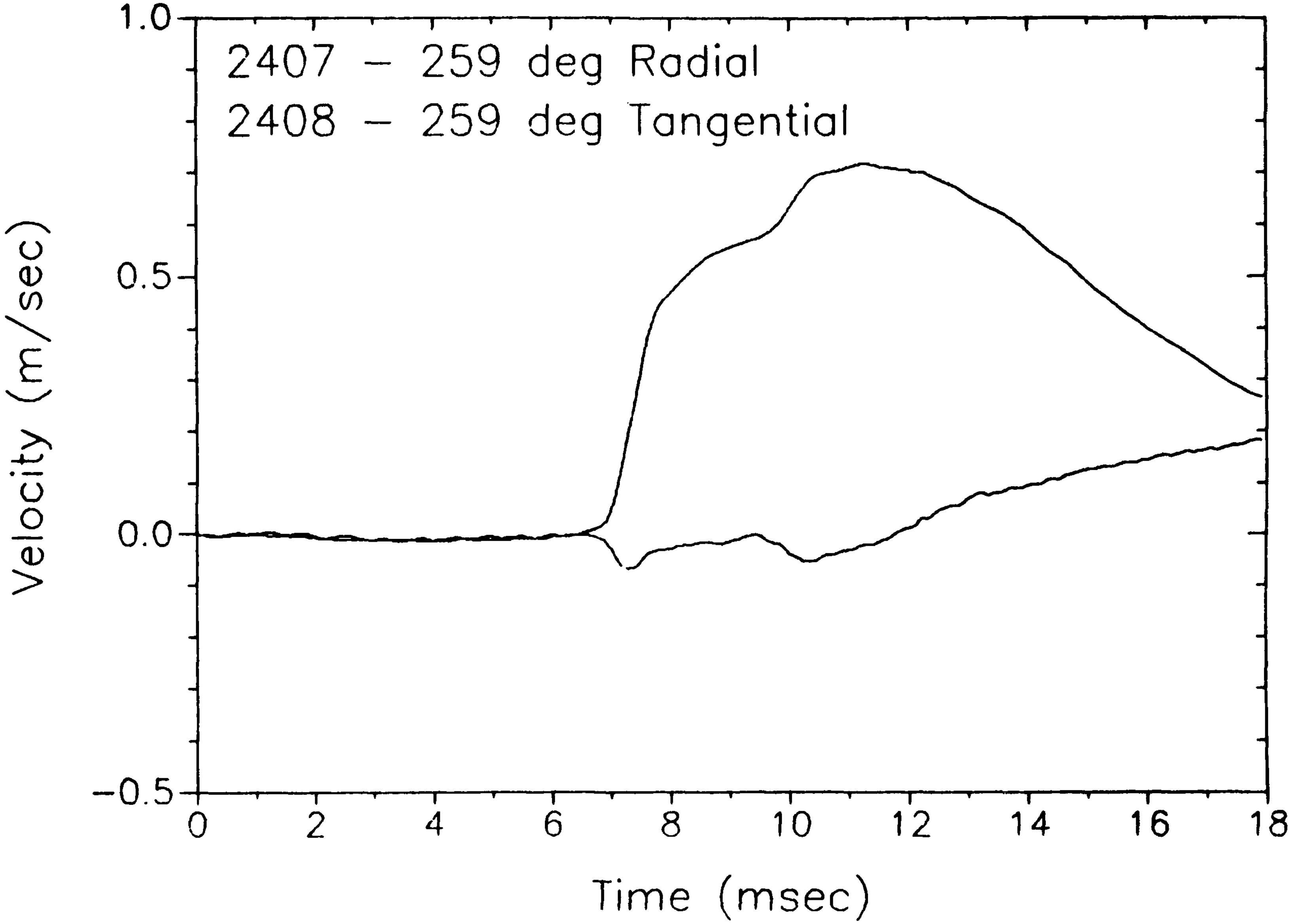

2407 – 259 deg Radial
2408 – 259 deg Tangential
0.08
0.06
0.04
0.02
0.00
−0.02
−0.04
Acceleration (kg)
0
2
4
6
8
10
12
14
16
18
Time (msec)

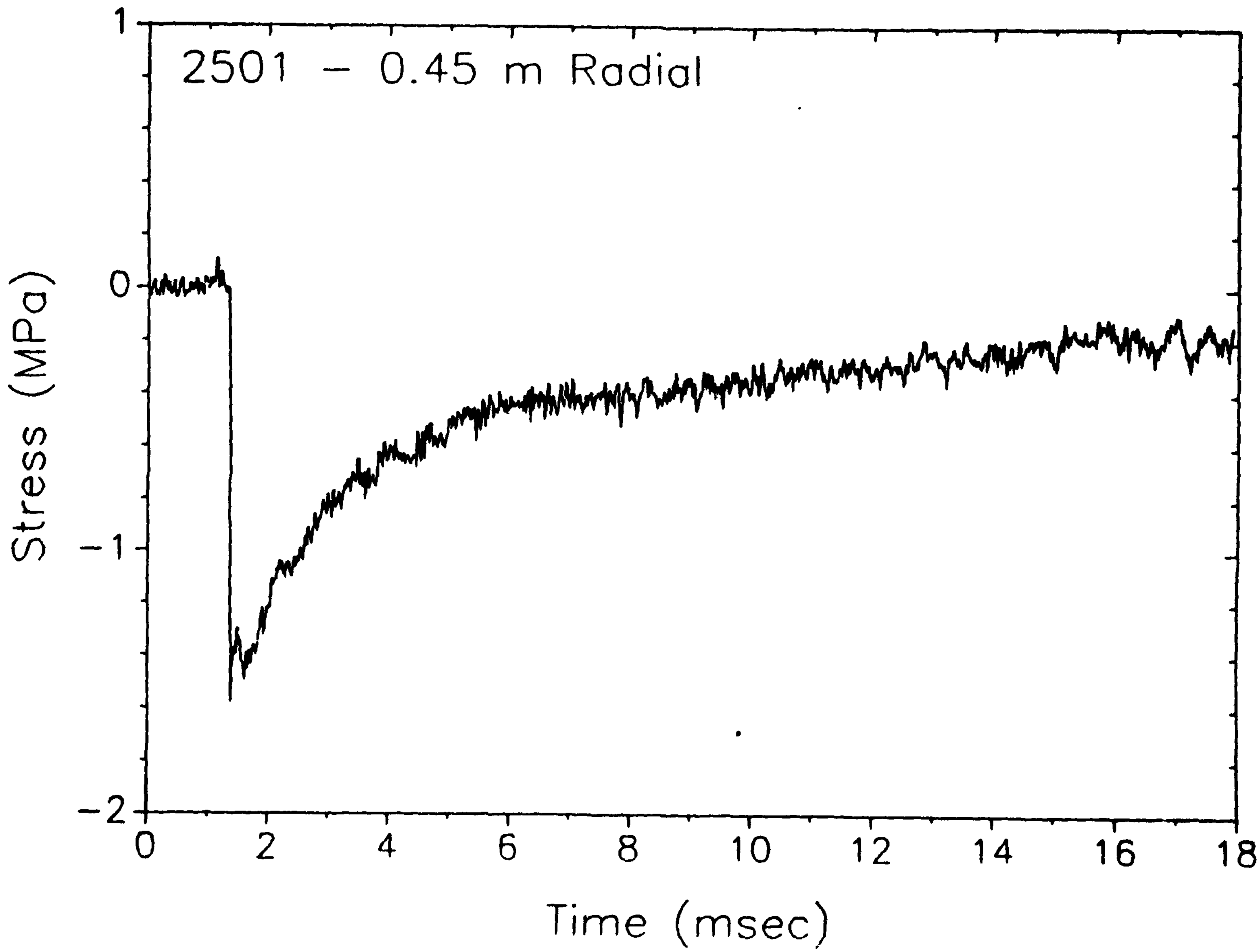

2401 – 349 deg Radial
2402 – 349 deg Tangential
1.0
0.5
0.0
−0.5
Velocity (m/sec)
0
2
4
6
8
10
12
14
16
18
Time (msec)

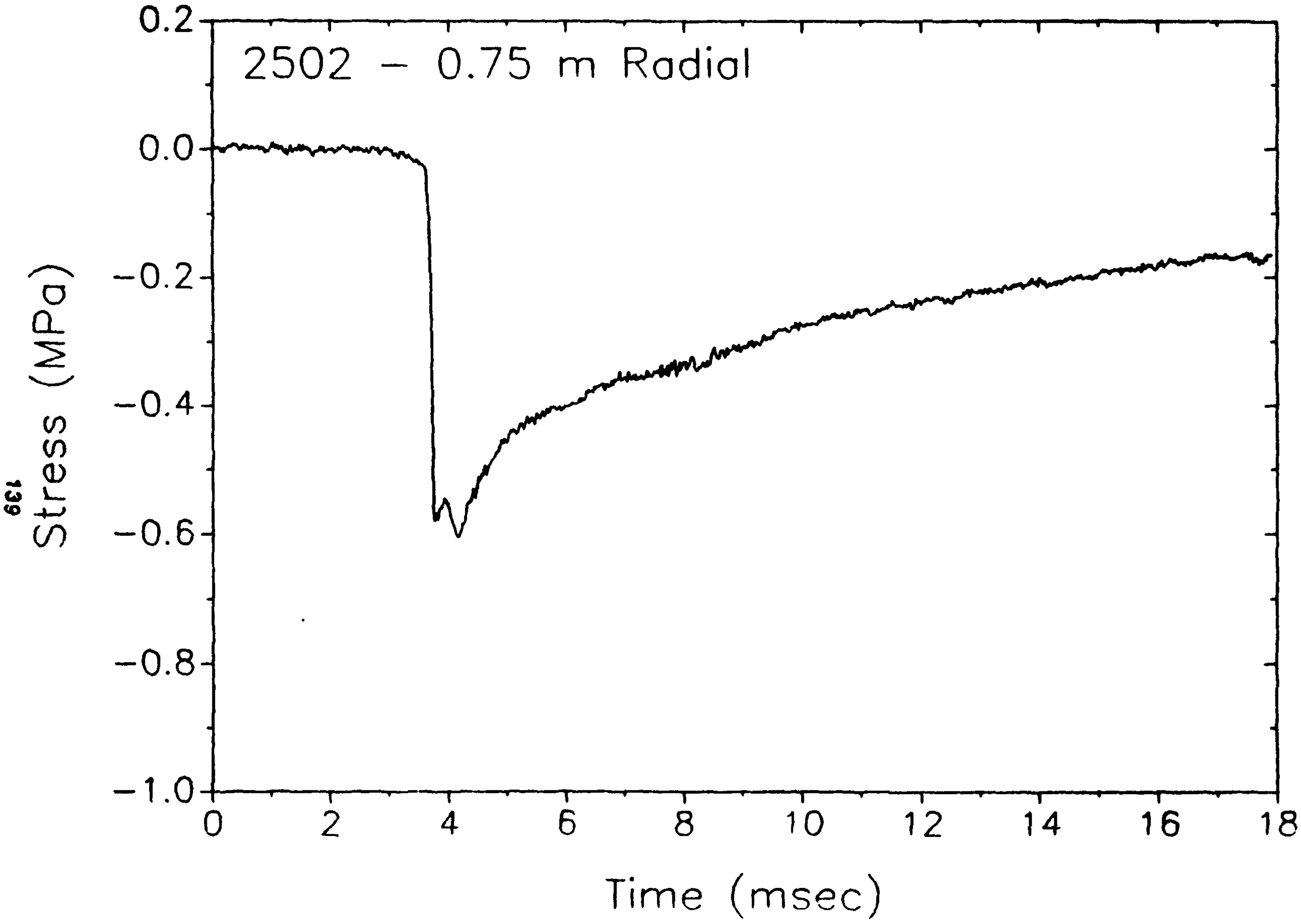

2404 – 79 deg Radial
2403 – 79 deg Tangential
Velocity (m/sec)
Time (msec)
1.0
0.5
0.0
-0.5
0
2
4
6
8
10
12
14
16
18

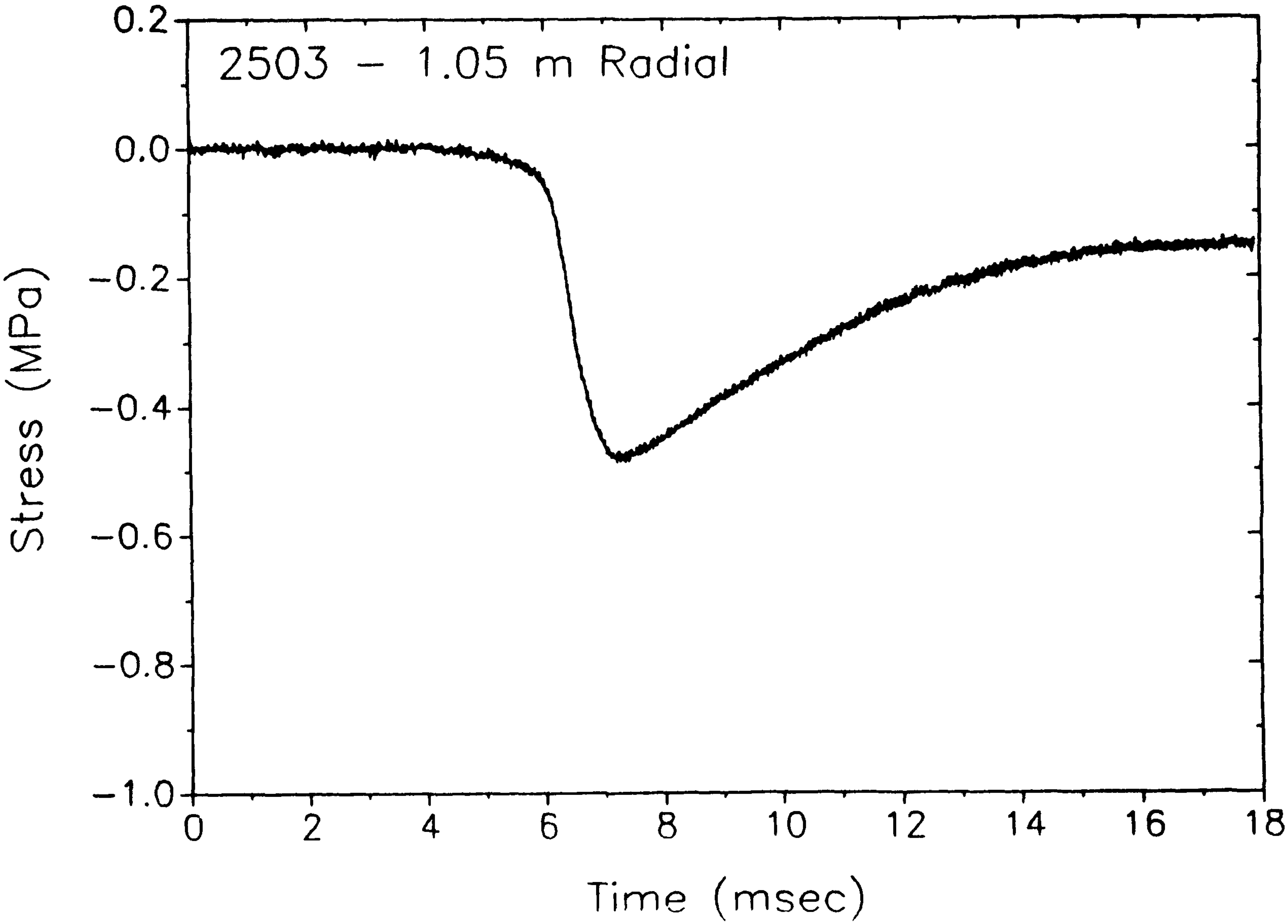


2406 – 169 deg Radial
2405 – 169 deg Tangential
Velocity (m/sec)
Time (msec)
1.0
0.5
0.0
–0.5
0
2
4
6
8
10
12
14
16
18


2407 – 259 deg Radial
2408 – 259 deg Tangential
Velocity (m/sec)
1.0
0.5
0.0
–0.5
0
2
4
6
8
10
12
14
16
18
Time (msec)

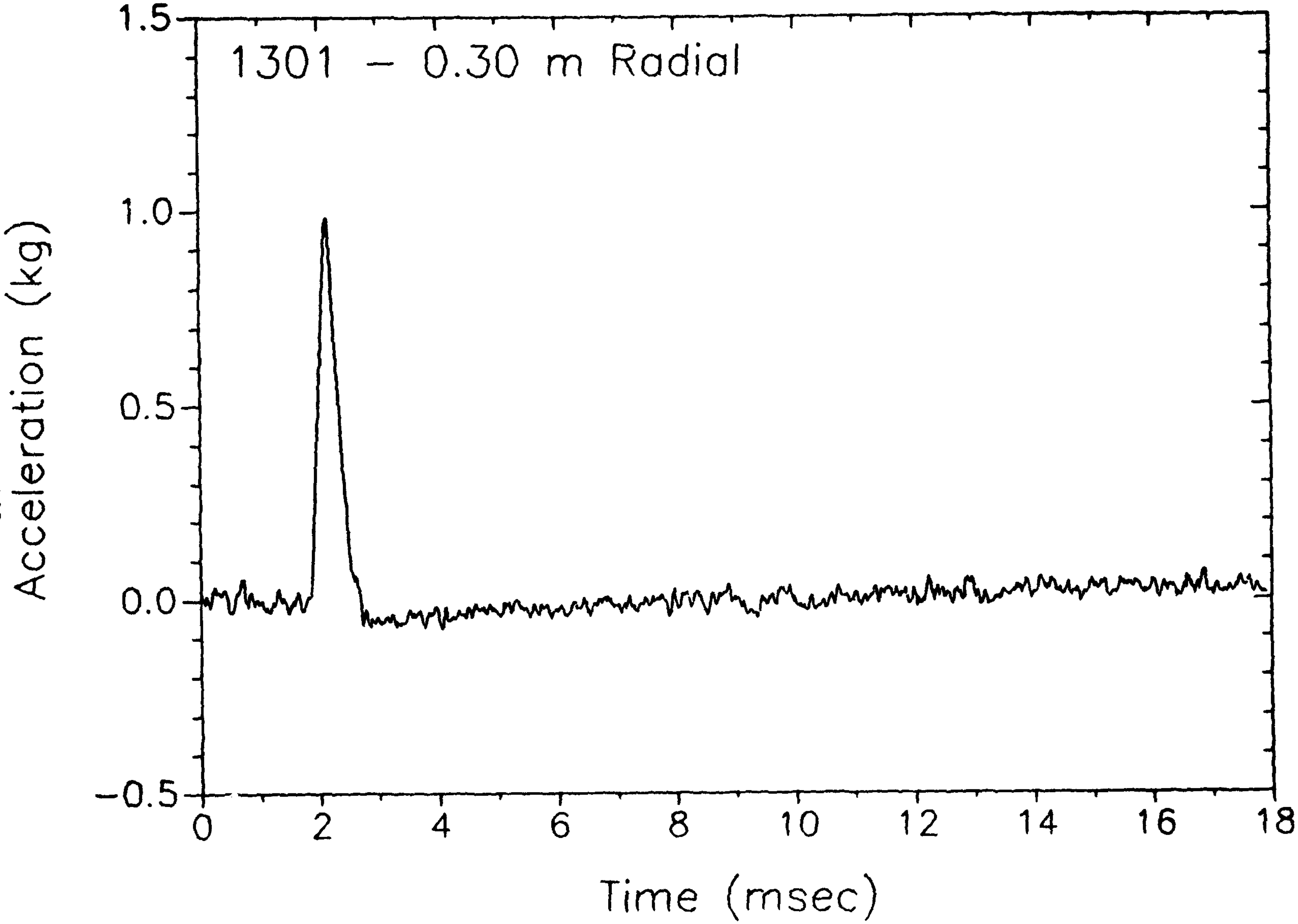

2501 – 0.45 m Radial
Stress (MPa)
1
0
−1
−2
0
2
4
6
8
10
12
14
16
18
Time (msec)

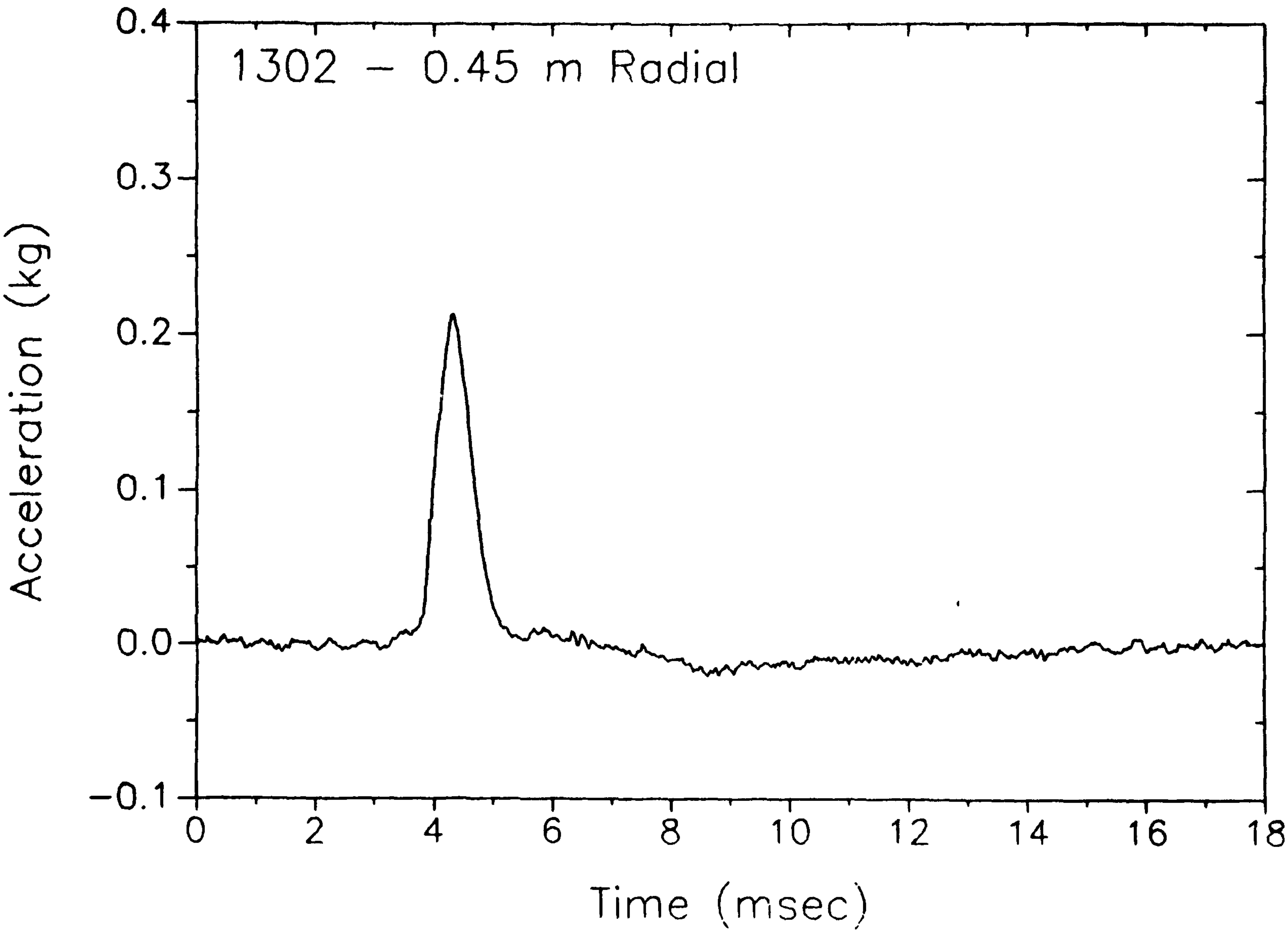

2502 – 0.75 m Radial
Stress (MPa)
Time (msec)
0.2
0.0
−0.2
−0.4
−0.6
−0.8
−1.0
0
2
4
6
8
10
12
14
16
18

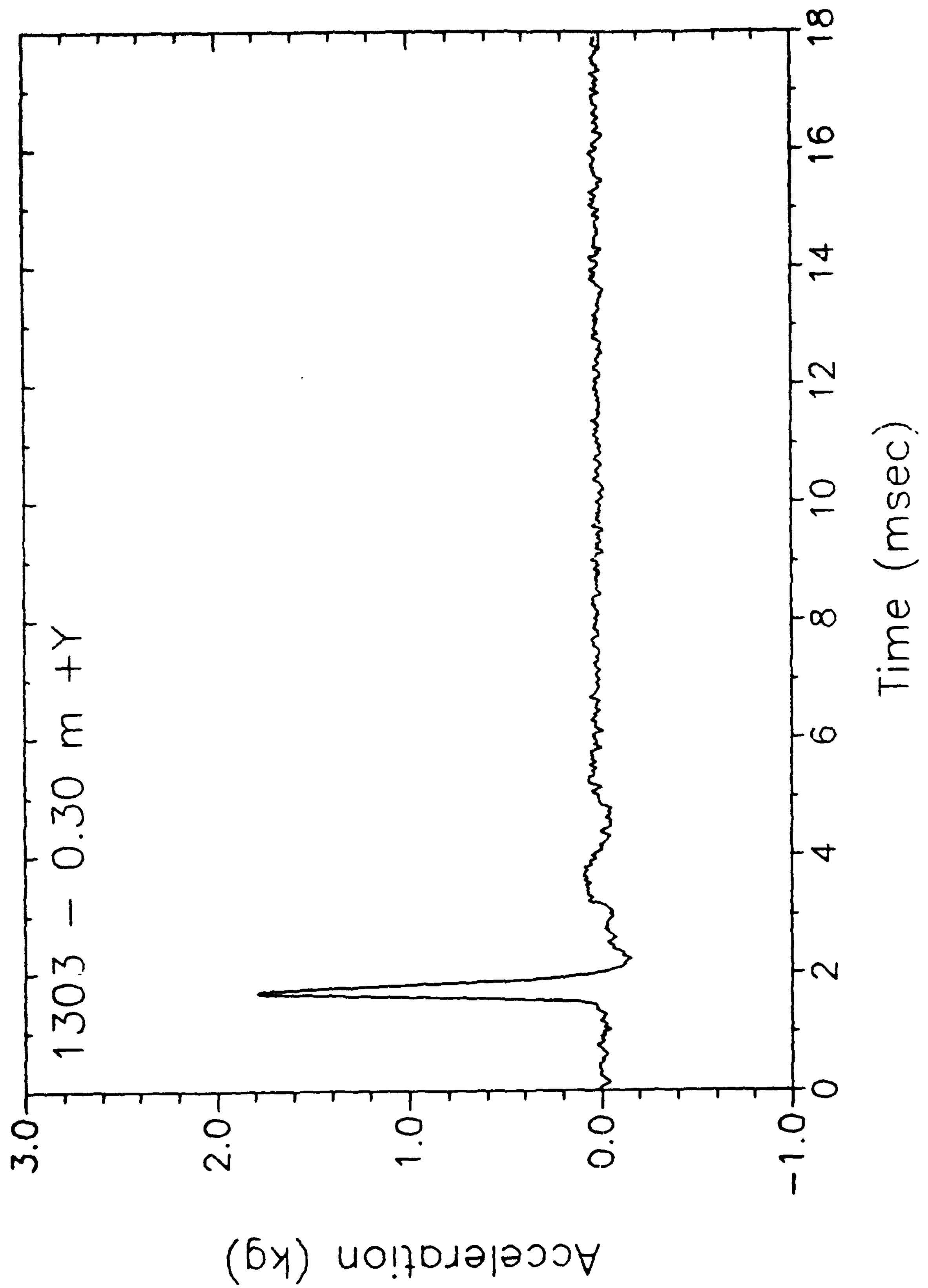

2503 – 1.05 m Radial
0.2
0.0
−0.2
−0.4
−0.6
−0.8
−1.0
Stress (MPa)
0
2
4
6
8
10
12
14
16
18
Time (msec)

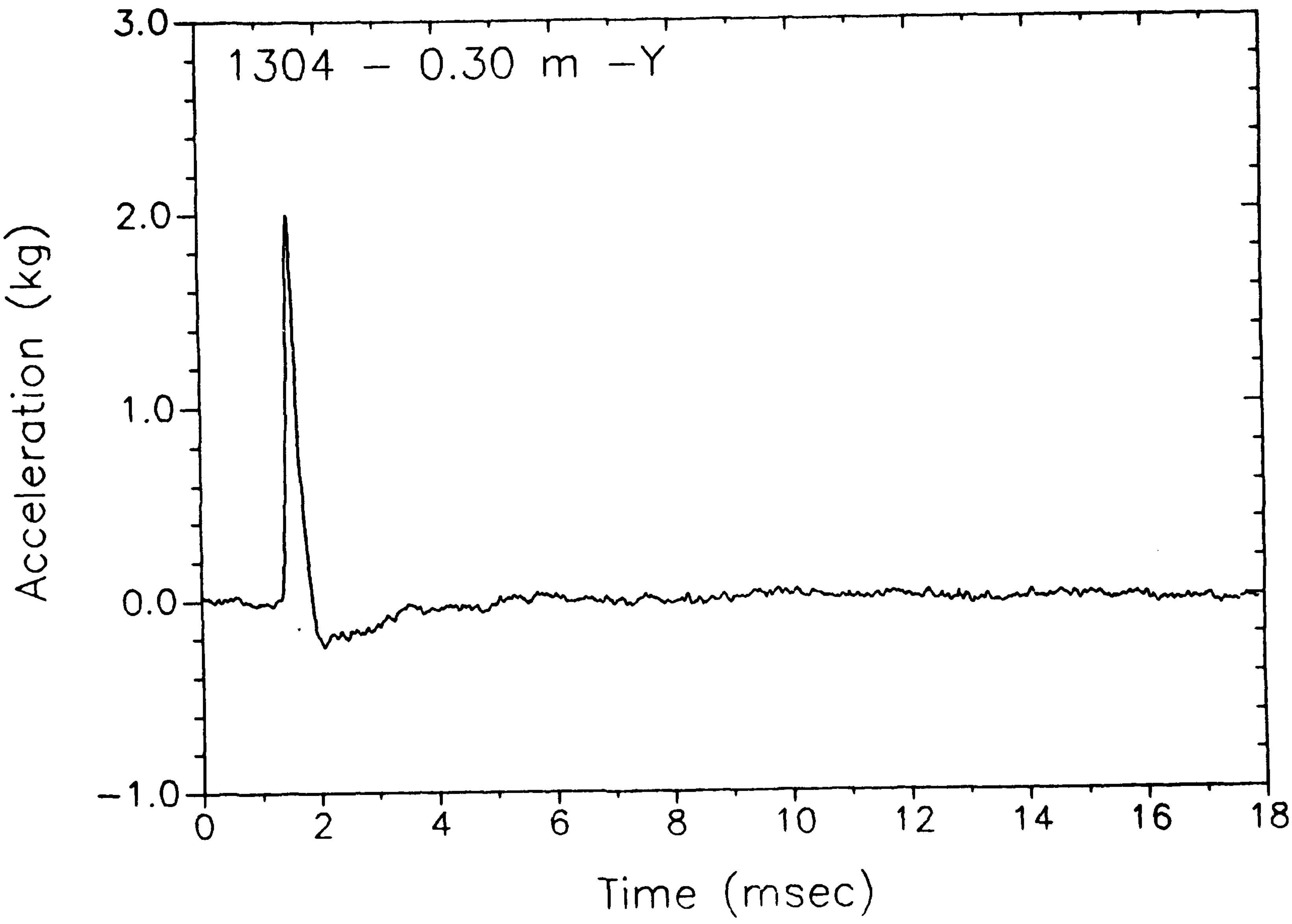
1/10 FROUDE SCALED TESTS

"LEAD/COAL"

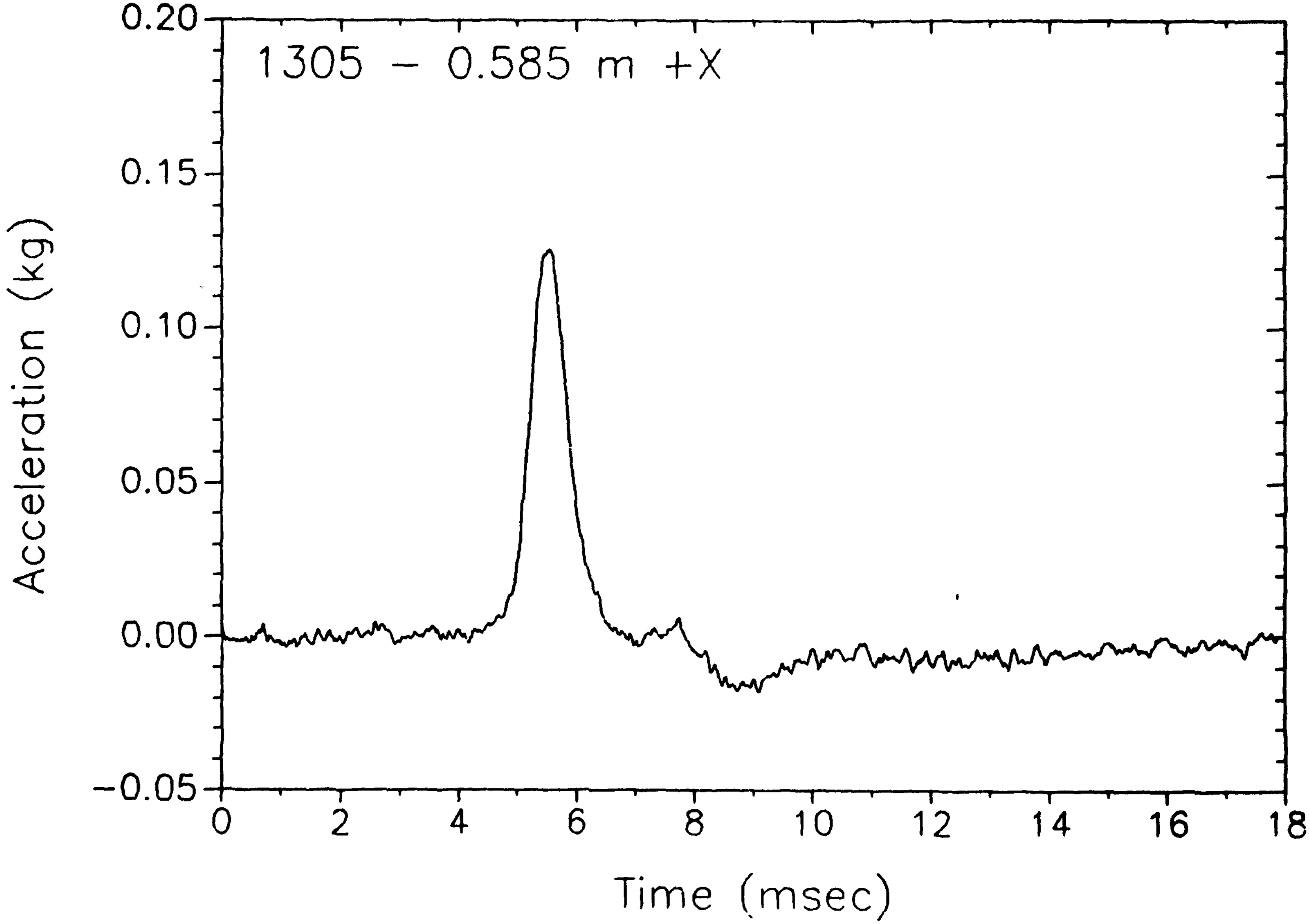

1301 – 0.30 m Radial
Acceleration (kg)
Time (msec)
1.5
1.0
0.5
0.0
−0.5
0
2
4
6
8
10
12
14
16
18

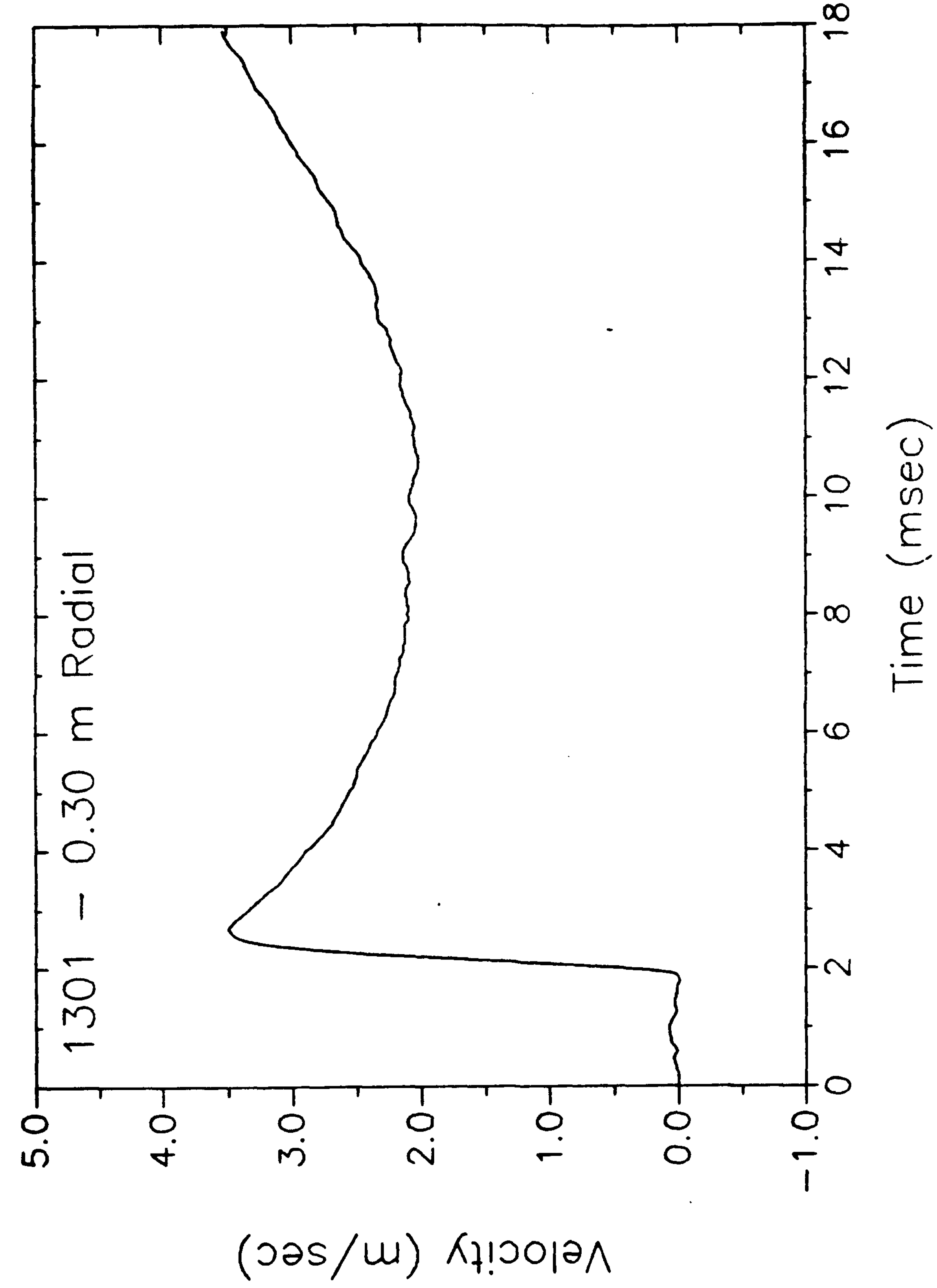

1302 – 0.45 m Radial
Acceleration (kg)
0.4
0.3
0.2
0.1
0.0
–0.1
0
2
4
6
8
10
12
14
16
18
Time (msec)

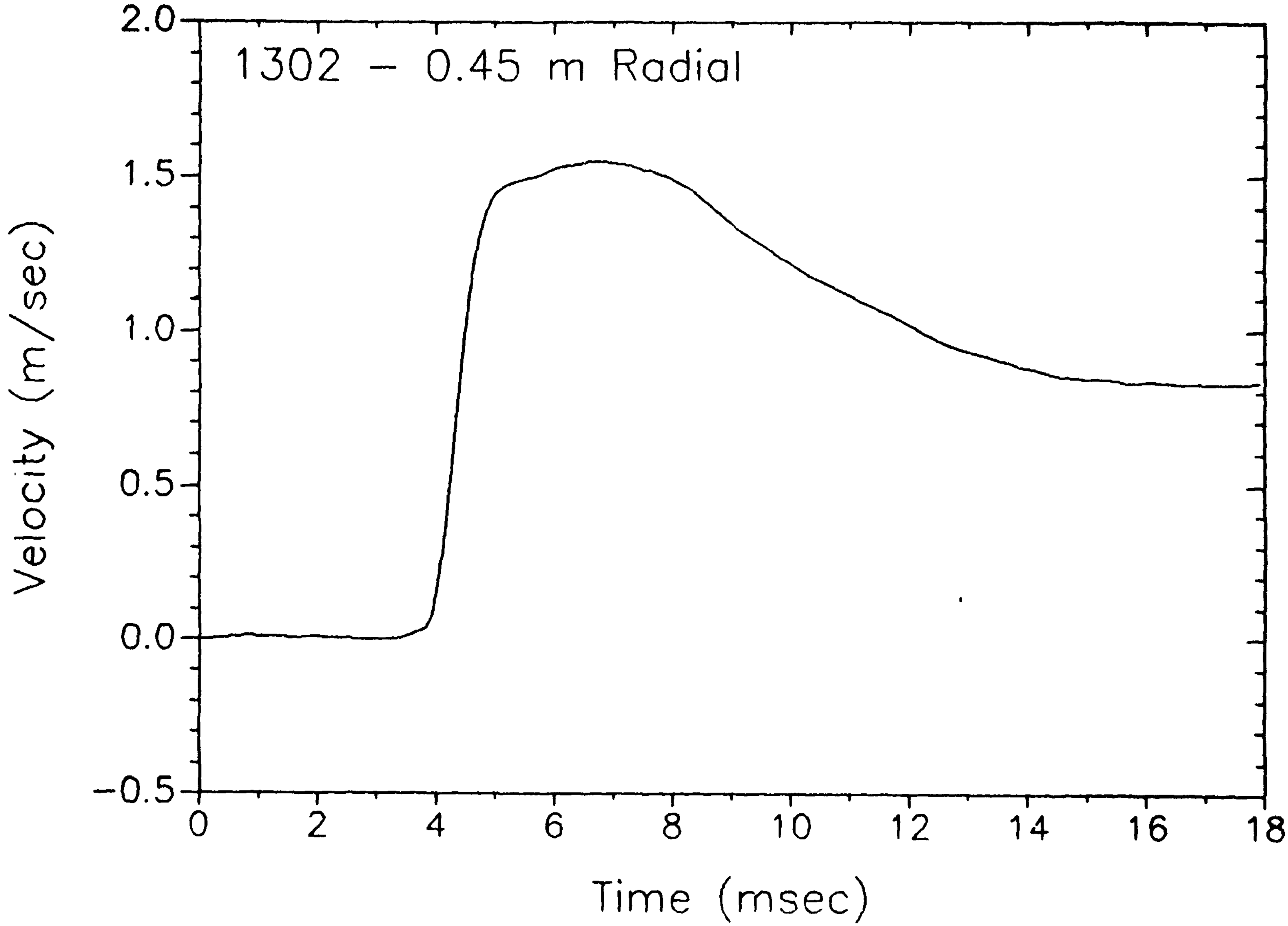

1303 – 0.30 m +Y
Acceleration (kg)
Time (msec)
3.0
2.0
1.0
0.0
–1.0
0
2
4
6
8
10
12
14
16
18



