

IMPACT EXPERIMENTS TO DETERMINE THE ROLE OF MATRIX MATERIAL PROPERTIES  
ON THE PIEZORESISTANCE RESPONSE OF FOILS

Satish C. Gupta and Y. M. Gupta  
Shock Dynamics Laboratory  
Department of Physics  
Washington State University  
Pullman, Washington 99164-2814

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Introduction

In this report we have summarized the results of our experiments designed to determine the influence of the matrix properties on the piezoresistance response of ytterbium and manganin foils. The two matrix materials considered in our work were: polymethylmethacrylate (PMMA) and polycrystalline aluminum oxide (Vistal). These two materials have widely different mechanical impedances (PMMA has very low impedance and Vistal has very high impedance) and serve as bounds for most other materials. Hence, the conclusions drawn from the present experiments should provide a good understanding of the role of matrix properties.

We have presented the experimental configuration and the resistance change profiles for all the gauges in each experiment.

To facilitate the numerical simulation we have presented the properties of the materials used in our experiments at the end of this report.

Experiments and Results

The gauges were cut into four terminal configurations from ytterbium sheets\* (nominally 48 micron thick) and manganin sheets\*\* (nominally 33 micron thick). The gauges were embedded into the matrix material in two configurations. In the first configuration, termed "ingroove," a gauge sized groove is cut into the surface of one piece of the matrix. The gauge is glued

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\*Supplied by Research Chemical Corporation, Phoenix, Arizona.

\*\*Supplied by Hamilton Tech., Lancaster, PA; obtained through D. D. Keough of SRI International.

into the groove, lapped flush with the matrix surface, and then bonded to the other piece of the matrix onto this surface. In this configuration the thickness of epoxy around the gauge may be about 1-2 micron thick. Hence, the gauge can be considered essentially as an inclusion in the matrix. In the second configuration, termed "surface," the gauge is sandwiched between the two plane surfaces of the matrix. Here the gauge is surrounded in the lateral direction by an epoxy layer of thickness equal to the thickness of the gauge.

The embedded gauges had two orientations: one with the major surface parallel to the shock front (termed longitudinal gauge) and the other with major surface perpendicular to the shock front (termed lateral gauge).

The experiments were done using the 63.5 mm gas gun at our laboratory. The details of all the experiments and the resistance change profiles are given in Appendix A.

The important experimental results are summarized as follows:

#### A. Longitudinal gauge

(i) For the same value of the matrix longitudinal stress, the ingroove manganin gauges show the same peak resistance change for the two matrix materials. However, the ingroove ytterbium gauges show lower resistance change (by about \_\_\_ at 25 kbar) in the Vistal matrix compared to that in the PMMA matrix.

(ii) In the Vistal matrix, the resistance change for the ytterbium surface gauge is much higher than the resistance change for the ingroove ytterbium gauge. The surface gauge response is closer to the response of the gauge embedded in the PMMA matrix.

(iii) In the PMMA matrix the resistance change for ytterbium surface gauge is about 5 percent higher than that for the ingroove ytterbium gauge.

## B. Lateral gauge

At 18.4 kbar and above, the ytterbium and manganin lateral gauges embedded in the PMMA matrix show qualitatively different resistance change profiles. In contrast, the ytterbium and manganin longitudinal gauges show similar profiles. The lateral manganin gauge shows a time dependent response. The qualitative difference in the lateral gauges is not seen below 15 kbars.

## Material Properties

In Appendix B we have included the electromechanical constant of ytterbium and manganin foils used in our experiments and the constitutive relations for PMMA and Vistal, the matrix material used in our study.

## Acknowledgments

We thank Martin Williams and Jerry Thompson for their technical assistance in building the targets and in performing the experiments.

Table I. Summary of Experiments\*

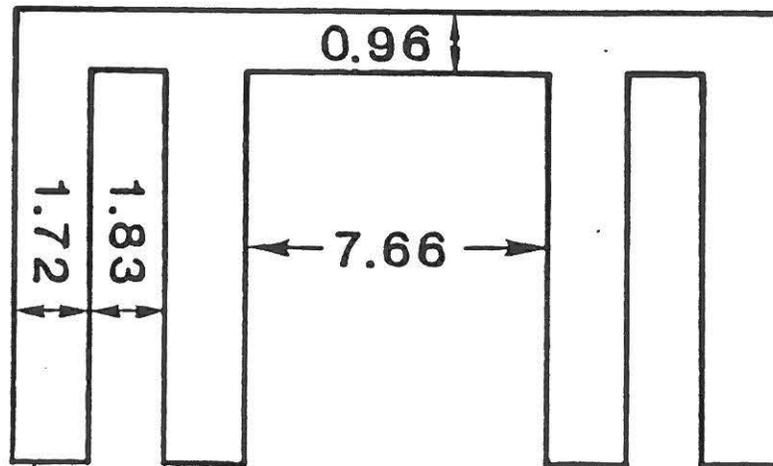
Experiment Number	Impactor Material	Impactor Velocity (mm/ $\mu$ sec)	Matrix Material	Matrix Stress (kbar)	Material	Configuration	Remarks
1. (84501)	Vistal	0.665	PMMA	24.4	Ytterbium Manganin	Ingroove Longitudinal Ingroove Lateral Ingroove Longitudinal Ingroove Lateral	In these two experiments manganin gauges showed the same response but ytterbium in Vistal showed lower resistance change than ytterbium in PMMA.
2. (84502)	PMMA	0.675	Vistal	24.6	Ytterbium Manganin	Ingroove Longitudinal Ingroove Longitudinal	
3. (84511)	PMMA	0.534	Vistal	19.0	Ytterbium	Ingroove Longitudinal Surface Longitudinal	The surface gauge showed higher resistance change than the ingroove one.
4. (84513)	Vistal	0.601	PMMA	21.6	Ytterbium	Ingroove Longitudinal Surface Longitudinal Ingroove Lateral	Resistance change for surface longitudinal is slightly higher than ingroove longitudinal.
5. (83526)	Fused Silica	0.605	PMMA	18.4	Ytterbium Manganin	Ingroove Longitudinal Ingroove Lateral Ingroove Longitudinal Ingroove Lateral	The resistance change profiles for longitudinal gauges are almost the same but the two lateral gauges are qualitatively different.
6. (83541)	Fused Silica	0.606	PMMA	18.4	Ytterbium Manganin	Ingroove Lateral Ingroove Lateral	Experiment did verify the qualitative behavior of lateral gauges.

\*Vistal is the trademark of Coors for polycrystalline  $Al_2O_3$  and is a replacement for Lucalox manufactured by GE.

## APPENDIX A

In this appendix we have given the experimental details and the results. Table I summarizes the results of all the experiments.

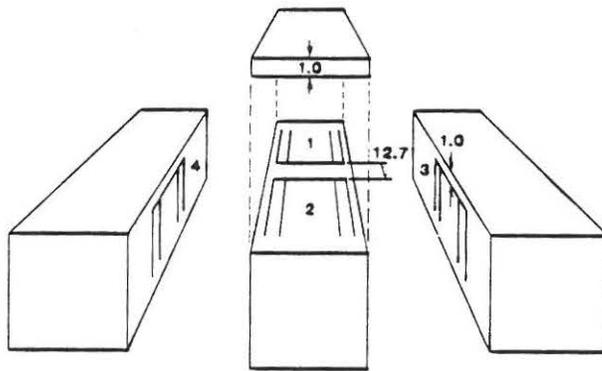
Figure a.1 gives the dimensions of the gauges used. For each experiment there is one sheet carrying the details of the experiment, followed by the resistance change profiles for each gauge used in that experiment.



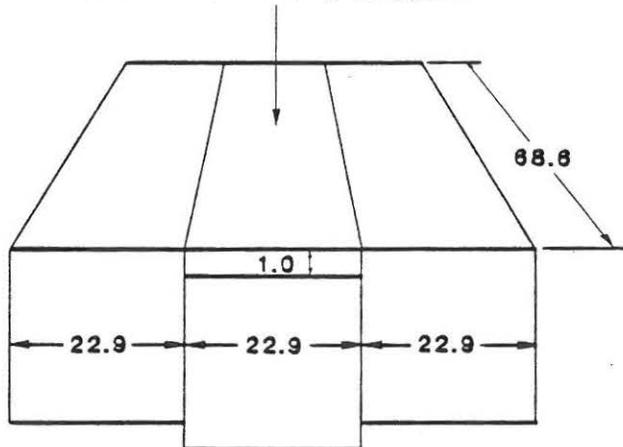
**Fig a.1. Dimension of the gauge used. All dimensions are in millimeters. Thickness of the ytterbium gauge was 48 micron and that of the manganin gauge was 33 micron.**

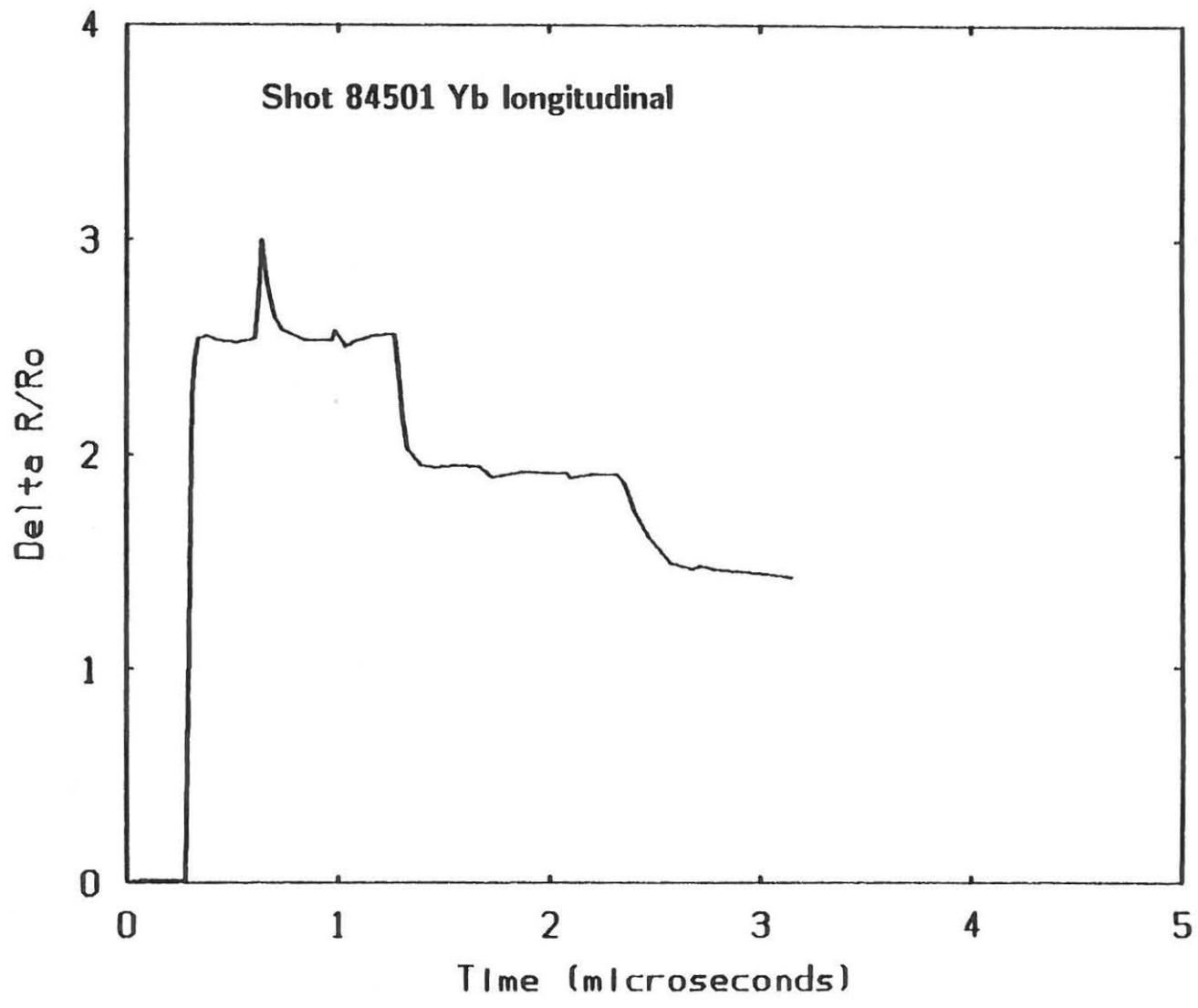
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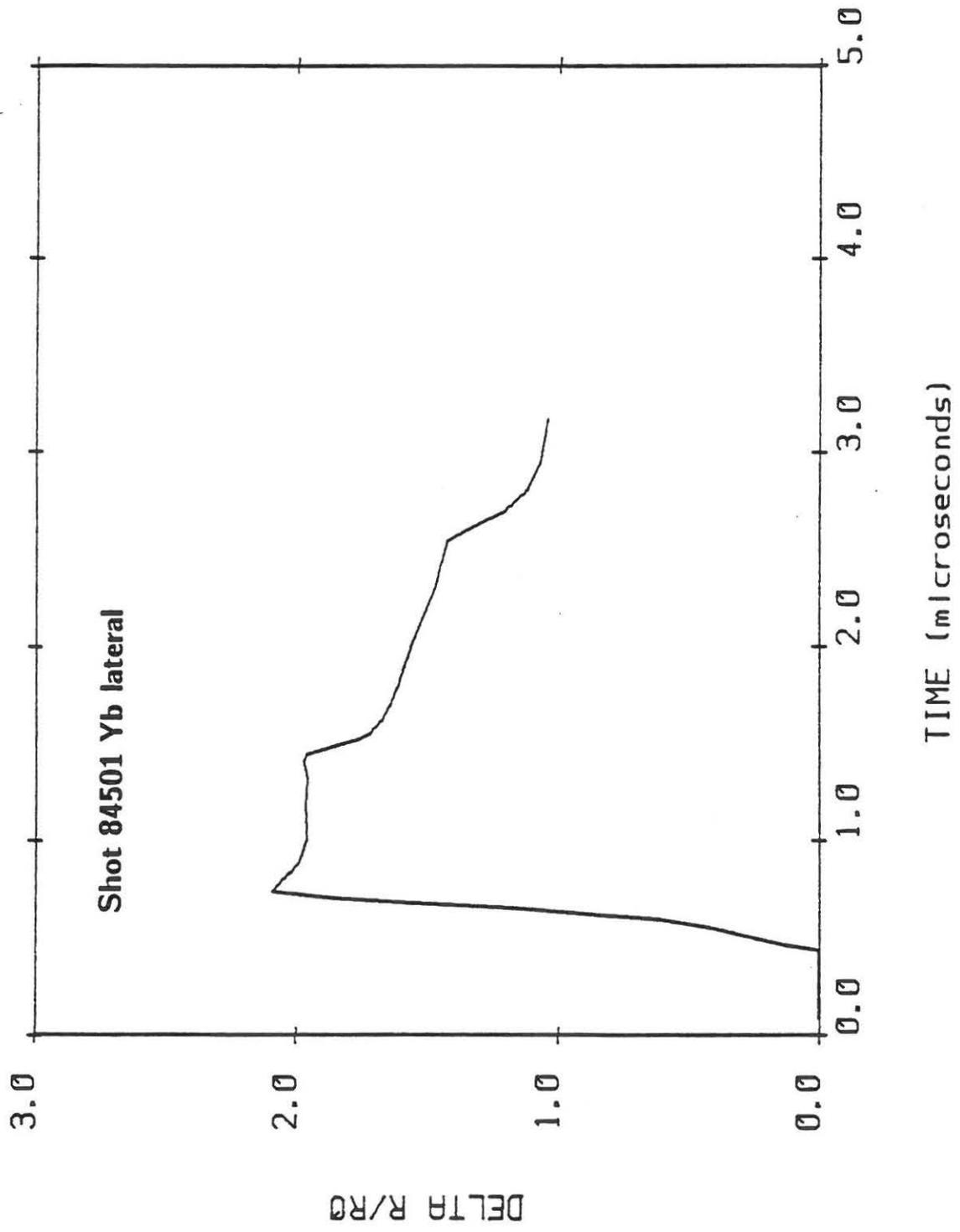
Projectile velocity: 0.665 mm/us  
Shock stress: 24.4 kbar  
Matrix material: PMMA  
Impactor material: Vistal  
Impactor thickness : 6.1 mm