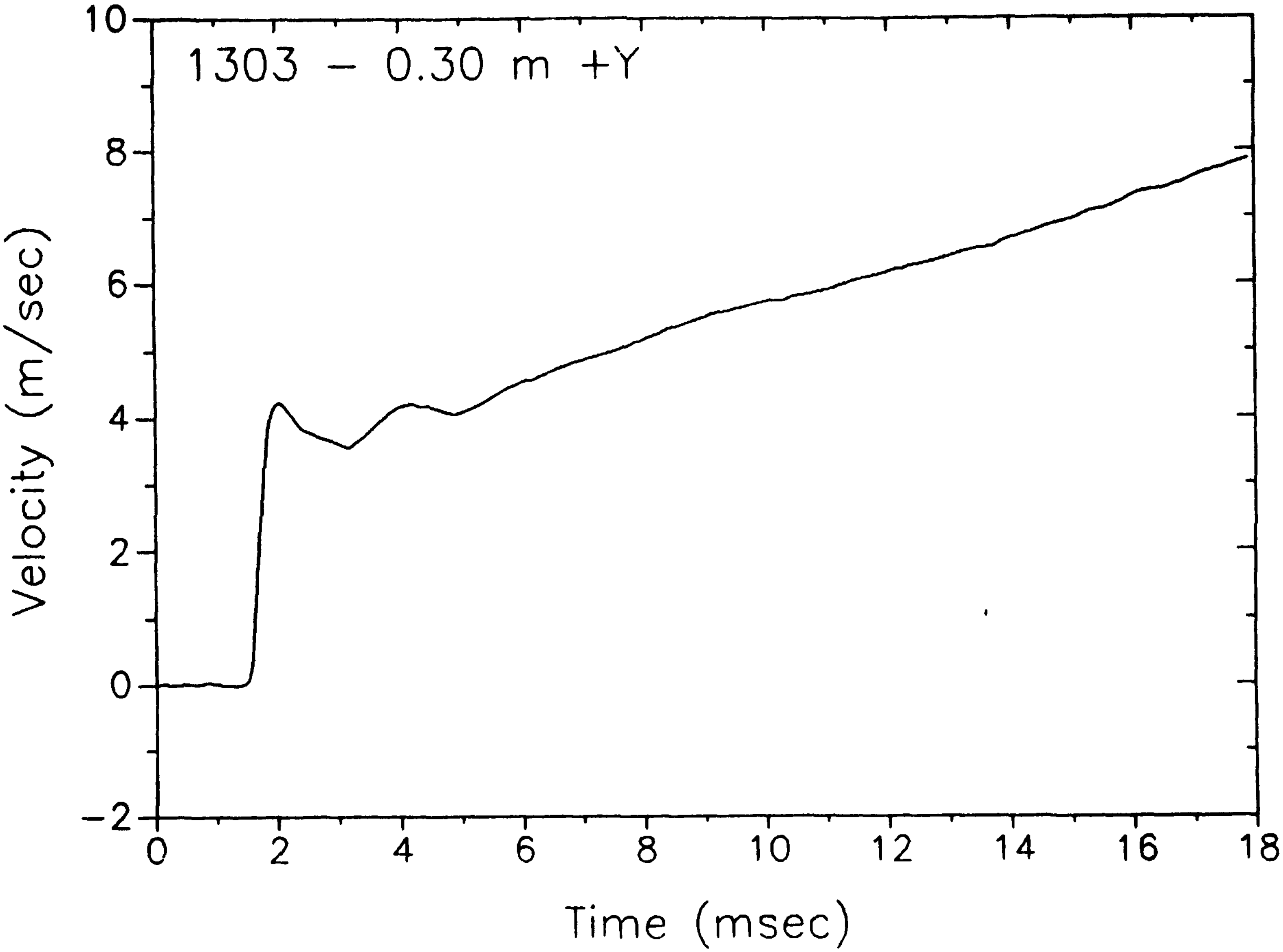
1304 – 0.30 m –Y
Acceleration (kg)
Time (msec)
3.0
2.0
1.0
0.0
–1.0
0
2
4
6
8
10
12
14
16
18

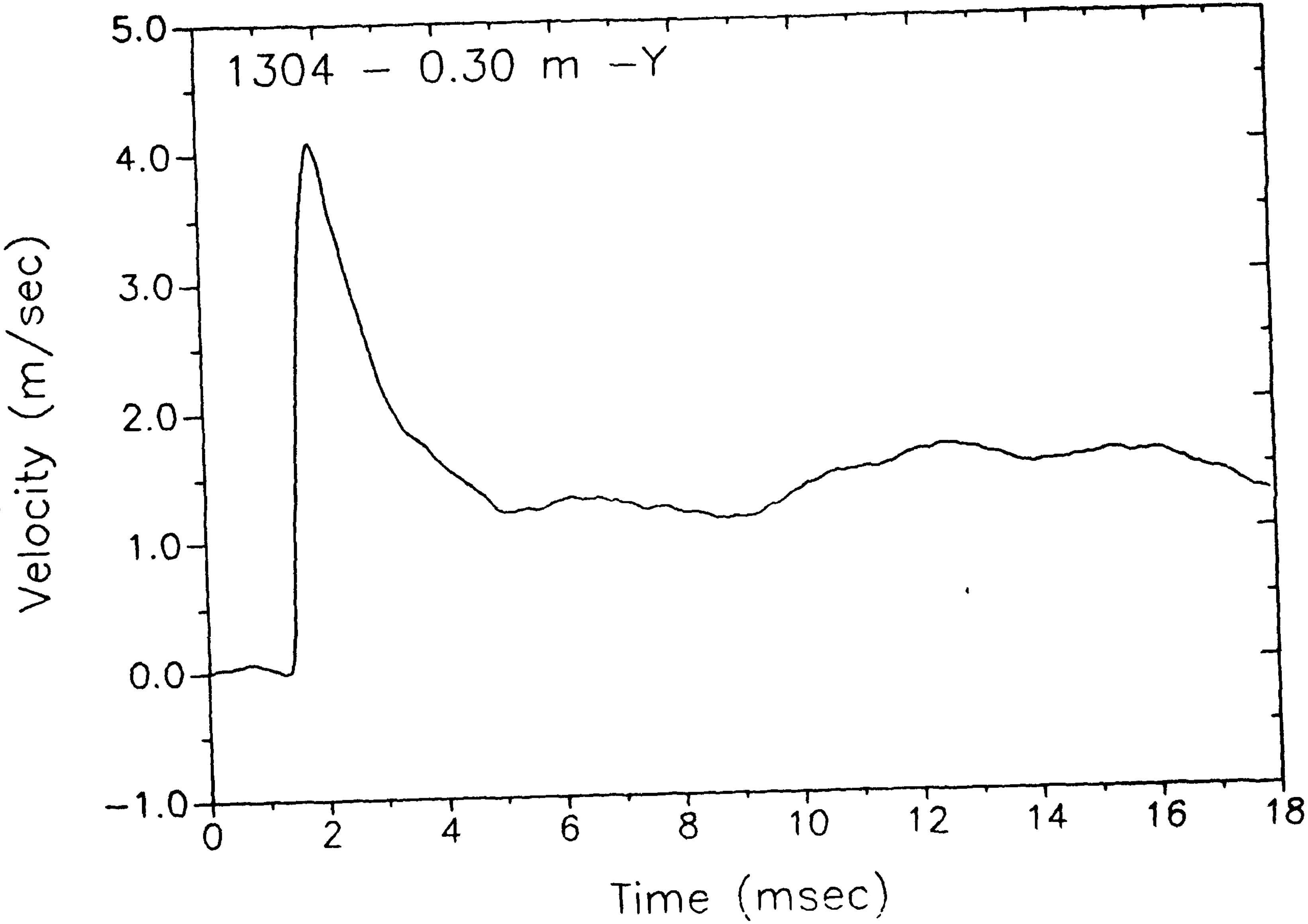

1305 – 0.585 m +X
Acceleration (kg)
0.20
0.15
0.10
0.05
0.00
−0.05
0
2
4
6
8
10
12
14
16
18
Time (msec)


1301 – 0.30 m Radial
Velocity (m/sec)
5.0
4.0
3.0
2.0
1.0
0.0
–1.0
Time (msec)
0
2
4
6
8
10
12
14
16
18

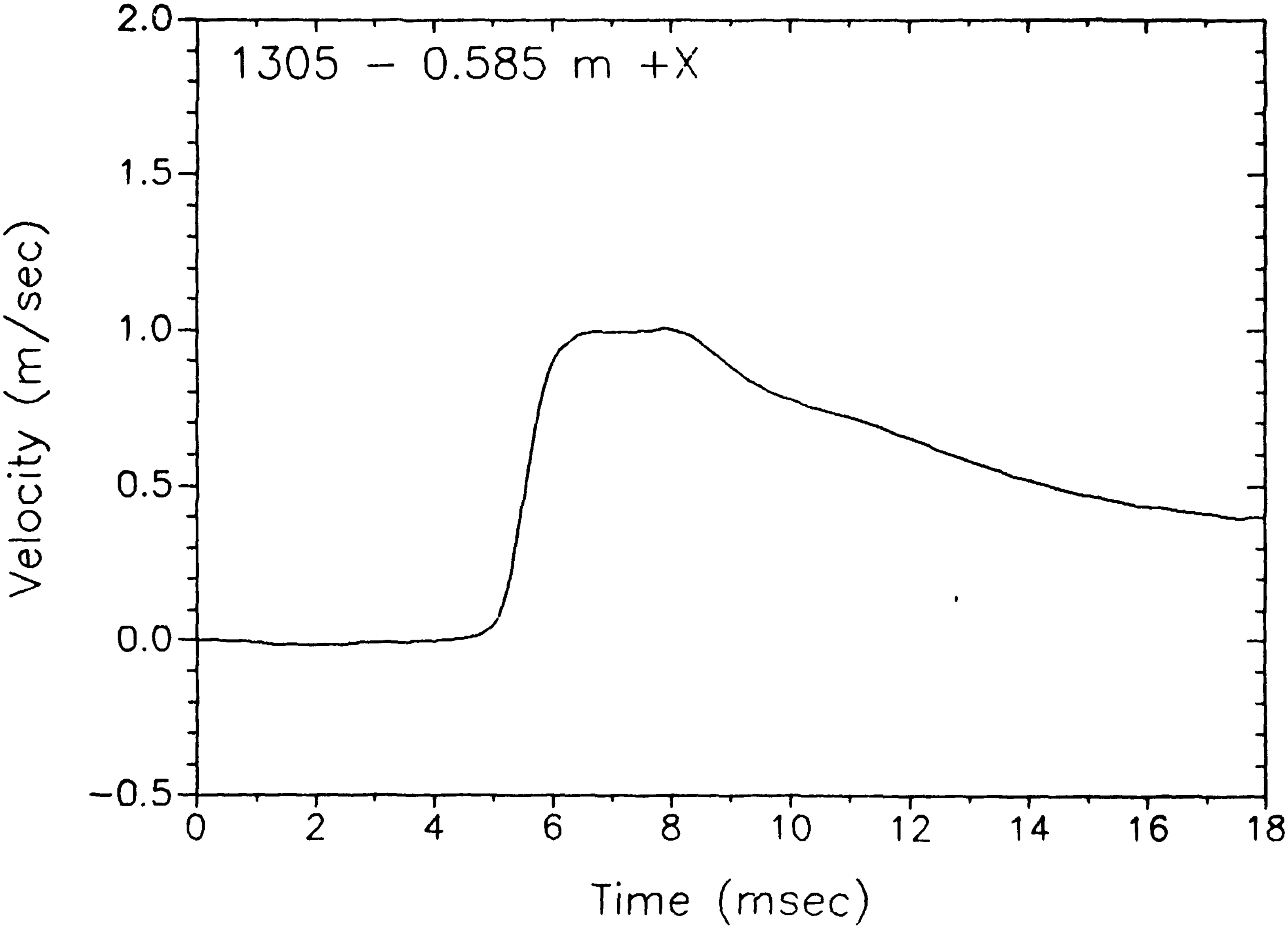


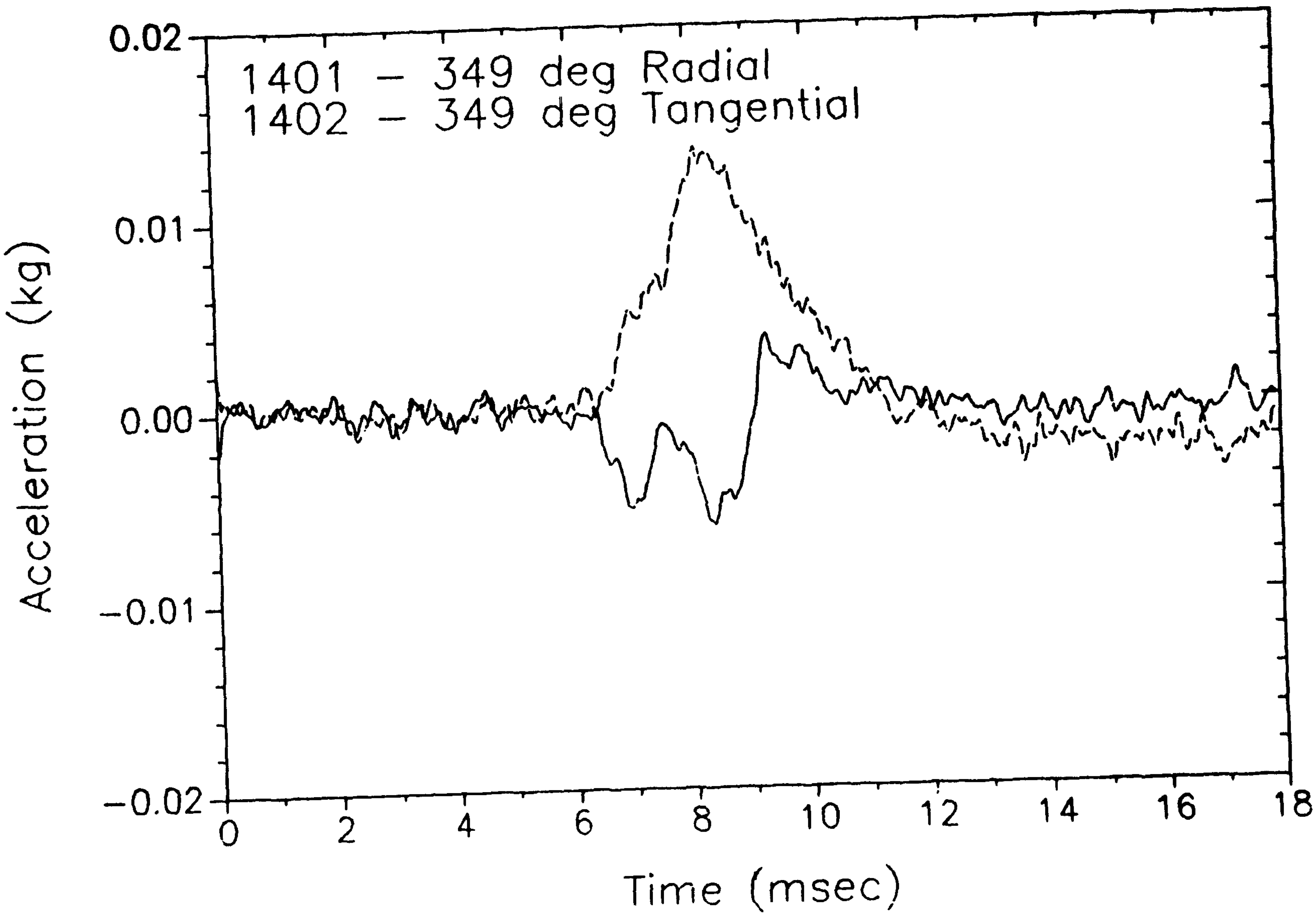
1302 – 0.45 m Radial
Velocity (m/sec)
Time (msec)
2.0
1.5
1.0
0.5
0.0
–0.5
0
2
4
6
8
10
12
14
16
18

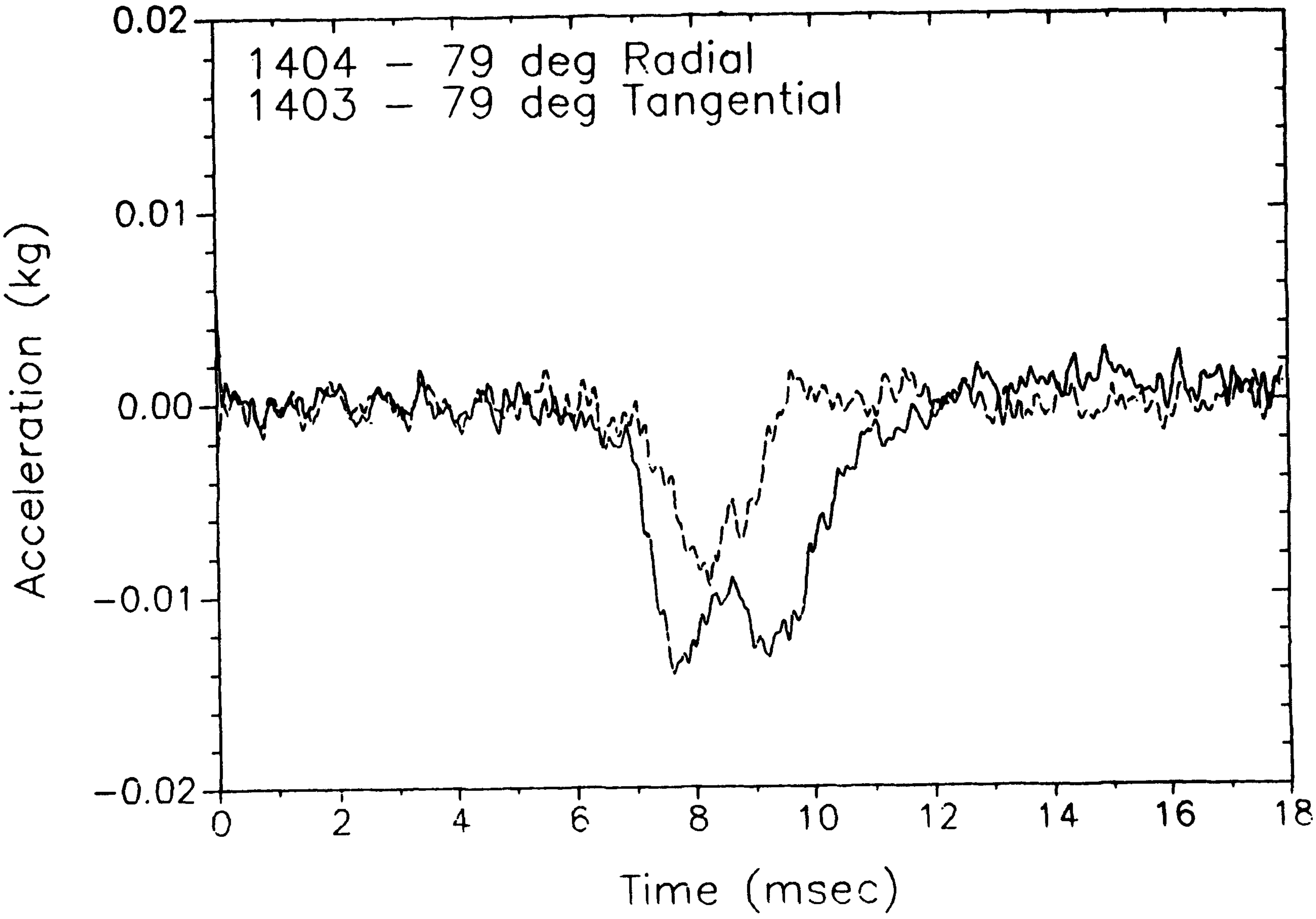

1303 – 0.30 m +Y
Velocity (m/sec)
Time (msec)
10
8
6
4
2
0
–2
0
2
4
6
8
10
12
14
16
18

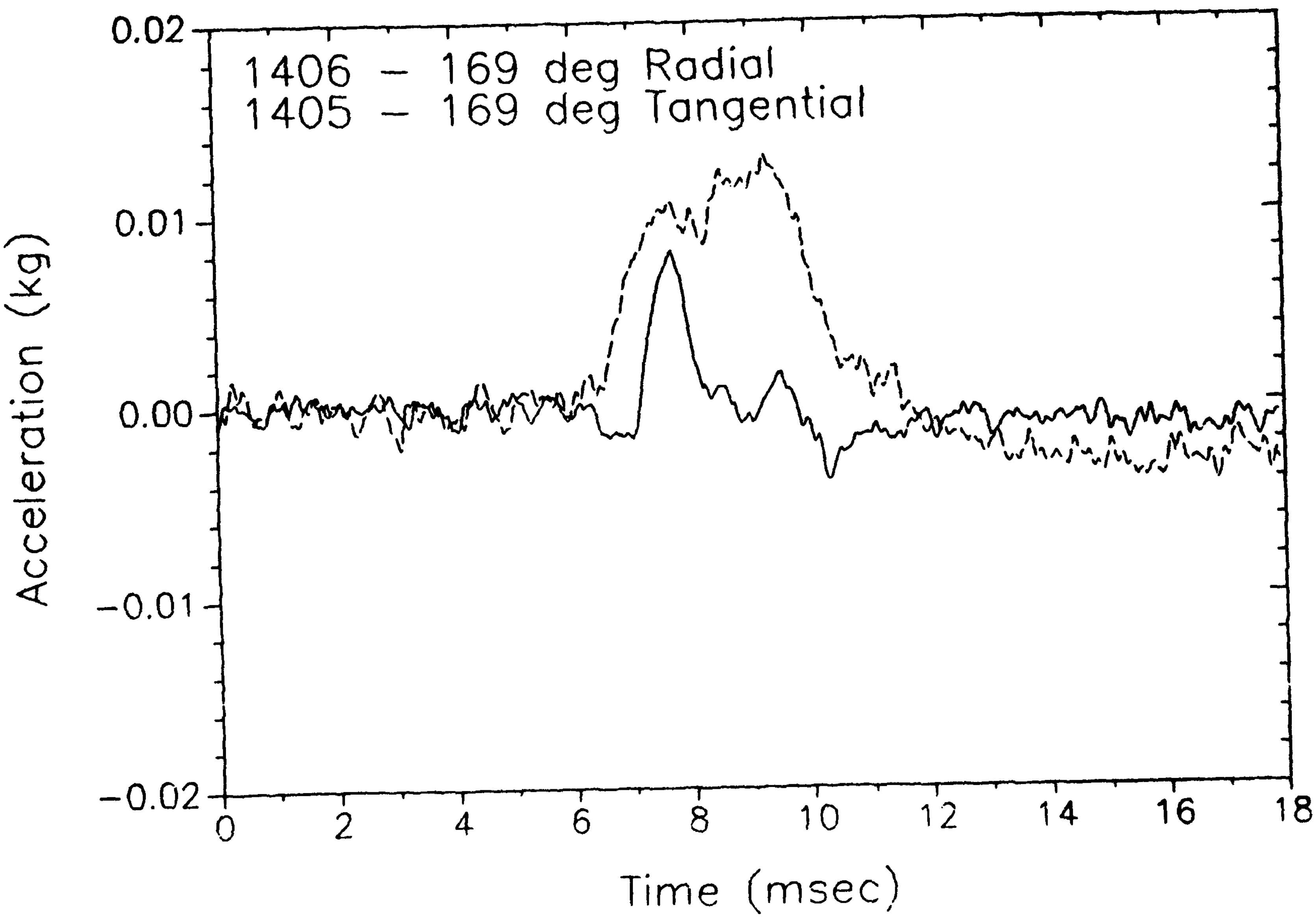


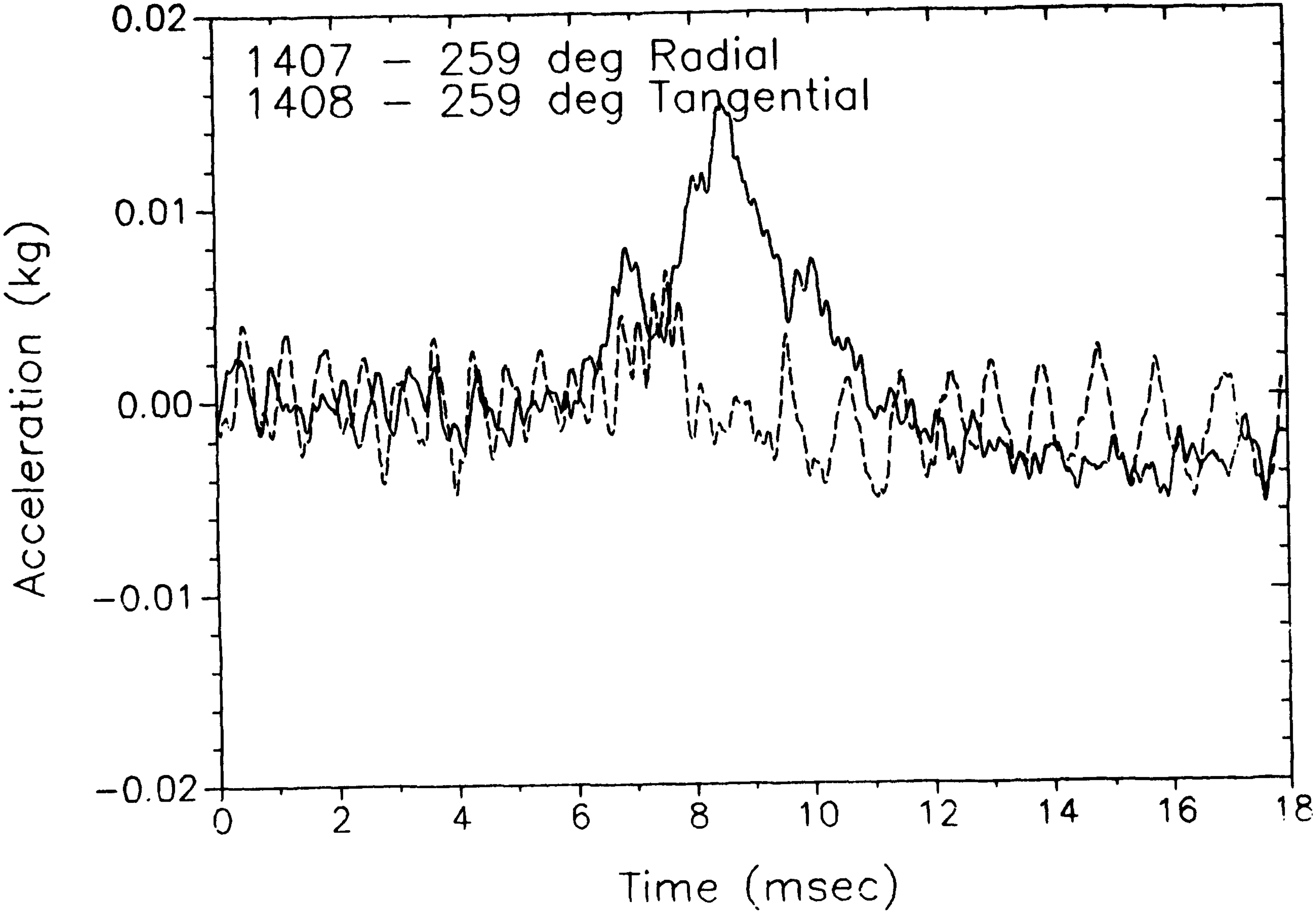
1304 – 0.30 m –Y
Velocity (m/sec)
5.0
4.0
3.0
2.0
1.0
0.0
−1.0
0
2
4
6
8
10
12
14
16
18
Time (msec)

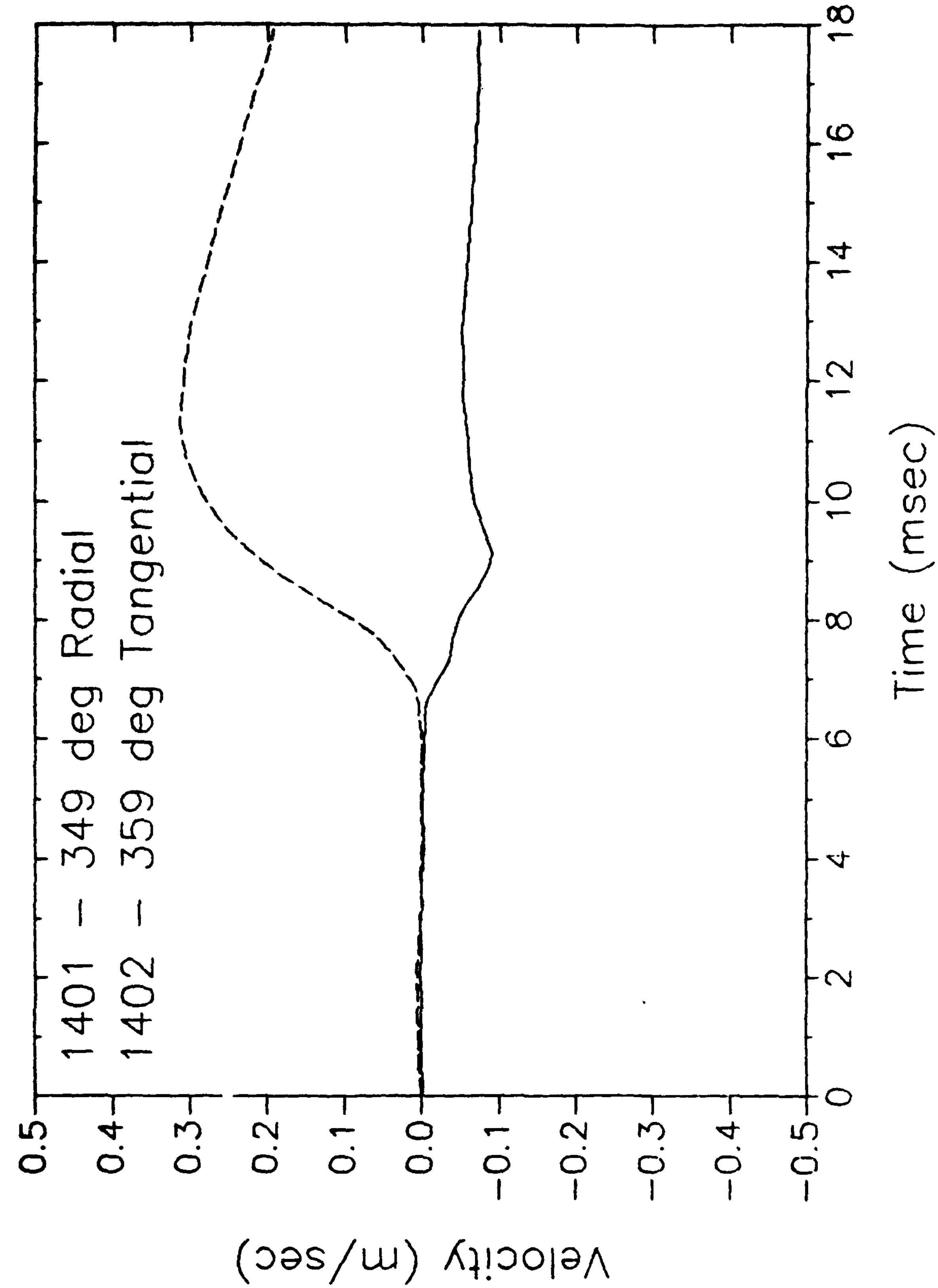

1305 – 0.585 m +X
Velocity (m/sec)
Time (msec)
2.0
1.5
1.0
0.5
0.0
–0.5
0
2
4
6
8
10
12
14
16
18

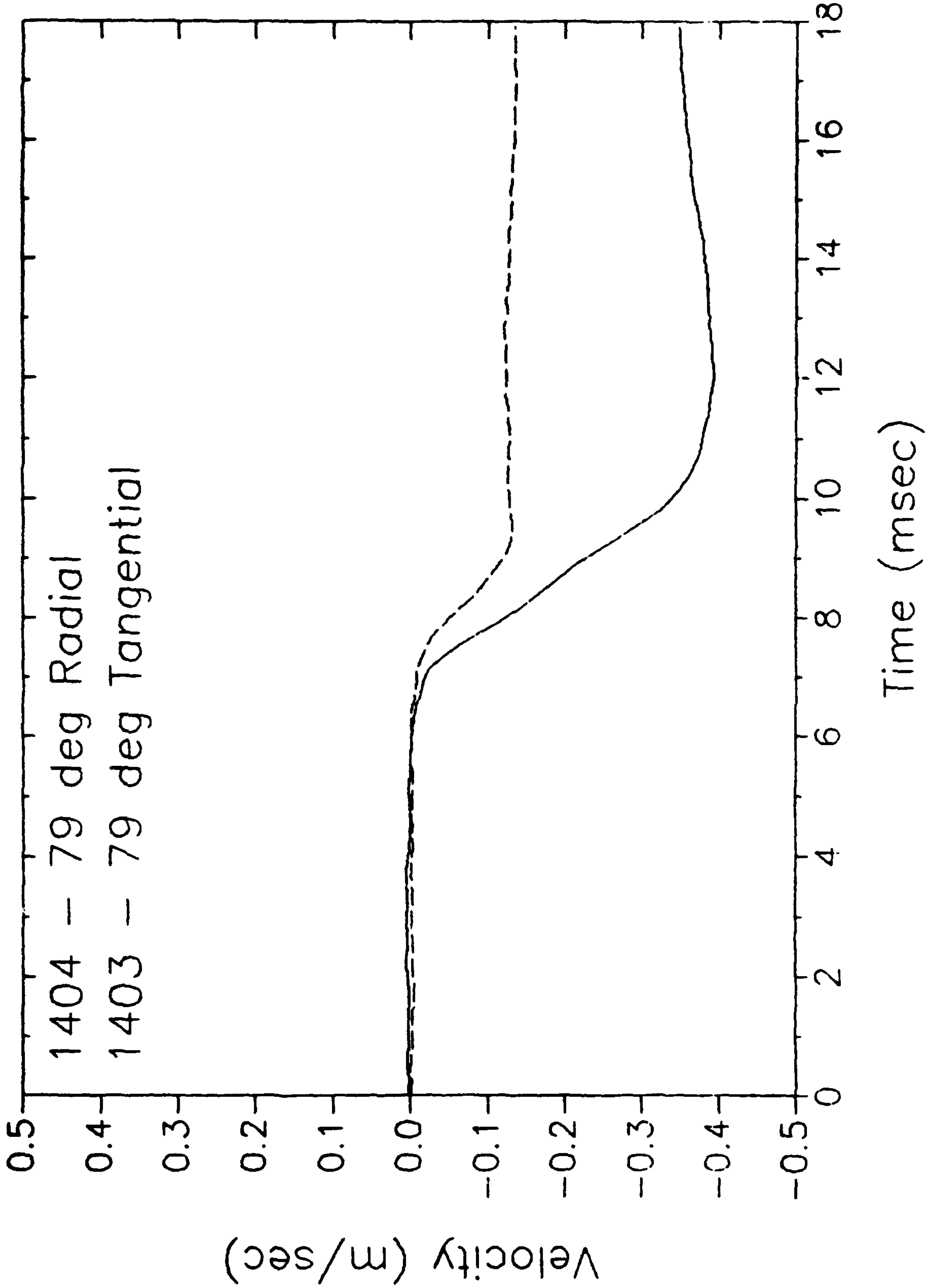

1401 – 349 deg Radial
1402 – 349 deg Tangential
0.02
0.01
0.00
–0.01
–0.02
Acceleration (kg)
0
2
4
6
8
10
12
14
16
18
Time (msec)


1404 – 79 deg Radial
1403 – 79 deg Tangential
Acceleration (kg)
0.02
0.01
0.00
−0.01
−0.02
0
2
4
6
8
10
12
14
16
18
Time (msec)

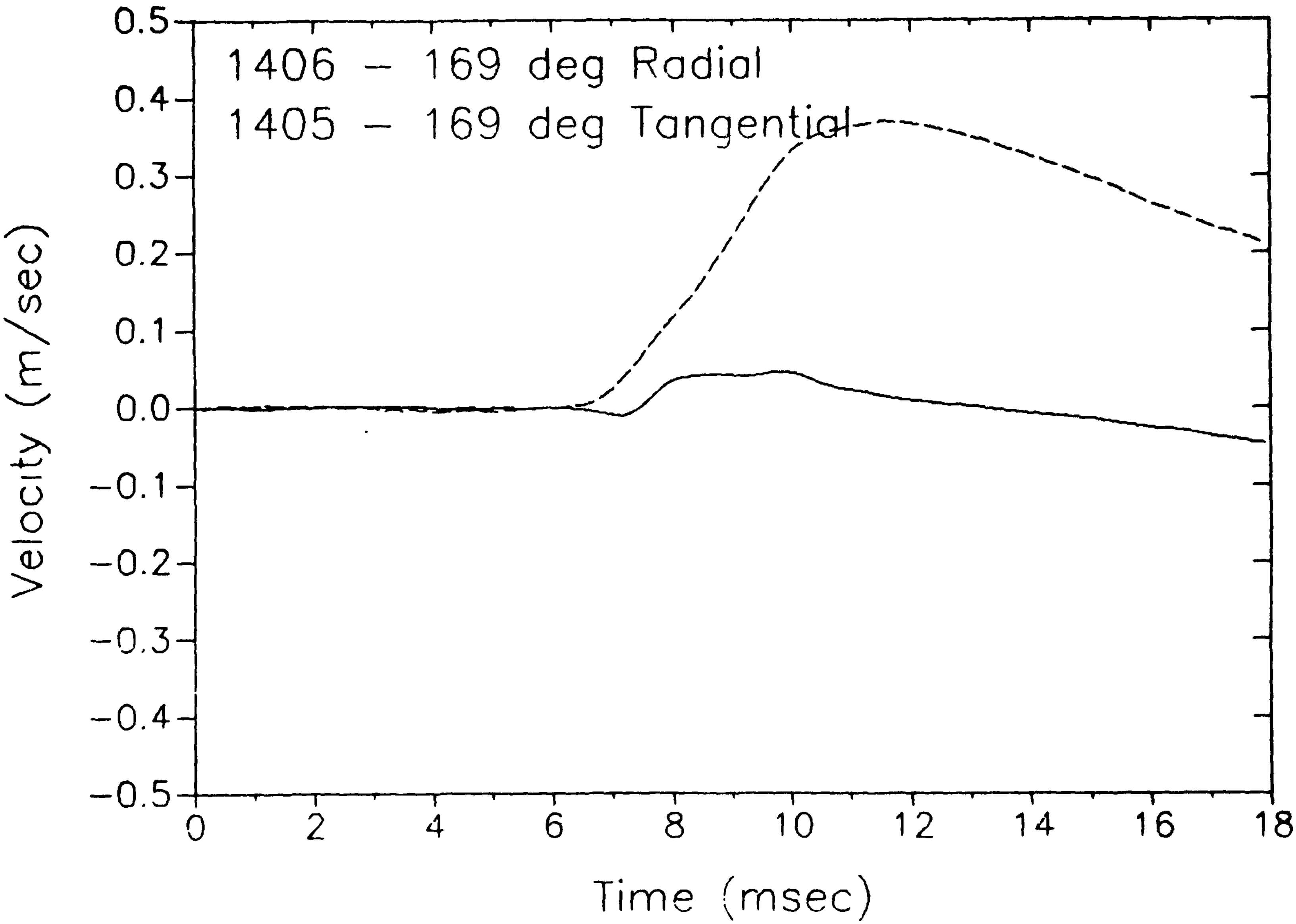

1406 – 169 deg Radial
1405 – 169 deg Tangential
0.02
0.01
0.00
−0.01
−0.02
Acceleration (kg)
0
2
4
6
8
10
12
14
16
18
Time (msec)


1407 – 259 deg Radial
1408 – 259 deg Tangential
0.02
0.01
0.00
−0.01
−0.02
Acceleration (kg)
0
2
4
6
8
10
12
14
16
18
Time (msec)

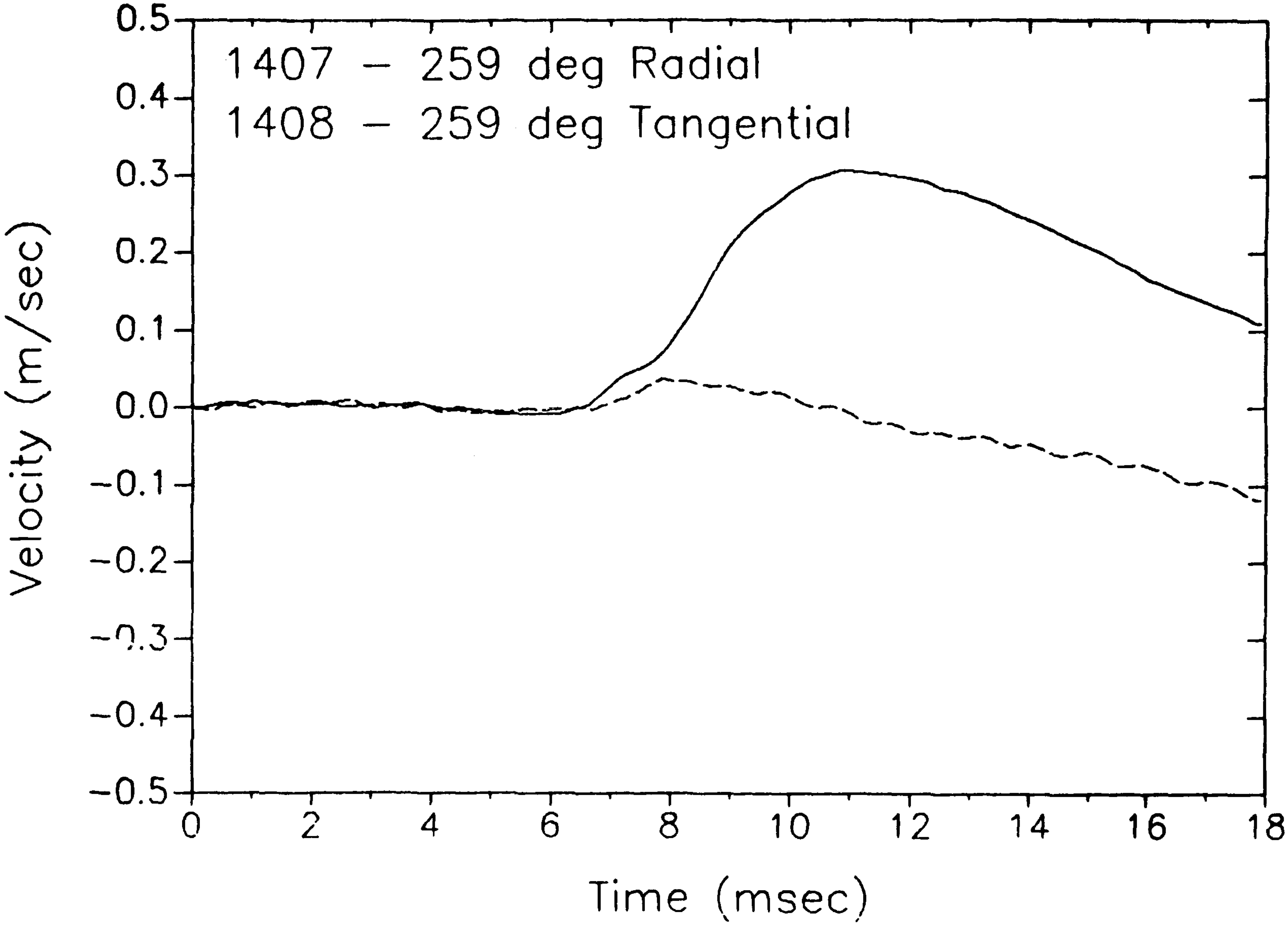

1401 - 349 deg Radial
1402 - 359 deg Tangential
Velocity (m/sec)
Time (msec)
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
0
2
4
6
8
10
12
14
16
18