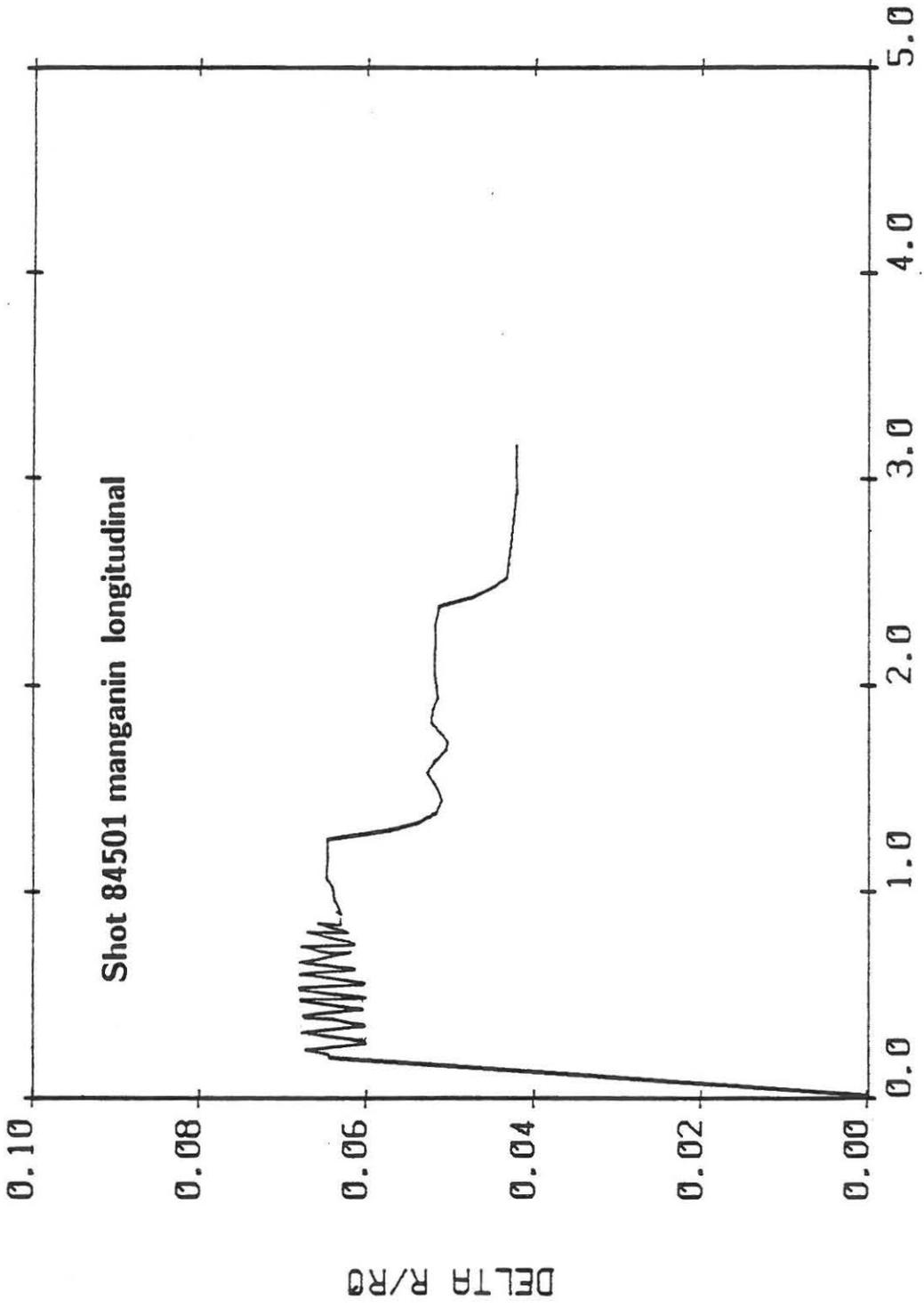


Direction of shock propagation

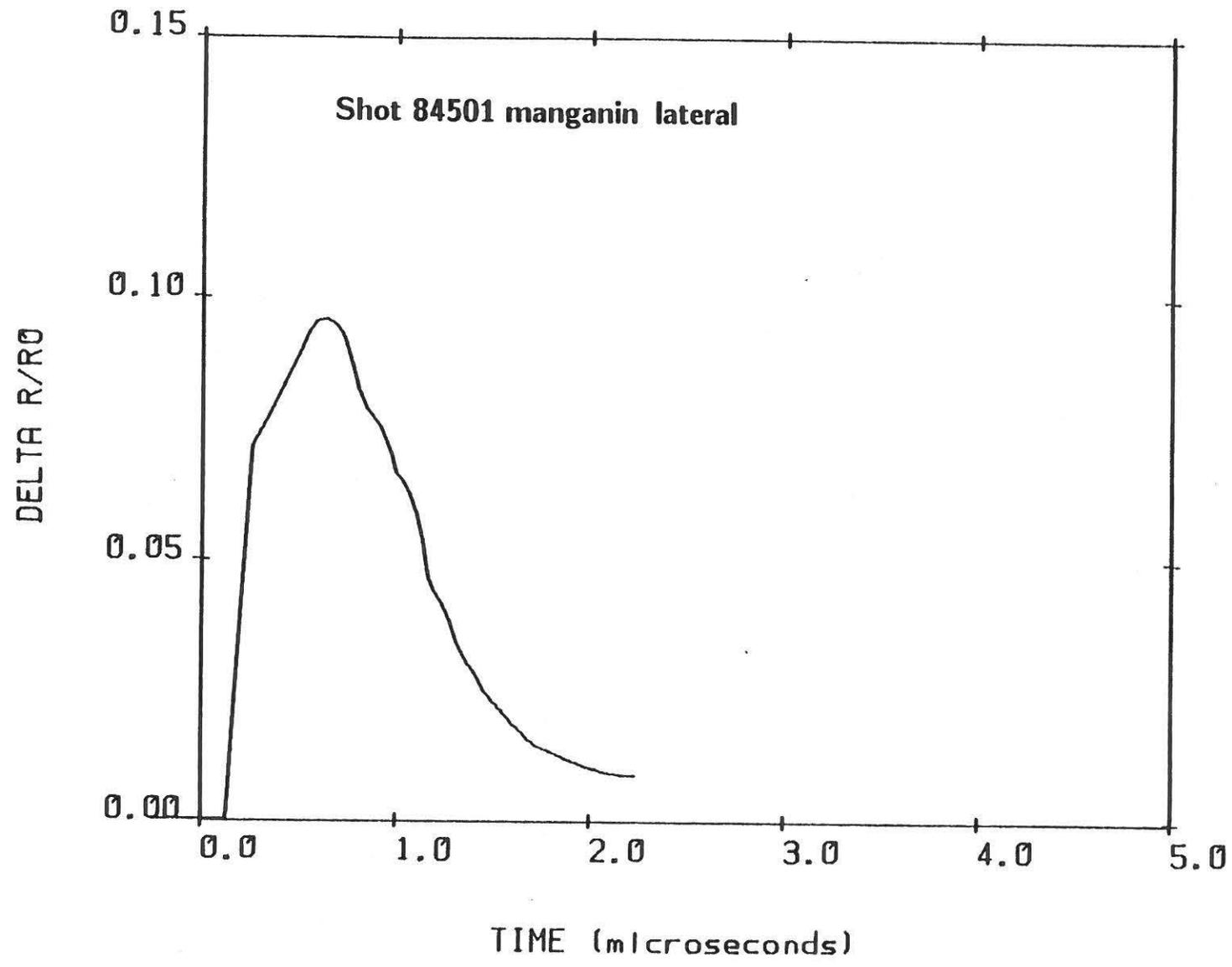






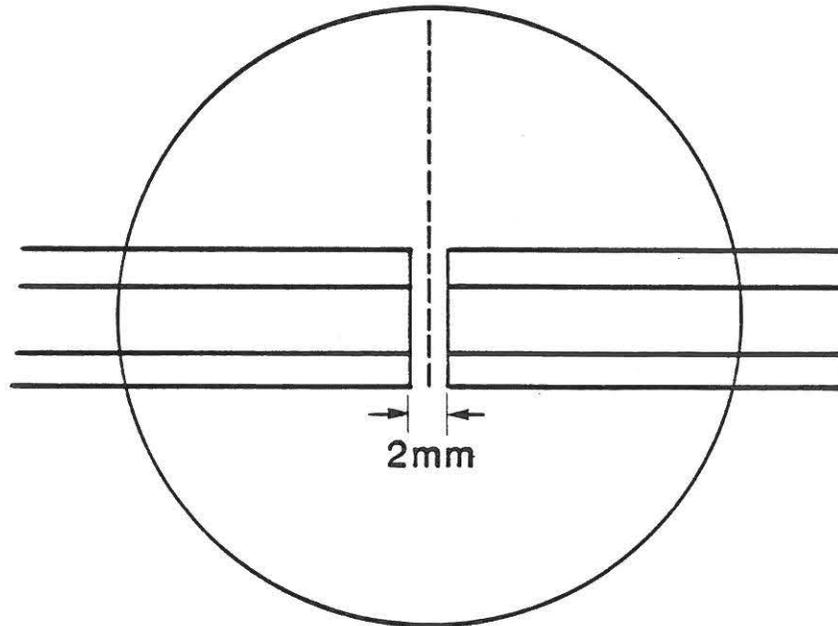
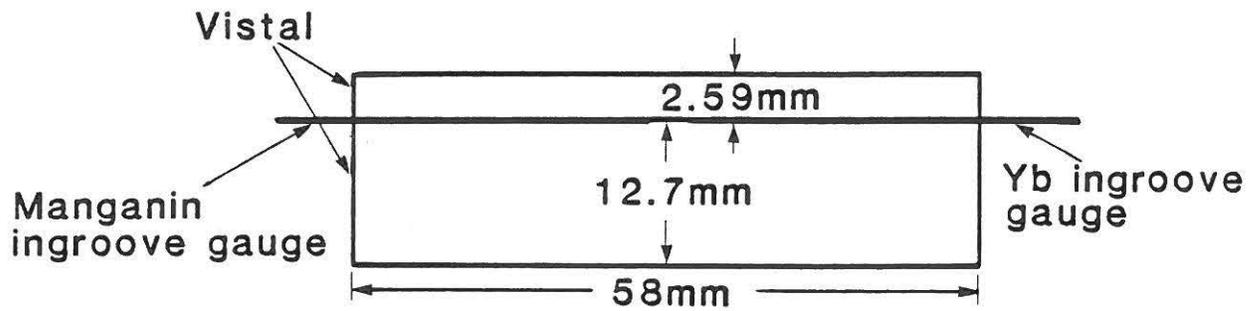


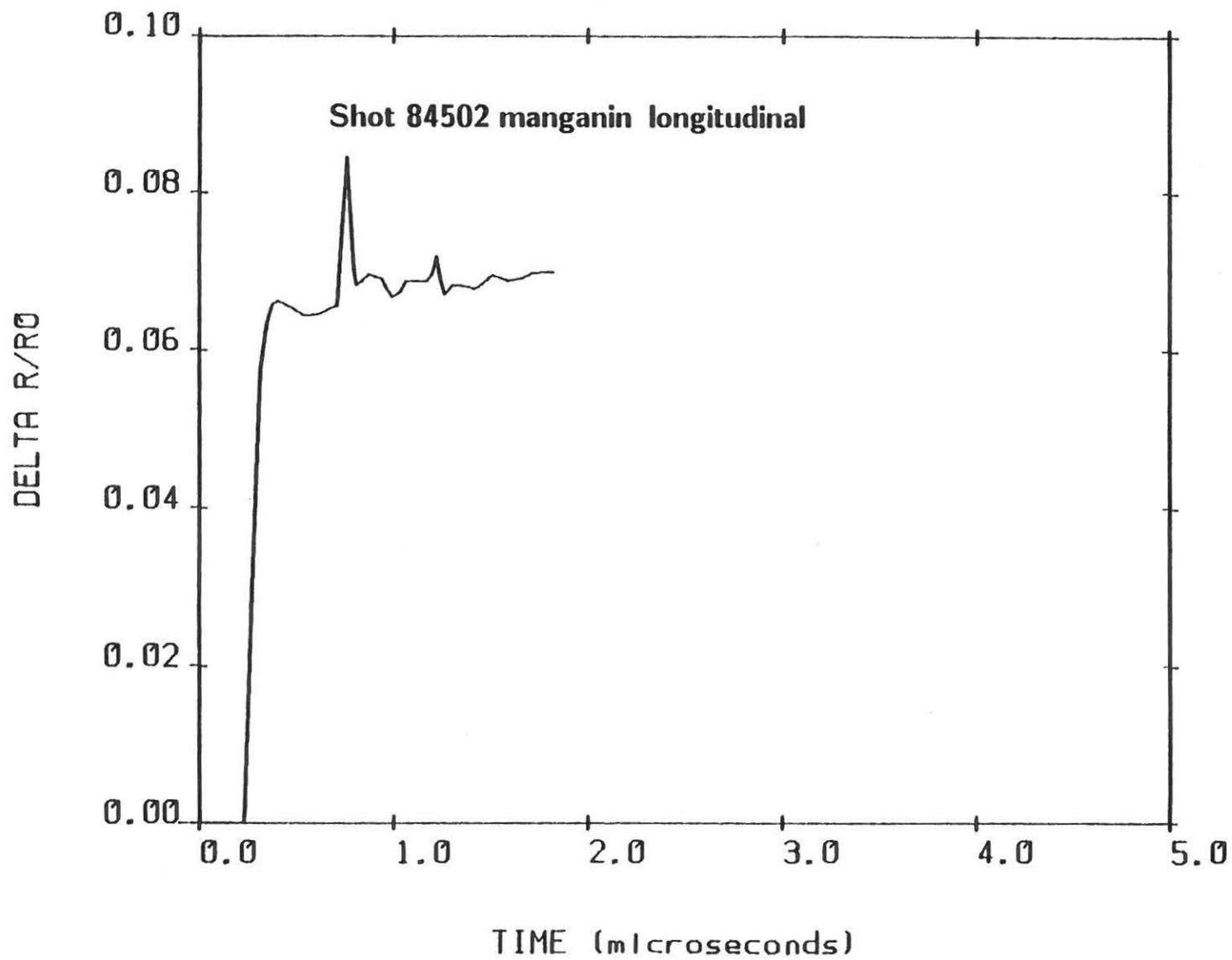
TIME (microseconds)

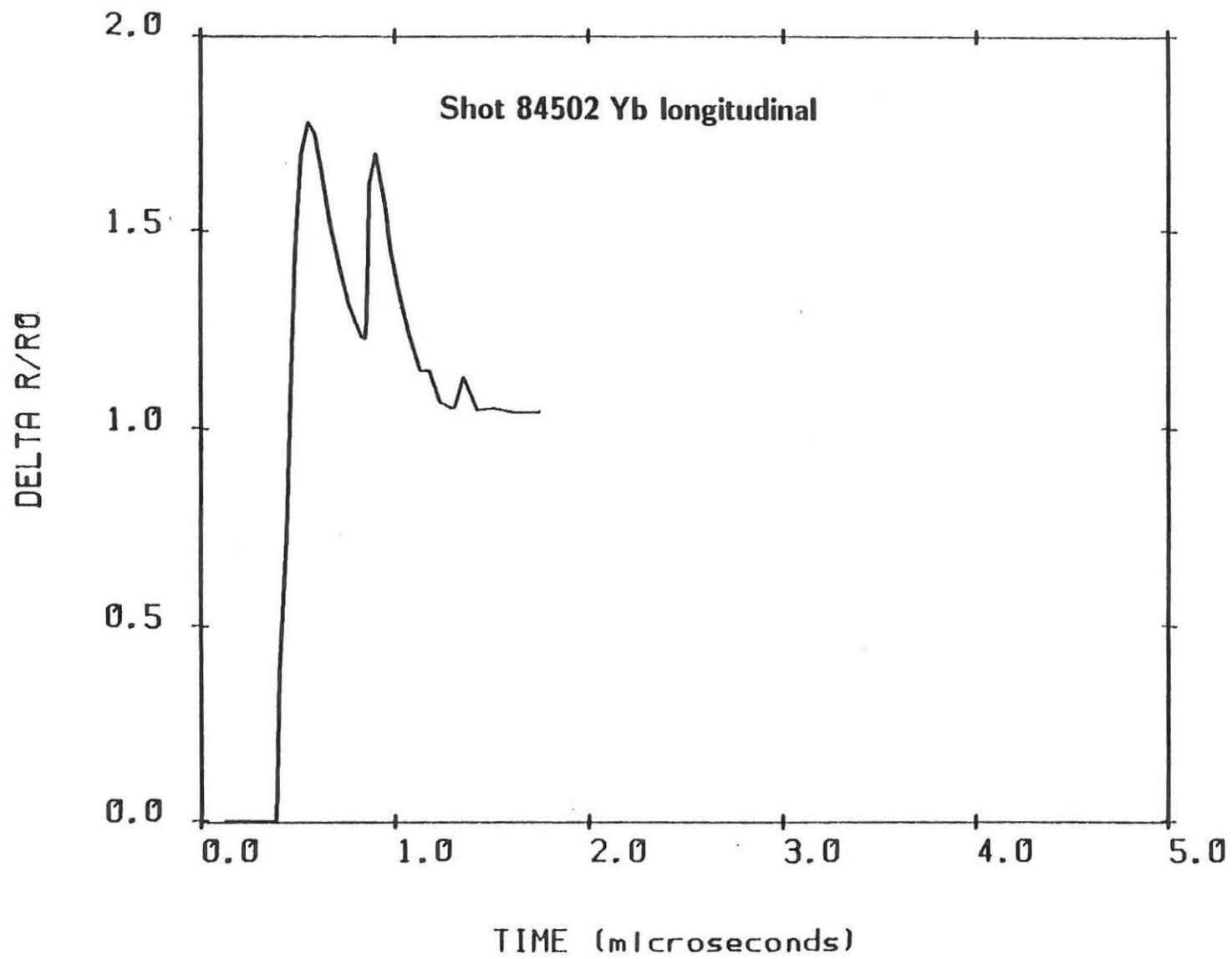


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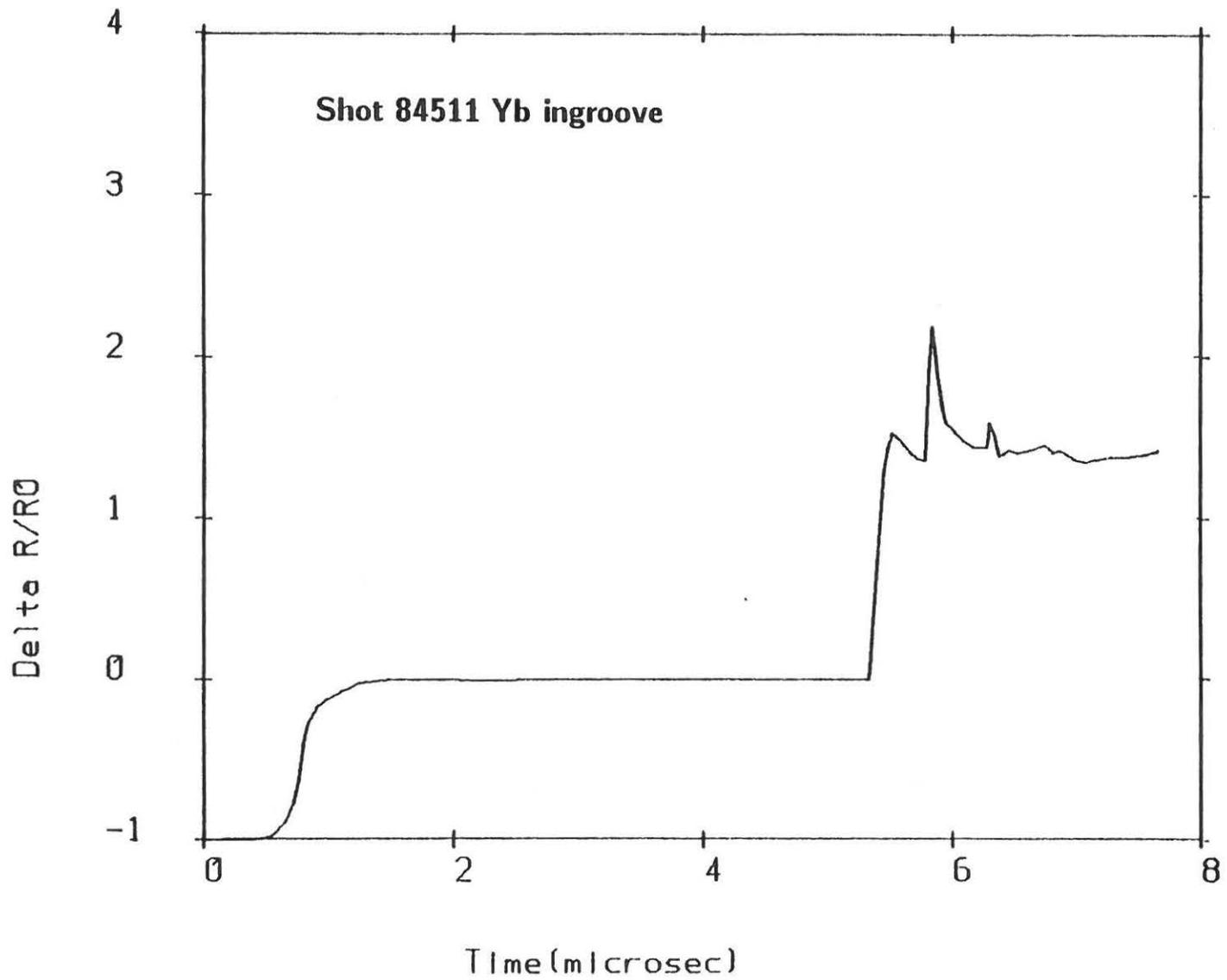
Projectile velocity: 0.675 mm/us  
Shock stress: 24.6 kbar  
Matrix material: Vistal  
Impactor material: PMMA  
Impactor thickness : 5.8 mm

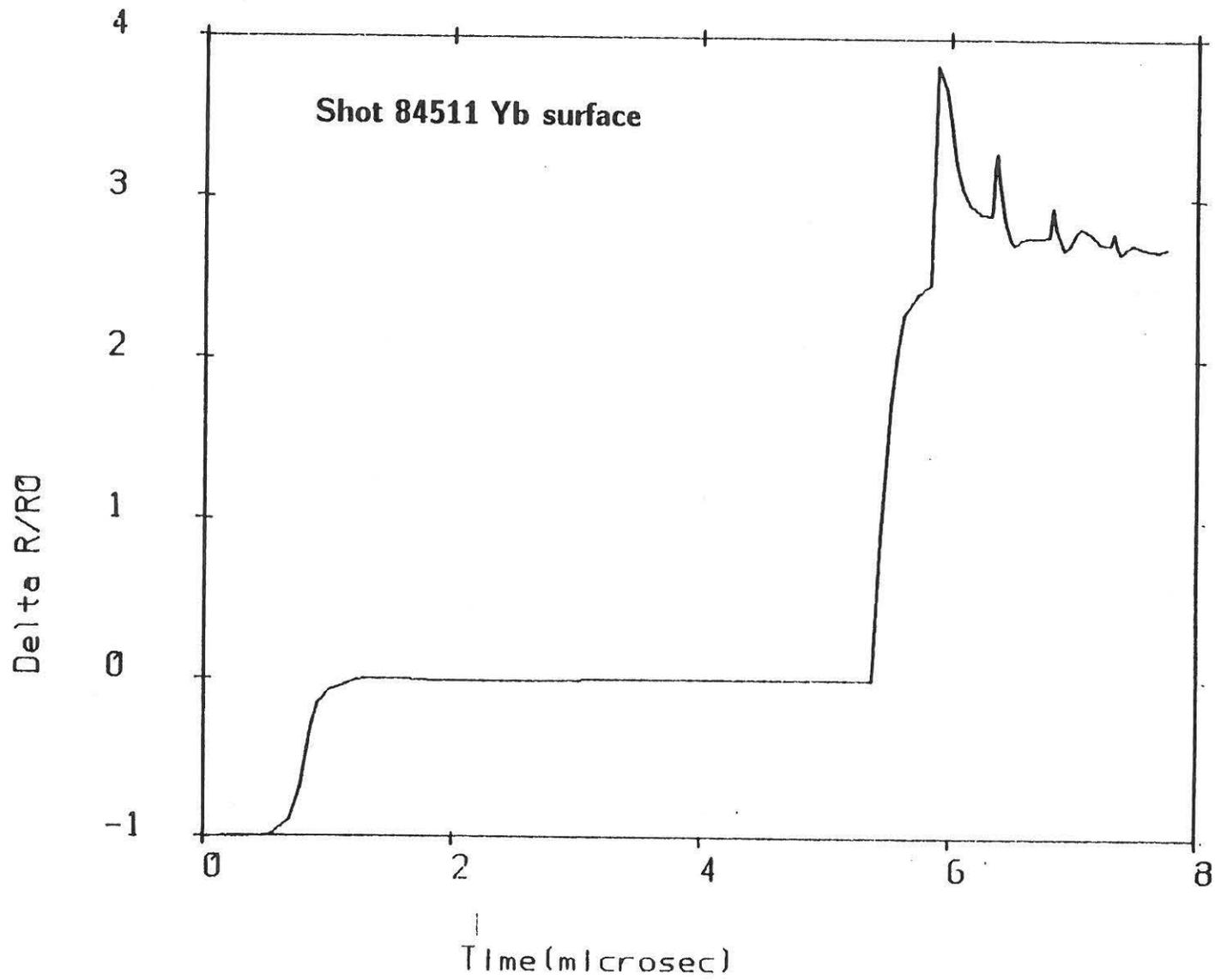






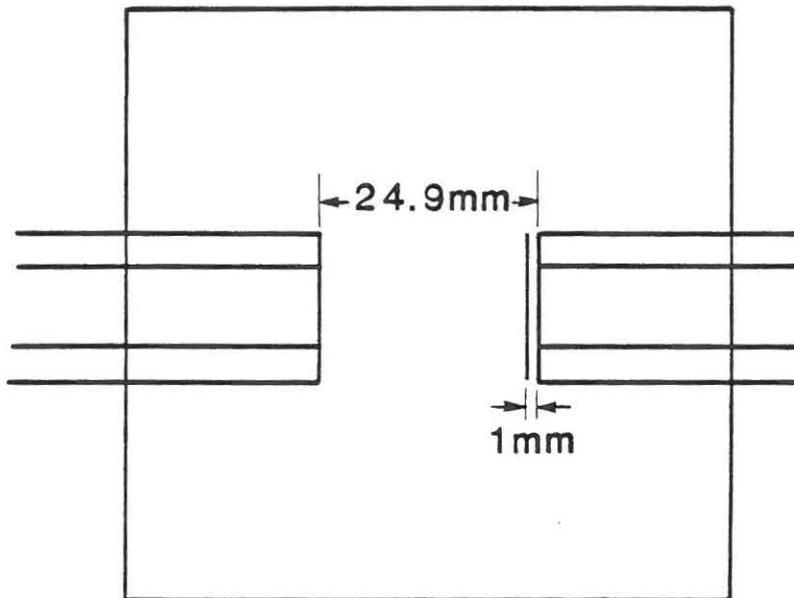
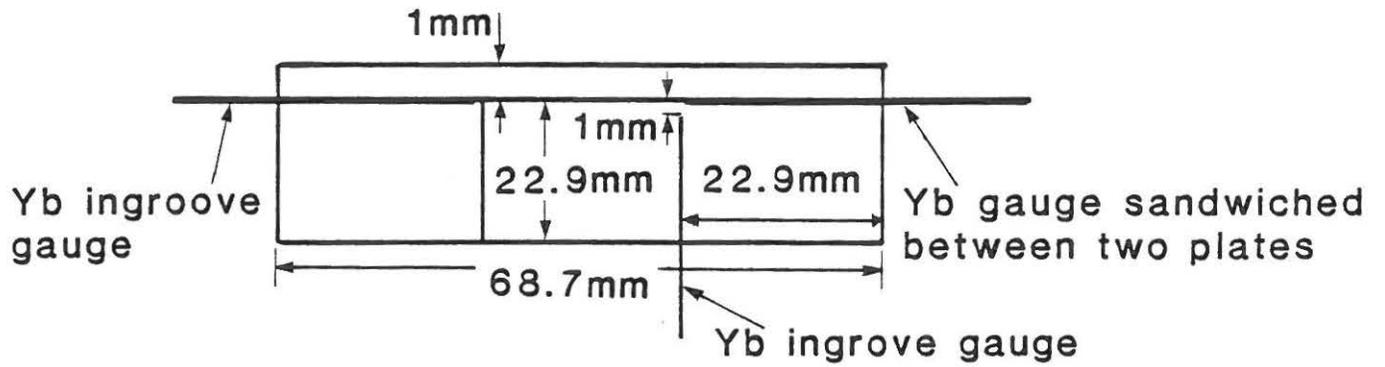