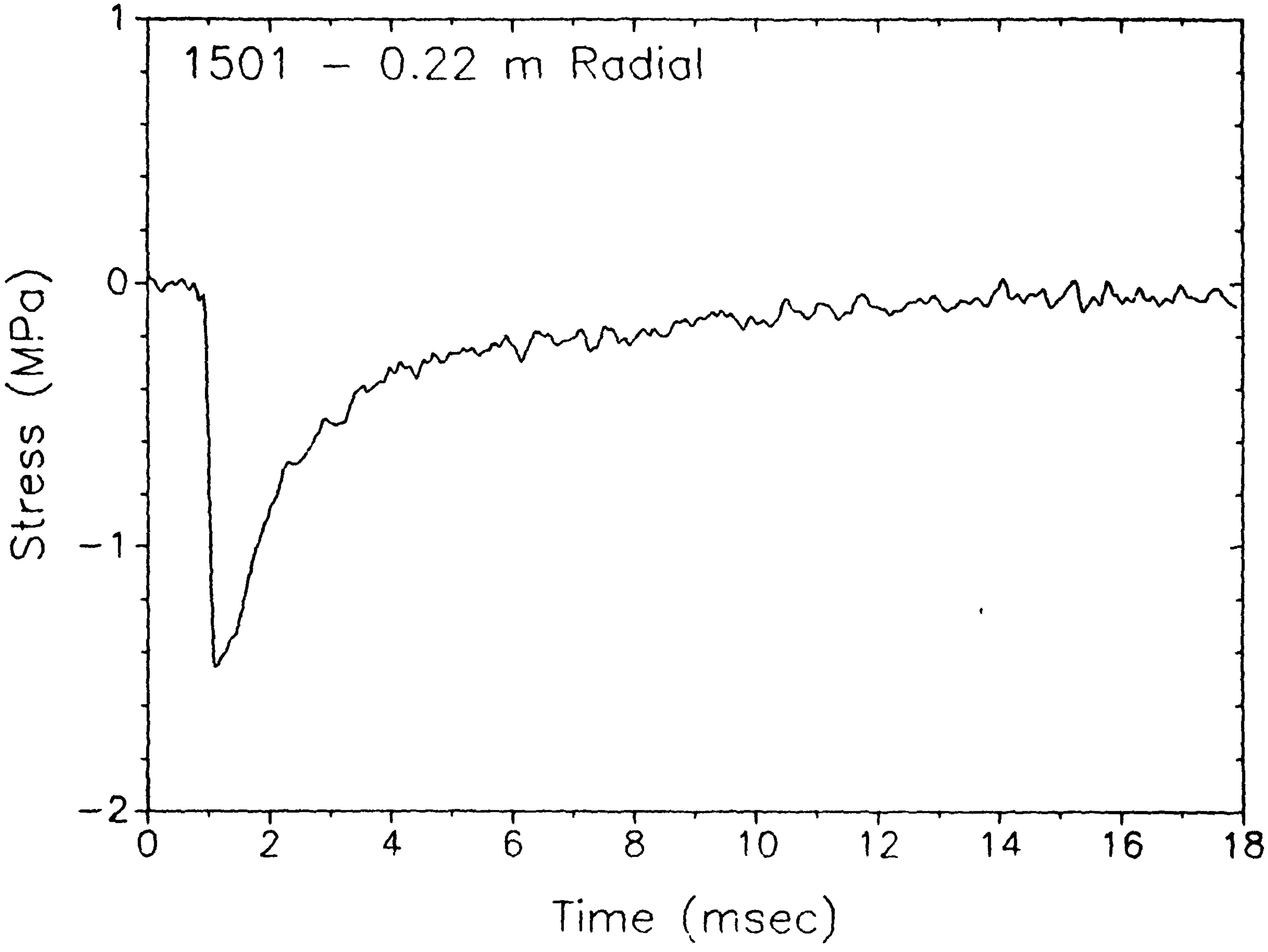


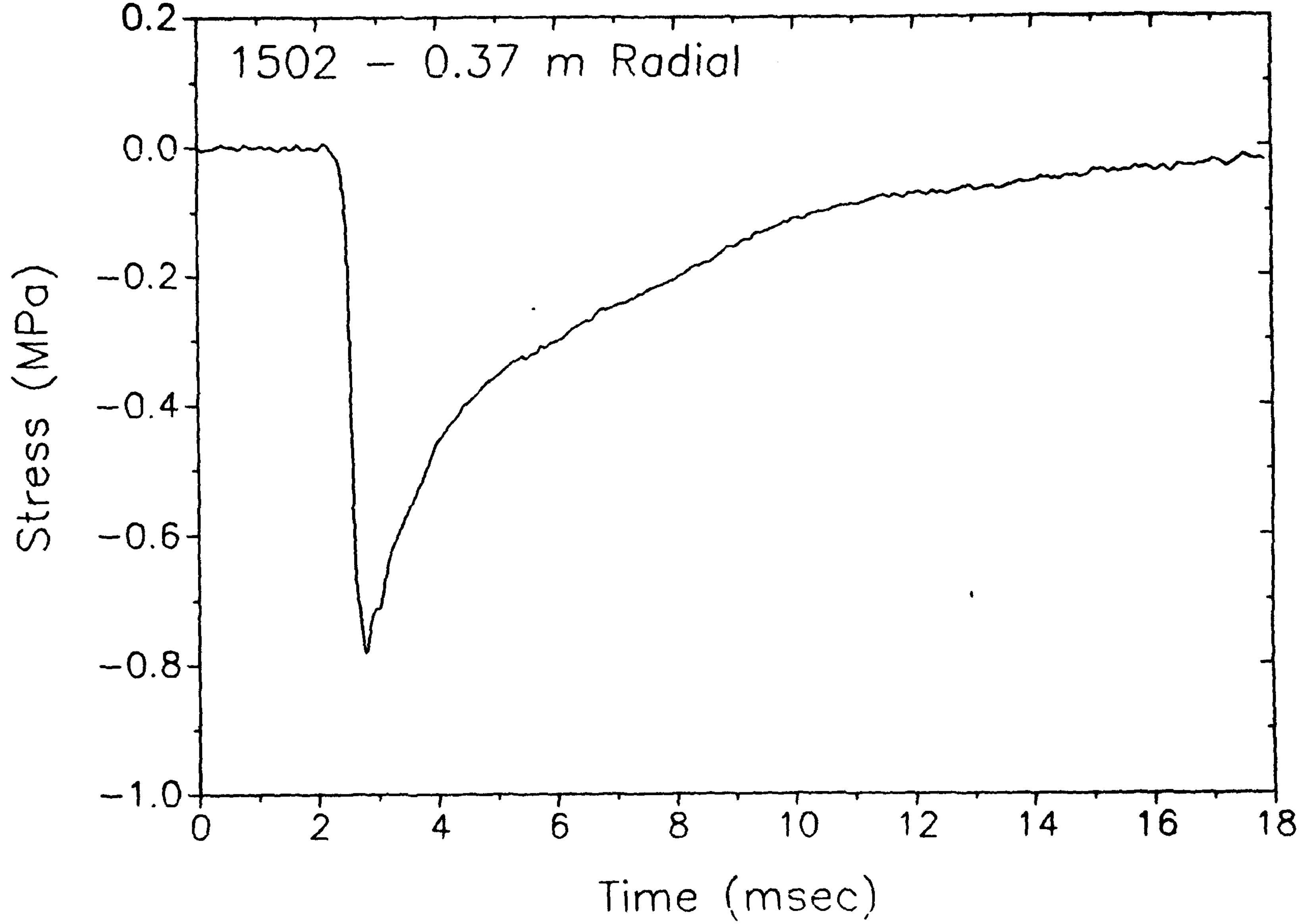
1404 — 79 deg Radial
1403 — 79 deg Tangential
Velocity (m/sec)
Time (msec)
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
0
2
4
6
8
10
12
14
16
18

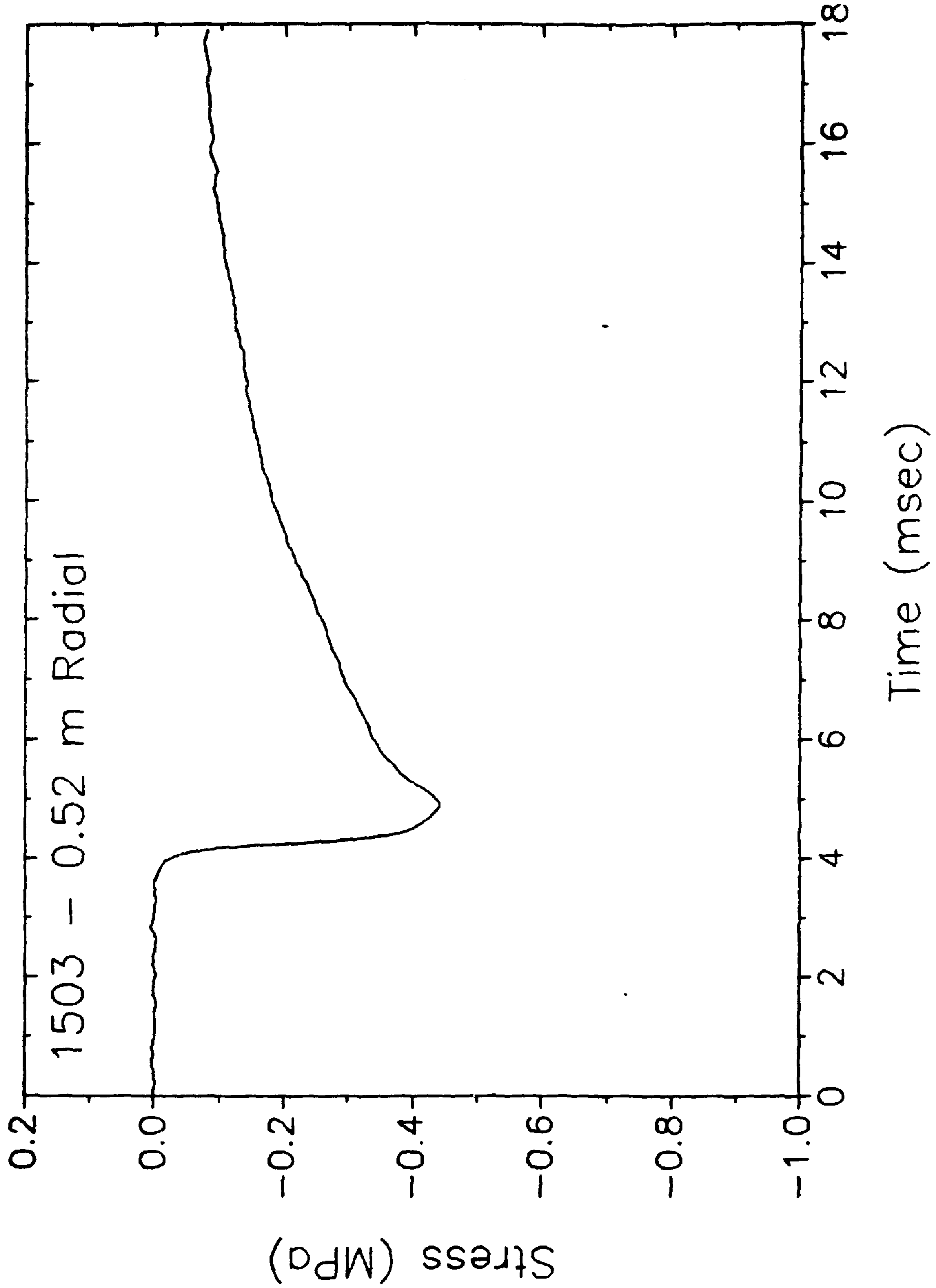


1406 – 169 deg Radial
1405 – 169 deg Tangential
Velocity (m/sec)
0.5
0.4
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
−0.4
−0.5
0
2
4
6
8
10
12
14
16
18
Time (msec)


1407 – 259 deg Radial
1408 – 259 deg Tangential
0.5
0.4
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.4
−0.5
Velocity (m/sec)
0
2
4
6
8
10
12
14
16
18
Time (msec)


1501 – 0.22 m Radial
Stress (MPa)
Time (msec)
1
0
–1
–2
0
2
4
6
8
10
12
14
16
18


1502 – 0.37 m Radial
0.2
0.0
–0.2
–0.4
–0.6
–0.8
–1.0
Stress (MPa)
0
2
4
6
8
10
12
14
16
18
Time (msec)



1503 – 0.52 m Radial
Stress (MPa)
Time (msec)
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
0
2
4
6
8
10
12
14
16
18

APPENDIX F

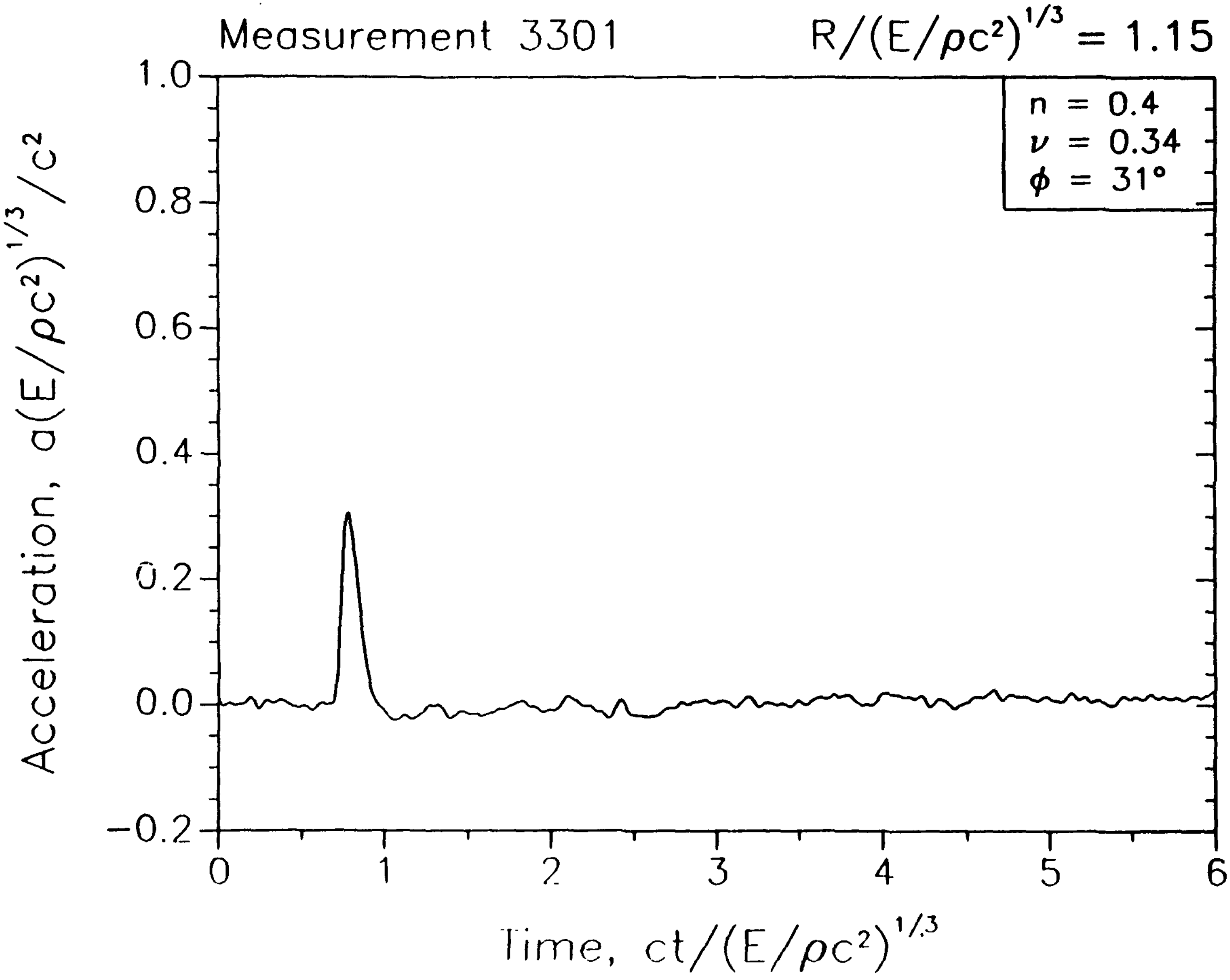
SCALED DATA PLOTS FROM DYNAMIC TESTS

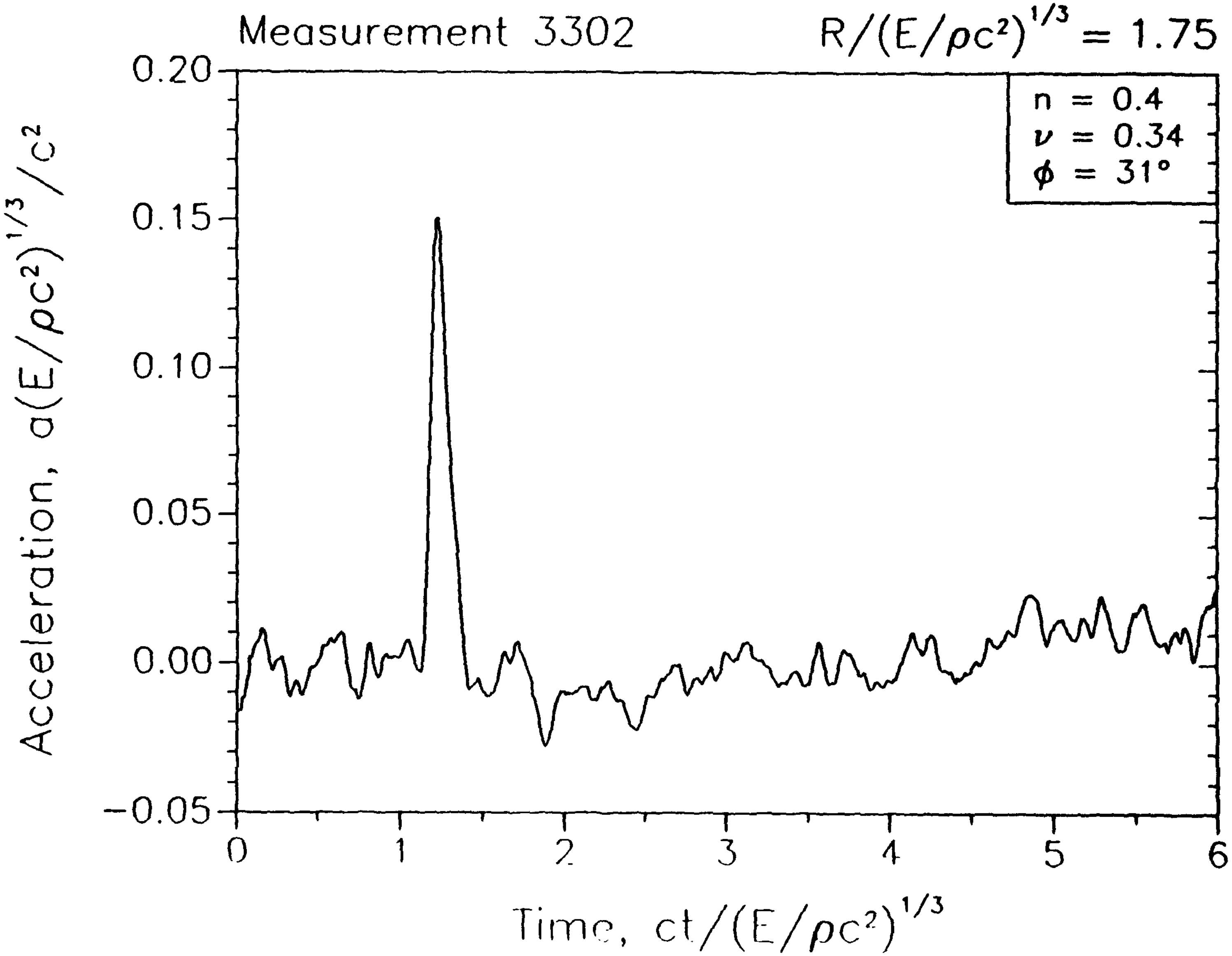
For the structure velocity plots, the sign of the data were changed where necessary so that all velocity vectors point in the same direction. Positive radial velocities point away from the charge; positive transverse velocities point upward, normal to the radial velocities.

a - acceleration
v - velocity
E - energy released by burst
ρ - density of soil
c - wave propagation velocity of soil
t - time
R - range from burst
η - porosity
ν - Poisson's ratio
ϕ - angle of internal friction
σ - stress

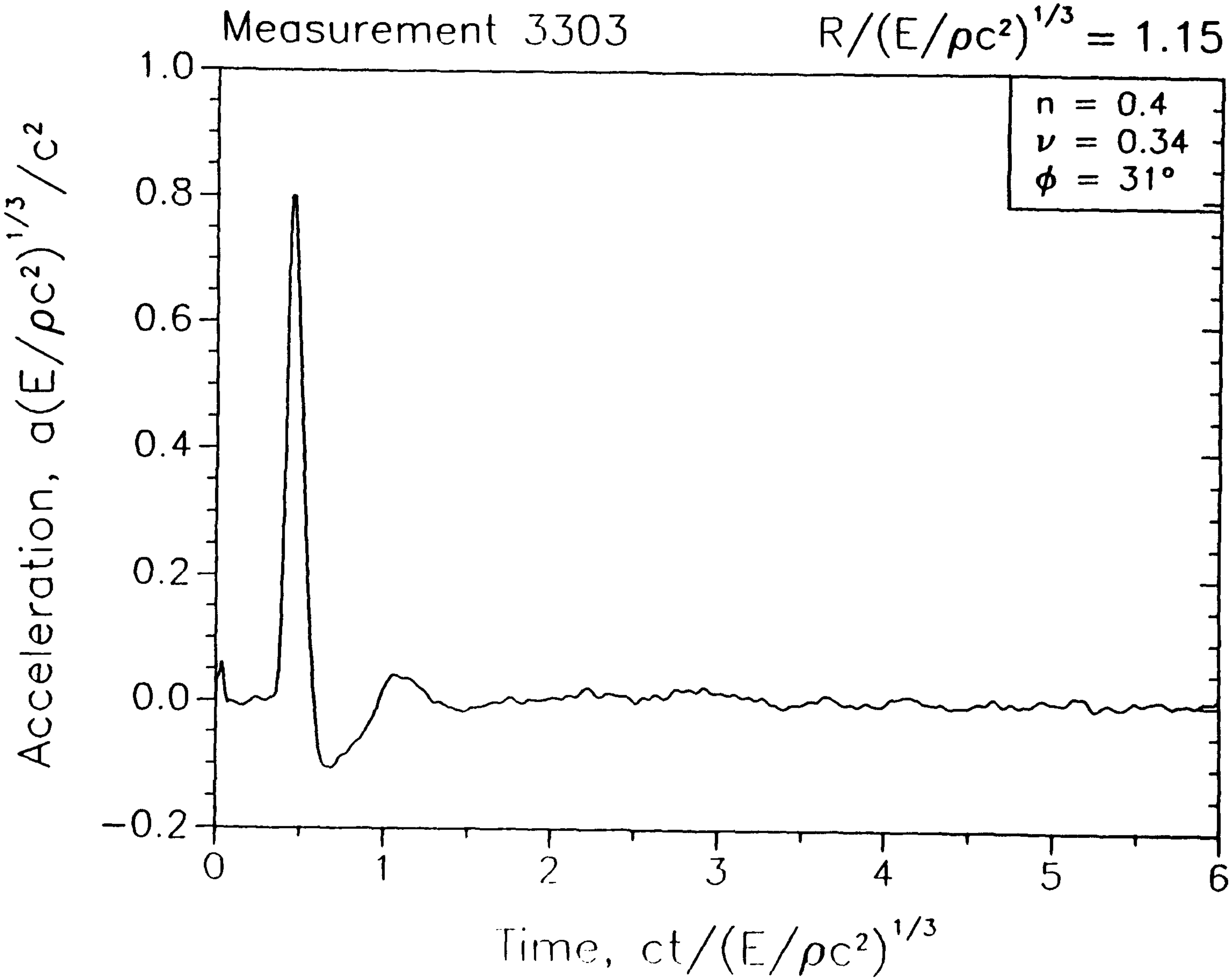
1/10 REPLICA SCALED TEST

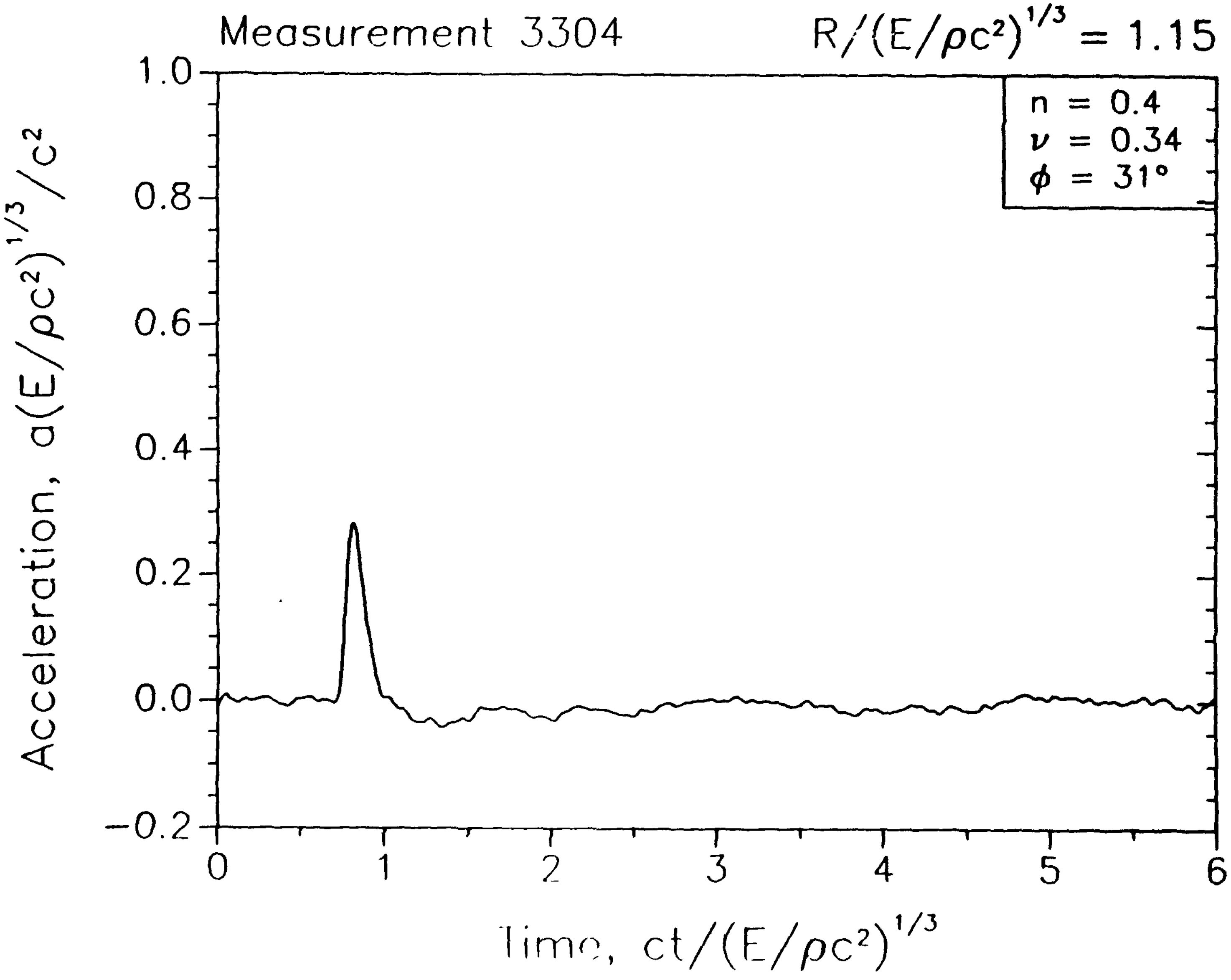
"SAND"

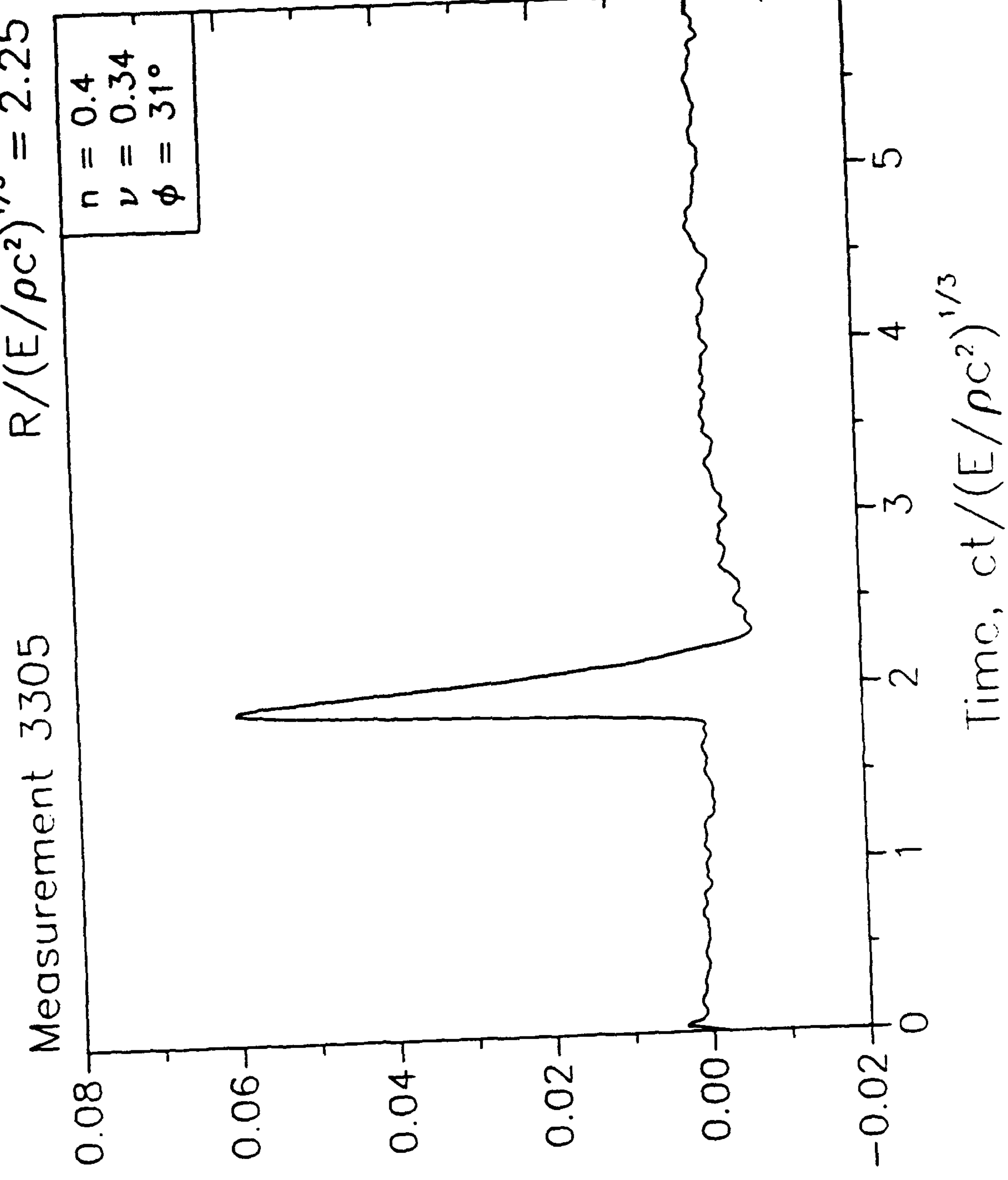

Measurement 3301
R/(E/ρc²)^1/3 = 1.15
n = 0.4
ν = 0.34
φ = 31°
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
0
1
2
3
4
5
6
Acceleration, a(E/ρc²)^1/3/c²
Time, ct/(E/ρc²)^1/3

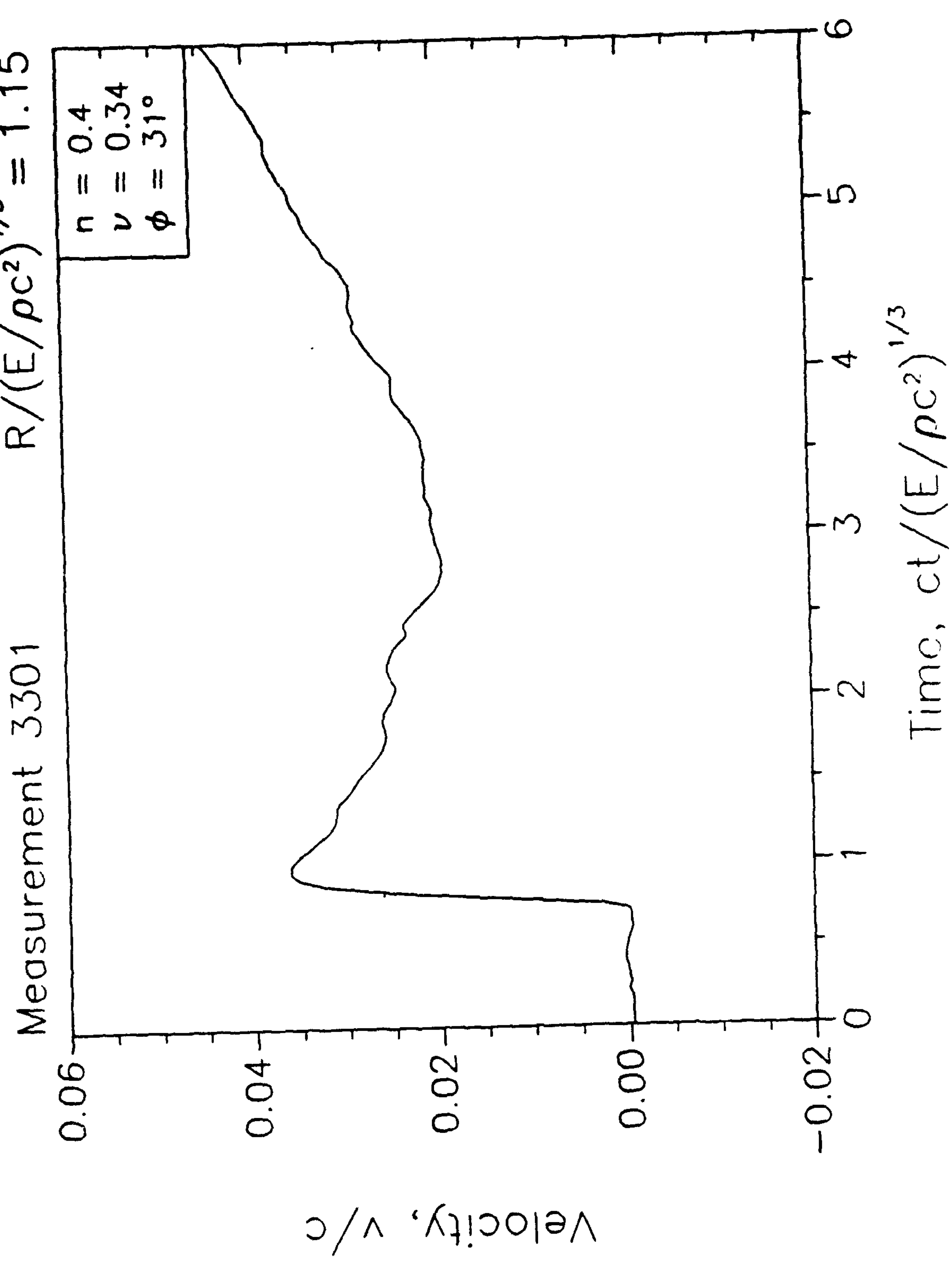


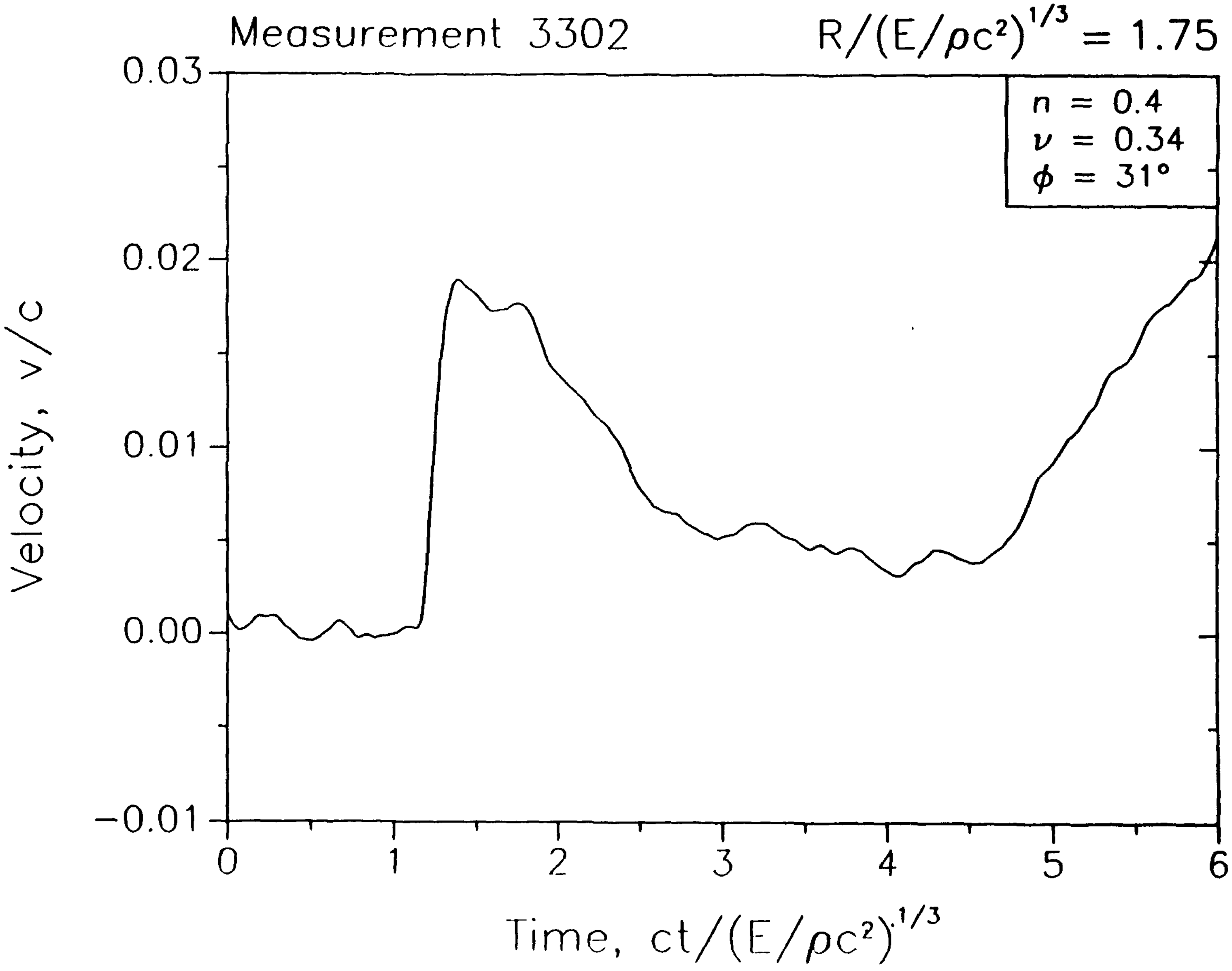
Measurement 3302
R/(E/ρc²)^1/3 = 1.75
n = 0.4
ν = 0.34
φ = 31°
0.20
0.15
0.10
0.05
0.00
−0.05
0
1
2
3
4
5
6
Acceleration, a(E/ρc²)^1/3/c²
Time, ct/(E/ρc²)^1/3


Measurement 3303
R/(E/ρc²)^1/3 = 1.15
n = 0.4
ν = 0.34
φ = 31°
Acceleration, a(E/ρc²)^1/3/c²
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
0
1
2
3
4
5
6
Time, ct/(E/ρc²)^1/3