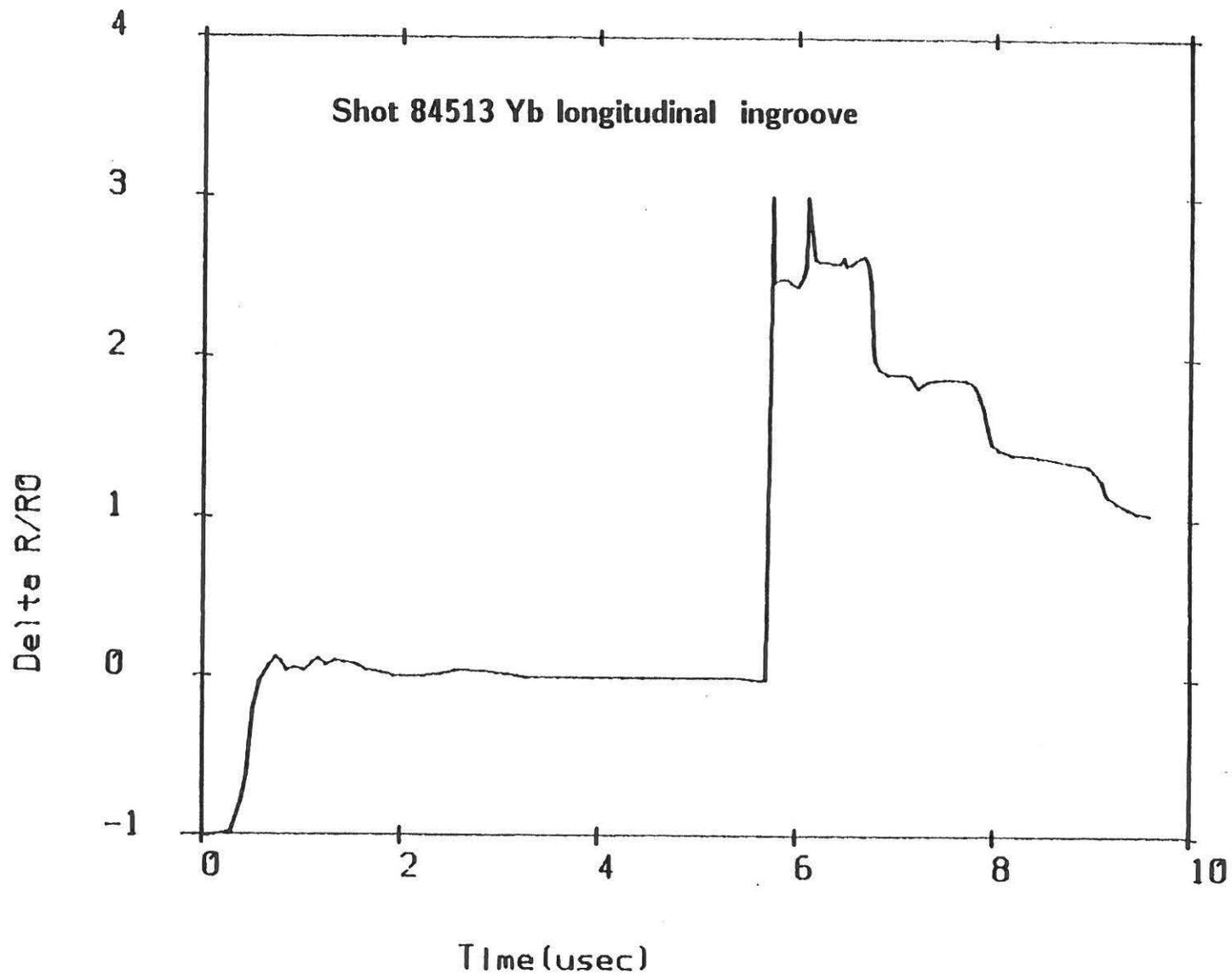


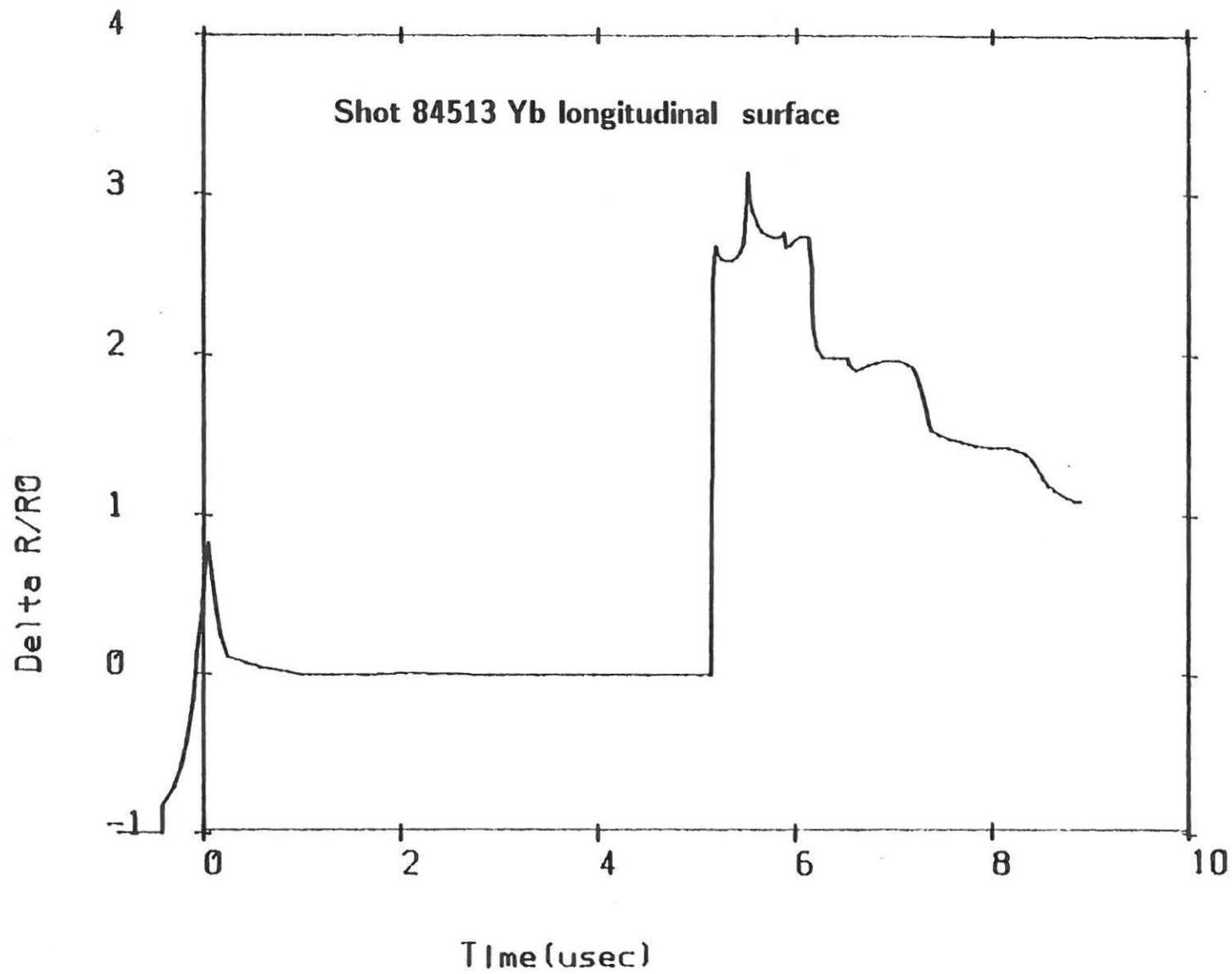


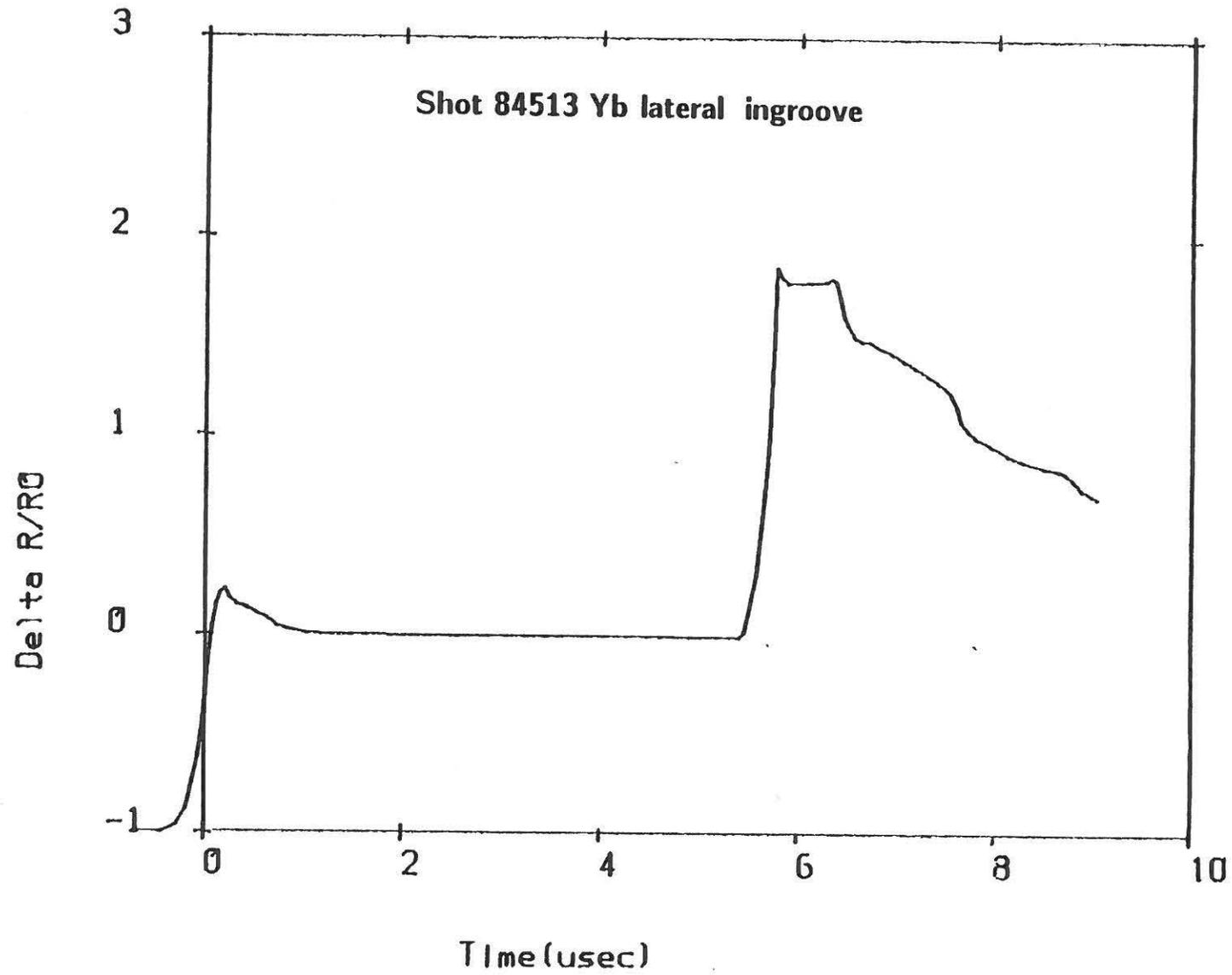
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Projectile velocity: 0.601 mm/us  
Shock stress: 21.6 kbar  
Matrix material: PMMA  
Impactor material: VISTAL  
Impactor thickness : 6 mm



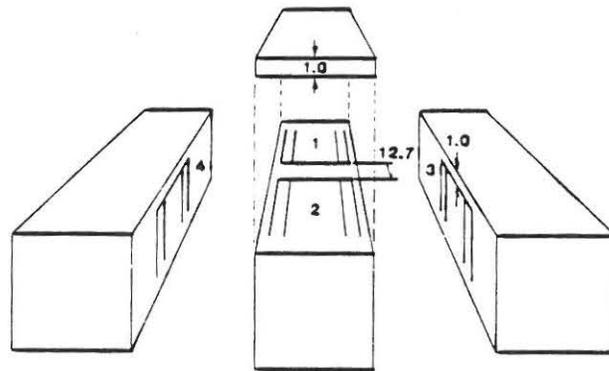




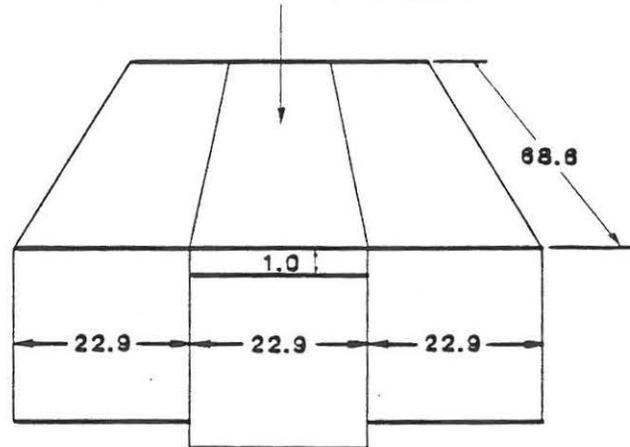


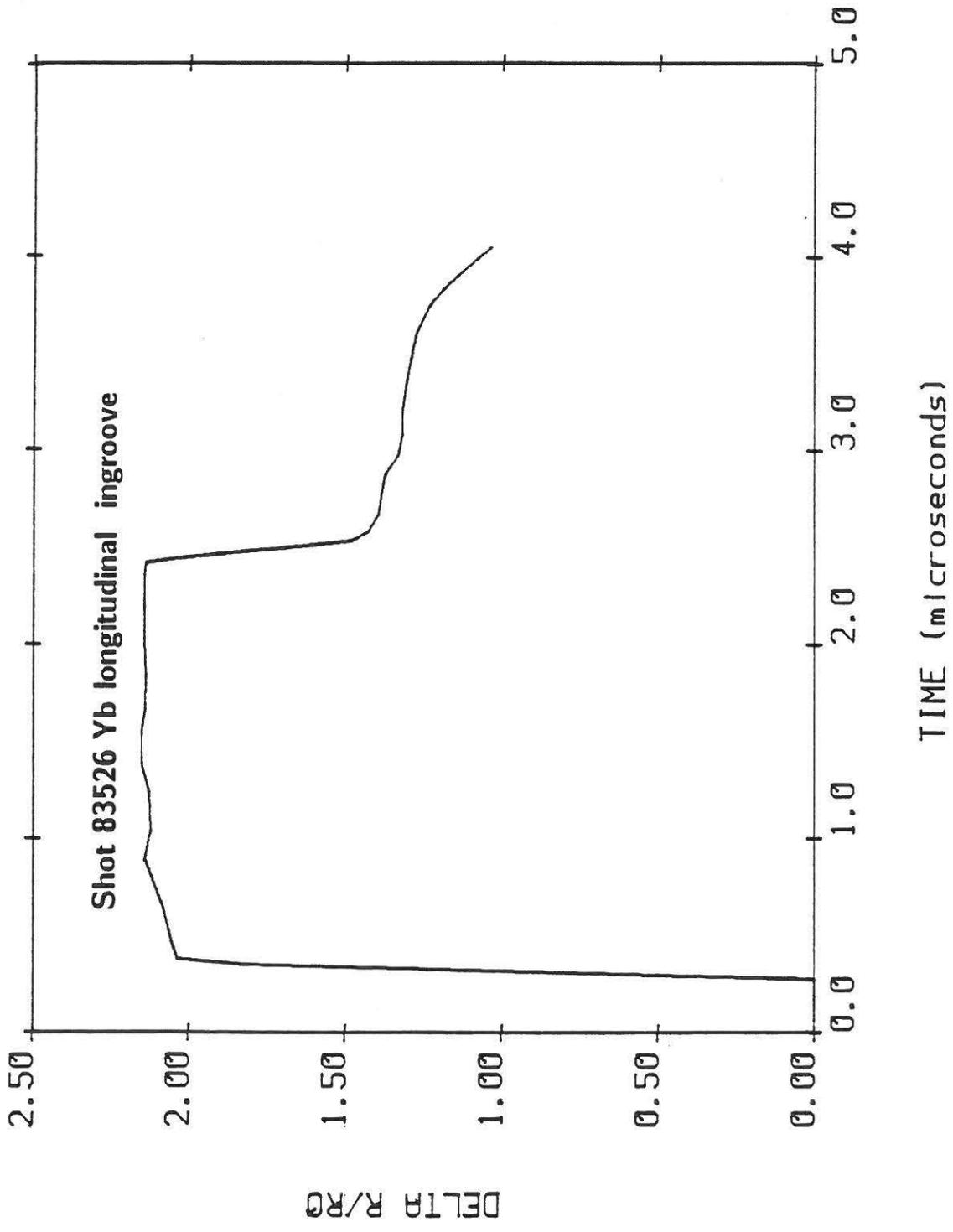
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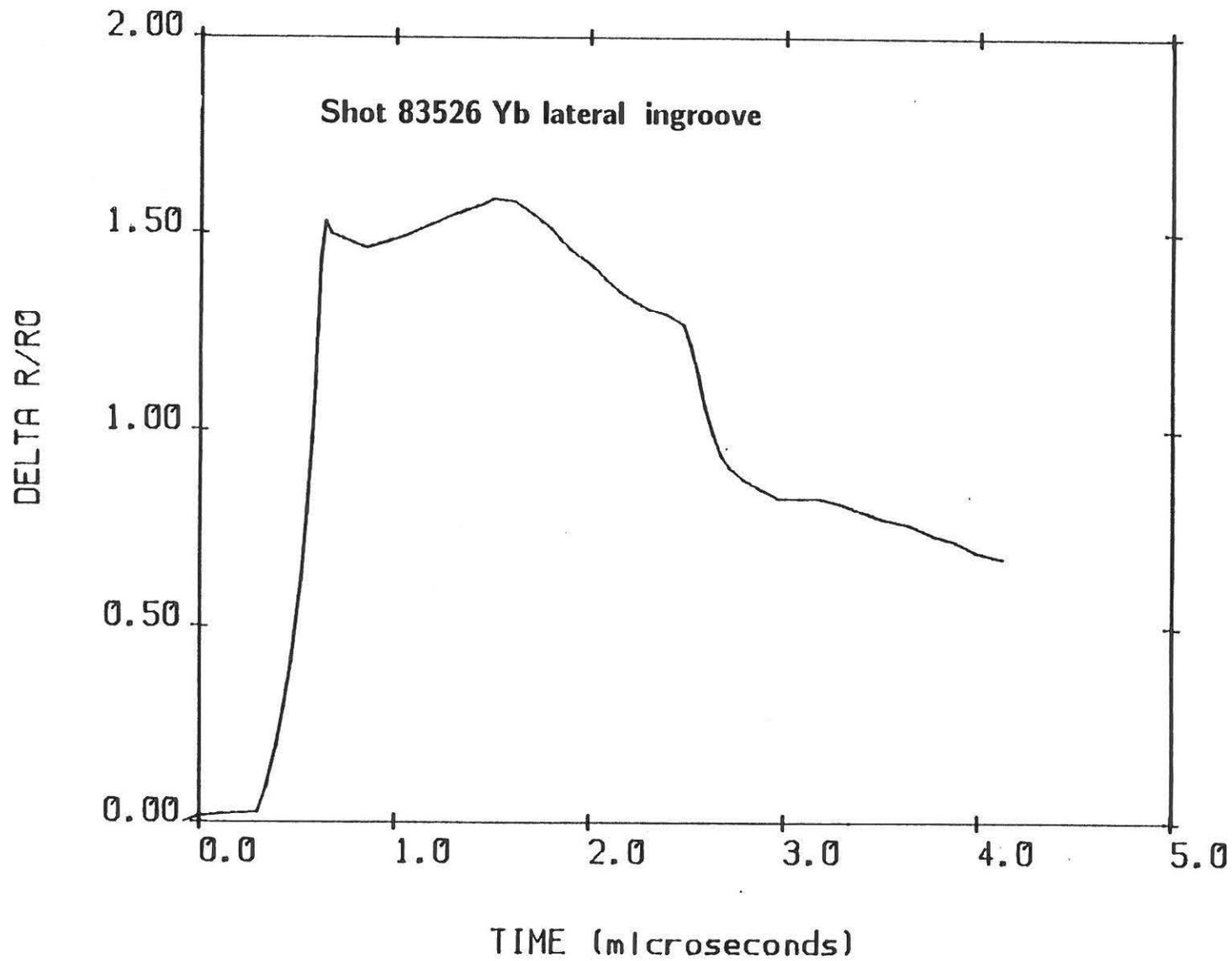
Projectile velocity: 0.605 mm/us  
Shock stress: 18.4 kbar  
Matrix material: PMMA  
Impactor material: Fused silica  
Impactor thickness : 6.35 mm