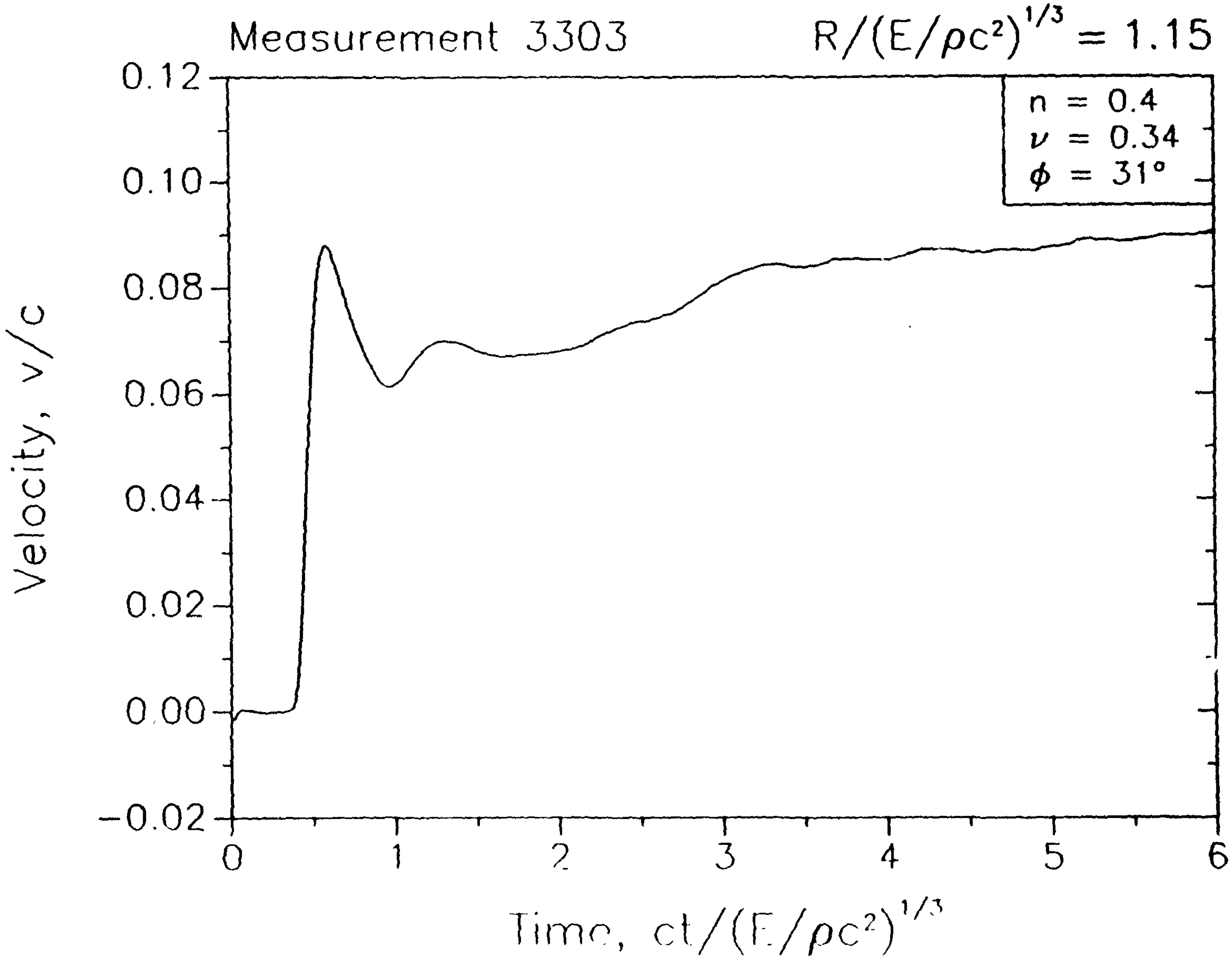

Measurement 3304
R/(E/ρc²)^1/3 = 1.15
n = 0.4
ν = 0.34
φ = 31°
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
Acceleration, a(E/ρc²)^1/3/c²
0
1
2
3
4
5
6
Time, ct/(E/ρc²)^1/3


Measurement 3305
R/(E/ρc²)^(1/3) = 2.25
n = 0.4
ν = 0.34
φ = 31°
0.08
0.06
0.04
0.02
0.00
−0.02
0
1
2
3
4
5
6
Acceleration, a(E/ρc²)^(1/3)/c²
Time, ct/(E/ρc²)^(1/3)

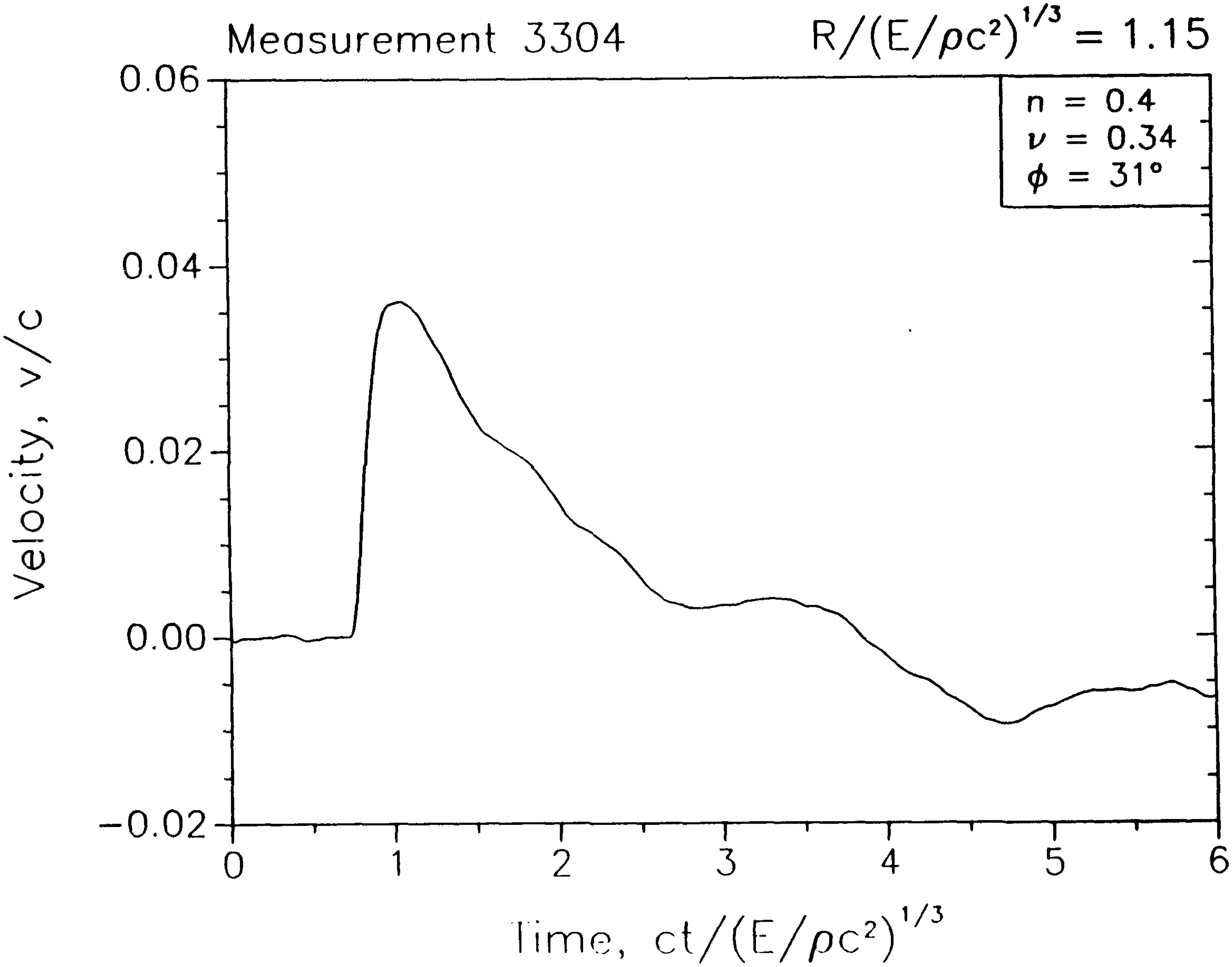

Measurement 3301
R/(E/ρc²)^1/3 = 1.15
n = 0.4
ν = 0.34
φ = 31°
Velocity, v/c
0.06
0.04
0.02
0.00
-0.02
0
1
2
3
4
5
6
Time, ct/(E/ρc²)^1/3



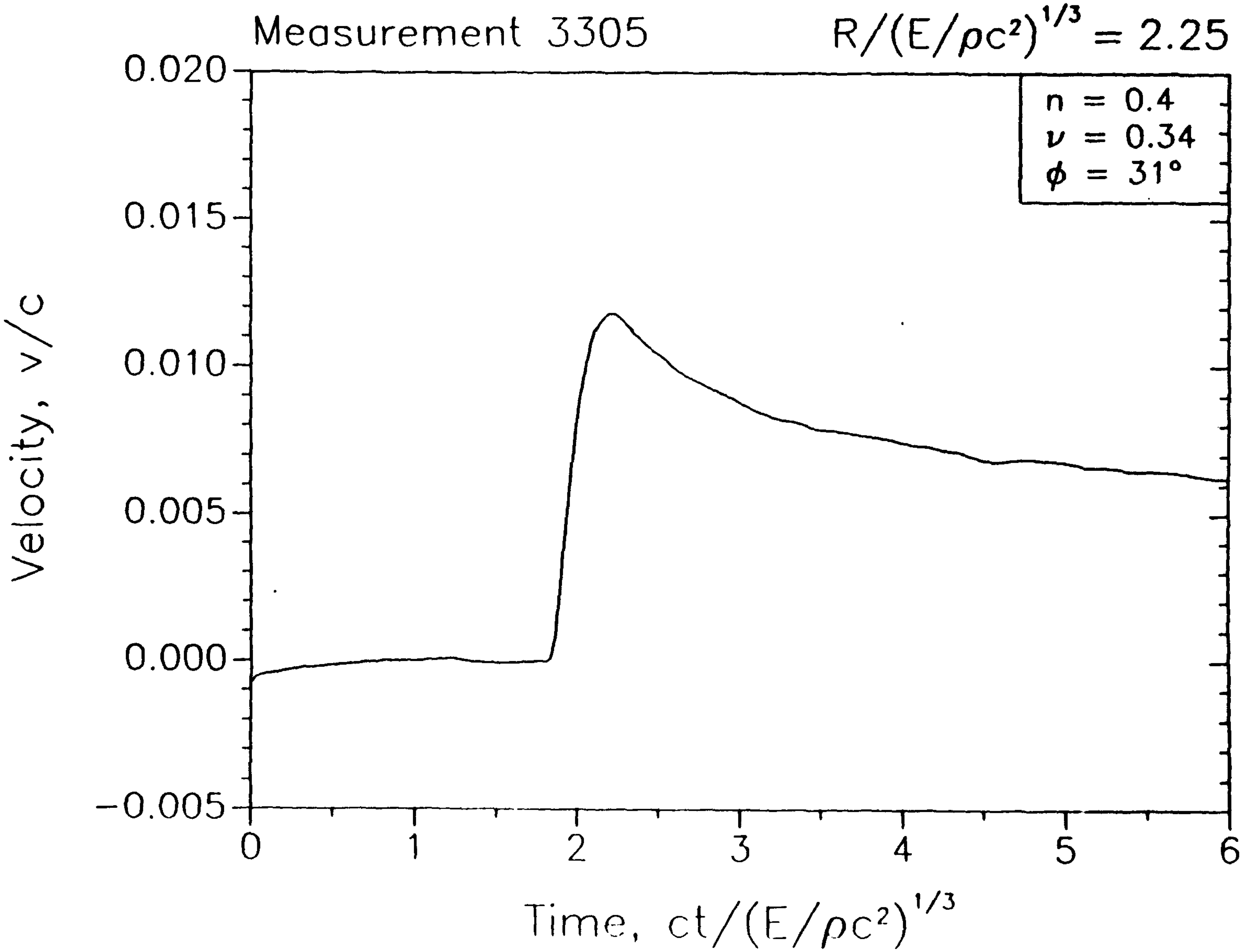
Measurement 3302
R/(E/ρc²)^1/3 = 1.75
n = 0.4
ν = 0.34
φ = 31°
Velocity, v/c
0.03
0.02
0.01
0.00
−0.01
0
1
2
3
4
5
6
Time, ct/(E/ρc²)^1/3



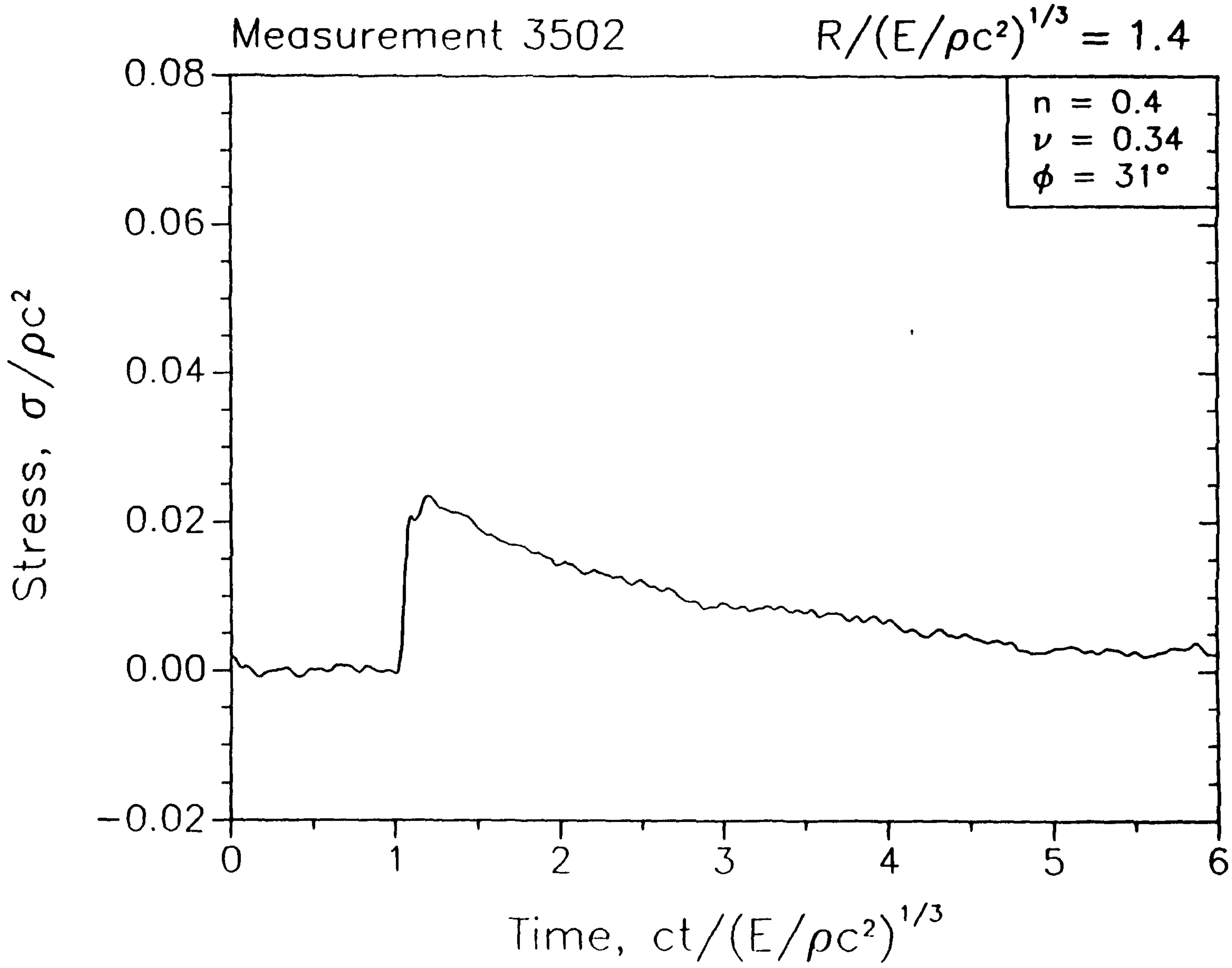
Measurement 3303
R/(E/ρc²)^1/3 = 1.15
n = 0.4
ν = 0.34
φ = 31°
Velocity, v/c
0.12
0.10
0.08
0.06
0.04
0.02
0.00
−0.02
0
1
2
3
4
5
6
Time, ct/(E/ρc²)^1/3

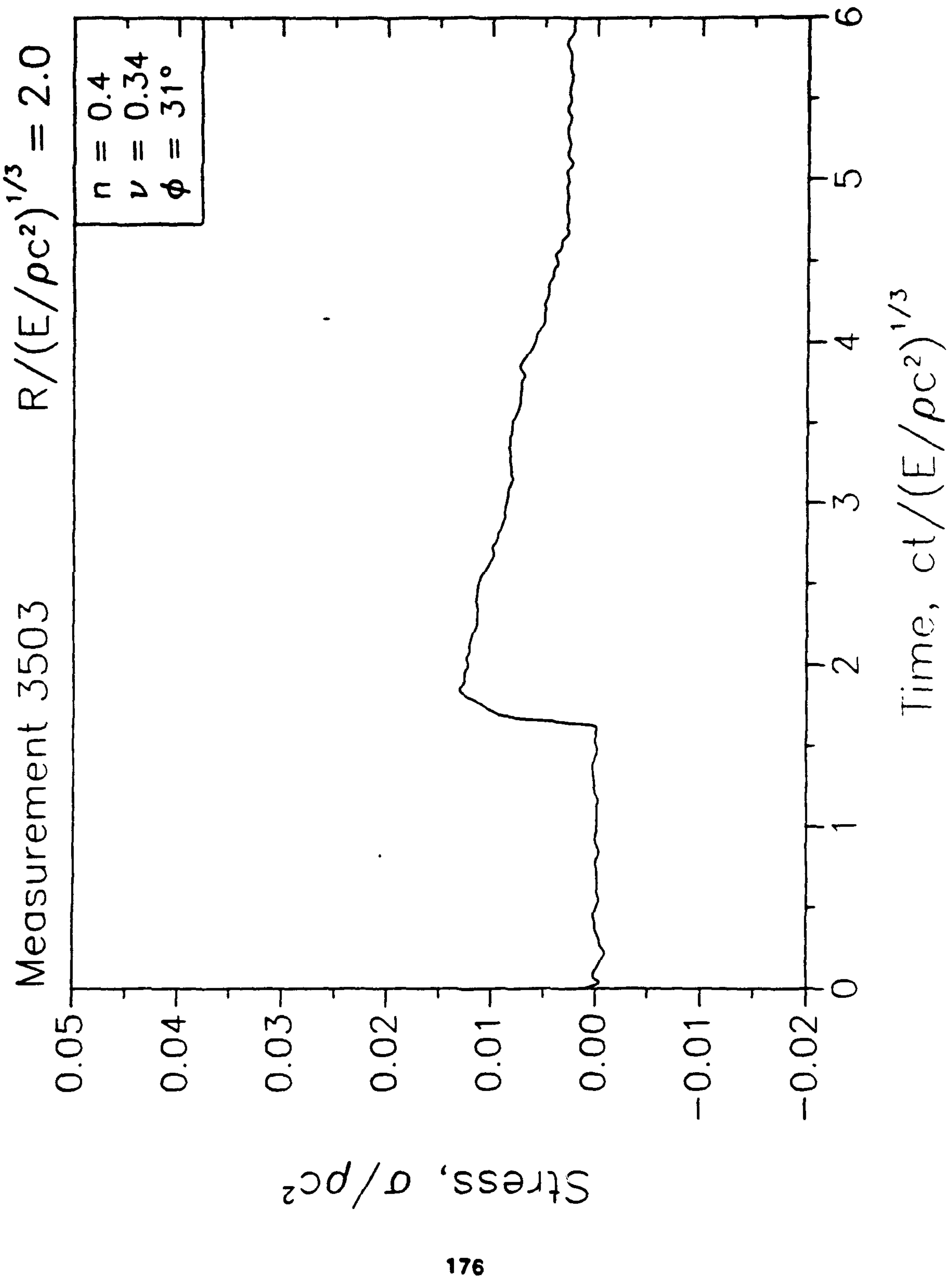


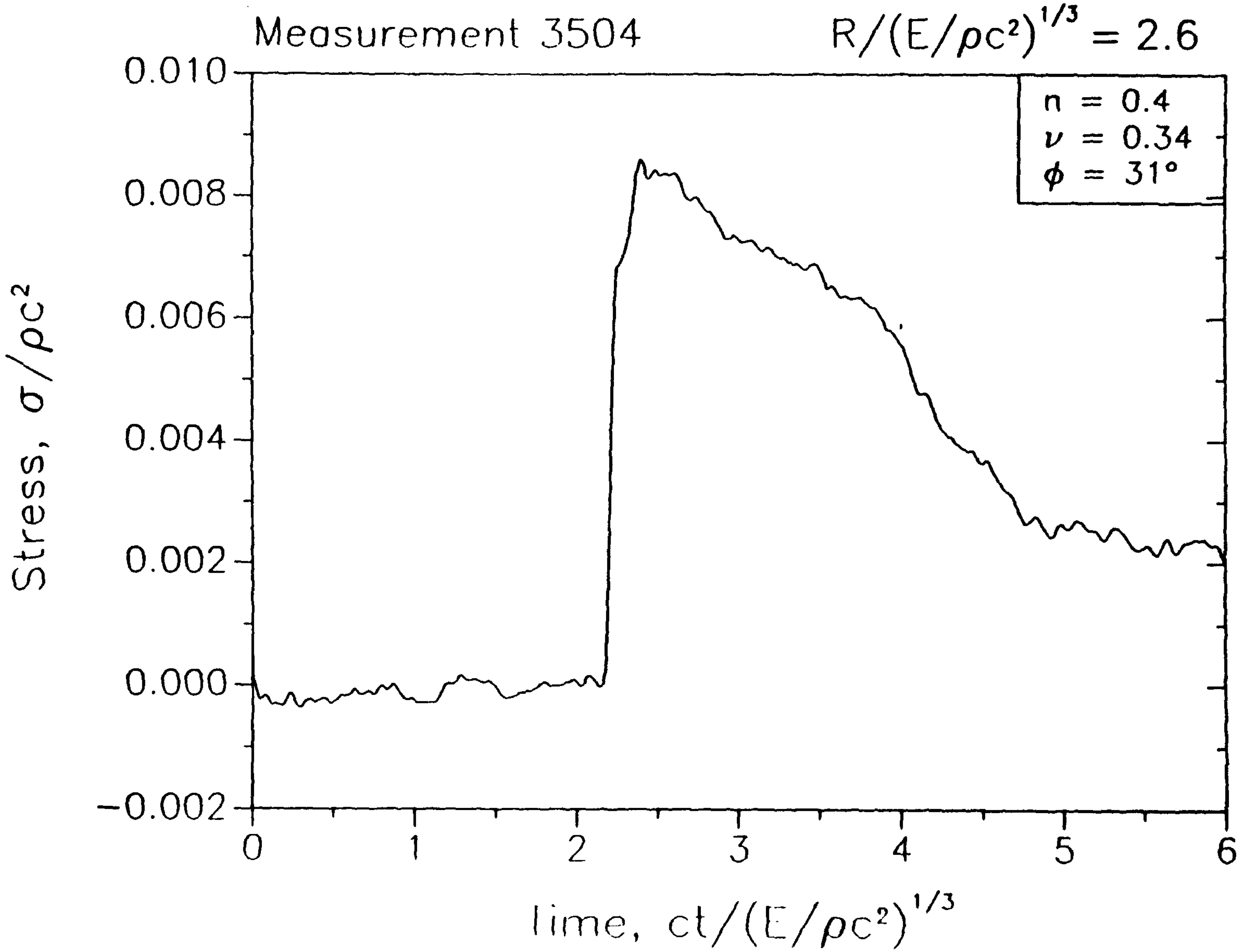
Measurement 3304
R/(E/ρc²)^1/3 = 1.15
n = 0.4
ν = 0.34
φ = 31°
0.06
0.04
0.02
0.00
−0.02
0
1
2
3
4
5
6
Velocity, v/c
Time, ct/(E/ρc²)^1/3

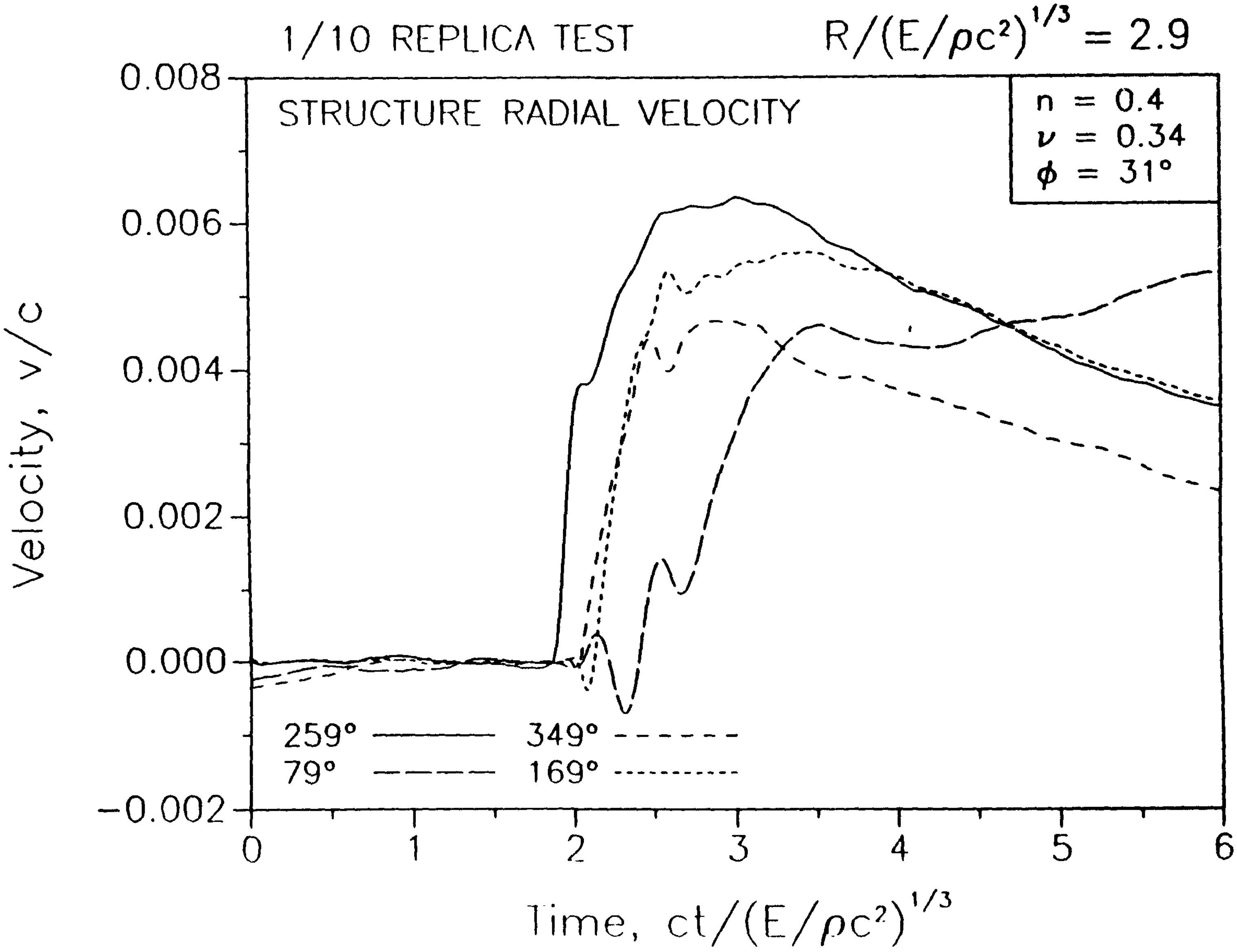


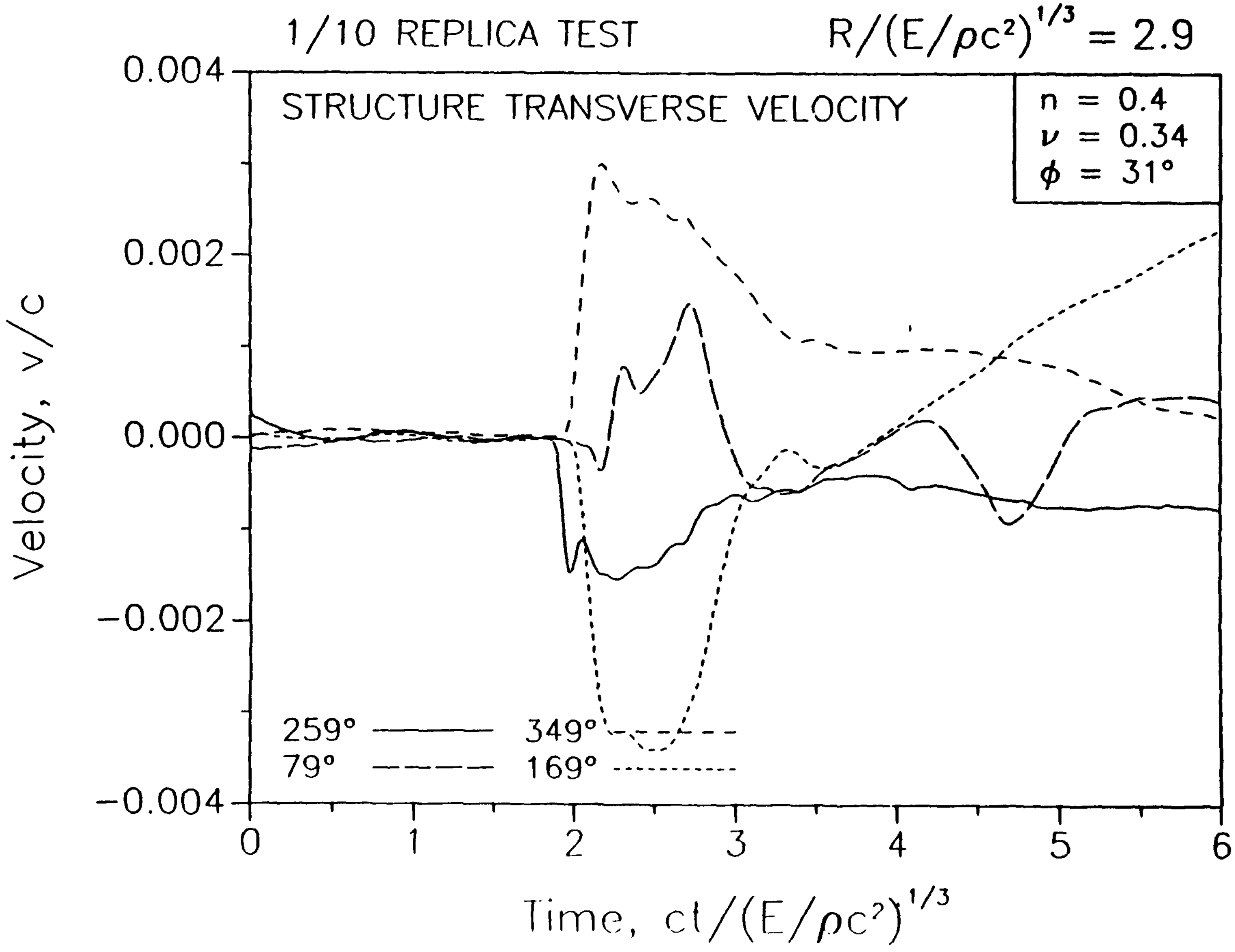
Measurement 3305
R/(E/ρc²)^1/3 = 2.25
n = 0.4
ν = 0.34
φ = 31°
0.020
0.015
0.010
0.005
0.000
−0.005
Velocity, v/c
0
1
2
3
4
5
6
Time, ct/(E/ρc²)^1/3


Measurement 3502
R/(E/ρc²)^1/3 = 1.4
n = 0.4
ν = 0.34
φ = 31°
Stress, σ/ρc²
0.08
0.06
0.04
0.02
0.00
−0.02
0
1
2
3
4
5
6
Time, ct/(E/ρc²)^1/3


Measurement 3503
R/(E/ρc²)^1/3 = 2.0
n = 0.4
ν = 0.34
φ = 31°
Stress, σ/ρc²
0.05
0.04
0.03
0.02
0.01
0.00
−0.01
−0.02
Time, ct/(E/ρc²)^1/3
0
1
2
3
4
5
6


Measurement 3504
R/(E/ρc²)^1/3 = 2.6
n = 0.4
ν = 0.34
φ = 31°
0.010
0.008
0.006
0.004
0.002
0.000
−0.002
0
1
2
3
4
5
6
Stress, σ/ρc²
Time, ct/(E/ρc²)^1/3

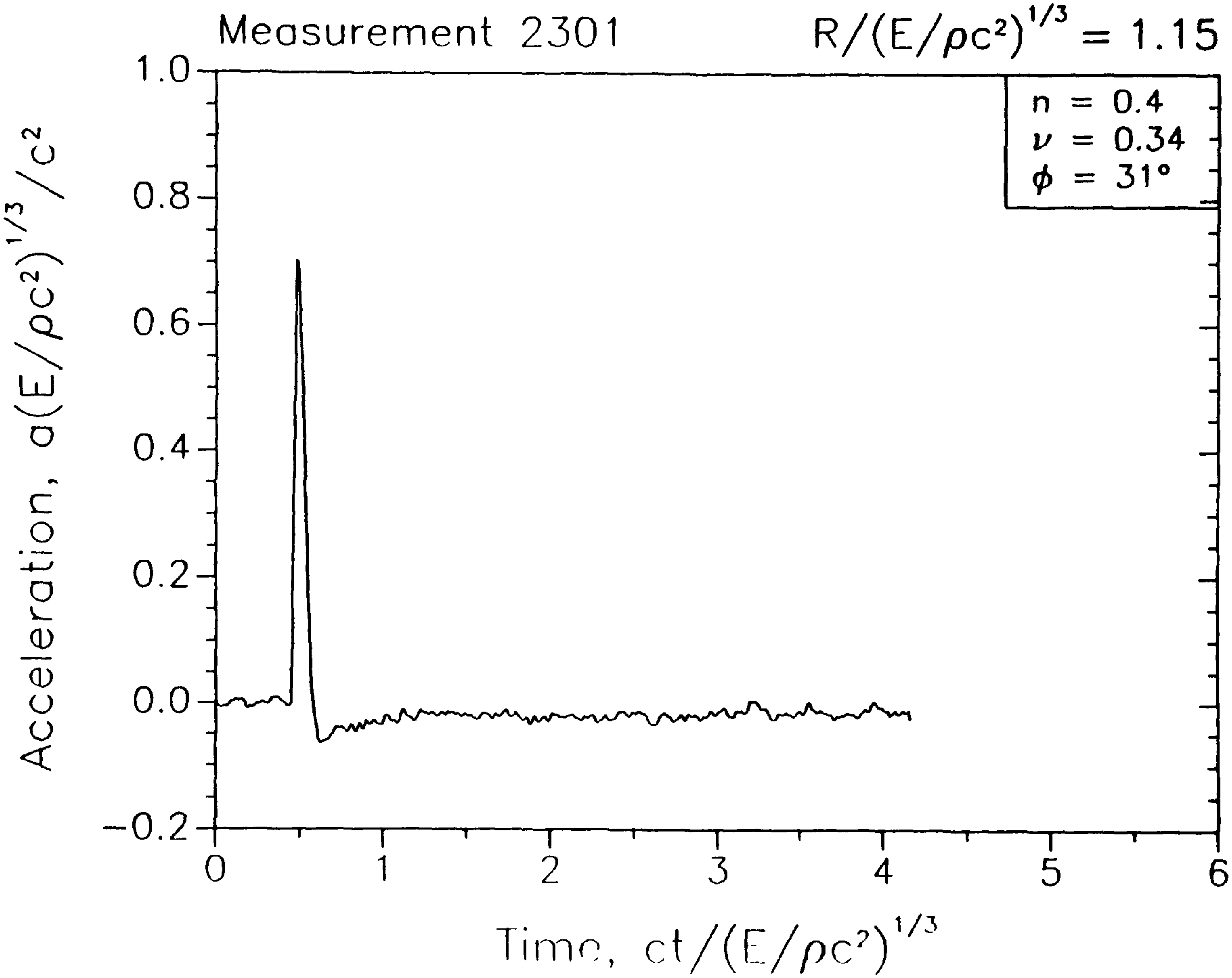

1/10 REPLICA TEST
R/(E/ρc²)^1/3 = 2.9
STRUCTURE RADIAL VELOCITY
n = 0.4
ν = 0.34
φ = 31°
259°
349°
79°
169°
Velocity, v/c
0.008
0.006
0.004
0.002
0.000
−0.002
0
1
2
3
4
5
6
Time, ct/(E/ρc²)^1/3

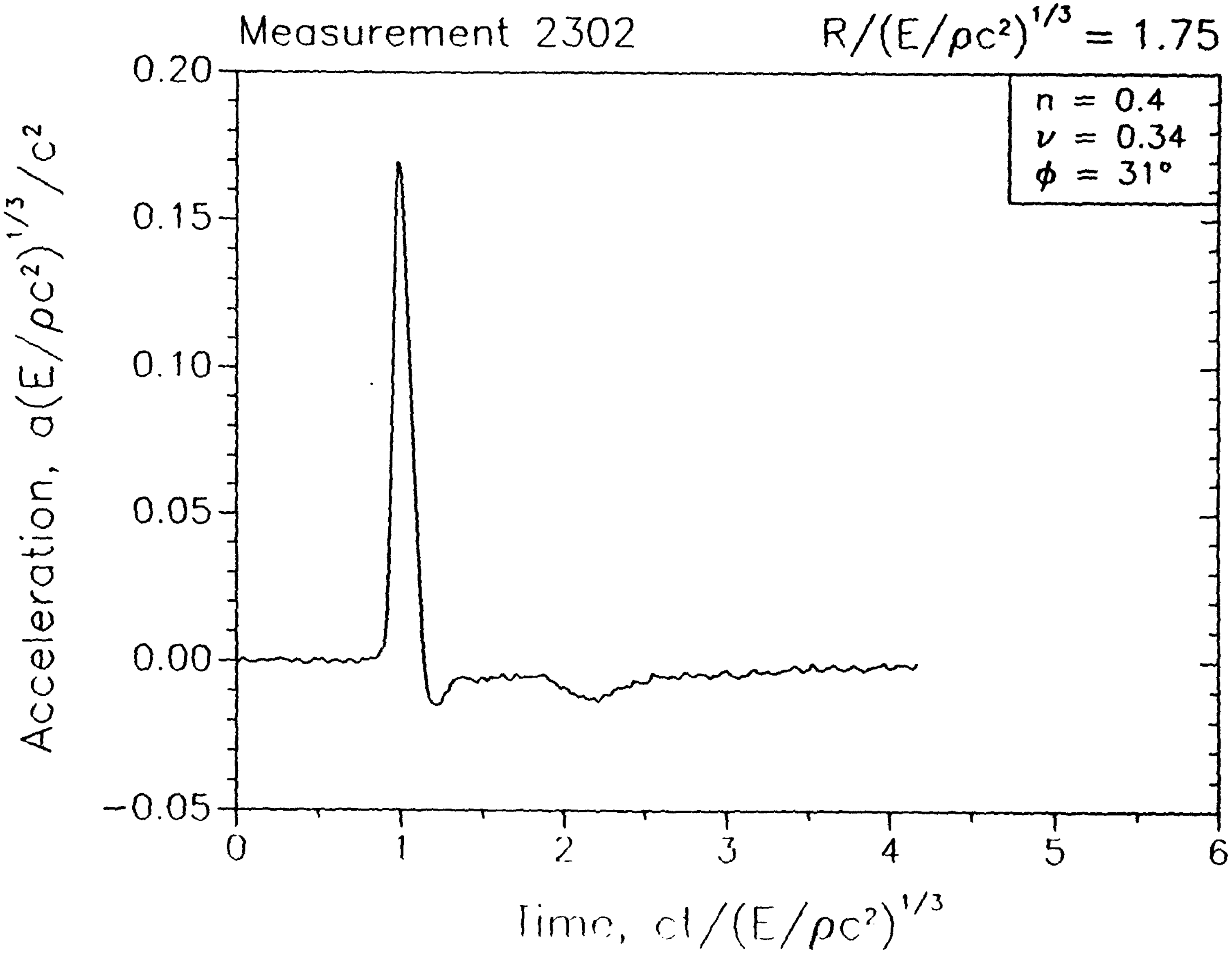


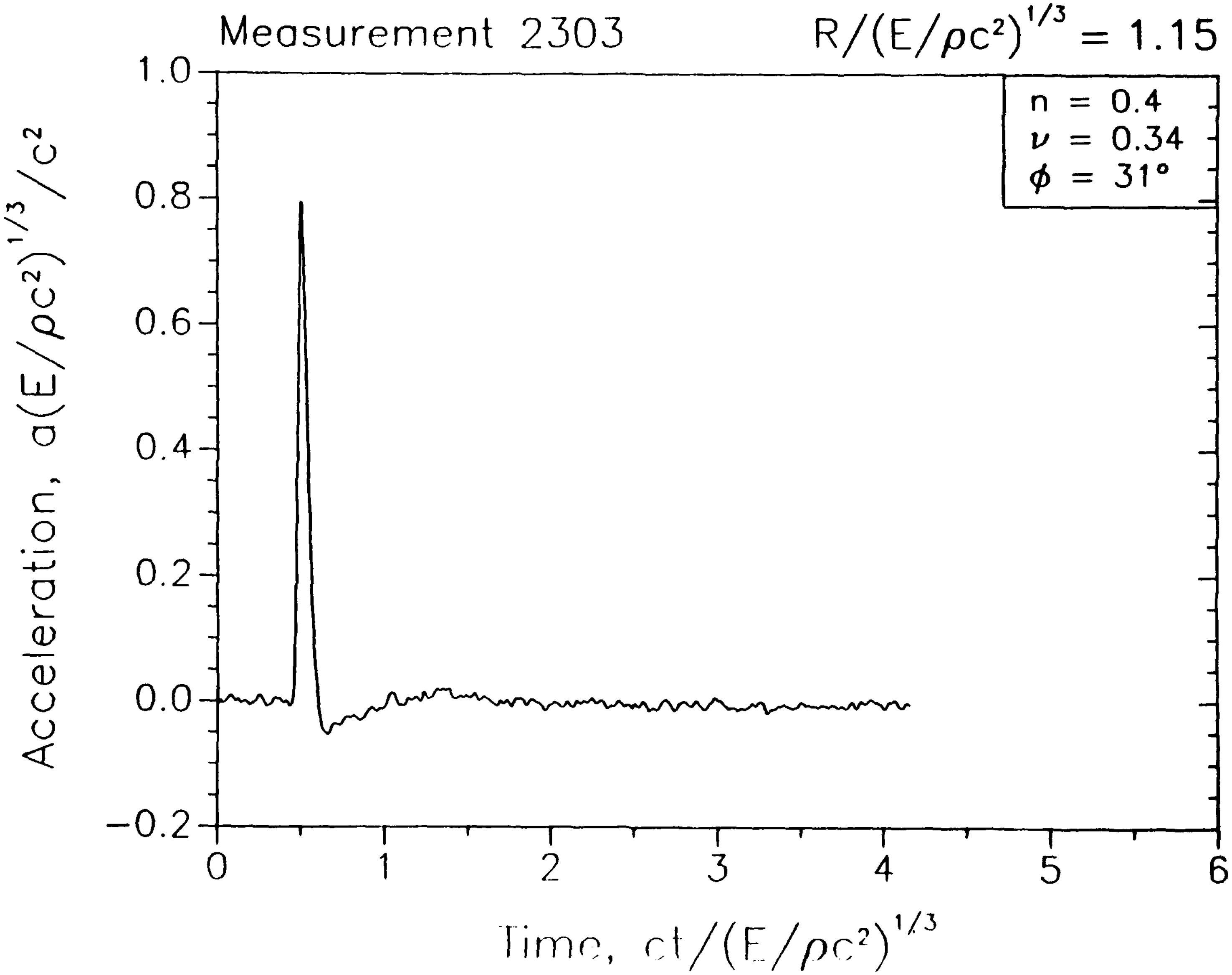
1/10 REPLICA TEST
R/(E/ρc²)^1/3 = 2.9
STRUCTURE TRANSVERSE VELOCITY
n = 0.4
ν = 0.34
φ = 31°
259°
349°
79°
169°
Velocity, v/c
0.004
0.002
0.000
−0.002
−0.004
0
1
2
3
4
5
6
Time, ct/(E/ρc²)^1/3

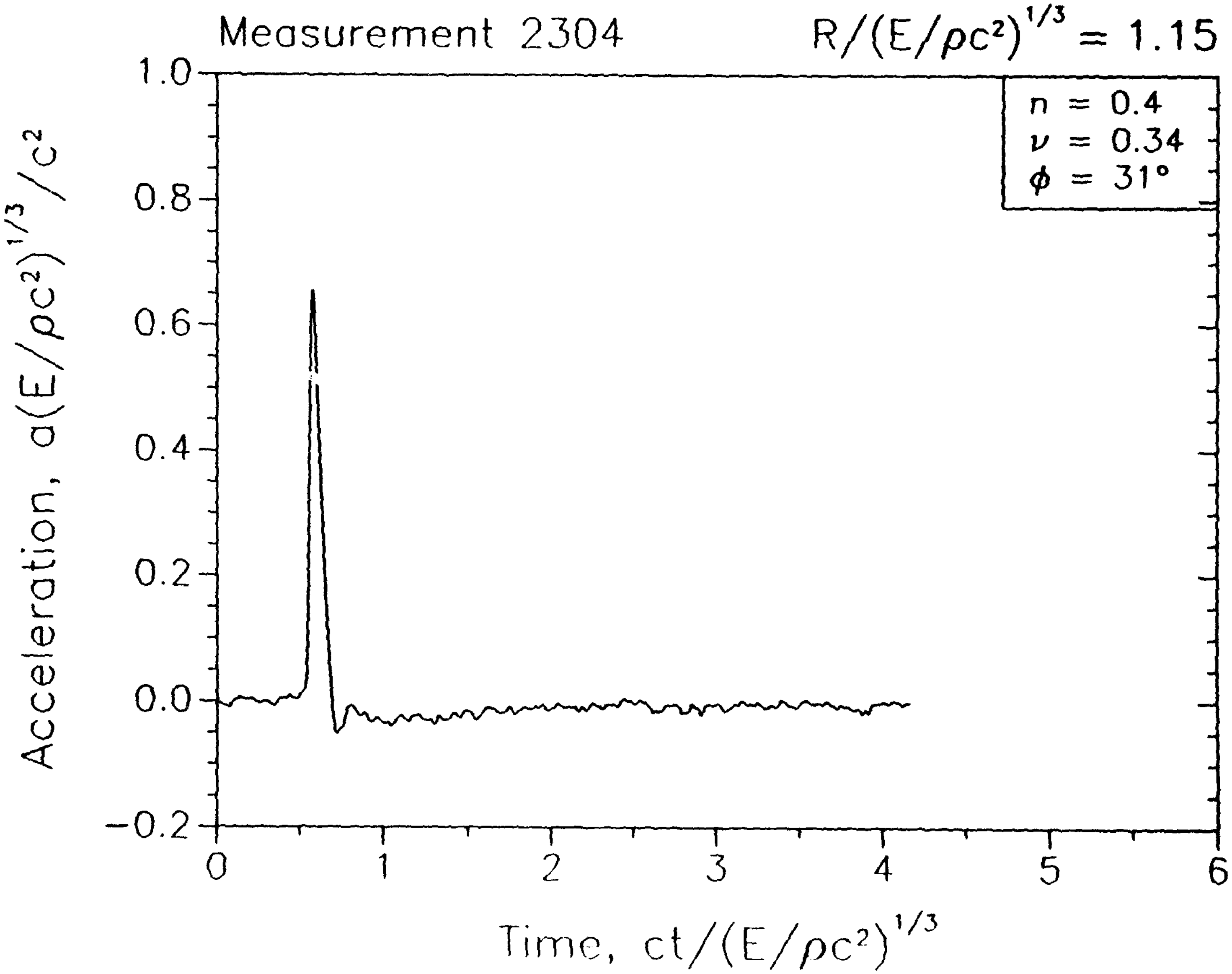
1/5 FROUDE SCALED TEST

"COAL"

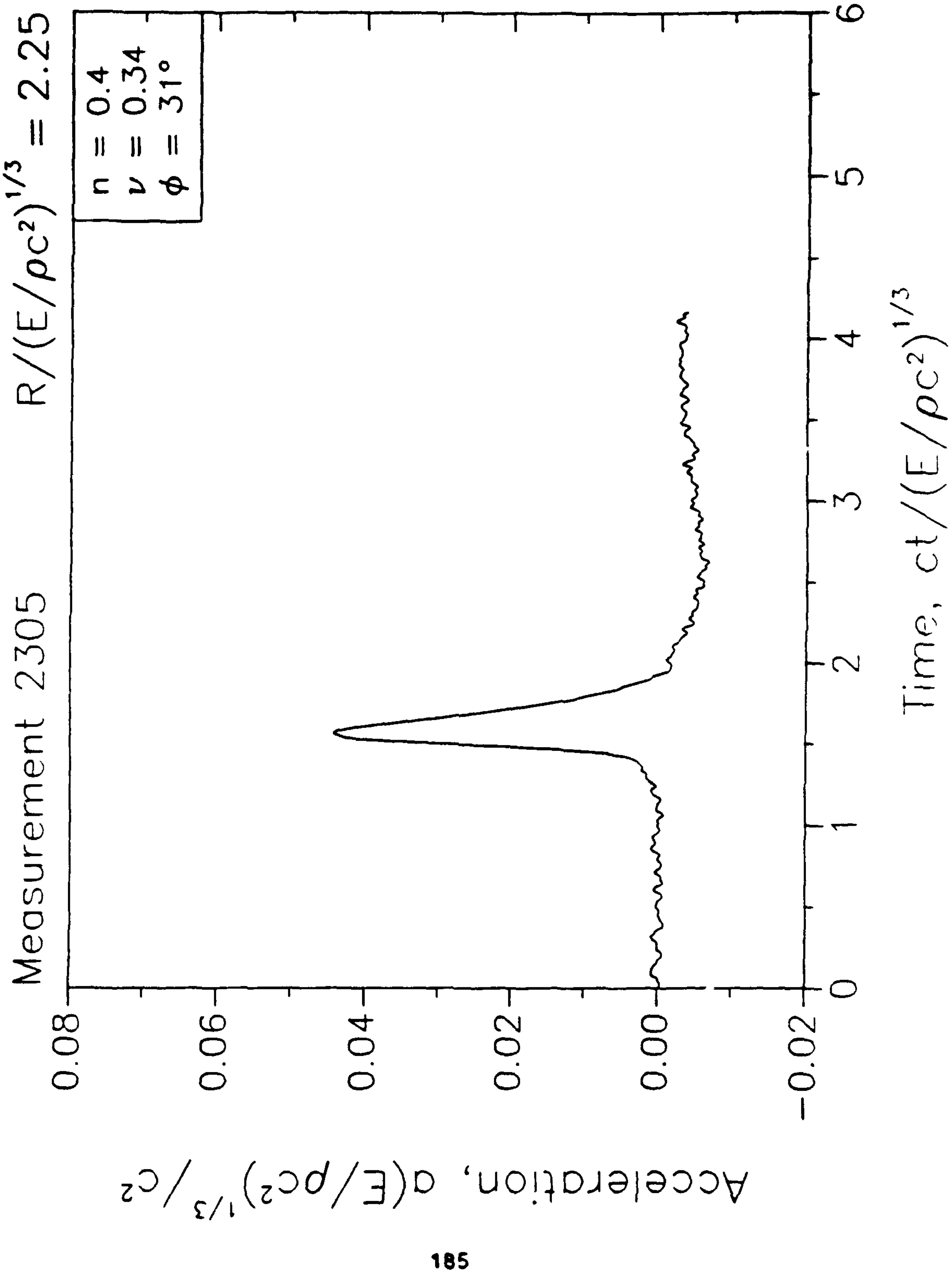

Measurement 2301
R/(E/ρc²)^1/3 = 1.15
n = 0.4
ν = 0.34
φ = 31°
Acceleration, a(E/ρc²)^1/3/c²
Time, ct/(E/ρc²)^1/3
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
0
1
2
3
4
5
6


Measurement 2302
R/(E/ρc²)^1/3 = 1.75
n = 0.4
ν = 0.34
φ = 31°
0.20
0.15
0.10
0.05
0.00
−0.05
Acceleration, a(E/ρc²)^1/3/c²
0
1
2
3
4
5
6
Time, ct/(E/ρc²)^1/3

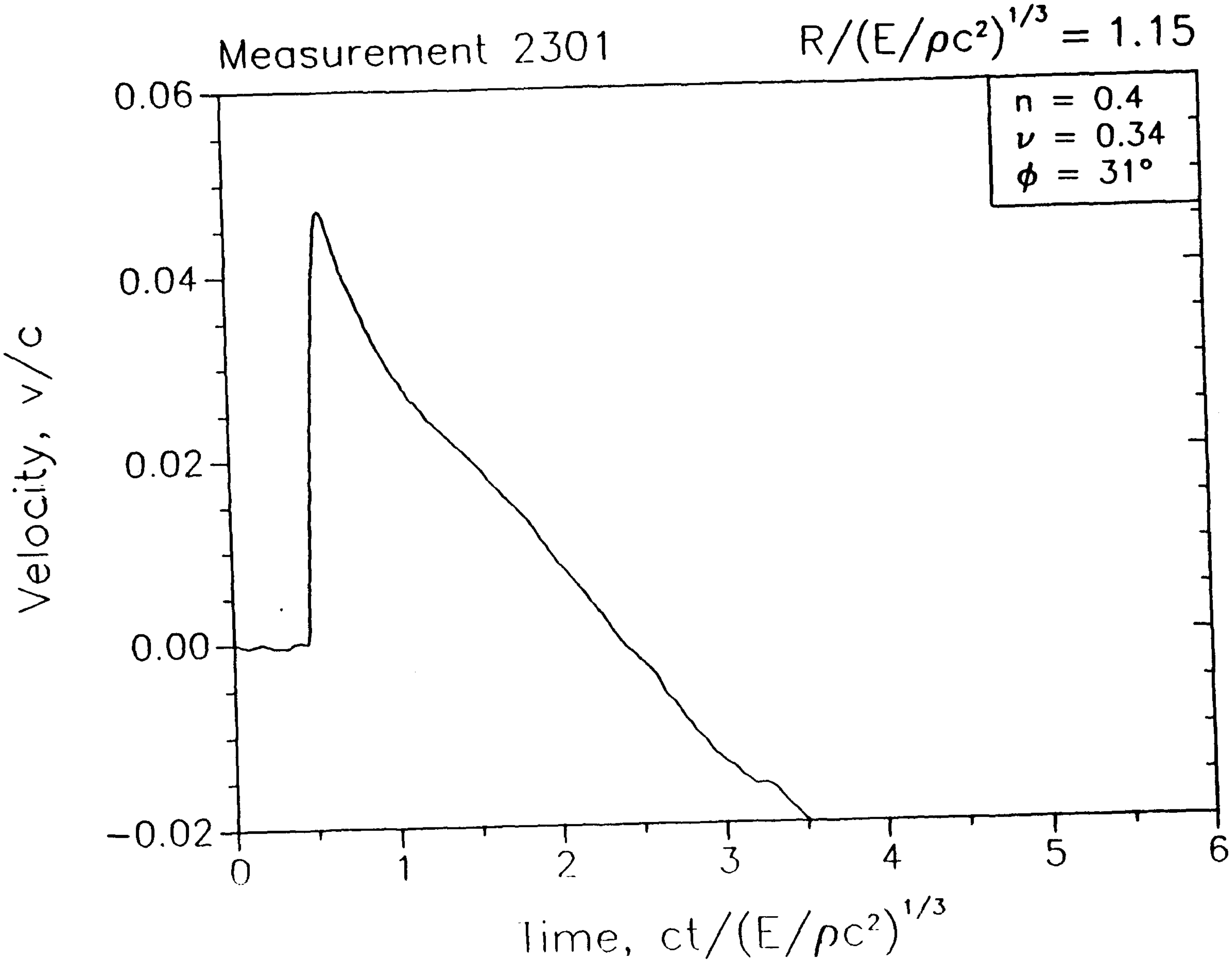

Measurement 2303
R/(E/ρc²)^1/3 = 1.15
n = 0.4
ν = 0.34
φ = 31°
Acceleration, a(E/ρc²)^1/3/c²
Time, ct/(E/ρc²)^1/3
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
0
1
2
3
4
5
6



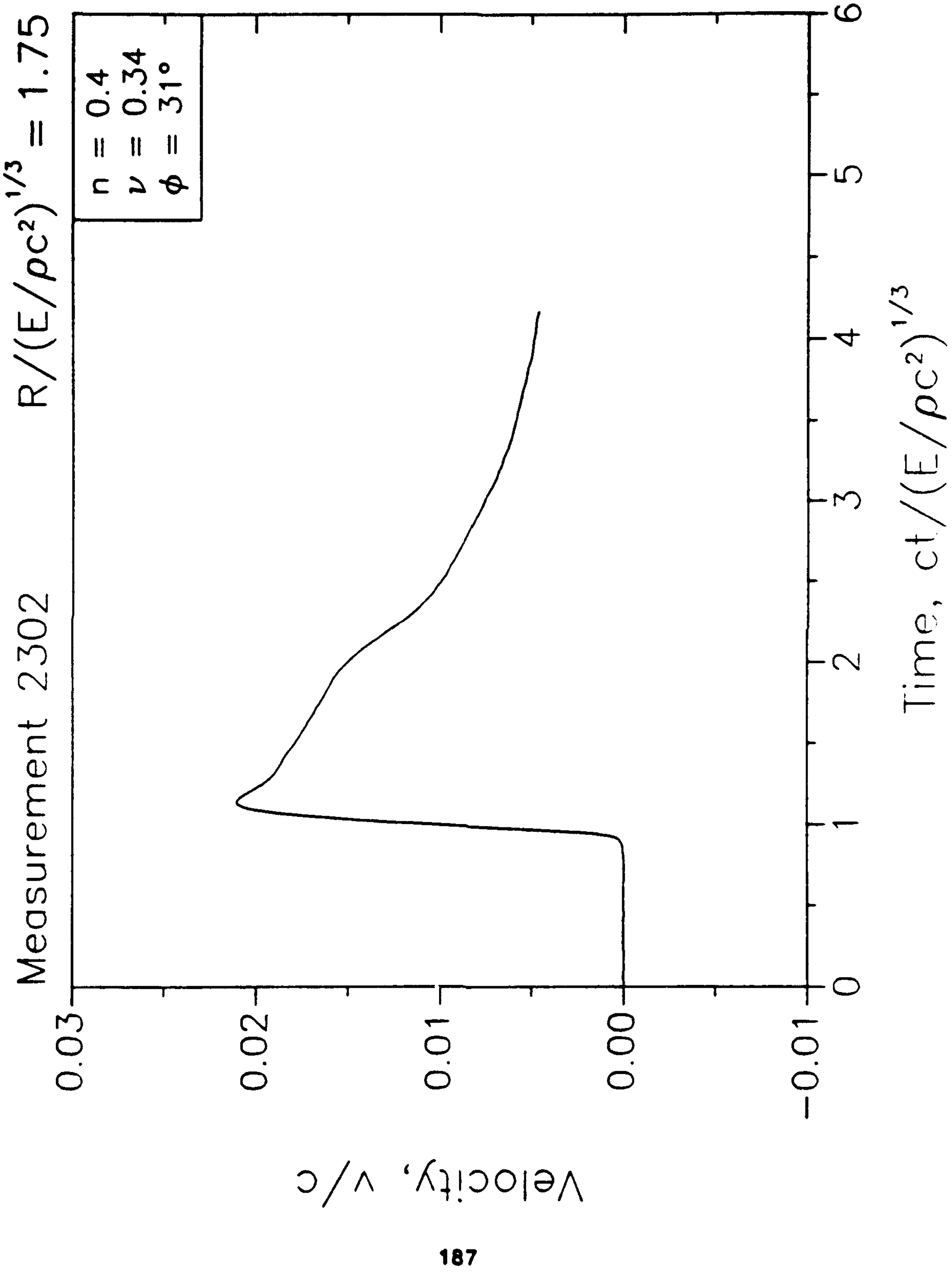
Measurement 2304
R/(E/ρc²)^(1/3) = 1.15
n = 0.4
ν = 0.34
φ = 31°
Acceleration, a(E/ρc²)^(1/3)/c²
Time, ct/(E/ρc²)^(1/3)
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
0
1
2
3
4
5
6

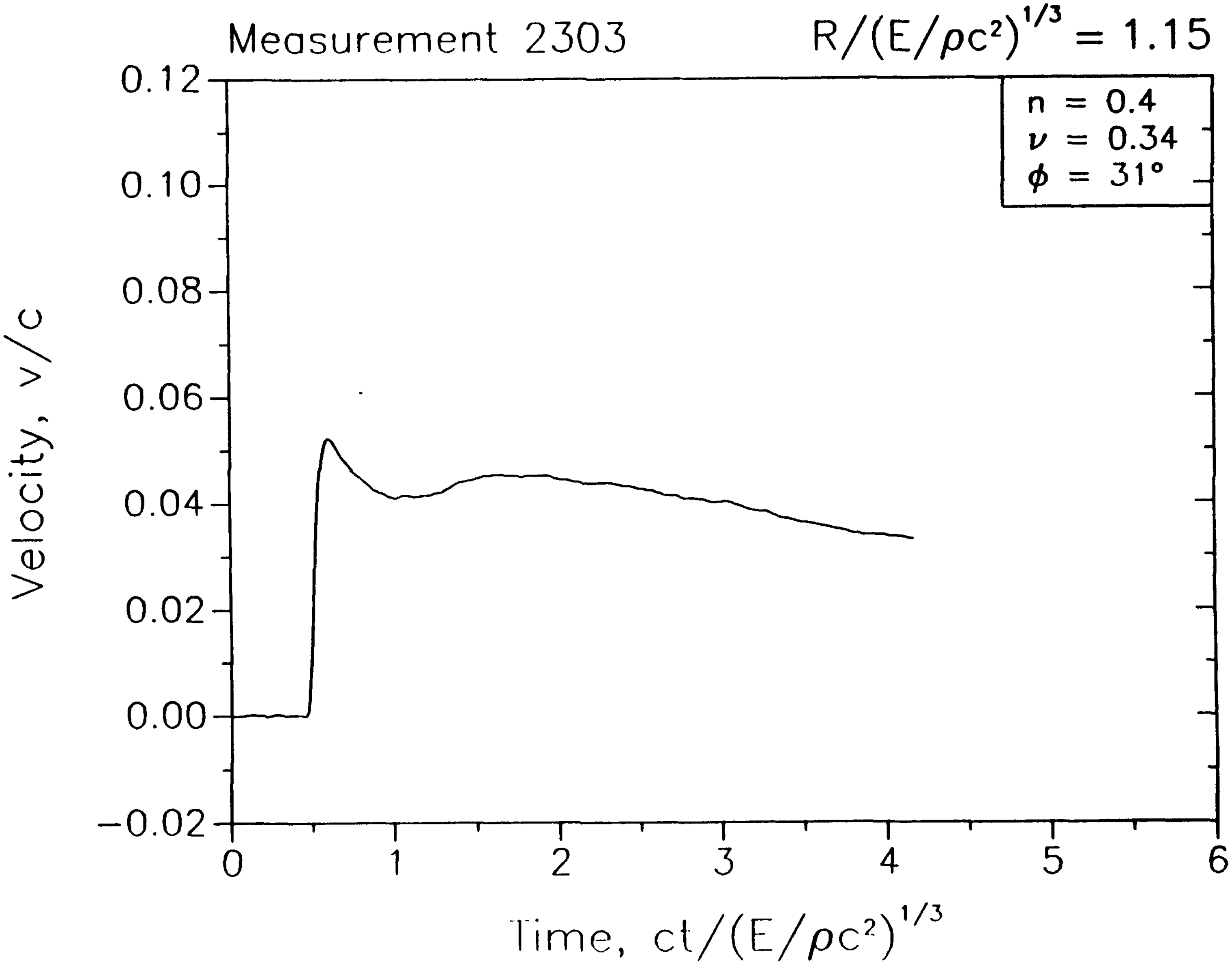


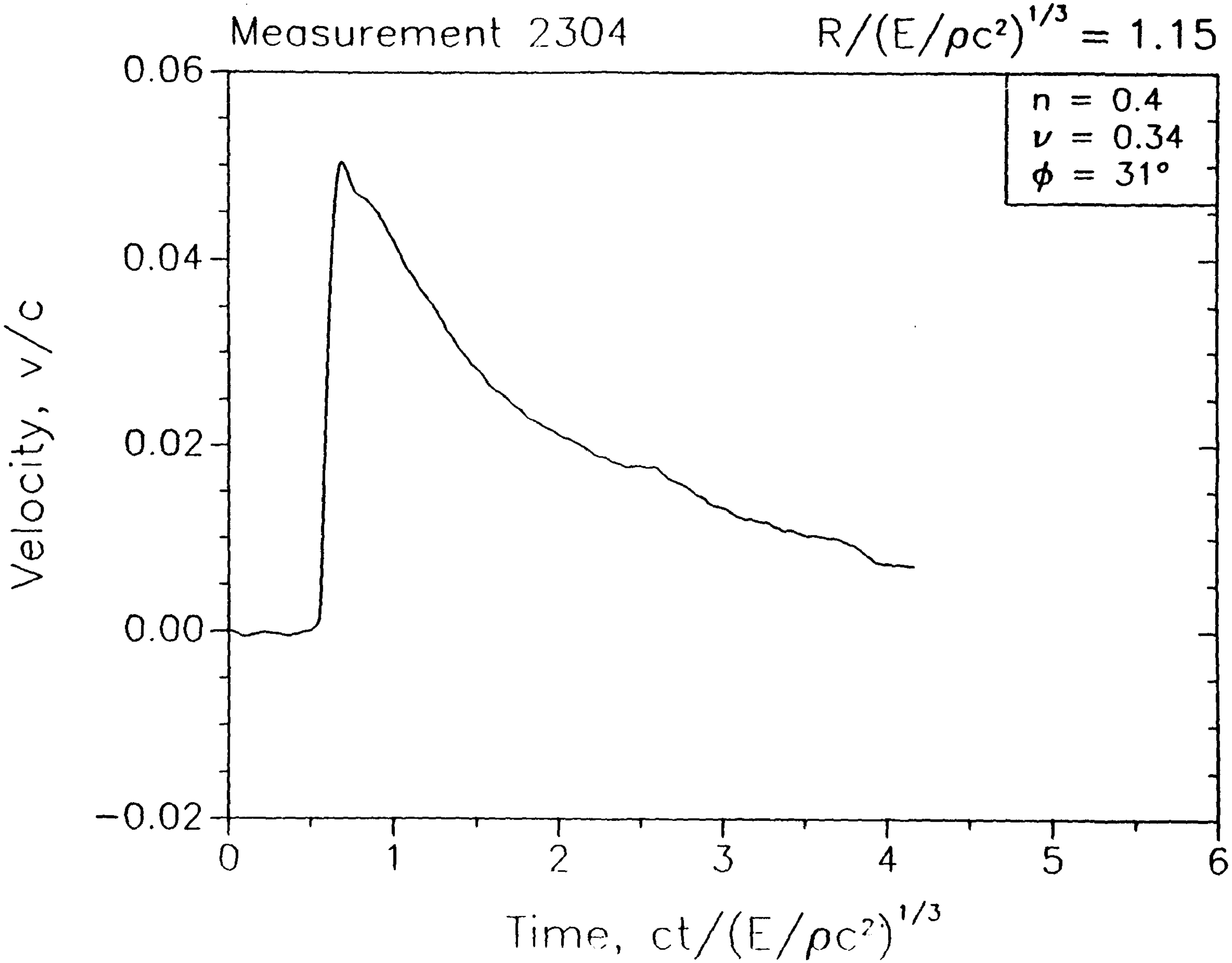
Measurement 2305
R/(E/ρc²)^1/3 = 2.25
n = 0.4
ν = 0.34
φ = 31°
Time, ct/(E/ρc²)^1/3
Acceleration, a(E/ρc²)^1/3/c²
0.08
0.06
0.04
0.02
0.00
−0.02
0
1
2
3
4
5
6

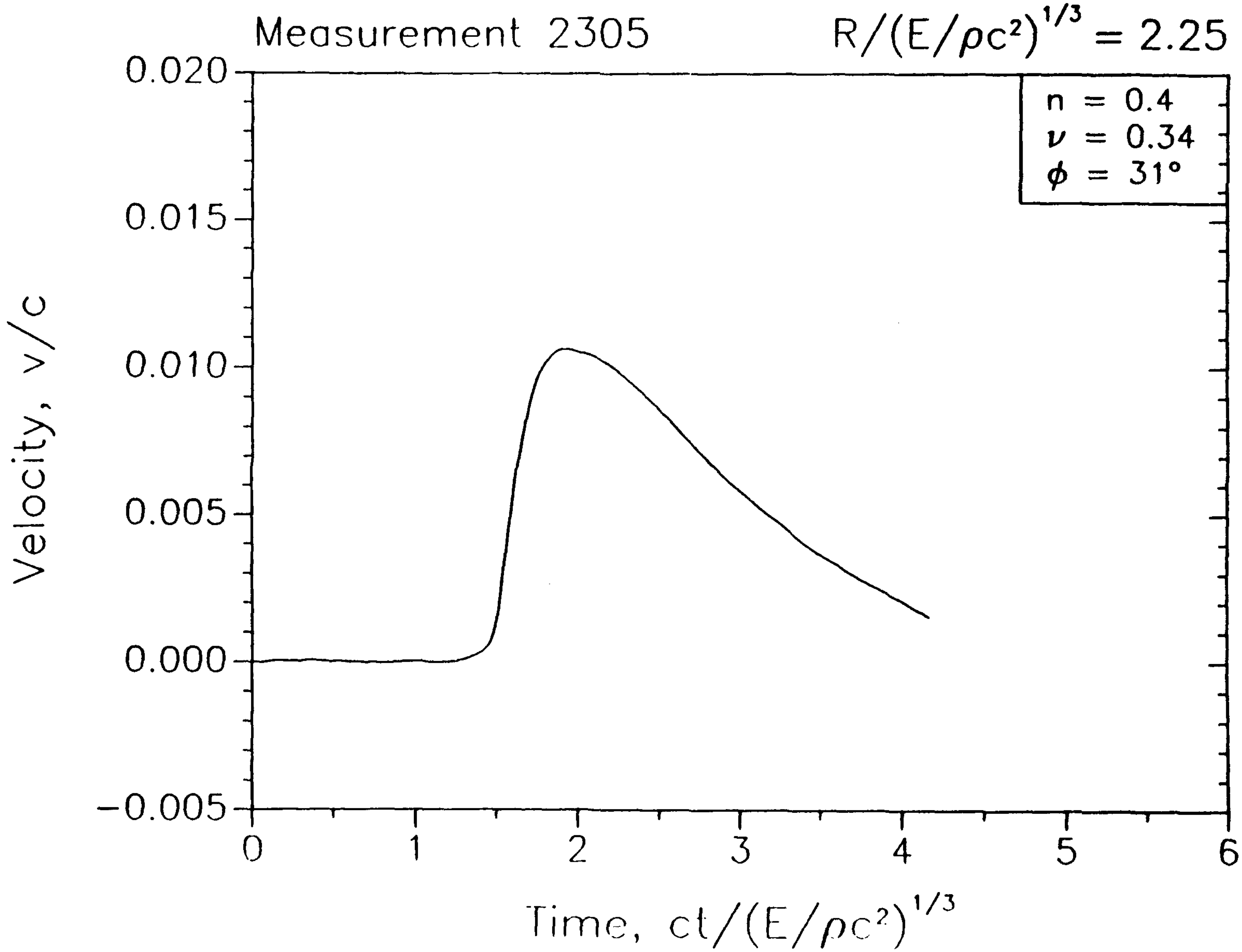


Measurement 2301
R/(E/ρc²)^1/3 = 1.15
n = 0.4
ν = 0.34
φ = 31°
0.06
0.04
0.02
0.00
−0.02
Velocity, v/c
0
1
2
3
4
5
6
Time, ct/(E/ρc²)^1/3

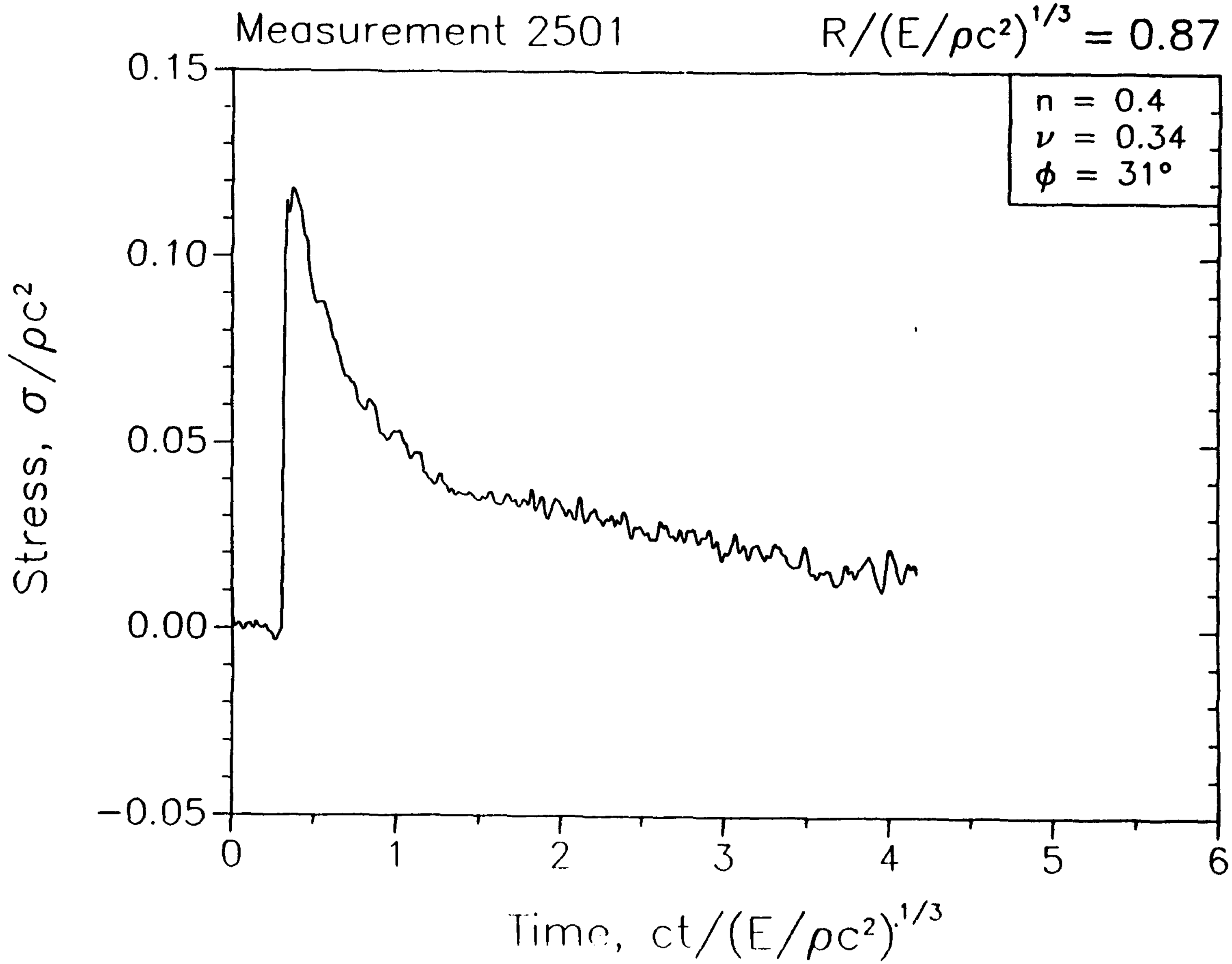

Measurement 2302
R/(E/ρc²)^1/3 = 1.75
n = 0.4
ν = 0.34
φ = 31°
Velocity, v/c
Time, ct/(E/ρc²)^1/3
0.03
0.02
0.01
0.00
-0.01
0
1
2
3
4
5
6


Measurement 2303
R/(E/ρc²)^1/3 = 1.15
n = 0.4
ν = 0.34
φ = 31°
0.12
0.10
0.08
0.06
0.04
0.02
0.00
−0.02
Velocity, v/c
0
1
2
3
4
5
6
Time, ct/(E/ρc²)^1/3

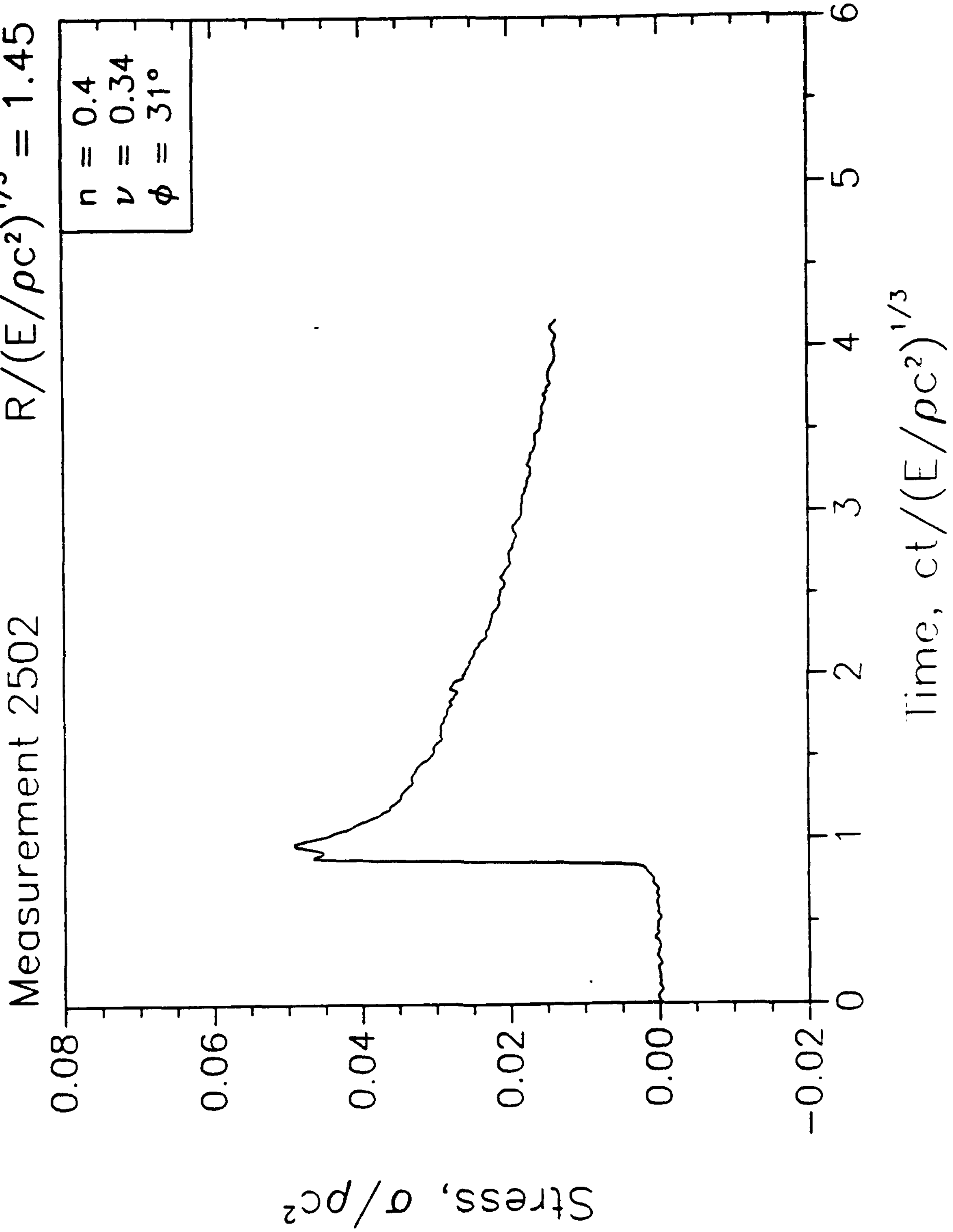

Measurement 2304
R/(E/ρc²)^1/3 = 1.15
n = 0.4
ν = 0.34
φ = 31°
Velocity, v/c
0.06
0.04
0.02
0.00
−0.02
0
1
2
3
4
5
6
Time, ct/(E/ρc²)^1/3



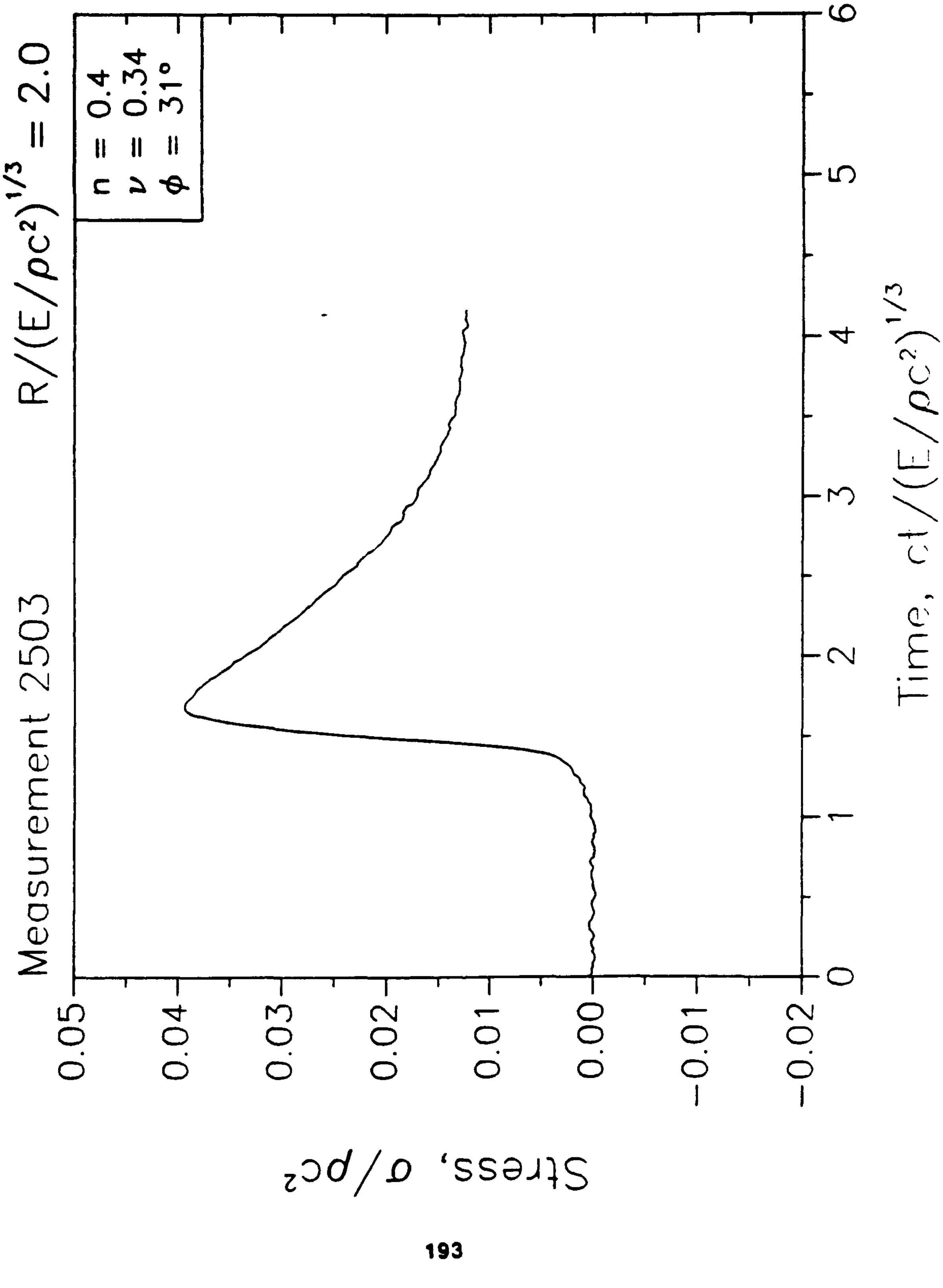
Measurement 2305
R/(E/ρc²)^1/3 = 2.25
n = 0.4
ν = 0.34
φ = 31°
0.020
0.015
0.010
0.005
0.000
−0.005
0
1
2
3
4
5
6
Velocity, v/c
Time, ct/(E/ρc²)^1/3