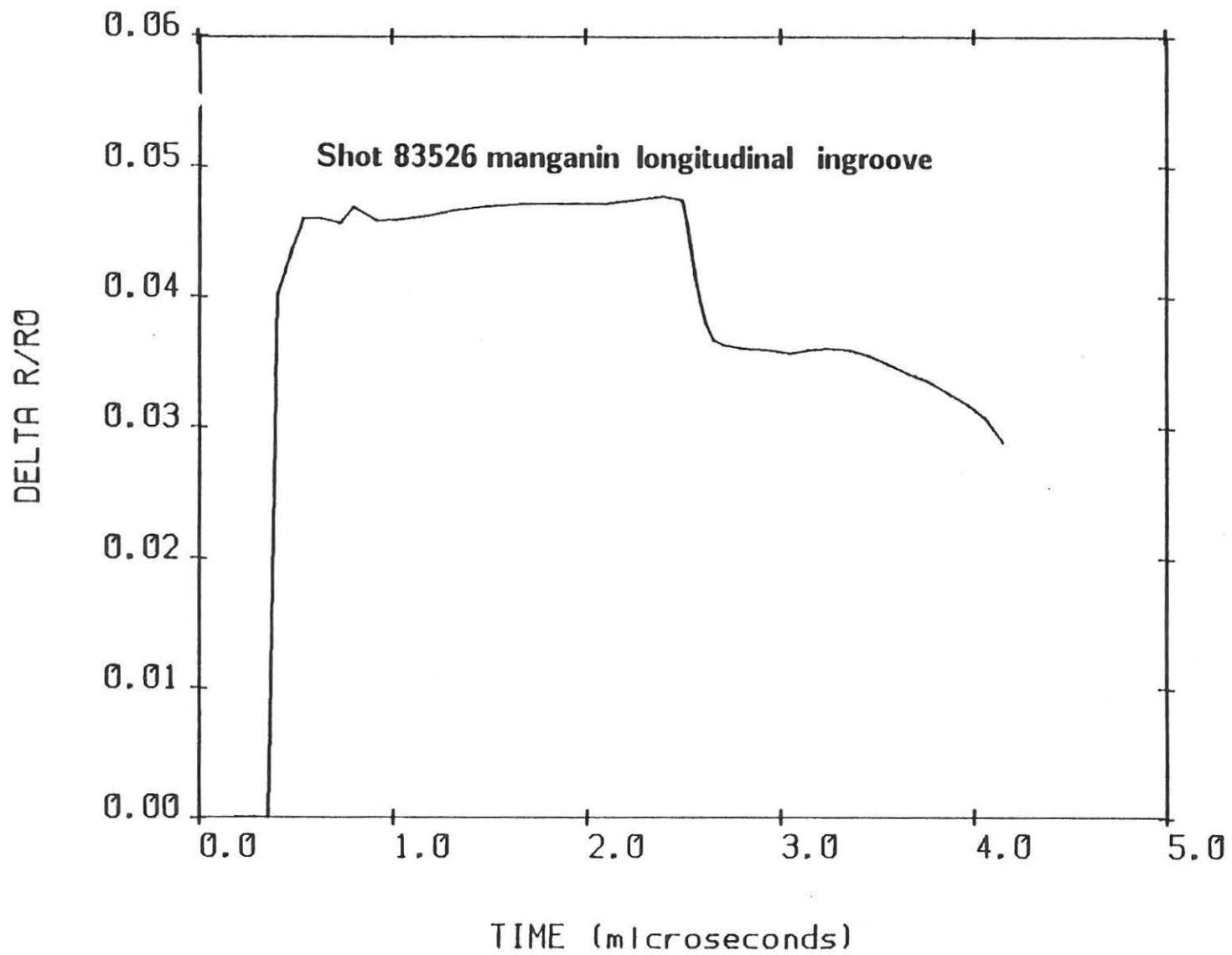


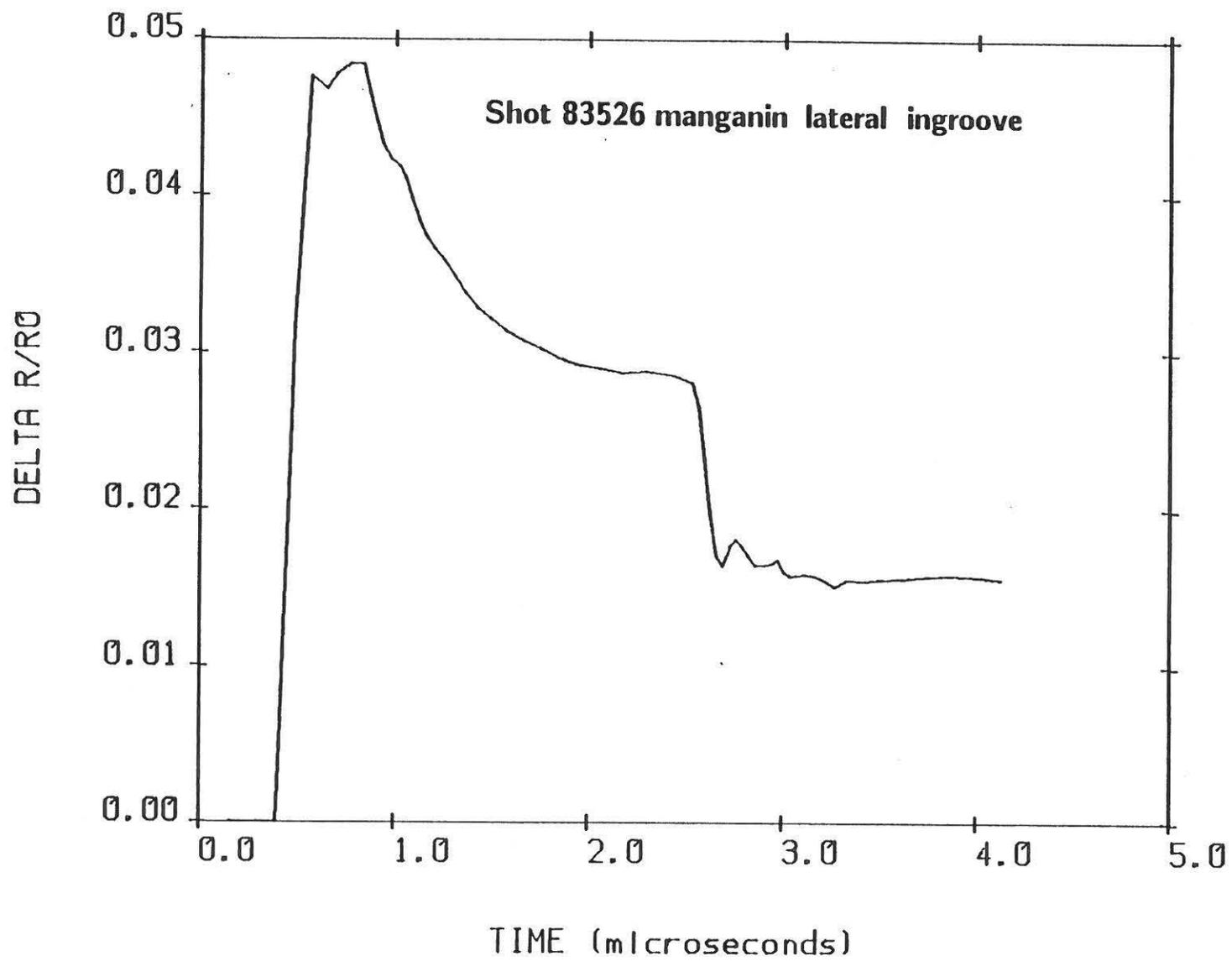
Direction of shock propagation





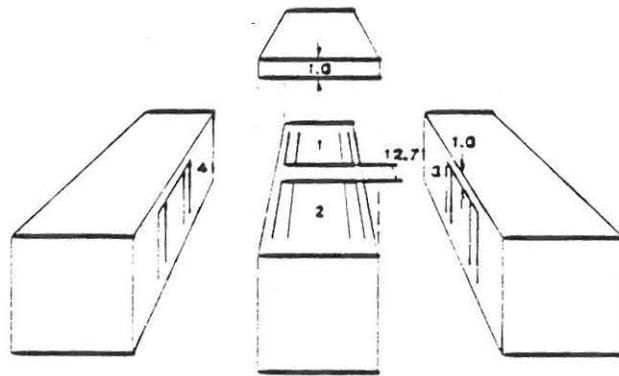




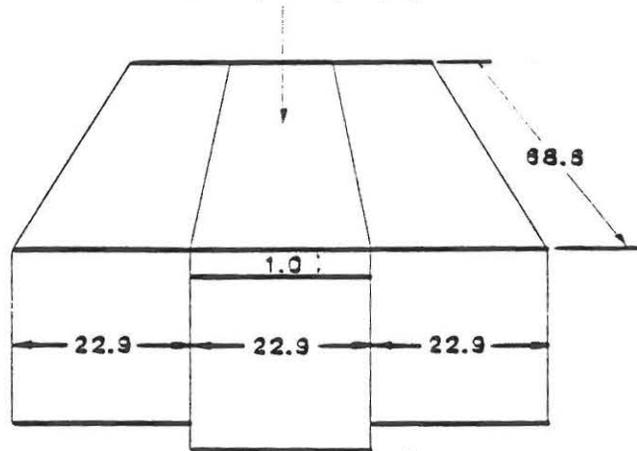


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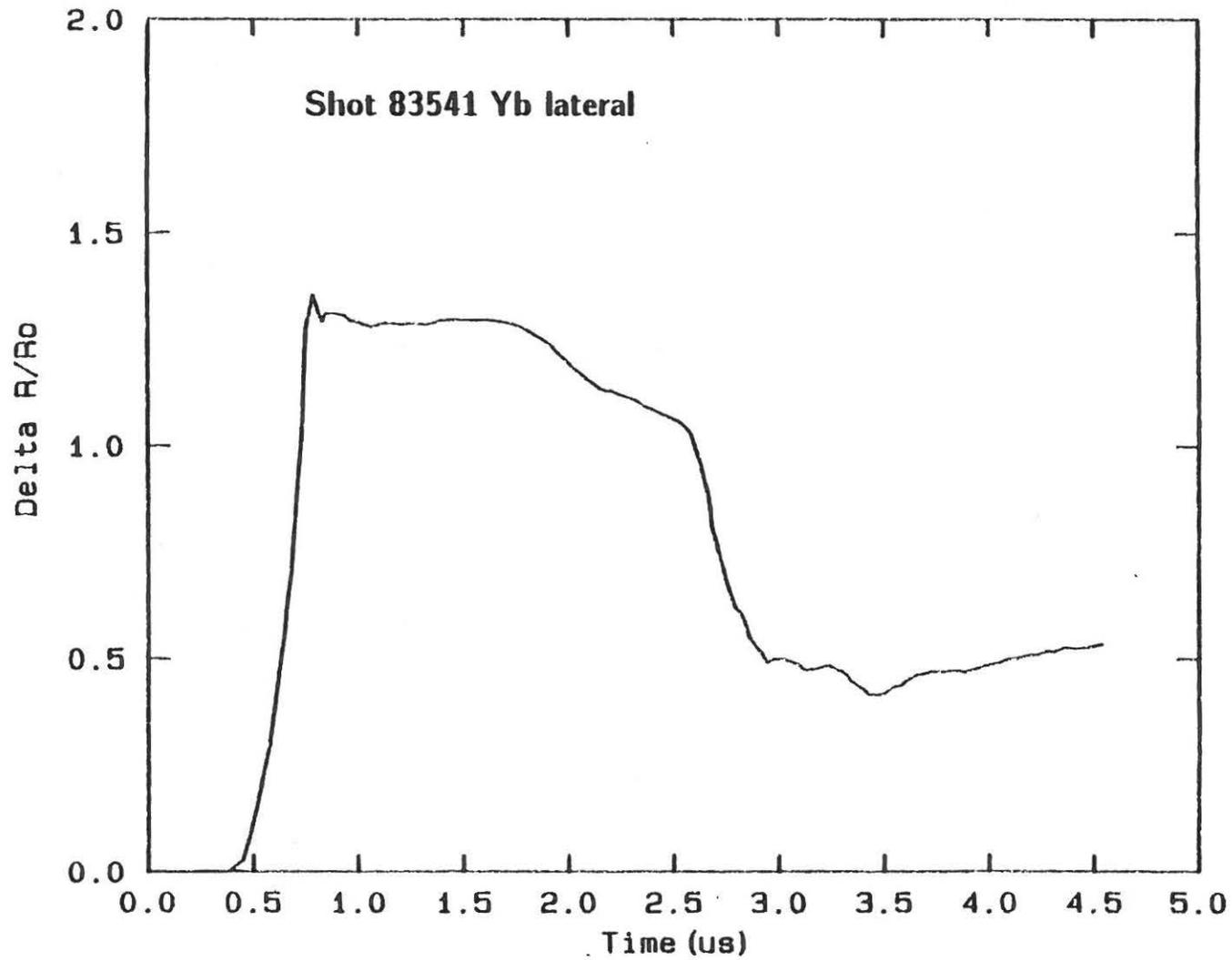
Projectile velocity: 0.606 mm/us  
Shock stress: 18.4 kbar  
Matrix material: PMMA  
Impactor material: Fused silica  
Impactor thickness : 6.35 mm

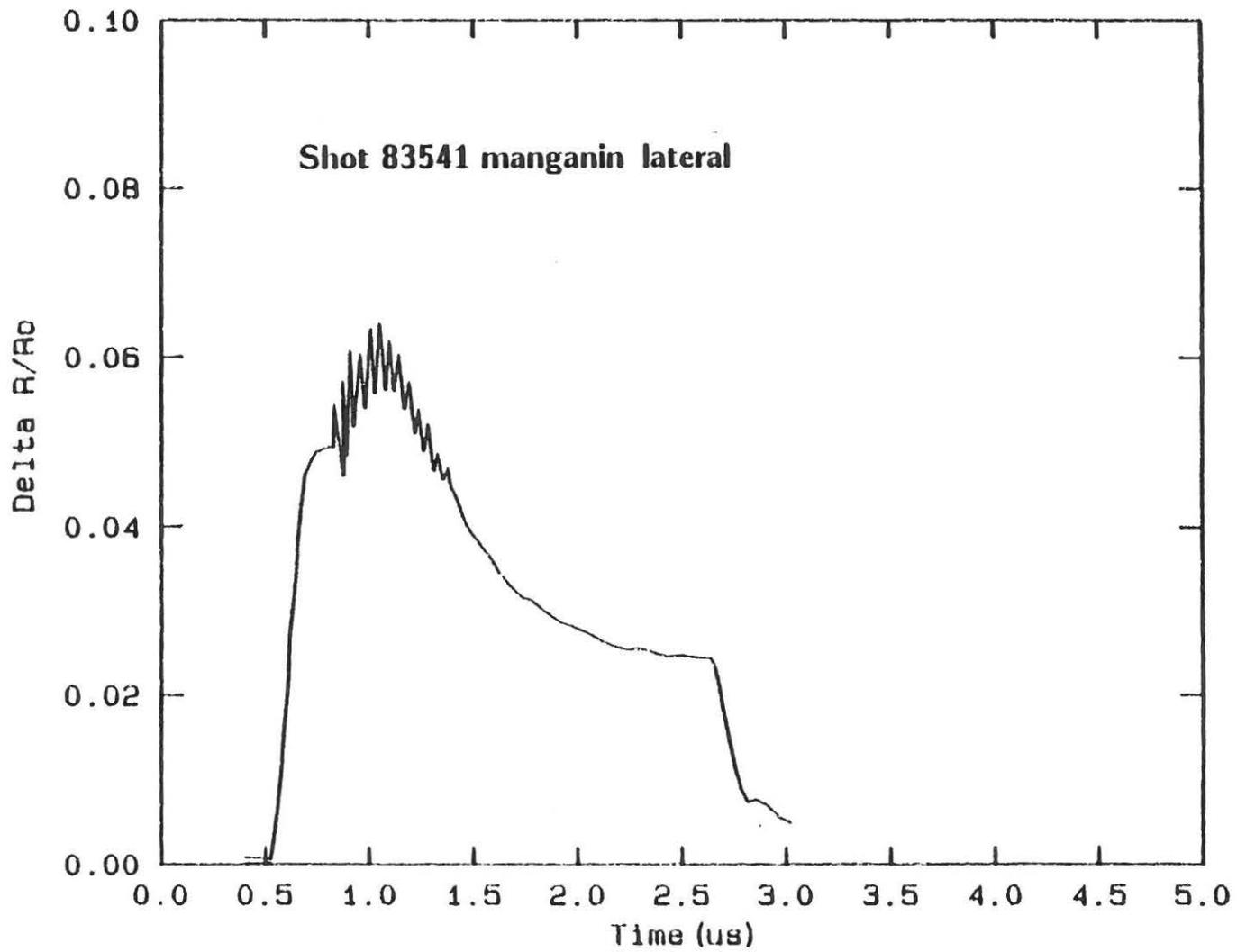


Direction of shock propagation



*longitudinal gauges were not present in this experiment.*





## APPENDIX B

In this appendix we have given the properties of the materials used in our experiments. In Section B.1 we define the electromechanical constants of piezoresistance gauges. In Section B.2 we give the constants for ytterbium and manganin and in Section B.3 the material properties of  $\text{Al}_2\text{O}_3$  (Vistal) and PMMA.