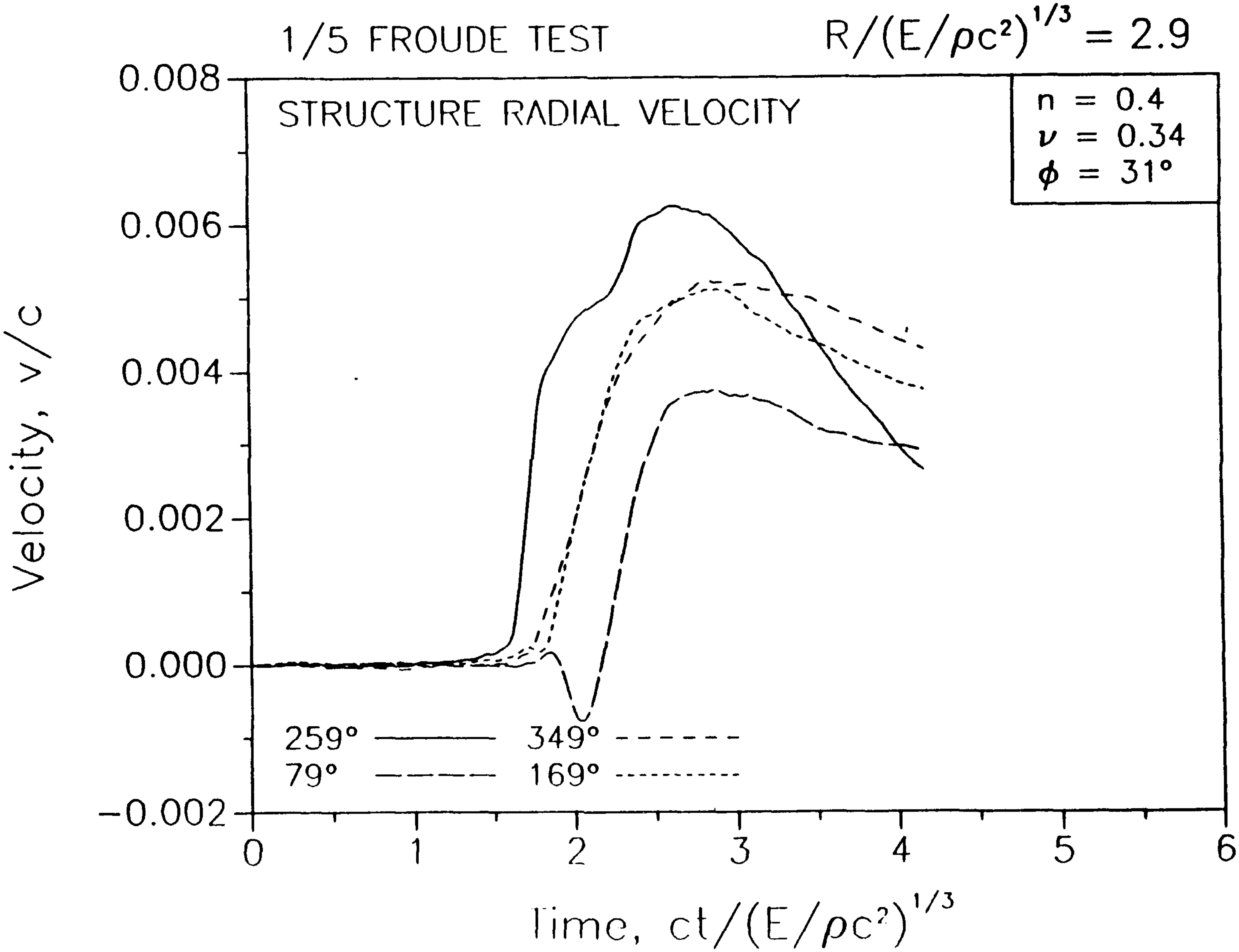


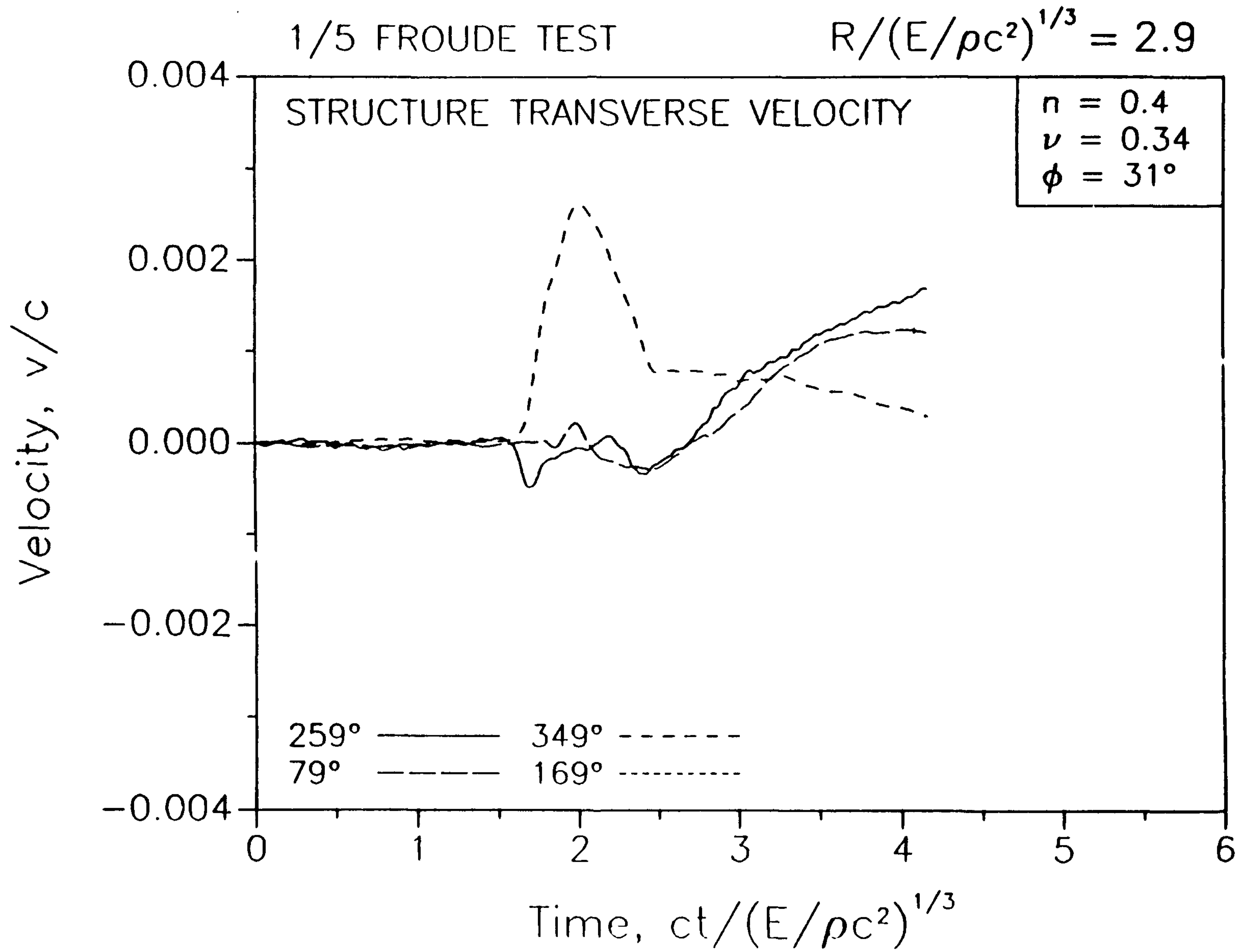
Measurement 2501
R/(E/ρc²)^1/3 = 0.87
n = 0.4
ν = 0.34
φ = 31°
0.15
0.10
0.05
0.00
−0.05
Stress, σ/ρc²
0
1
2
3
4
5
6
Time, ct/(E/ρc²)^1/3



Measurement 2502
R/(E/ρc²)^1/3 = 1.45
n = 0.4
ν = 0.34
φ = 31°
Stress, σ/ρc²
Time, ct/(E/ρc²)^1/3
0.08
0.06
0.04
0.02
0.00
−0.02
0
1
2
3
4
5
6

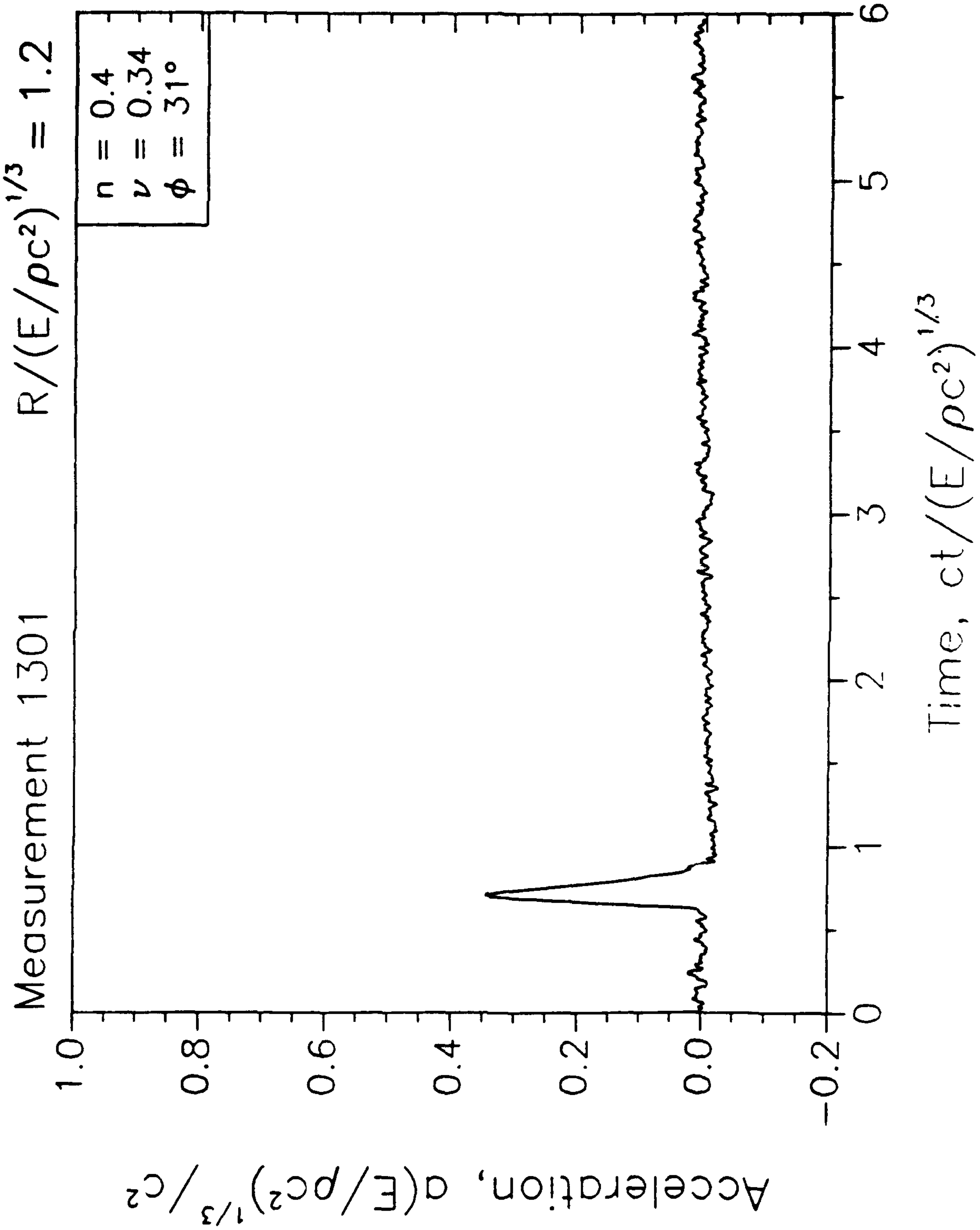

Measurement 2503
R/(E/ρc²)^1/3 = 2.0
n = 0.4
ν = 0.34
φ = 31°
Stress, σ/ρc²
0.05
0.04
0.03
0.02
0.01
0.00
−0.01
−0.02
Time, ct/(E/ρc²)^1/3
0
1
2
3
4
5
6


1/5 FROUDE TEST
R/(E/ρc²)^1/3 = 2.9
STRUCTURE RADIAL VELOCITY
n = 0.4
ν = 0.34
φ = 31°
259°
349°
79°
169°
Velocity, v/c
0.008
0.006
0.004
0.002
0.000
−0.002
0
1
2
3
4
5
6
Time, ct/(E/ρc²)^1/3

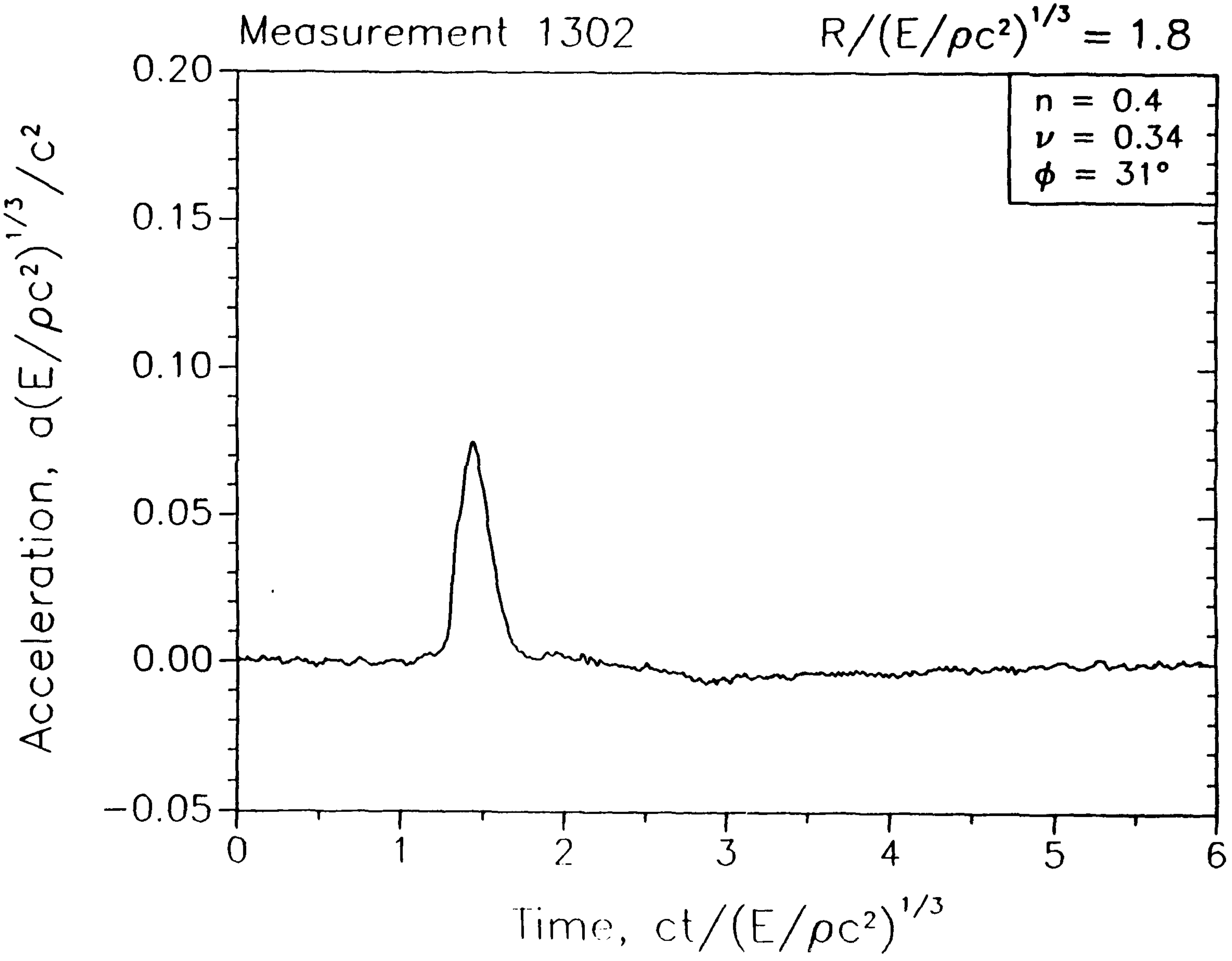

1/5 FROUDE TEST
R/(E/ρc²)^1/3 = 2.9
STRUCTURE TRANSVERSE VELOCITY
n = 0.4
ν = 0.34
ϕ = 31°
0.004
0.002
0.000
−0.002
−0.004
Velocity, v/c
259°
349°
79°
169°
0
1
2
3
4
5
6
Time, ct/(E/ρc²)^1/3

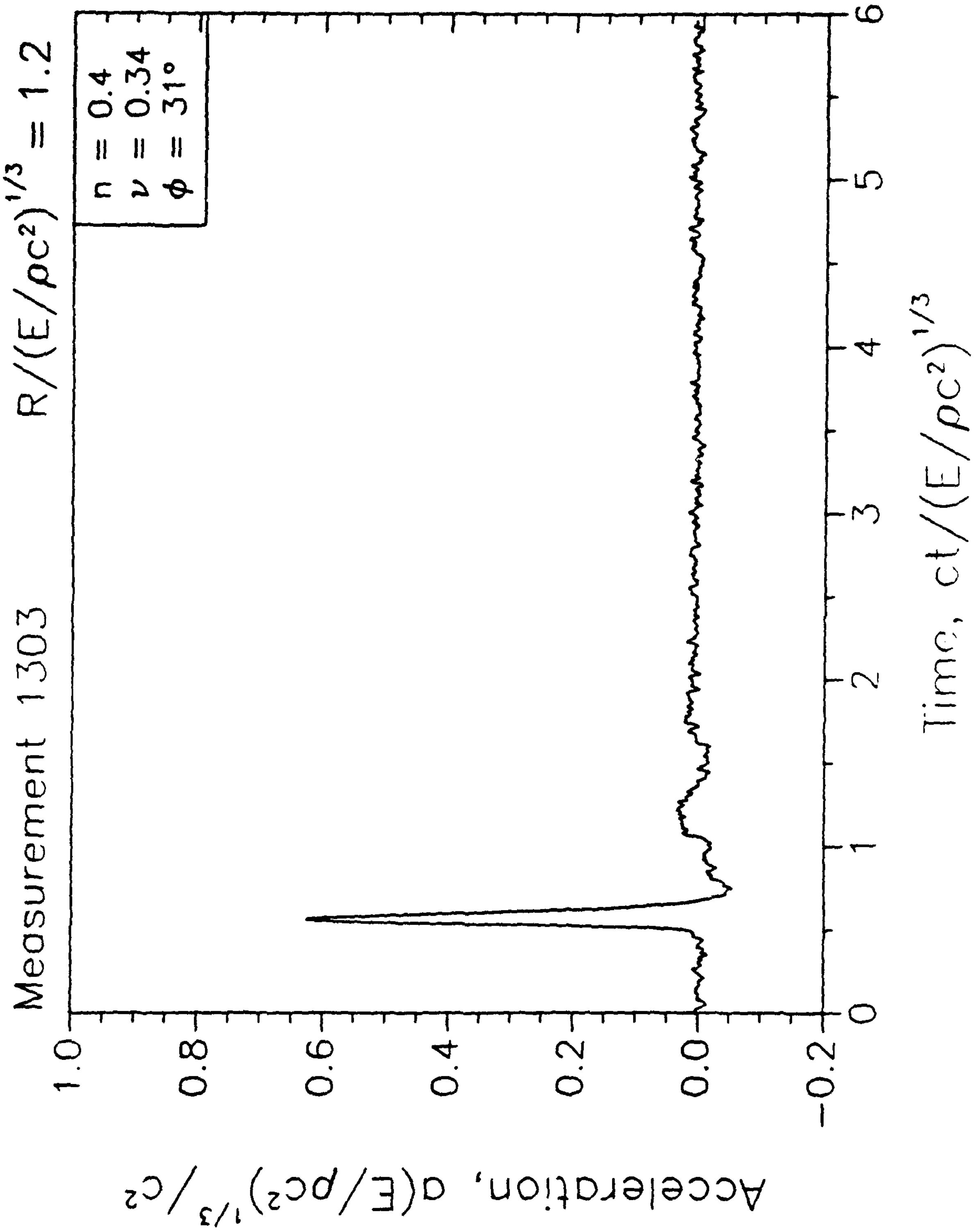
1/10 FROUDE SCALED TEST

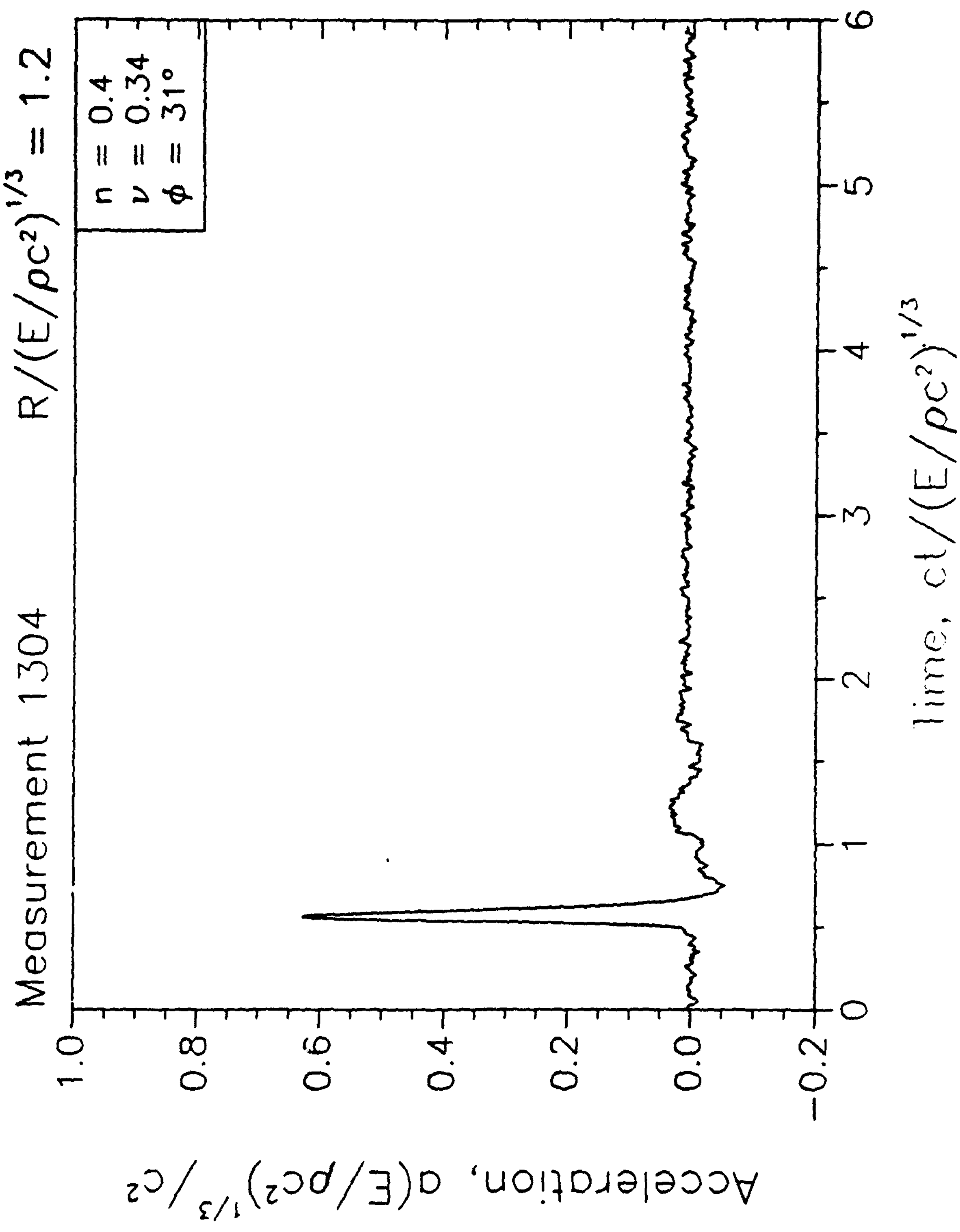
"LEAD/COAL"

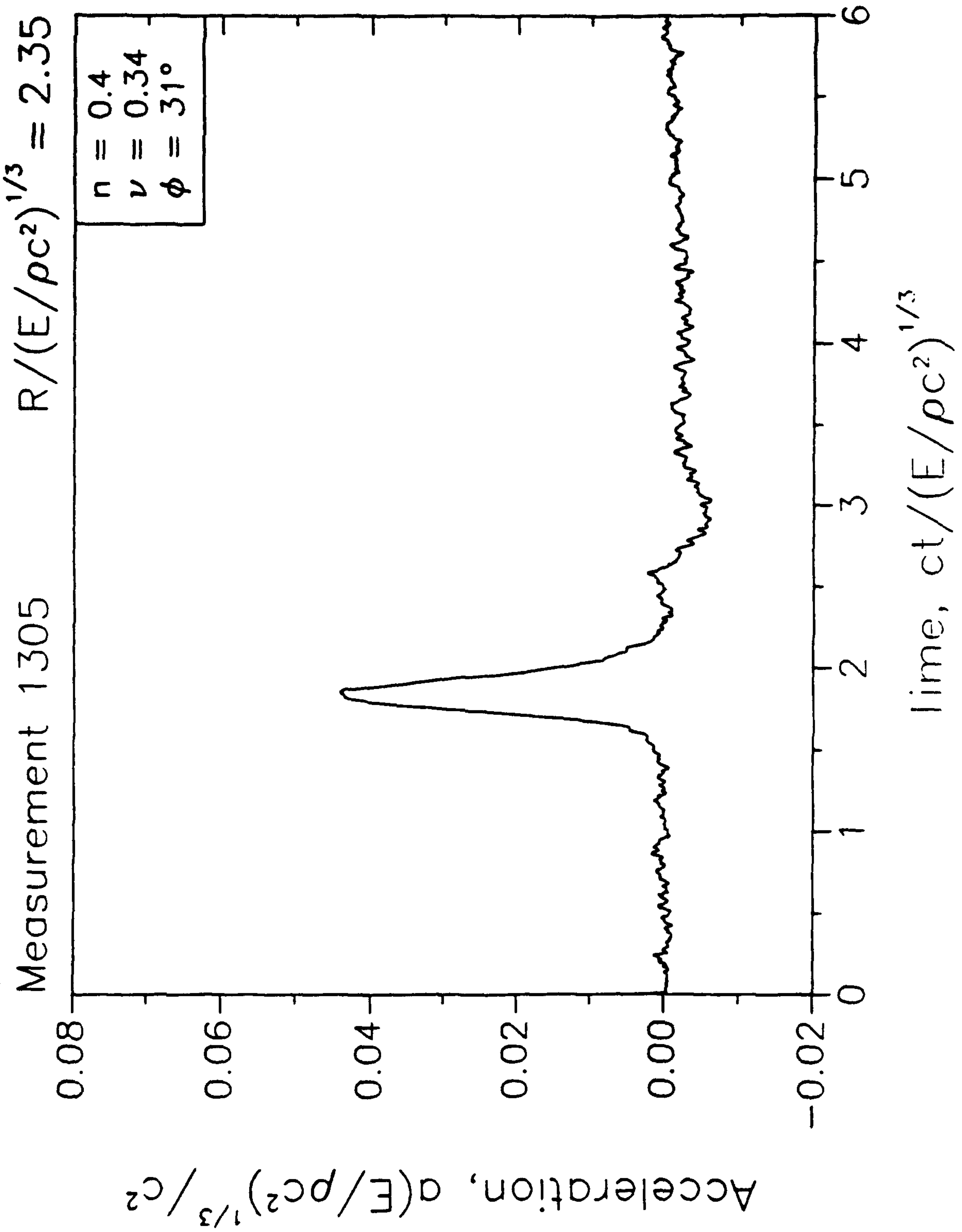


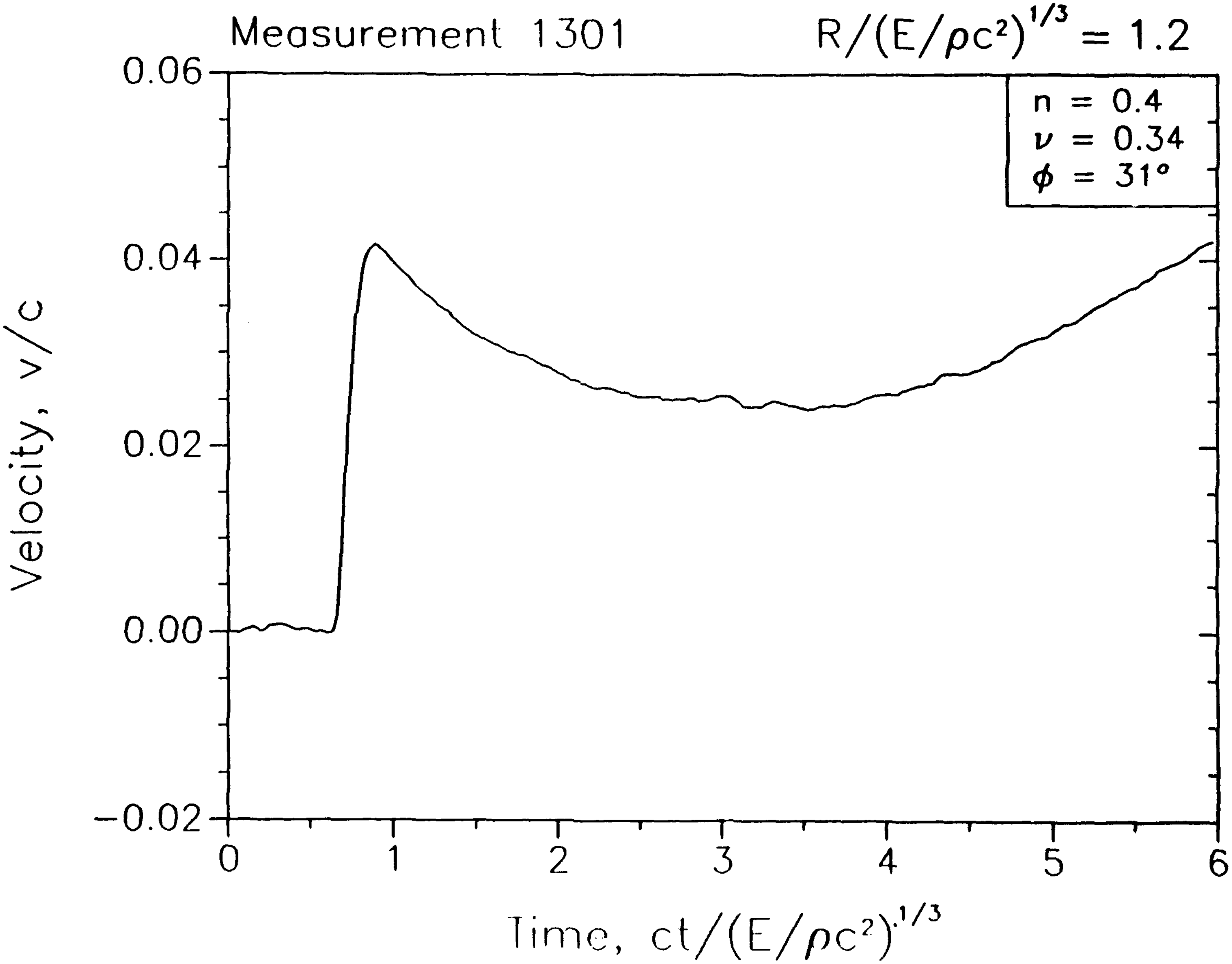
Measurement 1301
$R/(E/\rho c^2)^{1/3} = 1.2$
n = 0.4
ν = 0.34
ϕ = 31°
Time, $ct/(E/\rho c^2)^{1/3}$
Acceleration, $a(E/\rho c^2)^{1/3}/c^2$

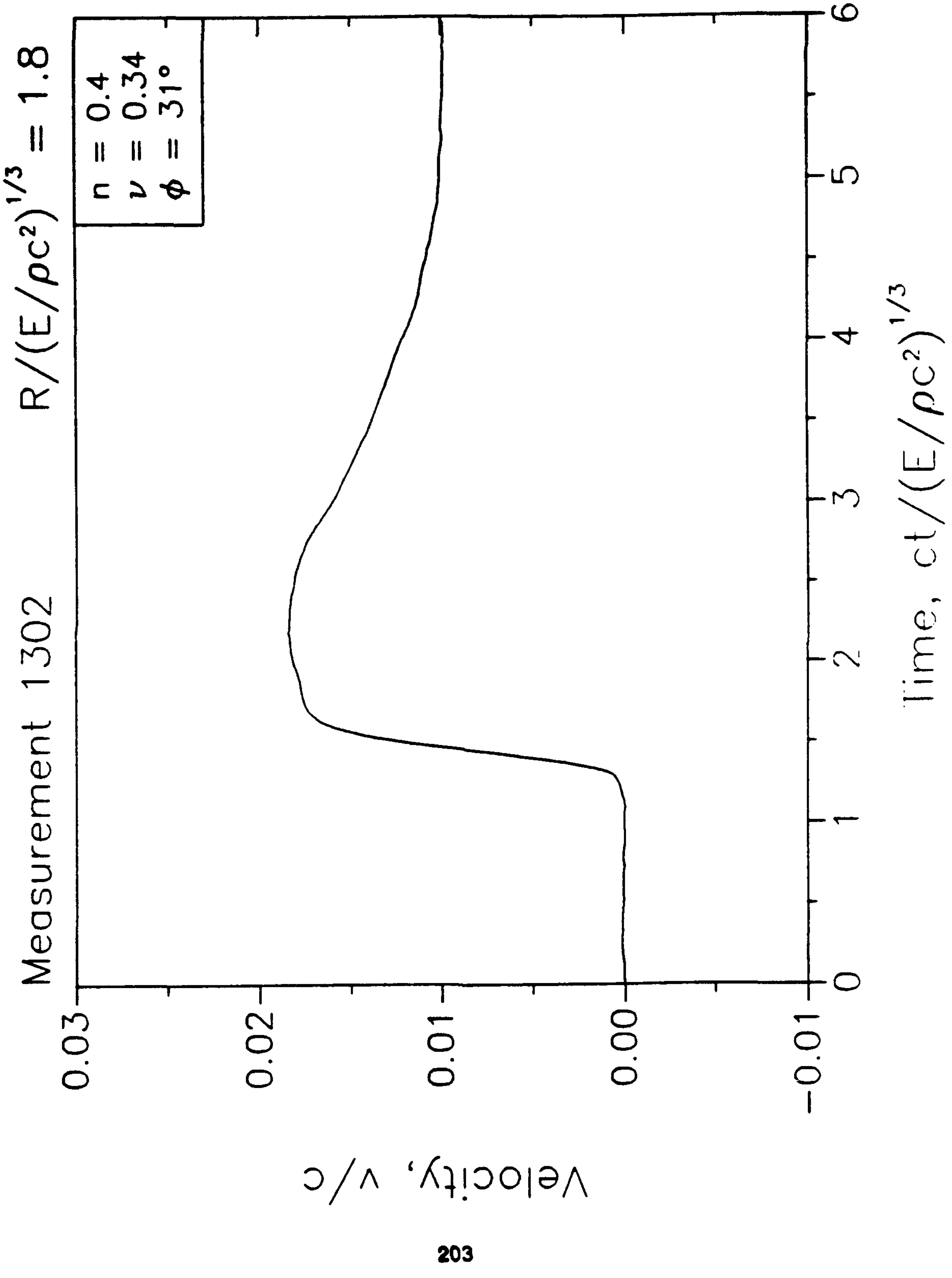

Measurement 1302
R/(E/ρc²)^1/3 = 1.8
n = 0.4
ν = 0.34
φ = 31°
0.20
0.15
0.10
0.05
0.00
−0.05
0
1
2
3
4
5
6
Acceleration, a(E/ρc²)^1/3/c²
Time, ct/(E/ρc²)^1/3

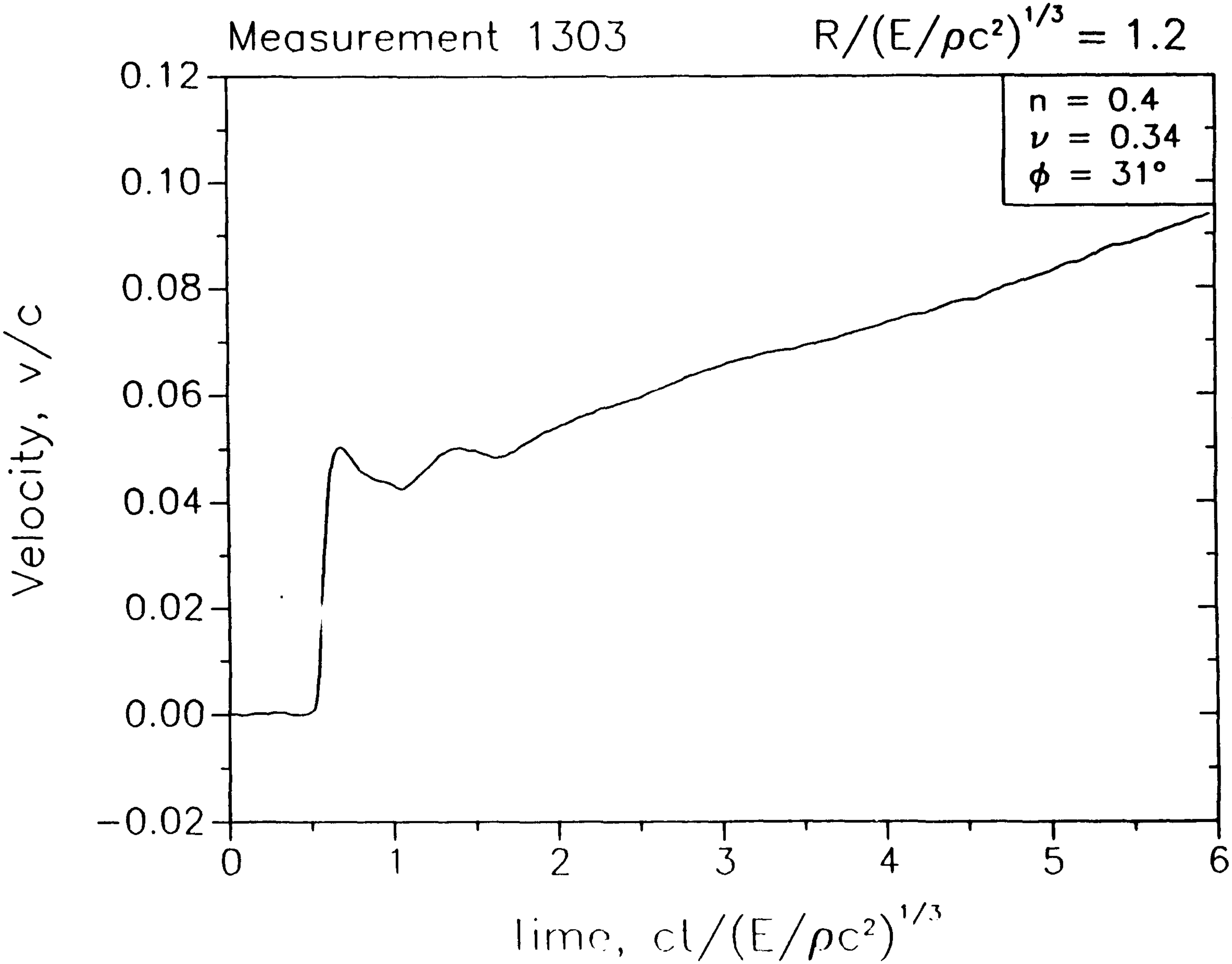

Measurement 1303
R/(E/ρc²)^1/3 = 1.2
n = 0.4
ν = 0.34
φ = 31°
Acceleration, a(E/ρc²)^1/3/c²
Time, ct/(E/ρc²)^1/3
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
0
1
2
3
4
5
6


Measurement 1304
R/(E/ρc²)^1/3 = 1.2
n = 0.4
ν = 0.34
φ = 31°
Time, ct/(E/ρc²)^1/3
Acceleration, a(E/ρc²)^1/3/c²
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
0
1
2
3
4
5
6

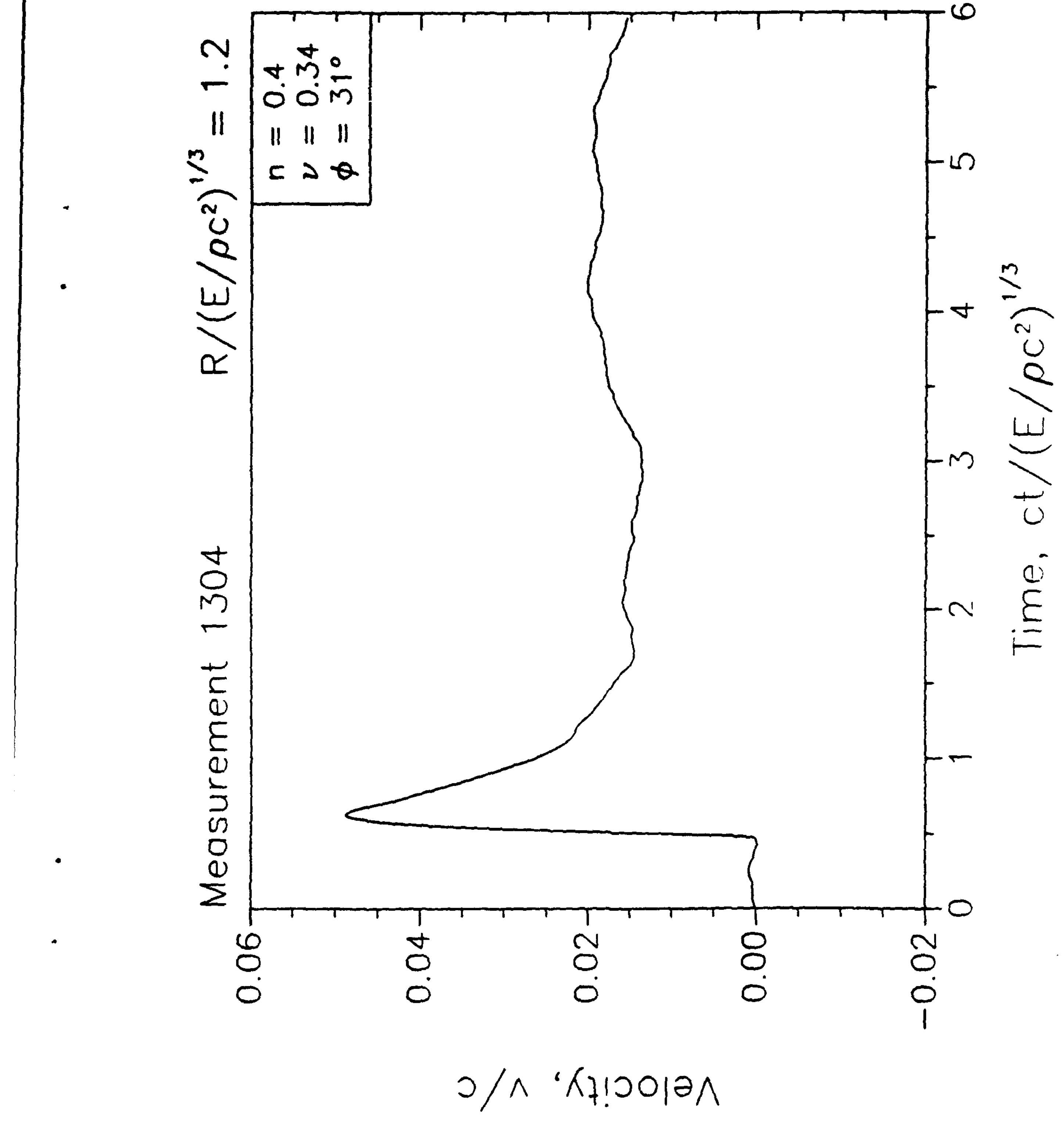

Measurement 1305
R/(E/ρc²)^1/3 = 2.35
n = 0.4
ν = 0.34
φ = 31°
0.08
0.06
0.04
0.02
0.00
−0.02
0
1
2
3
4
5
6
Time, ct/(E/ρc²)^1/3
Acceleration, a(E/ρc²)^1/3/c²


Measurement 1301
R/(E/ρc²)^1/3 = 1.2
n = 0.4
ν = 0.34
φ = 31°
Velocity, v/c
0.06
0.04
0.02
0.00
−0.02
0
1
2
3
4
5
6
Time, ct/(E/ρc²)^1/3

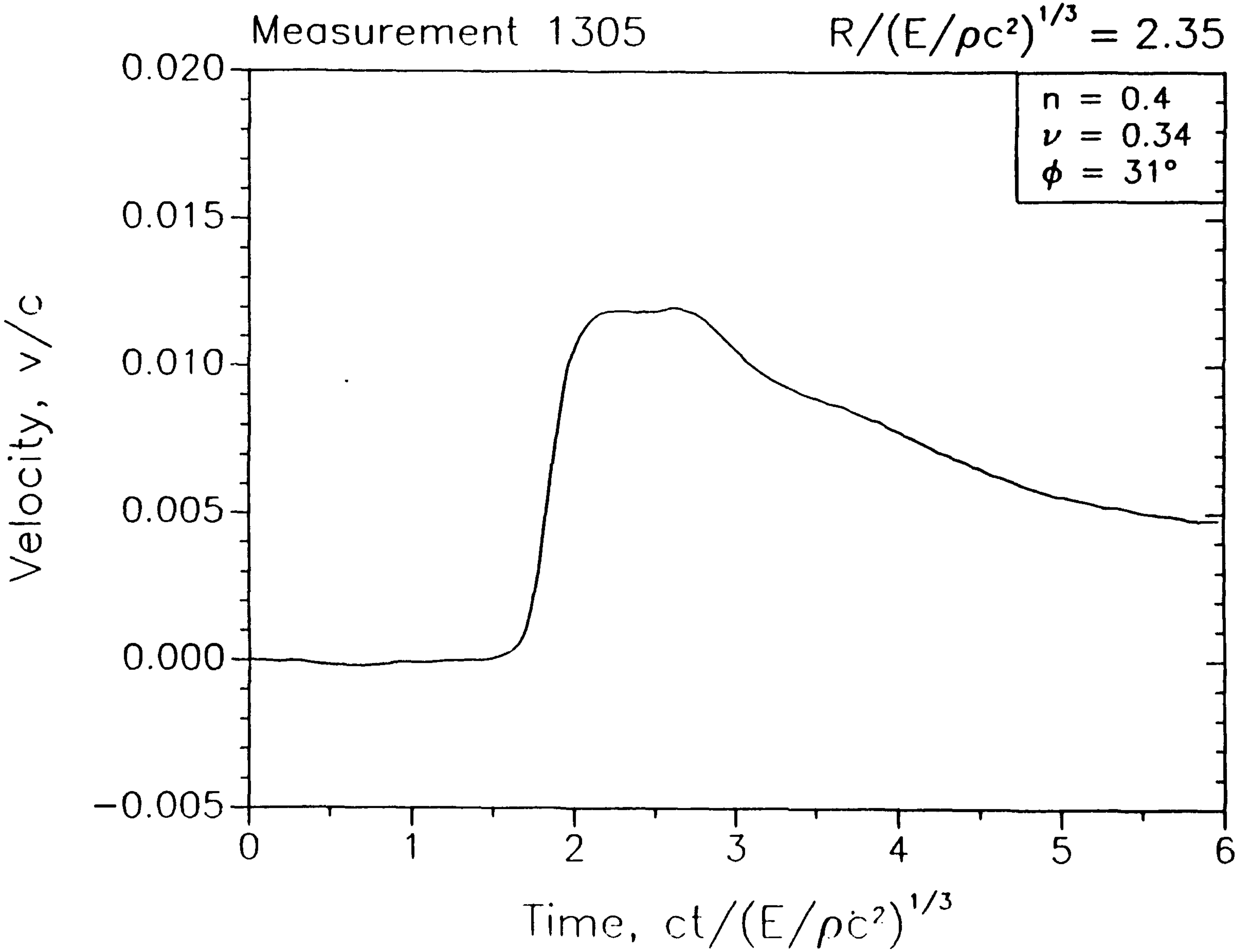

Measurement 1302
R/(E/ρc²)^1/3 = 1.8
n = 0.4
ν = 0.34
φ = 31°
Velocity, v/c
0.03
0.02
0.01
0.00
−0.01
0
1
2
3
4
5
6
Time, ct/(E/ρc²)^1/3

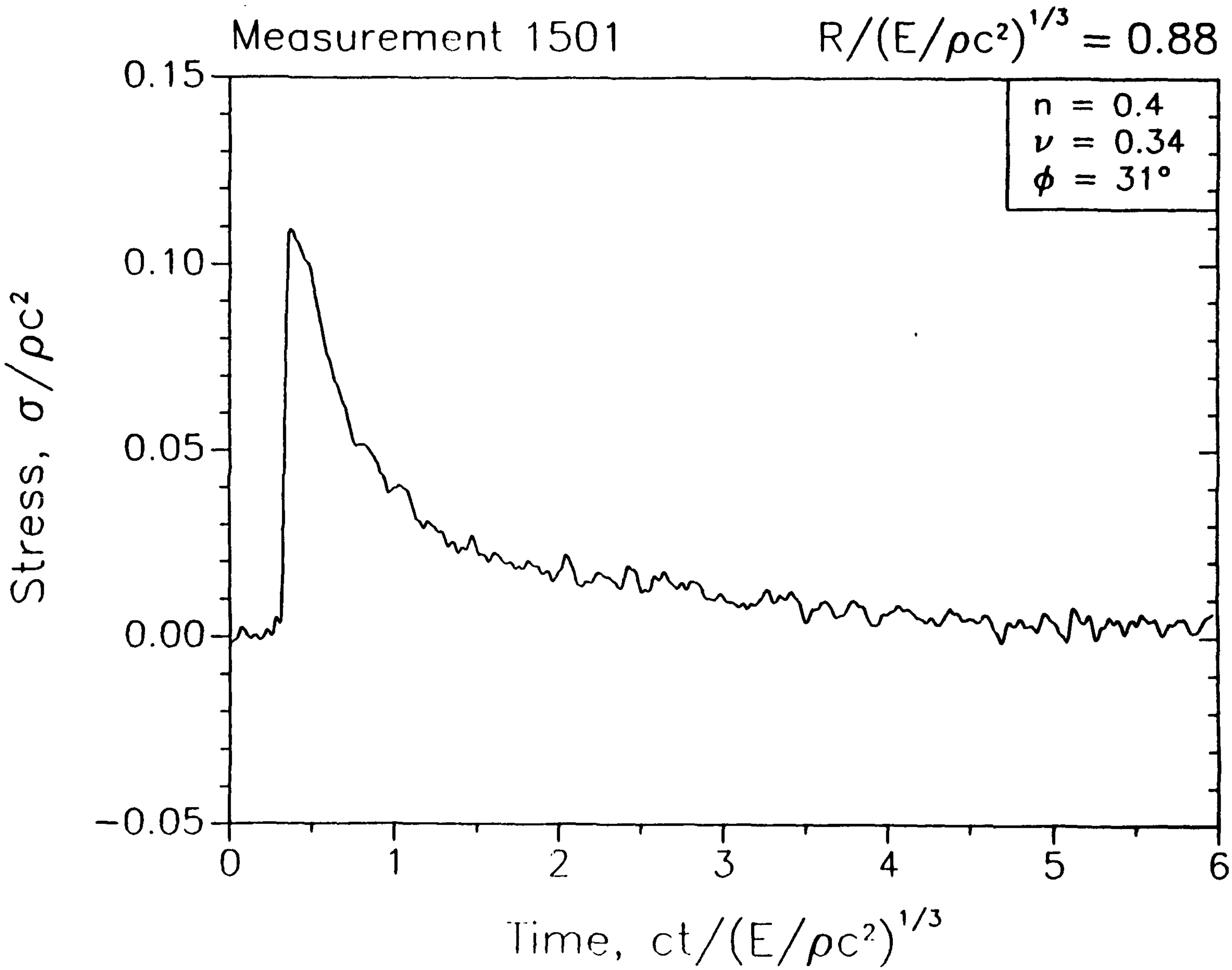


Measurement 1303
R/(E/ρc²)^1/3 = 1.2
n = 0.4
ν = 0.34
φ = 31°
Velocity, v/c
0.12
0.10
0.08
0.06
0.04
0.02
0.00
−0.02
0
1
2
3
4
5
6
Time, ct/(E/ρc²)^1/3

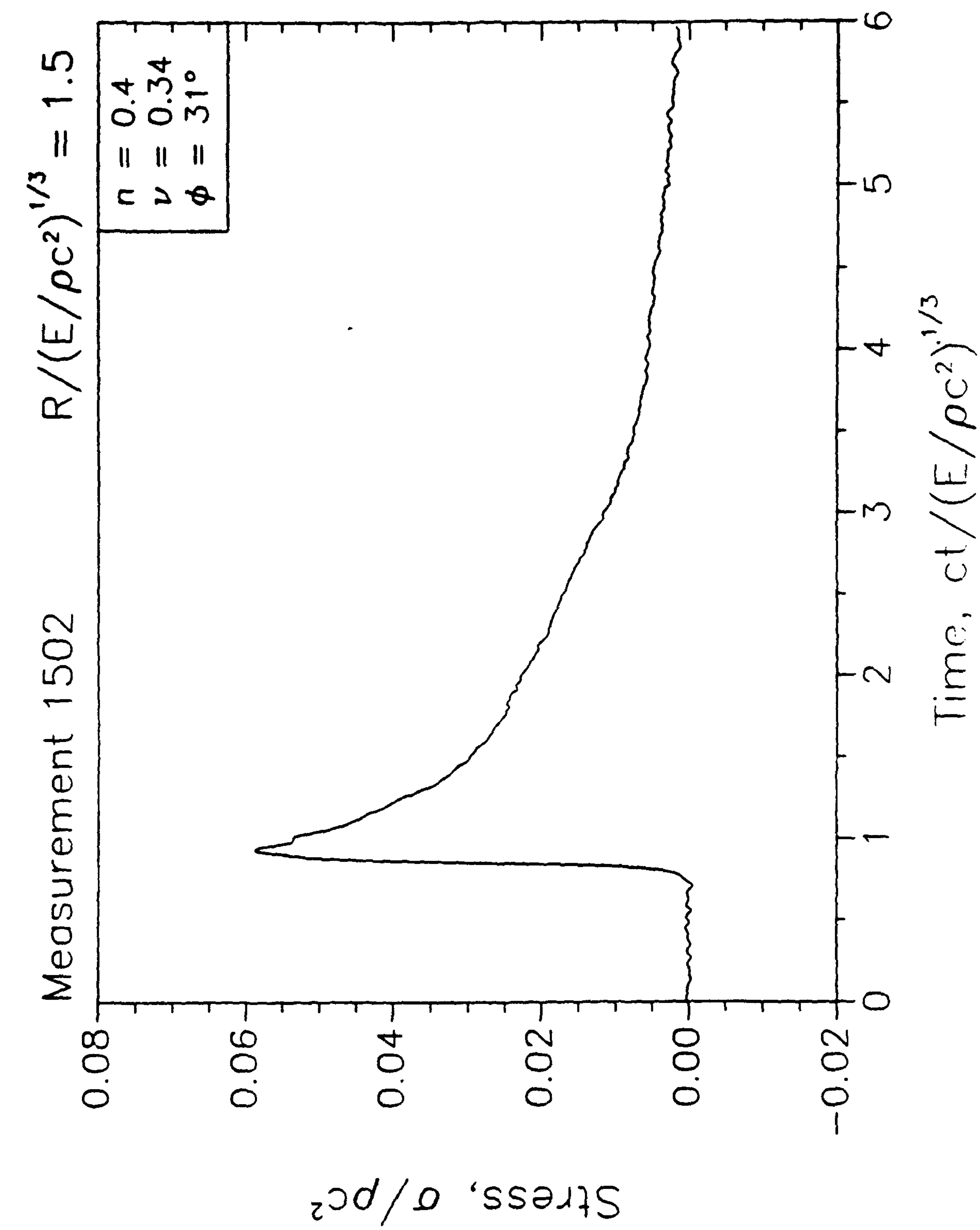


Measurement 1304
R/(E/ρc²)^1/3 = 1.2
n = 0.4
ν = 0.34
φ = 31°
Velocity, v/c
Time, ct/(E/ρc²)^1/3
0.06
0.04
0.02
0.00
-0.02
0
1
2
3
4
5
6

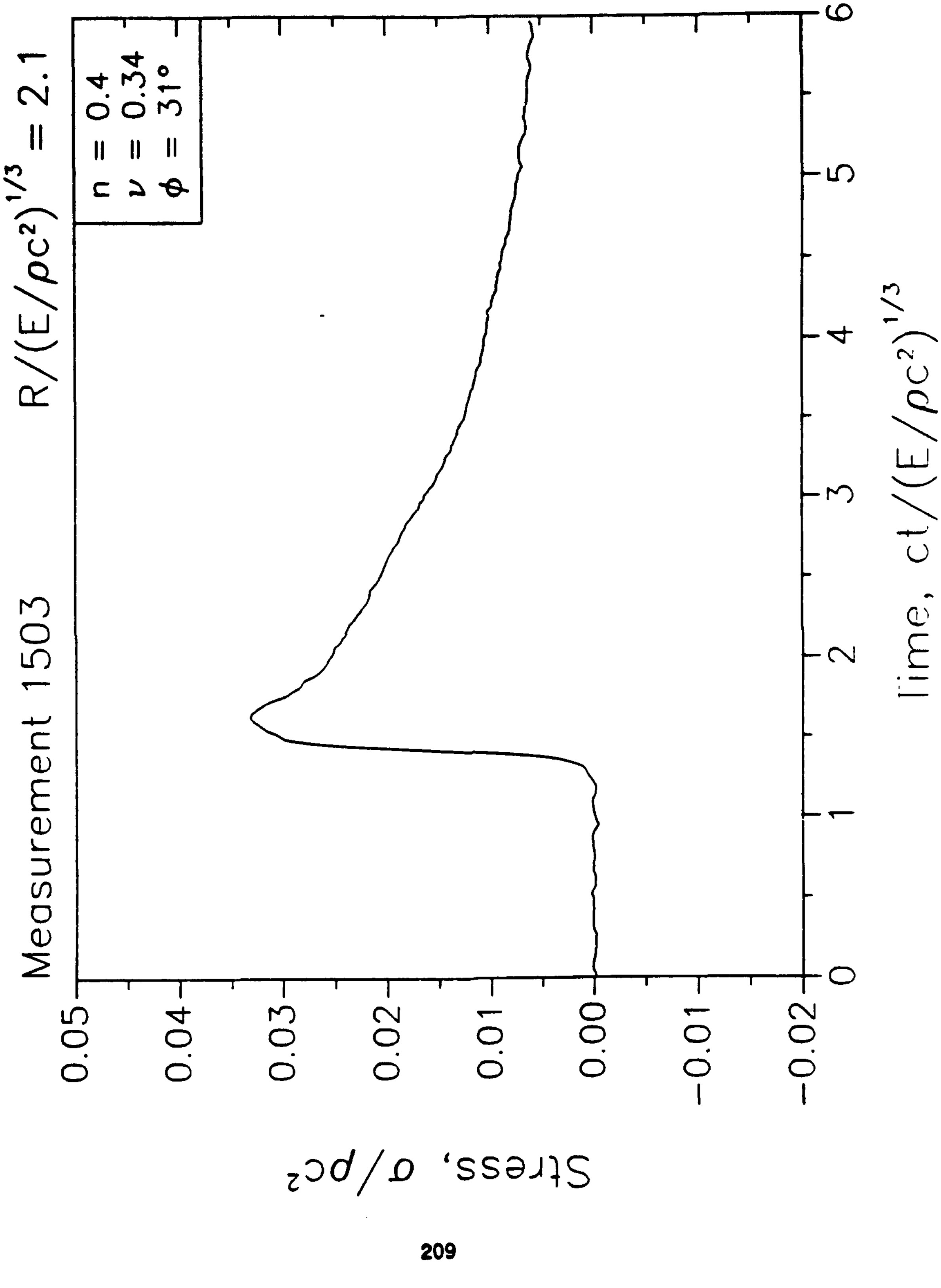

Measurement 1305
R/(E/ρc²)^1/3 = 2.35
n = 0.4
ν = 0.34
φ = 31°
Velocity, v/c
0.020
0.015
0.010
0.005
0.000
−0.005
0
1
2
3
4
5
6
Time, ct/(E/ρc²)^1/3

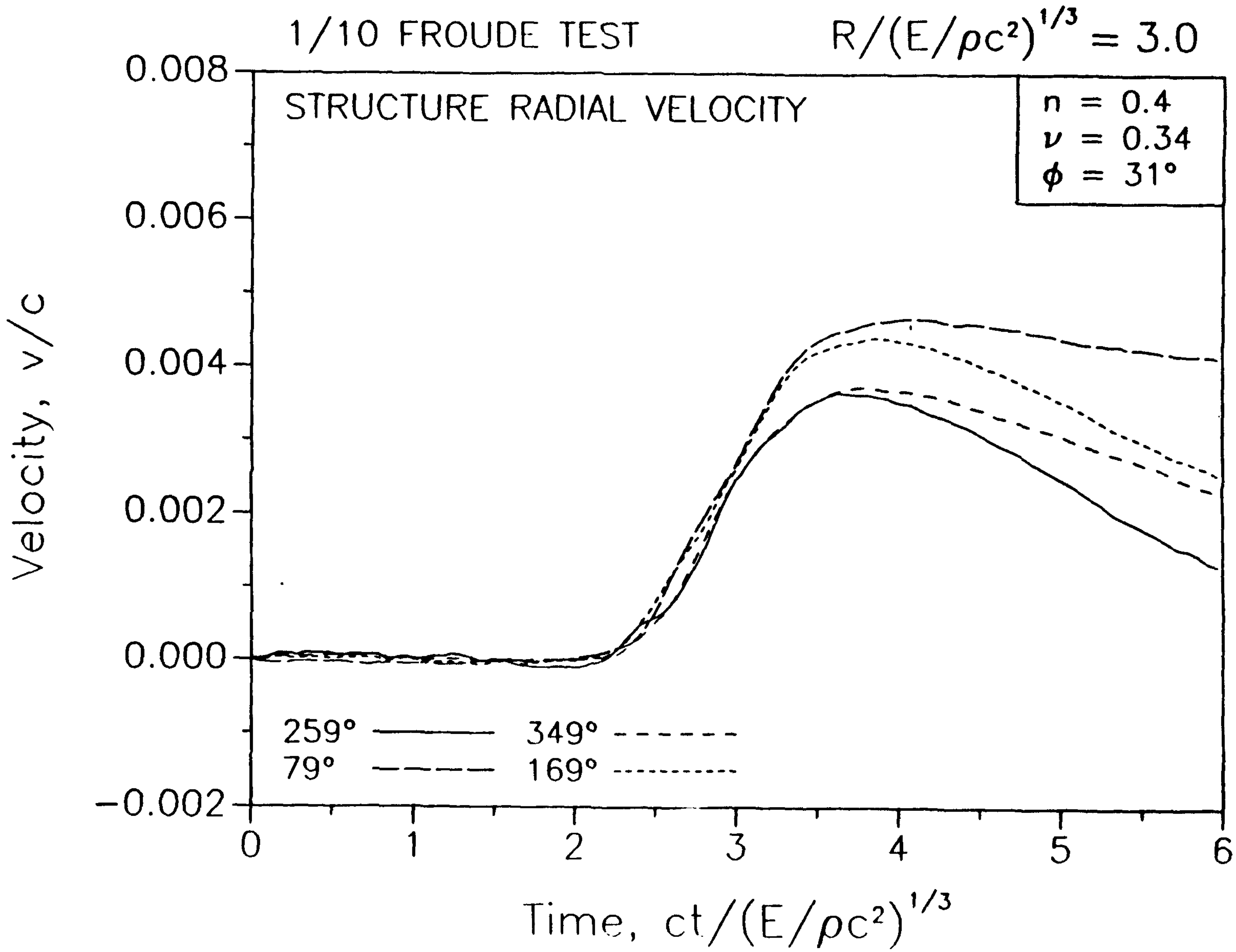


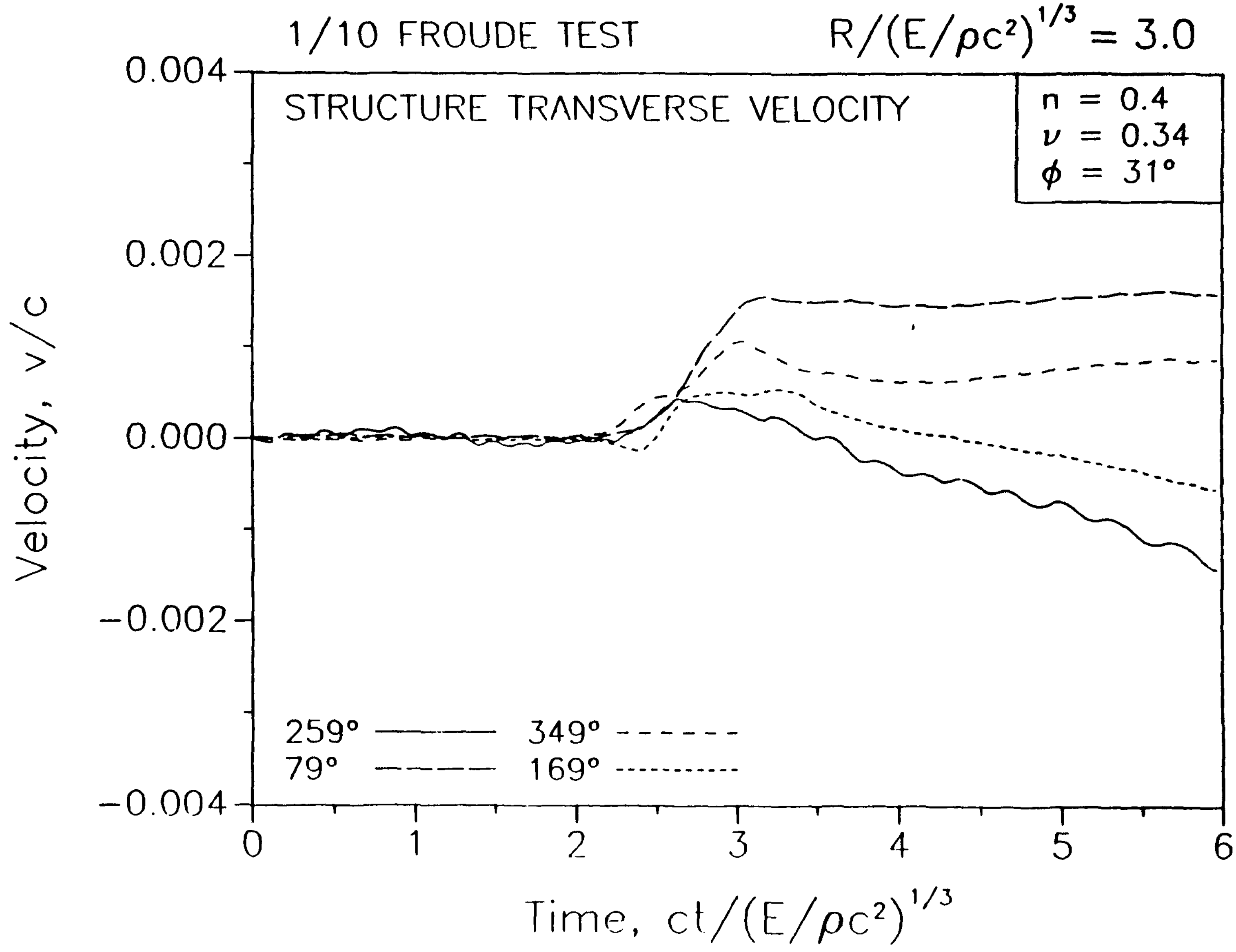
Measurement 1501
R/(E/ρc²)^1/3 = 0.88
n = 0.4
ν = 0.34
φ = 31°
0.15
0.10
0.05
0.00
−0.05
0
1
2
3
4
5
6
Stress, σ/ρc²
Time, ct/(E/ρc²)^1/3



Measurement 1502
R/(E/ρc²)^1/3 = 1.5
n = 0.4
ν = 0.34
φ = 31°
Stress, σ/ρc²
0.08
0.06
0.04
0.02
0.00
-0.02
Time, ct/(E/ρc²)^1/3
0
1
2
3
4
5
6


Measurement 1503
R/(E/ρc²)^1/3 = 2.1
n = 0.4
ν = 0.34
φ = 31°
Stress, σ/ρc²
0.05
0.04
0.03
0.02
0.01
0.00
−0.01
−0.02
Time, ct/(E/ρc²)^1/3
0
1
2
3
4
5
6

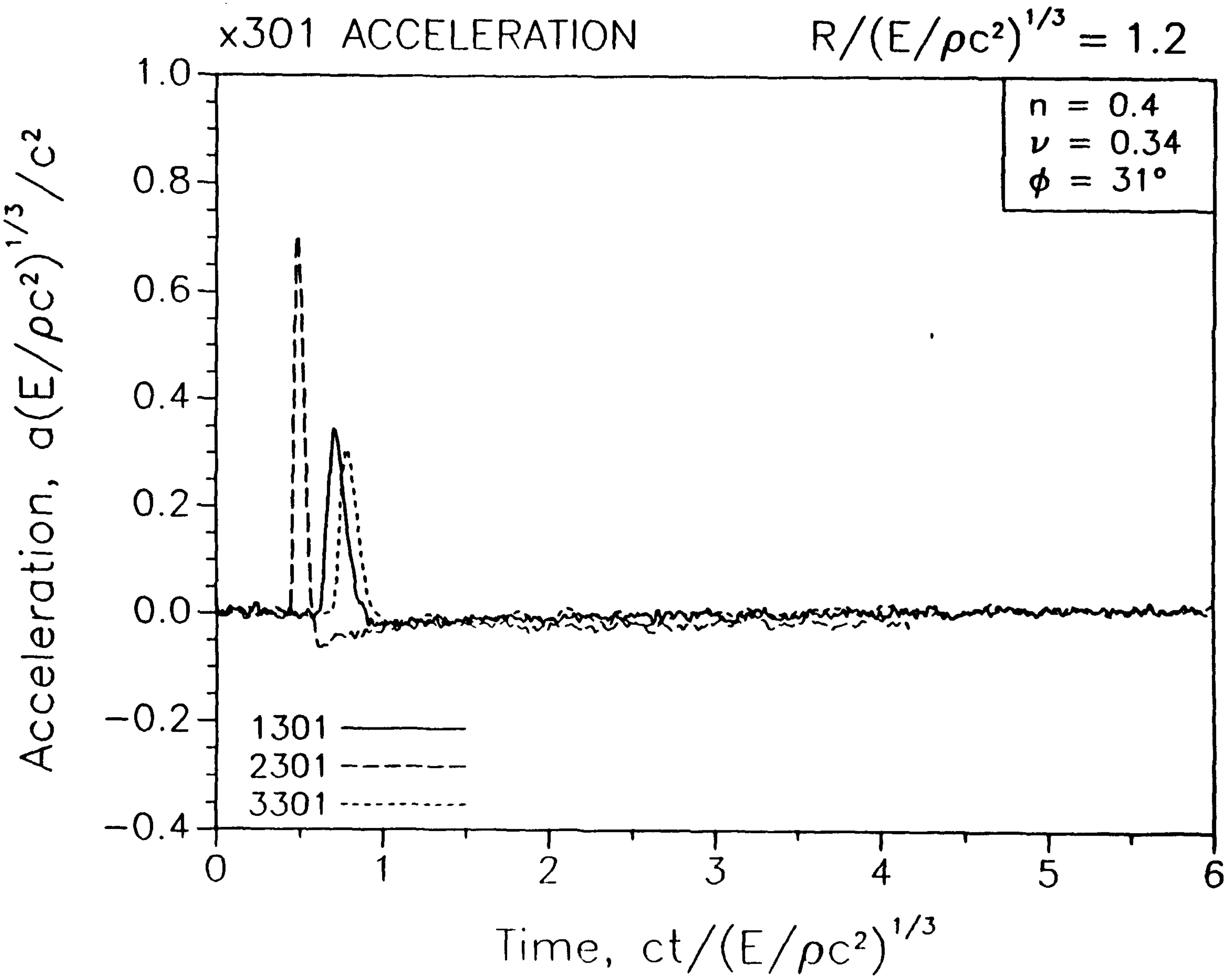

1/10 FROUDE TEST
R/(E/ρc²)^1/3 = 3.0
STRUCTURE RADIAL VELOCITY
n = 0.4
ν = 0.34
φ = 31°
259°
349°
79°
169°
0.008
0.006
0.004
0.002
0.000
−0.002
0
1
2
3
4
5
6
Velocity, v/c
Time, ct/(E/ρc²)^1/3

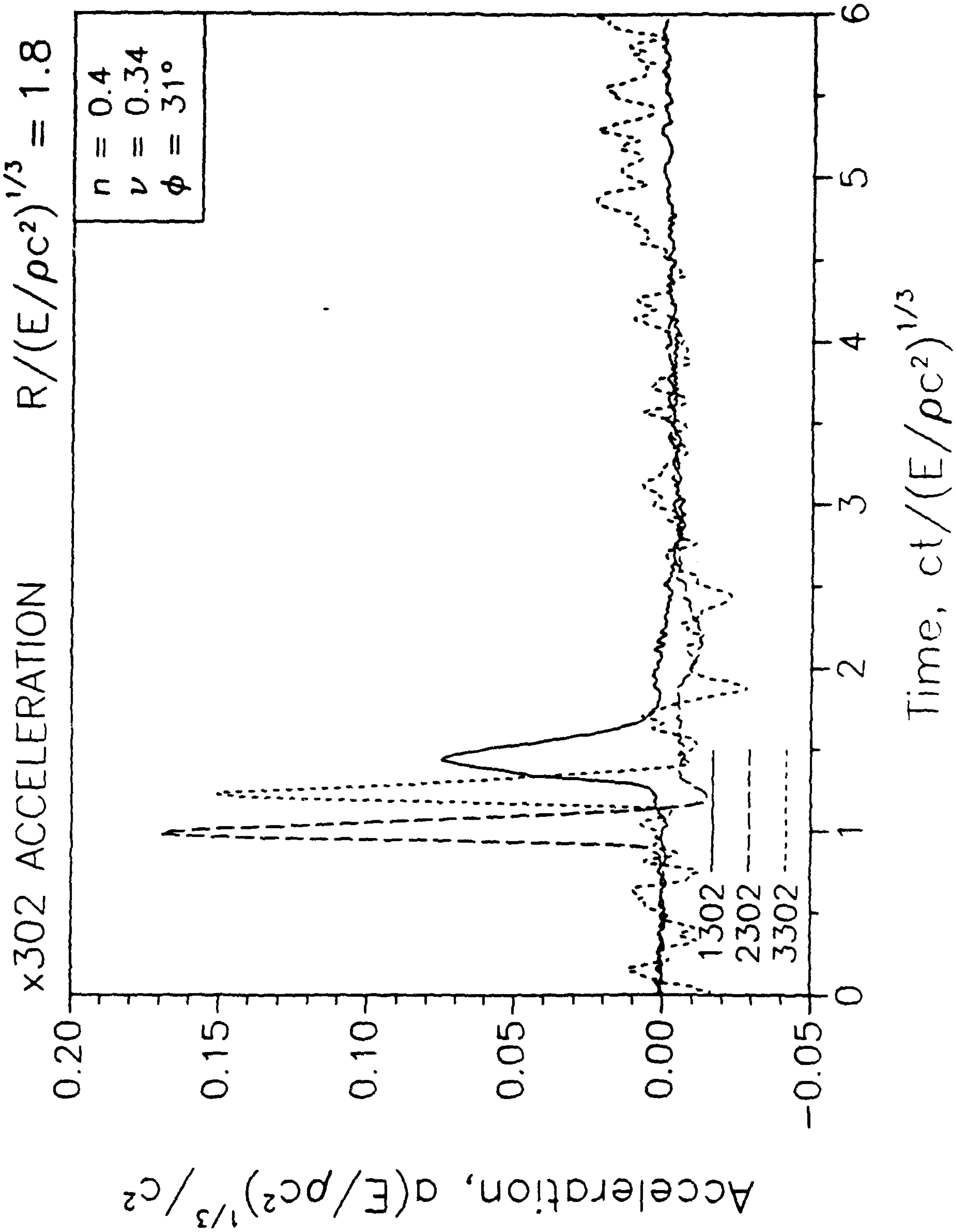


1/10 FROUDE TEST
R/(E/ρc²)^1/3 = 3.0
STRUCTURE TRANSVERSE VELOCITY
n = 0.4
ν = 0.34
φ = 31°
259°
349°
79°
169°
0.004
0.002
0.000
-0.002
-0.004
Velocity, v/c
0
1
2
3
4
5
6
Time, ct/(E/ρc²)^1/3

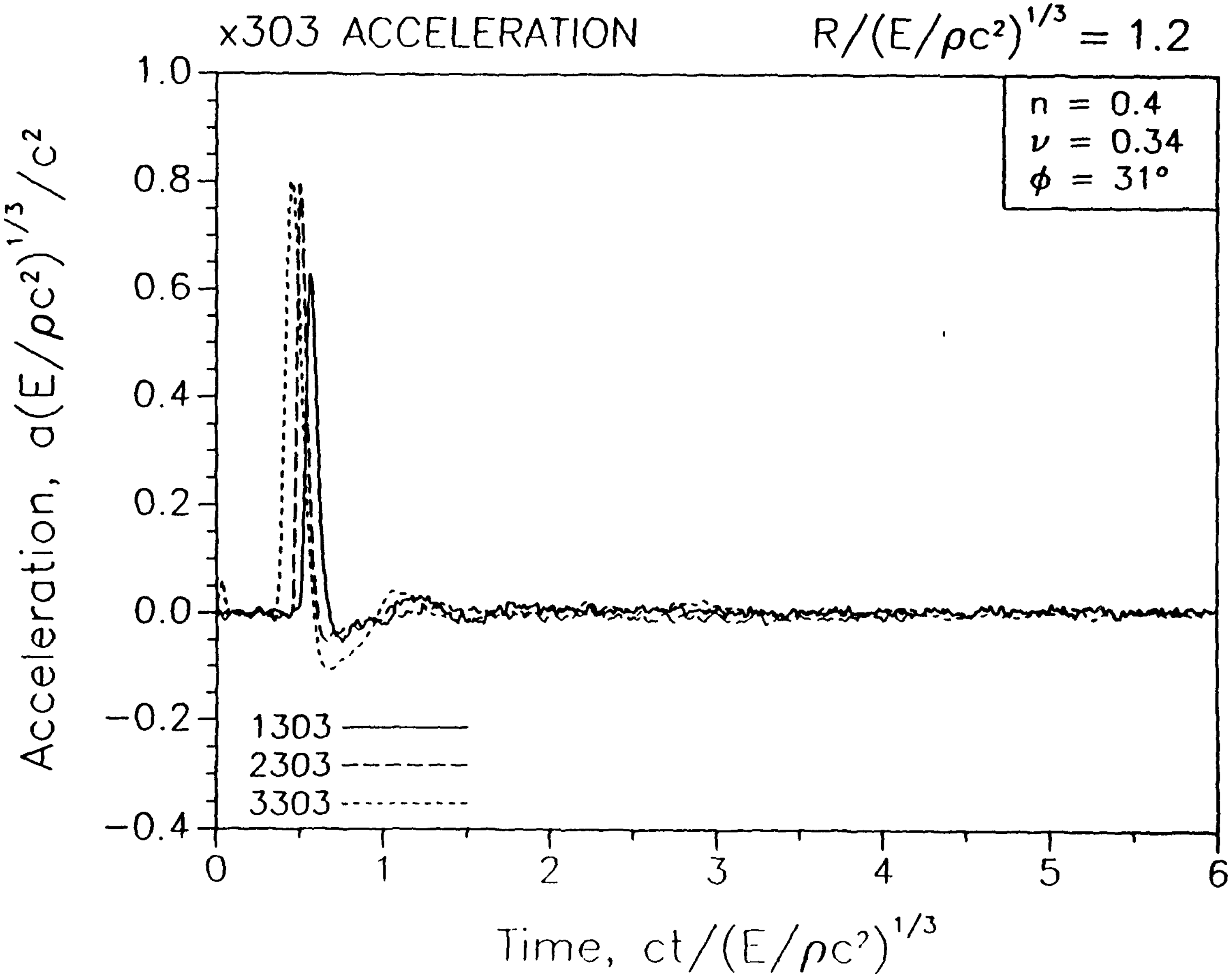
APPENDIX G

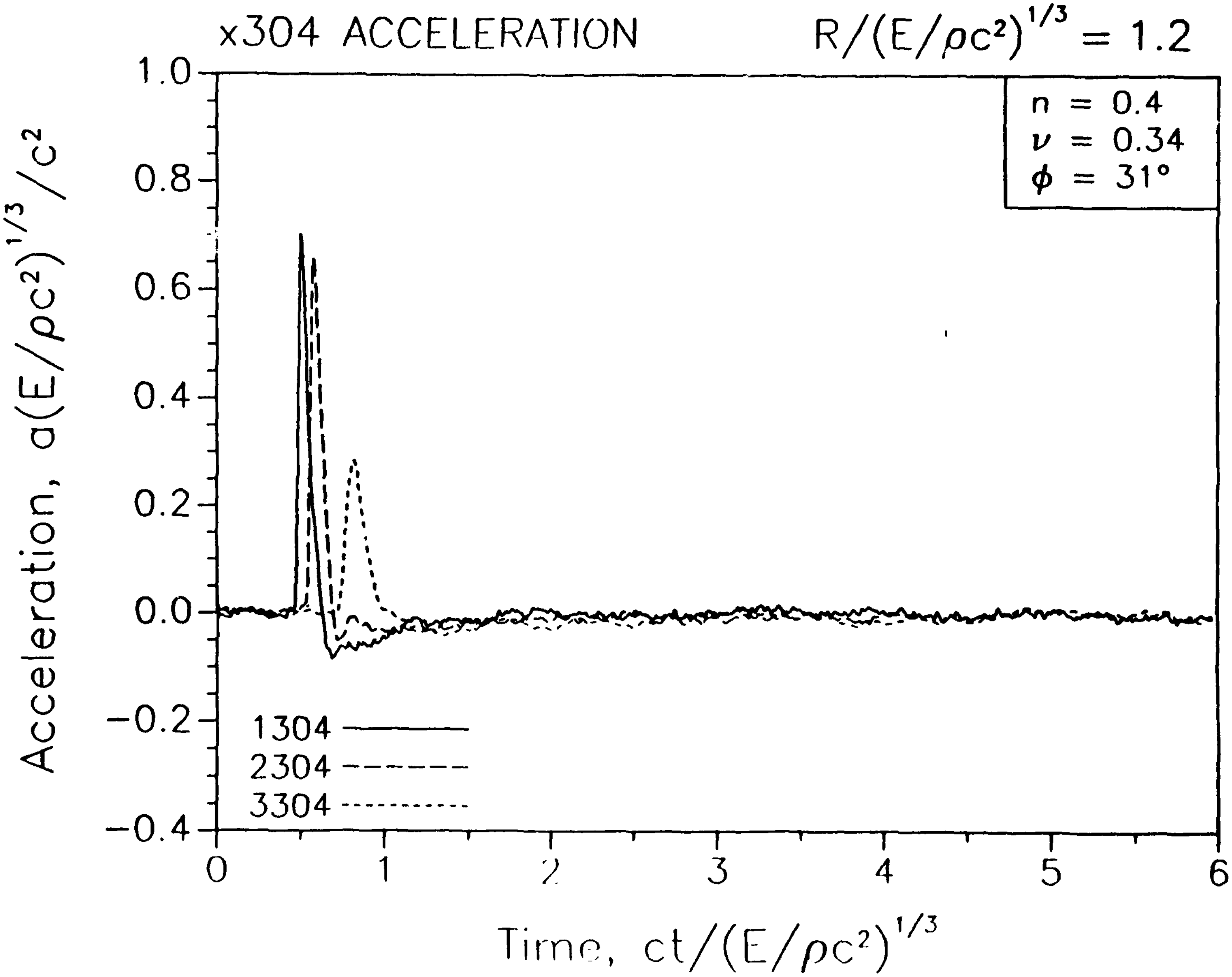
COMPOSITE NONDIMENSIONAL DATA PLOTS FROM DYNAMIC TESTS


x301 ACCELERATION
R/(E/ρc²)^{1/3} = 1.2
n = 0.4
ν = 0.34
φ = 31°
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
Acceleration, a(E/ρc²)^{1/3}/c²
1301
2301
3301
0
1
2
3
4
5
6
Time, ct/(E/ρc²)^{1/3}

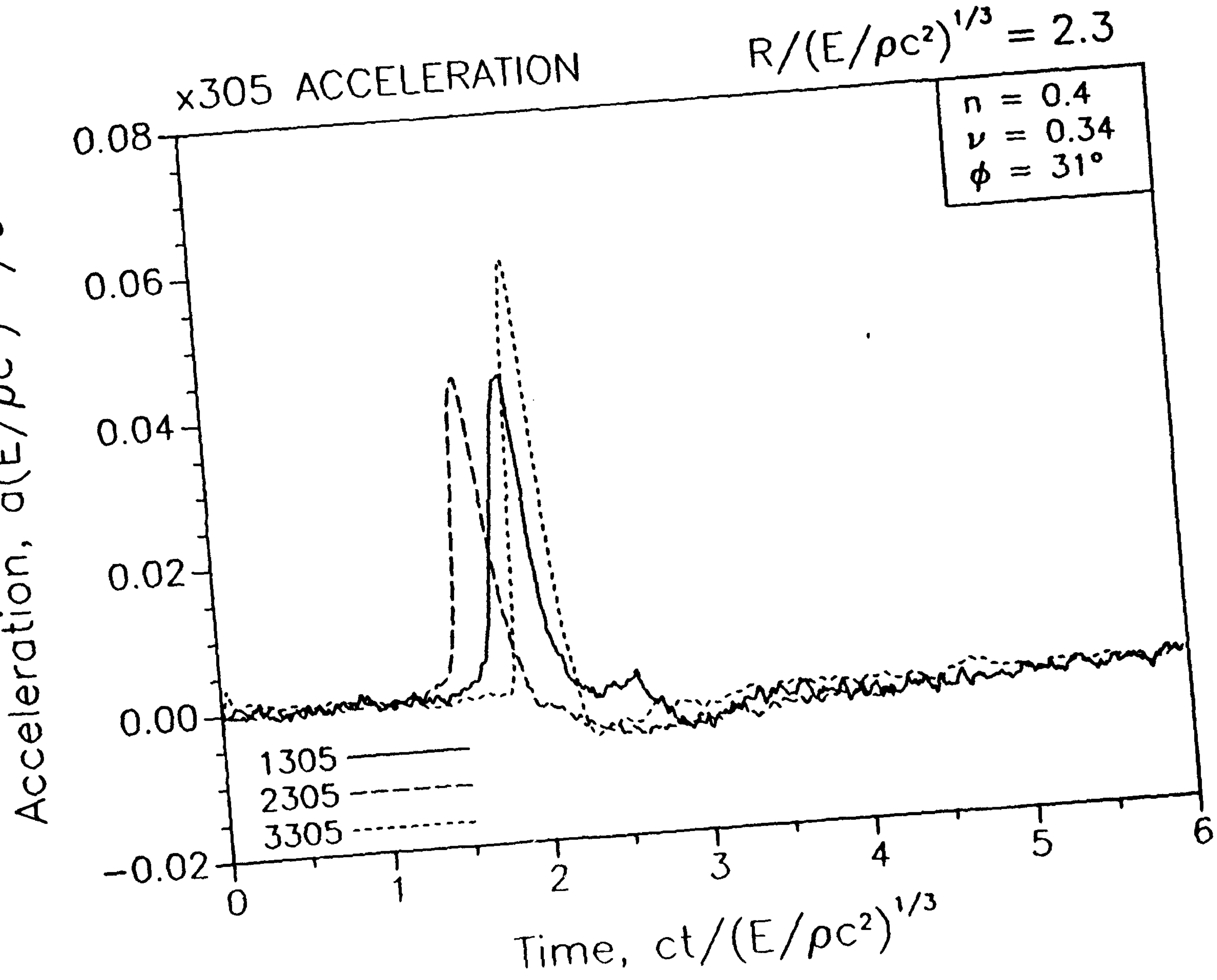


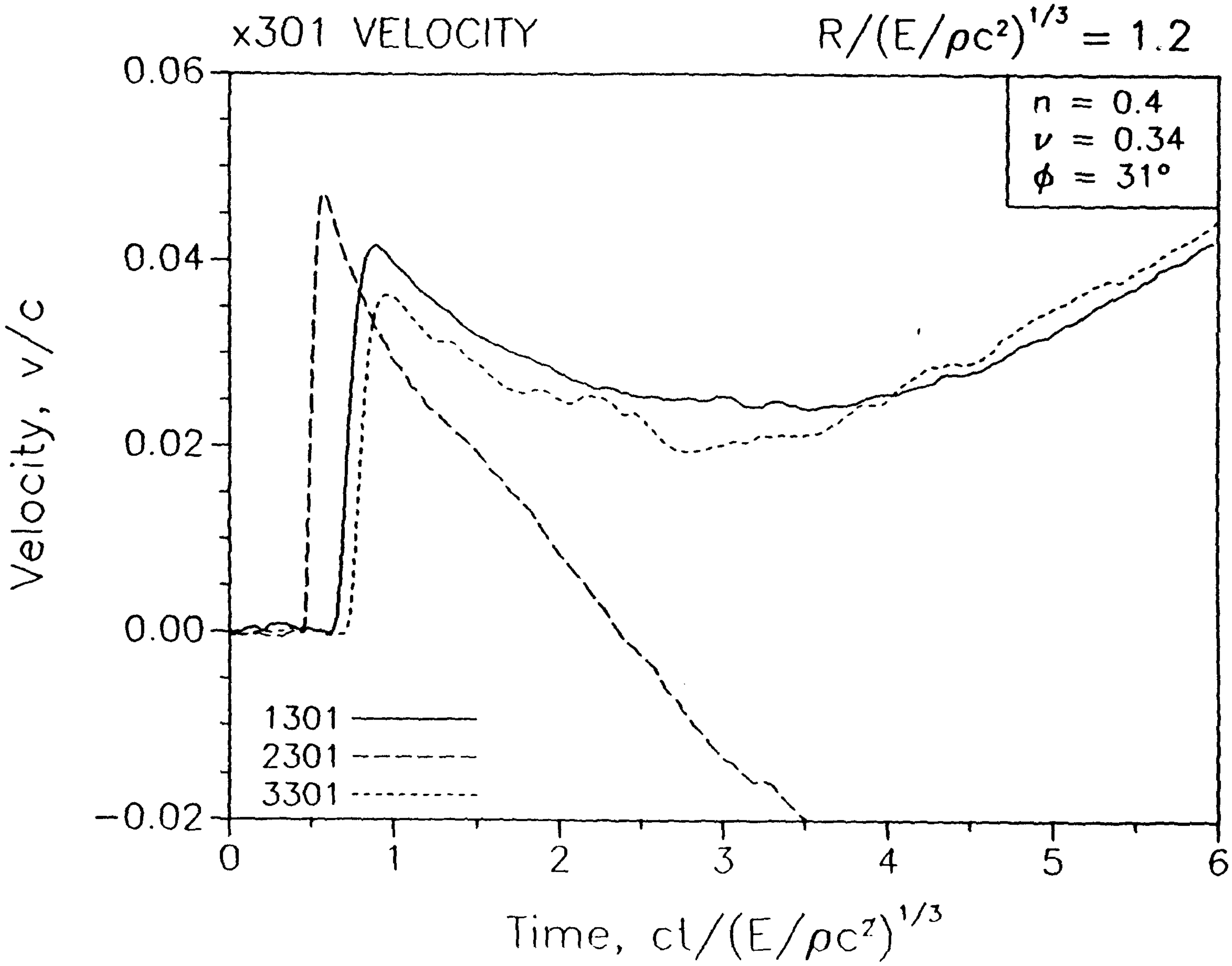
x302 ACCELERATION
R/(E/ρc²)^1/3 = 1.8
n = 0.4
ν = 0.34
φ = 31°
1302
2302
3302
0.20
0.15
0.10
0.05
0.00
−0.05
0
1
2
3
4
5
6
Acceleration, a(E/ρc²)^1/3/c²
Time, ct/(E/ρc²)^1/3

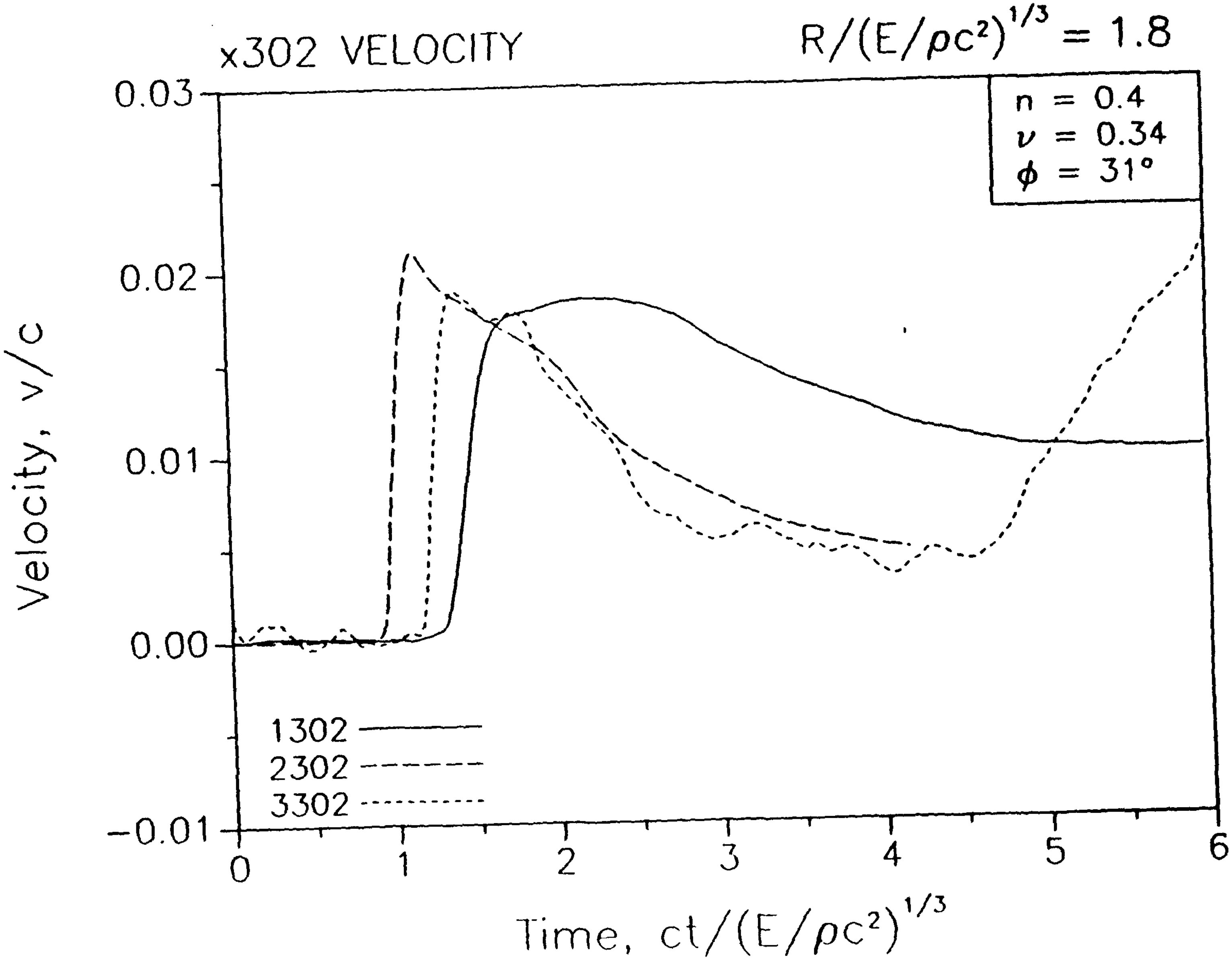

x303 ACCELERATION
R/(E/ρc²)^1/3 = 1.2
n = 0.4
ν = 0.34
φ = 31°
1303
2303
3303
Acceleration, a(E/ρc²)^1/3/c²
Time, ct/(E/ρc²)^1/3
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
0
1
2
3
4
5
6

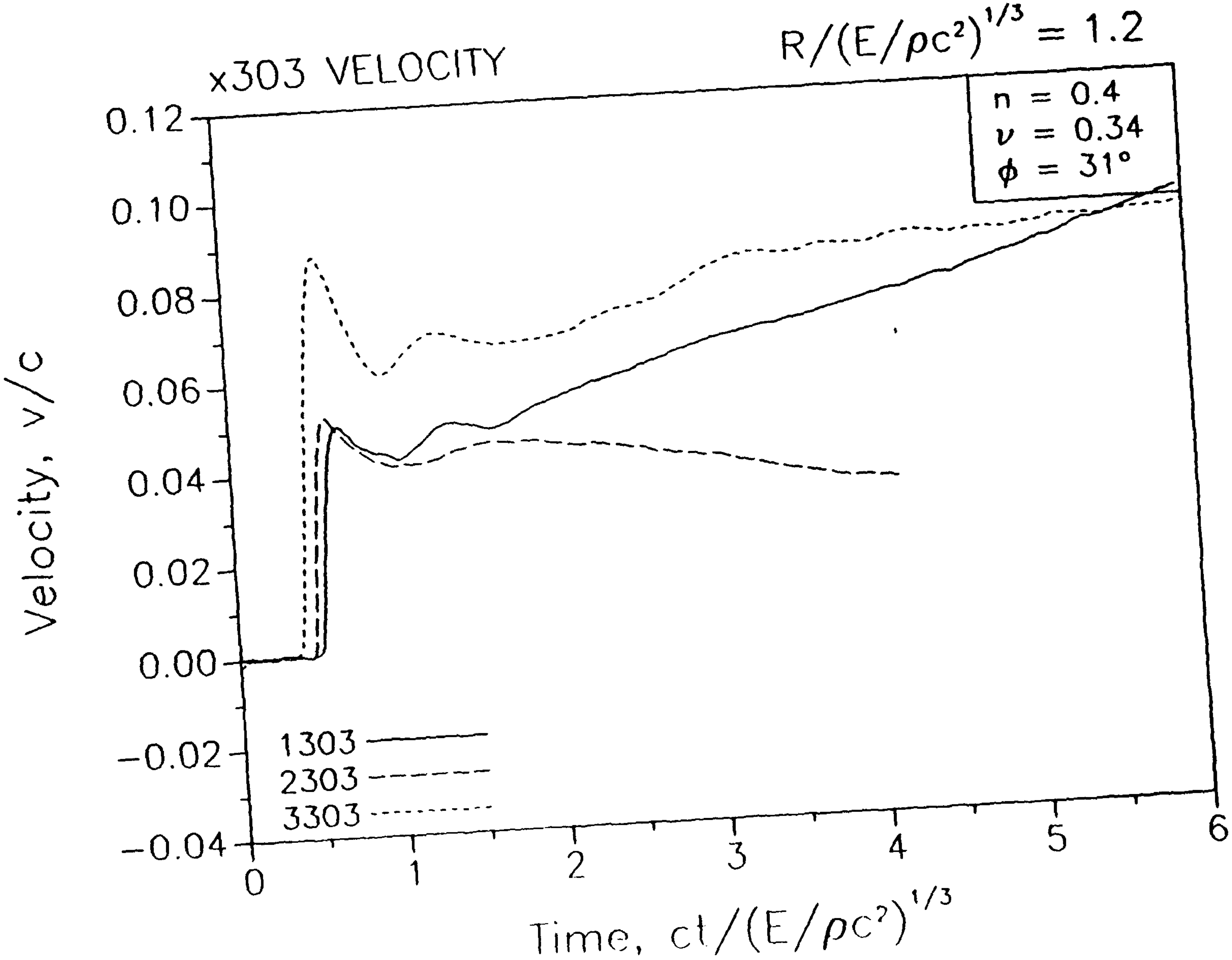


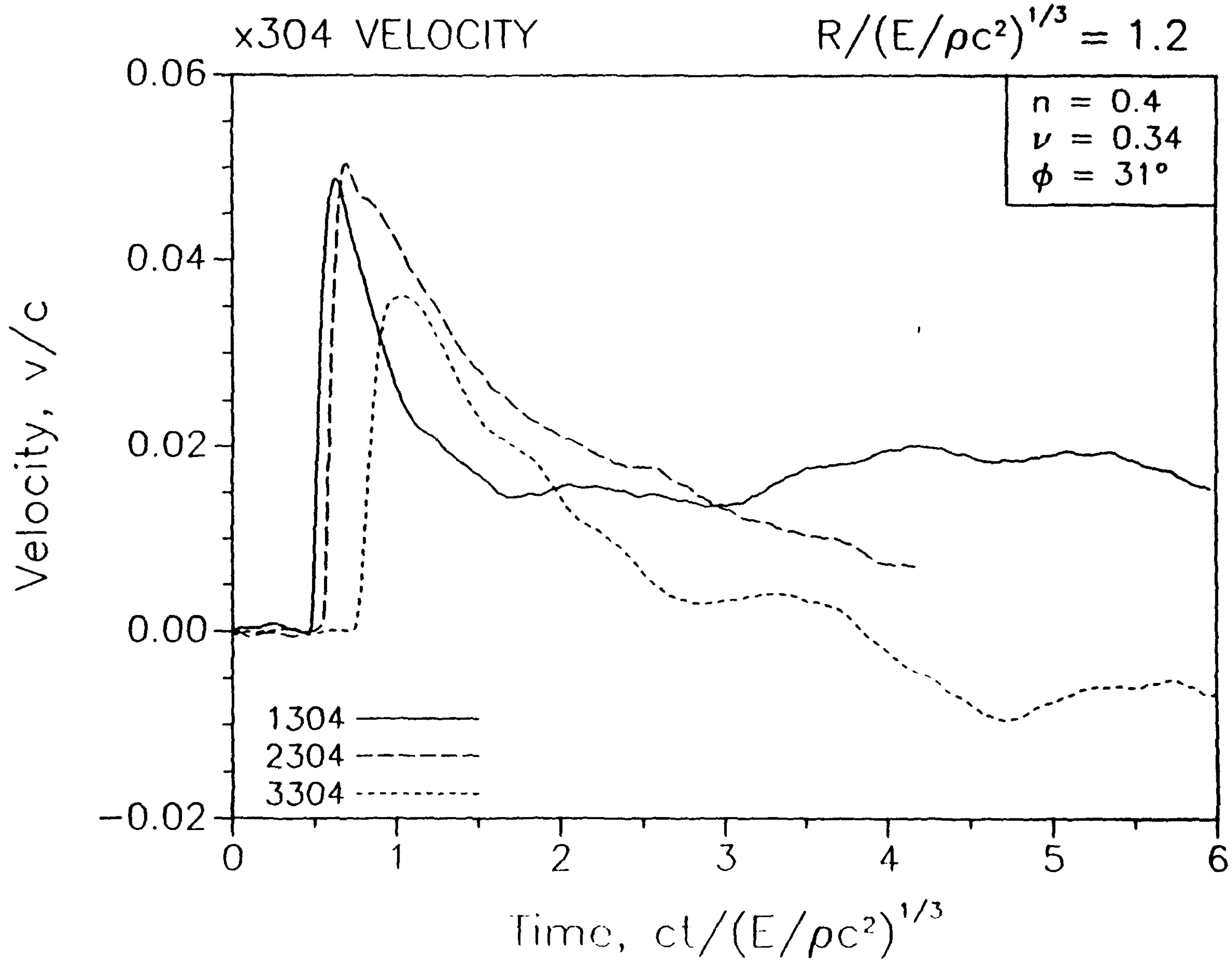
x304 ACCELERATION
R/(E/ρc²)^1/3 = 1.2
n = 0.4
ν = 0.34
φ = 31°
1304
2304
3304
Acceleration, a(E/ρc²)^1/3/c²
Time, ct/(E/ρc²)^1/3
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
0
1
2
3
4
5
6

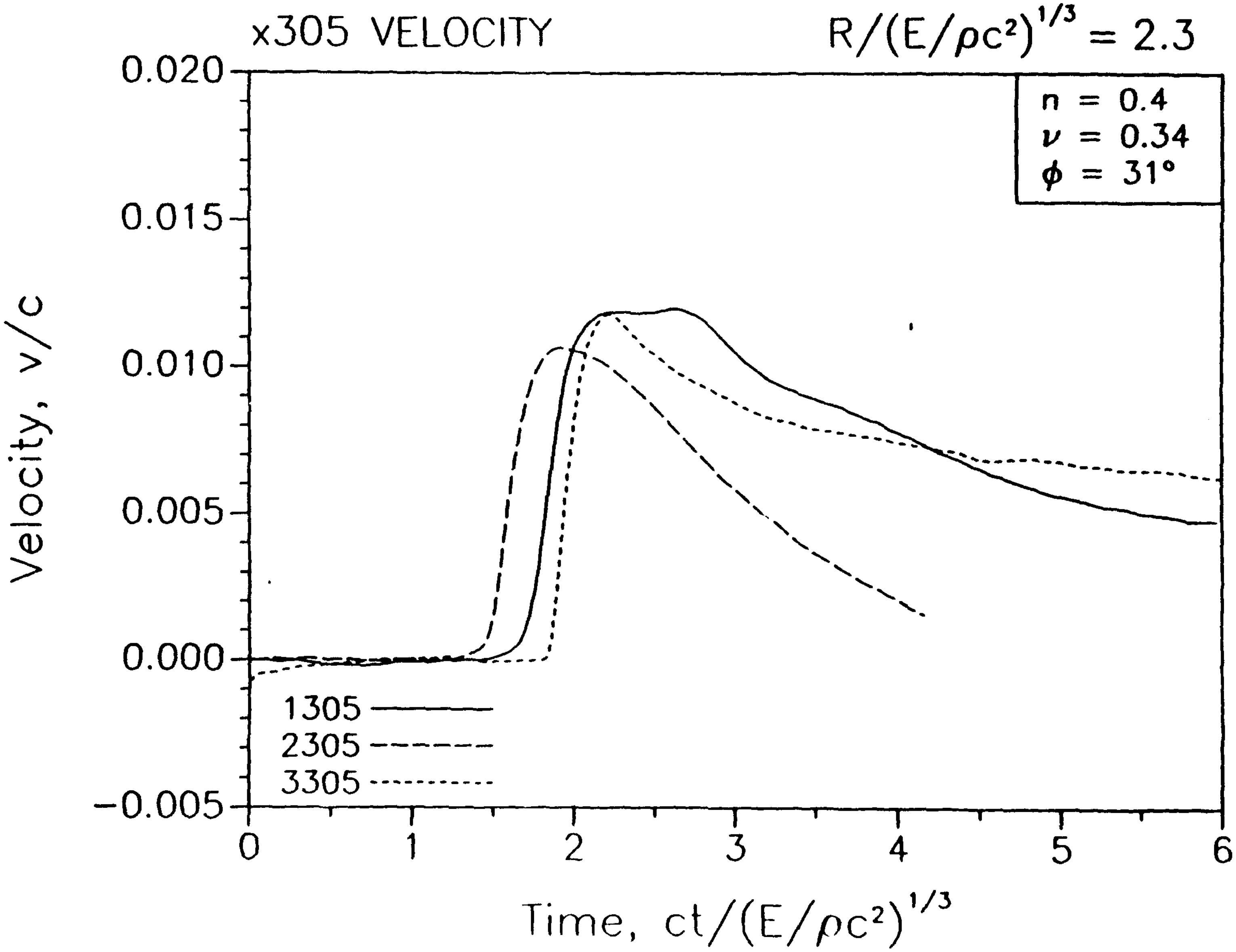

x305 ACCELERATION
R/(E/ρc²)^1/3 = 2.3
n = 0.4
ν = 0.34
φ = 31°
0.08
0.06
0.04
0.02
0.00
−0.02
0
1
2
3
4
5
6
1305
2305
3305
Acceleration, a(E/ρc²)^1/3/c²
Time, ct/(E/ρc²)^1/3

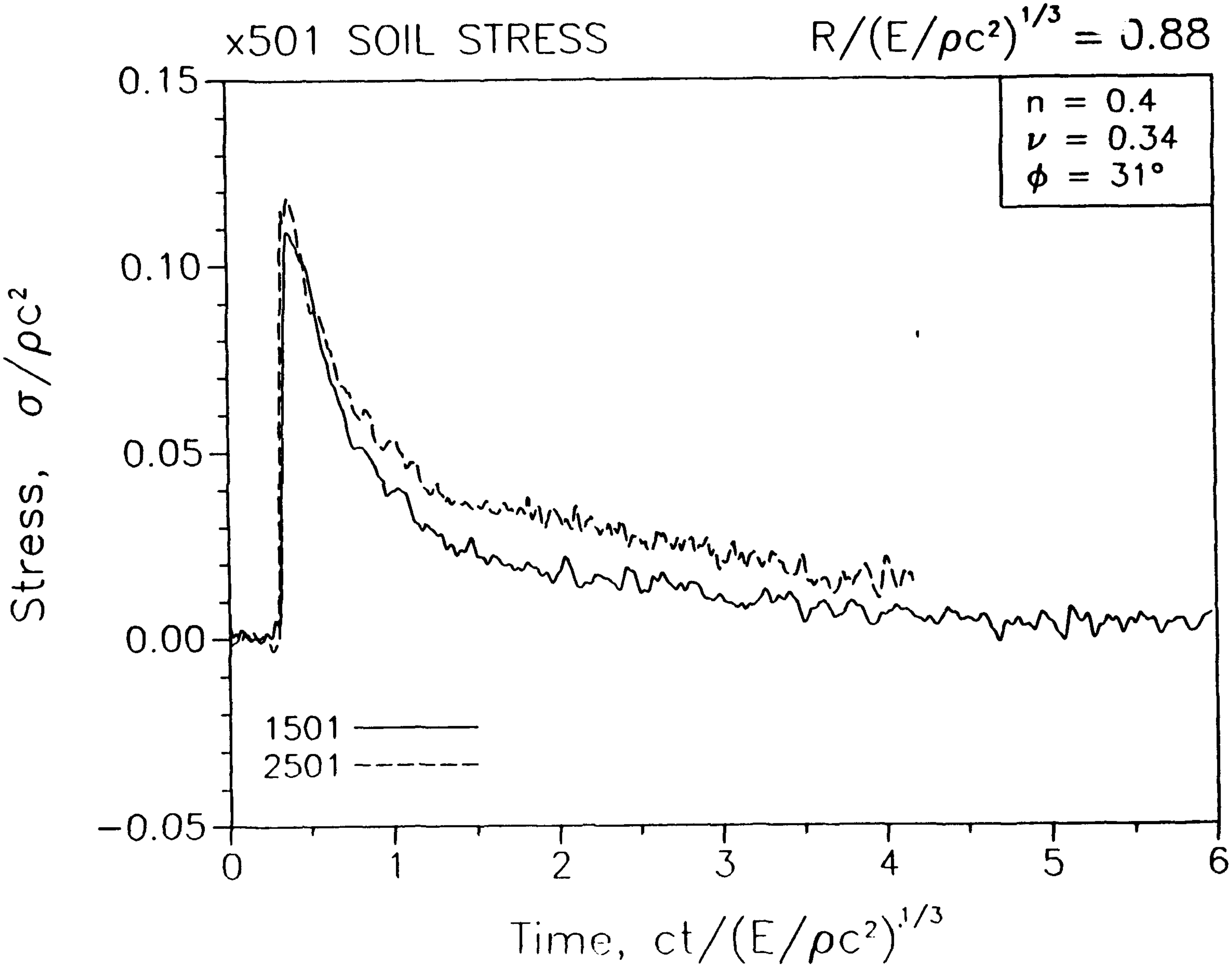

x301 VELOCITY
R/(E/ρc²)^1/3 = 1.2
n = 0.4
ν = 0.34
φ = 31°
Velocity, v/c
0.06
0.04
0.02
0.00
−0.02
1301
2301
3301
0
1
2
3
4
5
6
Time, ct/(E/ρc²)^1/3

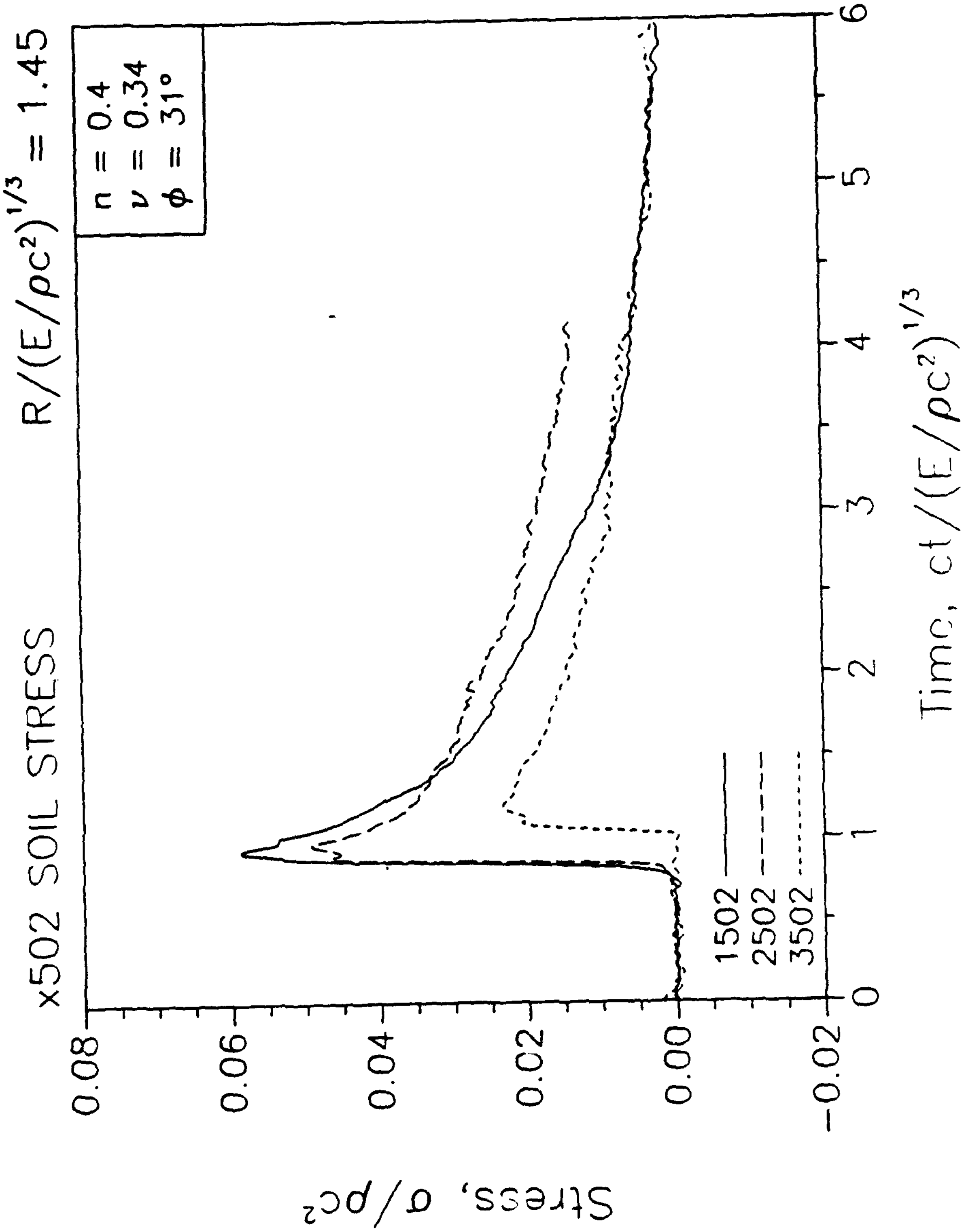

x302 VELOCITY
R/(E/ρc²)^1/3 = 1.8
n = 0.4
ν = 0.34
φ = 31°
0.03
0.02
0.01
0.00
−0.01
Velocity, v/c
1302
2302
3302
0
1
2
3
4
5
6
Time, ct/(E/ρc²)^1/3


x303 VELOCITY
R/(E/ρc²)^1/3 = 1.2
n = 0.4
ν = 0.34
φ = 31°
0.12
0.10
0.08
0.06
0.04
0.02
0.00
−0.02
−0.04
Velocity, v/c
1303
2303
3303
0
1
2
3
4
5
6
Time, ct/(E/ρc²)^1/3

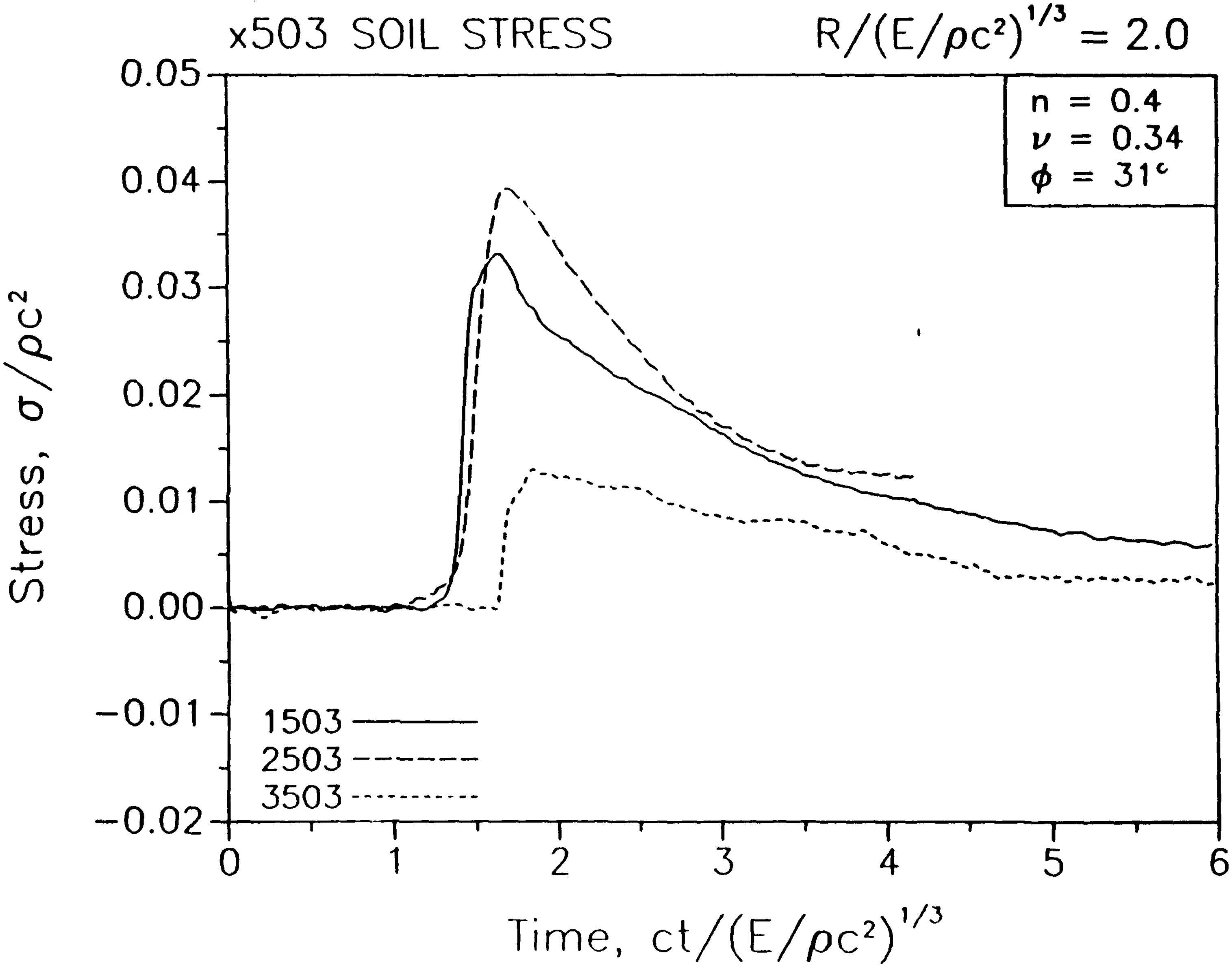

x304 VELOCITY
R/(E/ρc²)^1/3 = 1.2
n = 0.4
ν = 0.34
φ = 31°
0.06
0.04
0.02
0.00
−0.02
Velocity, v/c
0
1
2
3
4
5
6
Time, ct/(E/ρc²)^1/3
1304
2304
3304

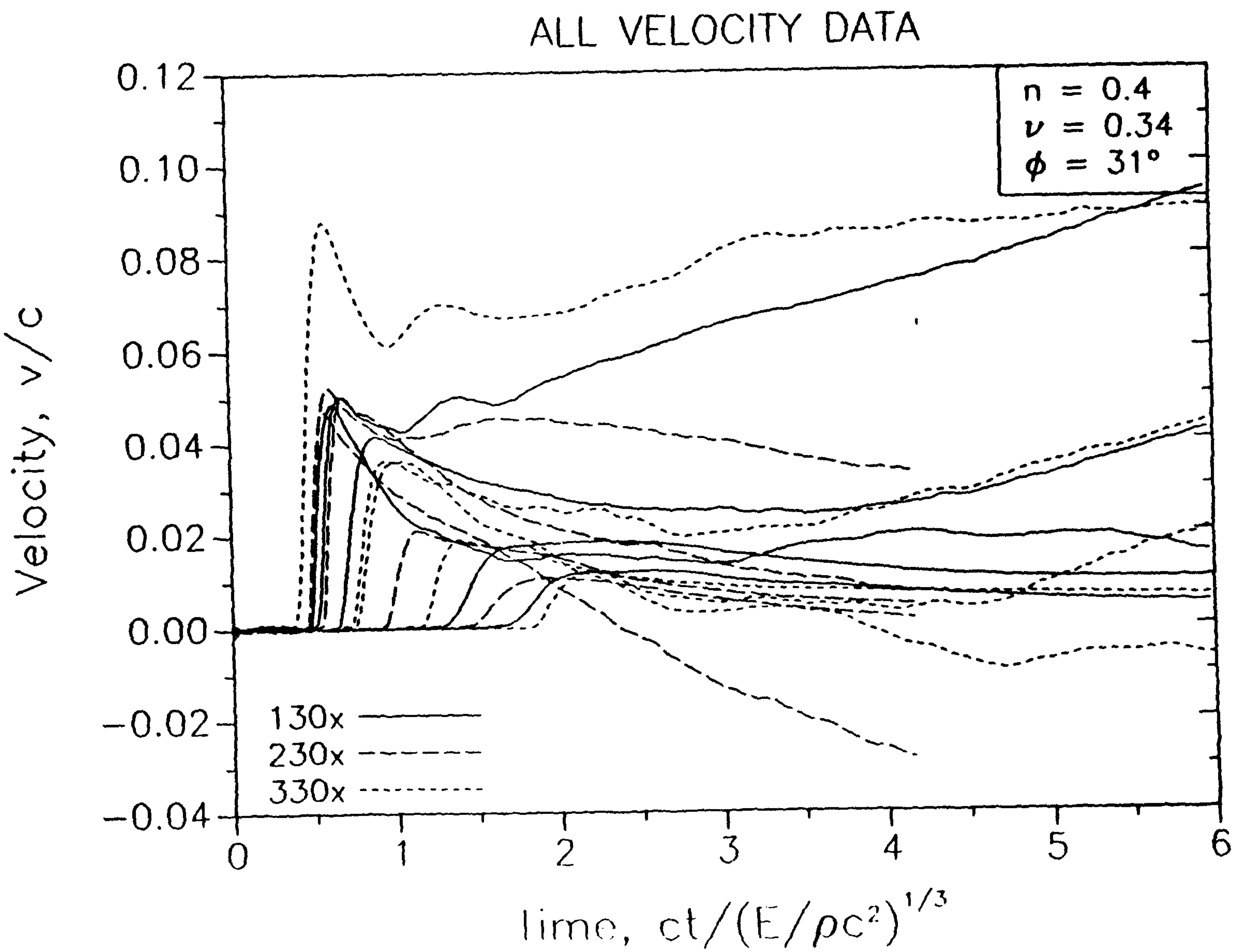

x305 VELOCITY
R/(E/ρc²)^1/3 = 2.3
n = 0.4
ν = 0.34
φ = 31°
0.020
0.015
0.010
0.005
0.000
−0.005
Velocity, v/c
0
1
2
3
4
5
6
Time, ct/(E/ρc²)^1/3
1305
2305
3305

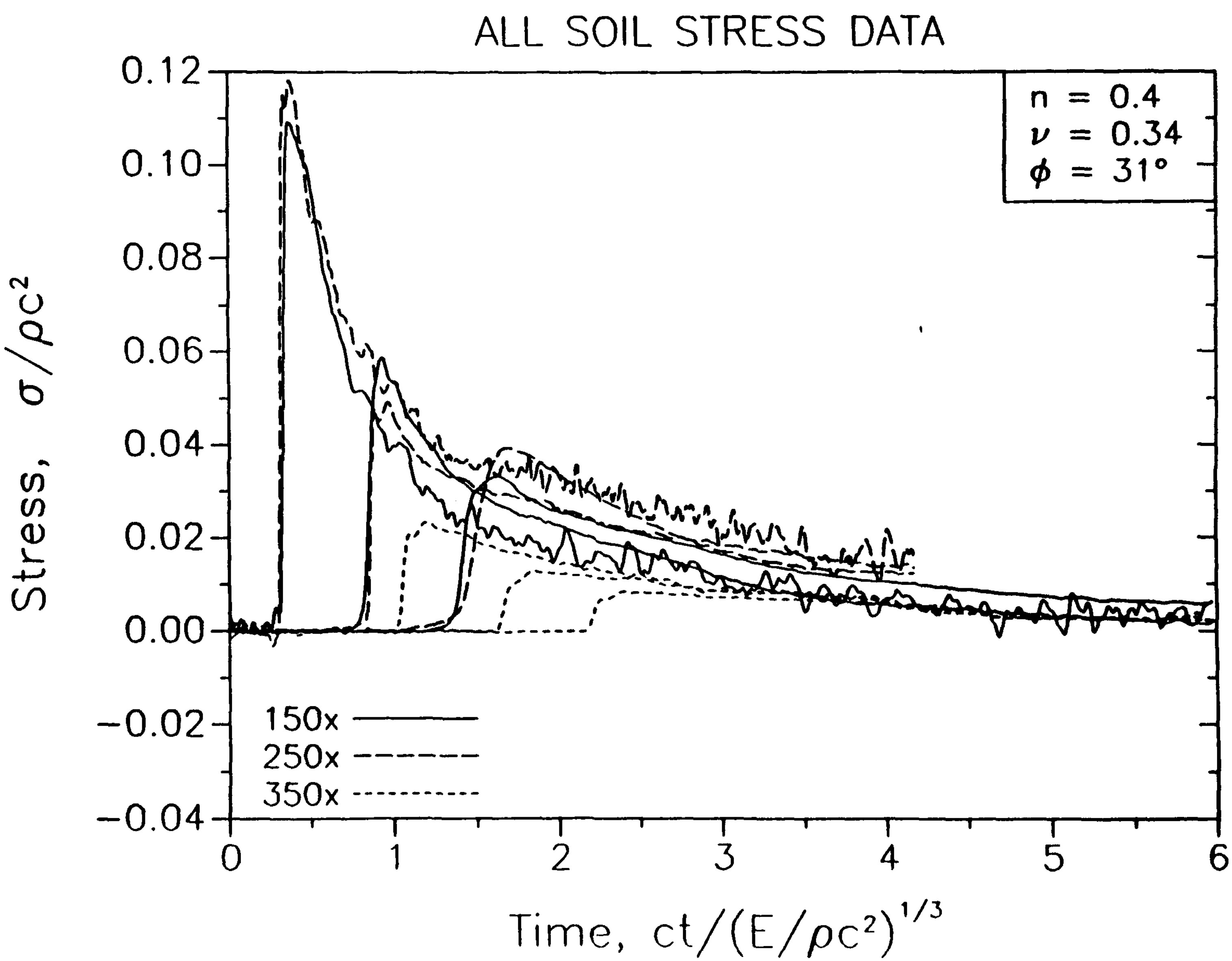

x501 SOIL STRESS
R/(E/ρc²)^1/3 = 0.88
n = 0.4
ν = 0.34
φ = 31°
0.15
0.10
0.05
0.00
−0.05
Stress, σ/ρc²
1501
2501
0
1
2
3
4
5
6
Time, ct/(E/ρc²)^1/3



x502 SOIL STRESS
R/(E/ρc²)^1/3 = 1.45
n = 0.4
ν = 0.34
φ = 31°
1502
2502
3502
0.08
0.06
0.04
0.02
0.00
-0.02
Stress, σ/ρc²
0
1
2
3
4
5
6
Time, ct/(E/ρc²)^1/3


x503 SOIL STRESS
R/(E/ρc²)^1/3 = 2.0
n = 0.4
ν = 0.34
φ = 31°
Stress, σ/ρc²
Time, ct/(E/ρc²)^1/3
1503
2503
3503
0.05
0.04
0.03
0.02
0.01
0.00
−0.01
−0.02
0
1
2
3
4
5
6


ALL VELOCITY DATA
n = 0.4
ν = 0.34
φ = 31°
0.12
0.10
0.08
0.06
0.04
0.02
0.00
−0.02
−0.04
Velocity, v/c
130x
230x
330x
0
1
2
3
4
5
6
Time, ct/(E/ρc²)^1/3


ALL SOIL STRESS DATA
n = 0.4
ν = 0.34
φ = 31°
Stress, σ/ρc²
0.12
0.10
0.08
0.06
0.04
0.02
0.00
−0.02
−0.04
0
1
2
3
4
5
6
Time, ct/(E/ρc²)^1/3
150x
250x
350x