### B.1. Definition of the Electromechanical Constants

The constants  $\pi_{11}$ ,  $\pi_{12}$ , and  $\eta$  for a piezoresistance gauge are defined by the resistance change equation.

$$\frac{\Delta R_3}{R_0} = \pi_{12}(\sigma_1 + \sigma_2) + \pi_{11}\sigma_3 - \varepsilon_1 - \varepsilon_2 + \varepsilon_3 + \eta\gamma_p$$

where  $\sigma$  and  $\varepsilon$  are the stresses and strains in the gauge element and are considered positive in tension. The gauge length is along the 3-direction, gauge thickness along the 2-direction, and width along the 1-direction.

$\gamma_p$  is a measure of plastic deformation in the element\* and is obtained by summing the increments

$$\gamma_p = \int d\gamma_p = \int \sqrt{\frac{1}{6} [(d\varepsilon_1^p - d\varepsilon_2^p)^2 + (d\varepsilon_2^p - d\varepsilon_3^p)^2 + (d\varepsilon_3^p - d\varepsilon_1^p)^2]}$$

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$$*\gamma_p \text{ is } \sqrt{I_2^p} \text{ and for proportional loading } \Delta\sqrt{I_2^p} = \sqrt{\Delta I_2^p}.$$

## B.2. Material Properties of Ytterbium and Manganin Foils

Property	Ytterbium	Manganin	Remarks
Density	6.98 g/cm <sup>3</sup>	8.41 g/cm <sup>3</sup>	
Mean pressure relation	$P = 148 \mu$	$P = 1160 \mu + 4120 \mu^2$	$\mu = \frac{\rho - \rho_0}{\rho_0}$ ; P is in kbar and is positive in compression.
Shear modulus	43.9 kbar	318.7 kbar	
$Y_0$	0.29 kbar	1.33 kbar	Yield curve is $\sqrt{J_2^T} - Y_0 - M\gamma_p = 0$ where $\sqrt{J_2^T}$ is in kb. $\gamma_p$ defined in Sec. B.
M	3.04	16.5	
$\pi_{11}$	$- 0.042 - 0.0008 P$	$- 1.06 \times 10^{-3}$	P in kbar $\pi_{11}, \pi_{12}, \eta$ are defined in Sec. B.1.
$\pi_{12}$	$- 0.00788 - 0.0008 P$	$- 0.44 \times 10^{-3}$	
$\eta$	see fig. b.1	see fig. b.2	

The work-hardening coefficients M was derived from data that extended to a few percent strain. The validity of the M value to 20-30 percent strain is certainly questionable. P is the pressure and is taken to be positive in compression ( $P \equiv -\sigma_{mm}/3$ ).

### B.3. Matrix Properties

- i) The  $\text{Al}_2\text{O}_3$  is considered as a linear elastic material with the following material properties:

$$\text{Density } (\rho_0) = 3.965 \text{ g/cm}^3$$

$$\text{Bulk Modulus} = 2470 \text{ kbar}$$

$$\text{Shear Modulus} = 1600 \text{ kbar}$$

- ii) PMMA is treated as an elastic-plastic material with the pressure-volumetric strain given by (also see Fig. b.3)

$\mu = \rho/\rho_0 - 1$	$P \equiv -\sigma_{\text{mm}}/3 \text{ (kbar)}$	$-\sigma_1$
0.0125	0.857	1.25 kb
0.018	1.277	1.85
0.0345	2.427	3.60
0.05	3.60	5.40
0.06	4.30	6.50
0.067	4.88	7.40
0.072	5.33	8.0
0.078	5.83	8.50
0.101	7.93	10.6
0.141	12.43	15.1
0.166	15.68	18.35

$$\text{Initial Density } (\rho_0) = 1.185 \text{ gm/cc}$$

$$\text{Shear Modulus} = 22.5 \text{ kbar}$$

$$\text{Yield Strength (in terms of } \sqrt{J_2}') = 2.3 \text{ kbar}$$

Note, the P values shown above are those that give the  $-\sigma_1$  values presented in Barker and Hollenbach's paper. We also make the assumption of plastic incompressibility and no work-hardening.

Although the model of PMMA considered here is artificial, it should provide a good approximation for carrying out numerical calculations. Higher pressure values can be obtained by extrapolating the curves corresponding to the above values.

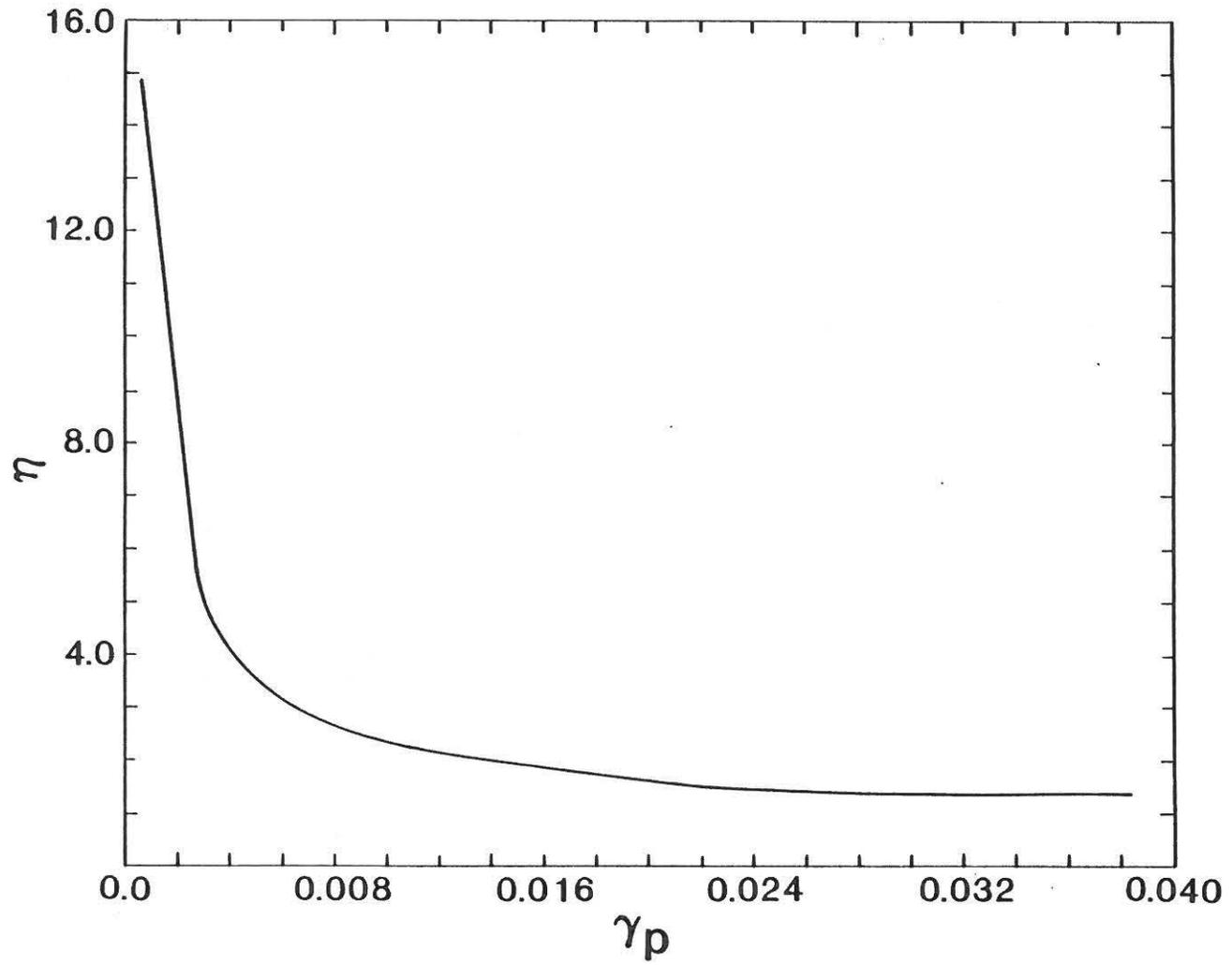


Fig b.1. value of  $\eta$  as a function of  $\gamma_p$  for yttrium foils.

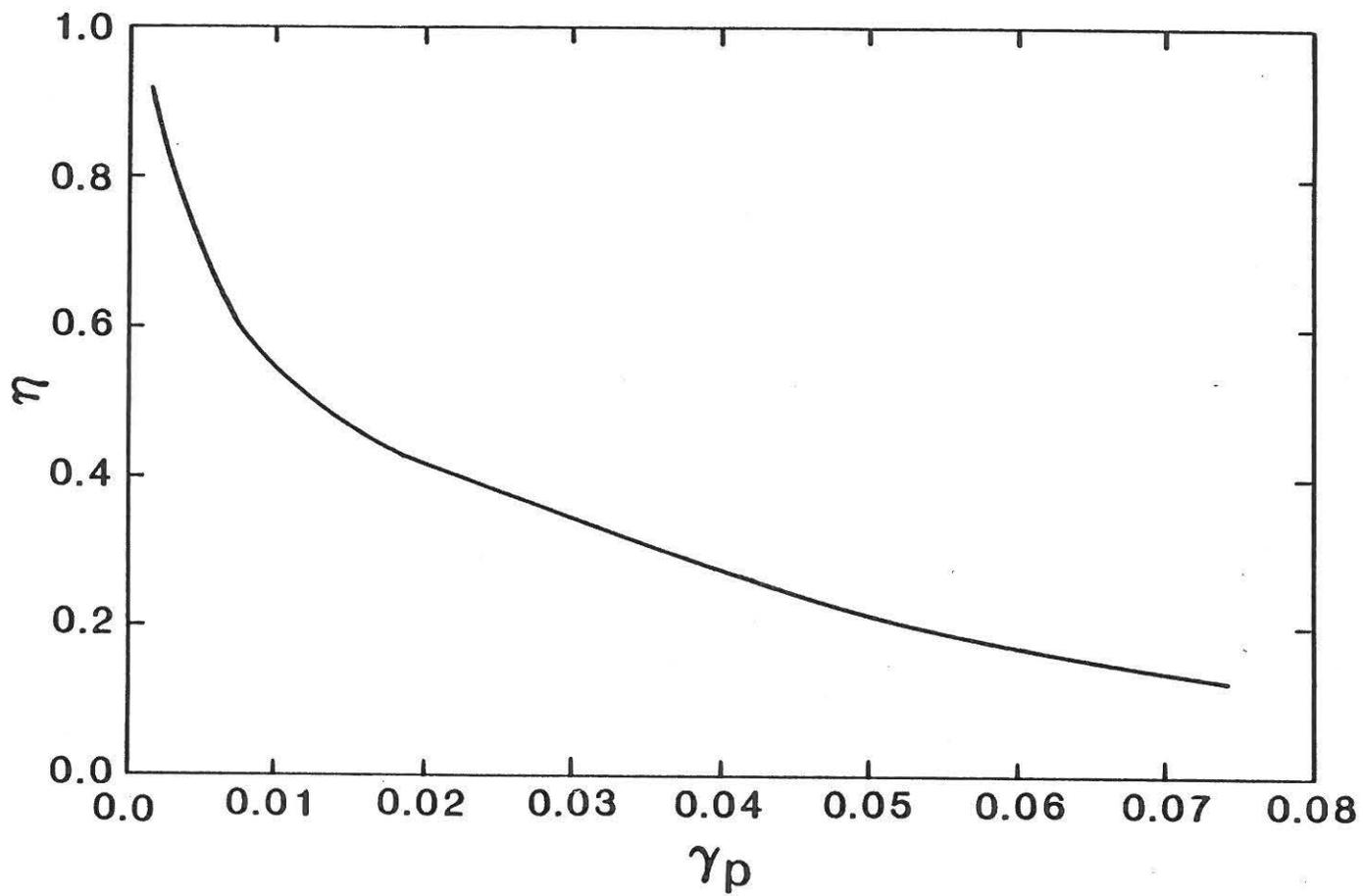


Fig b.2. value of  $\eta$  as a function of  $\gamma_p$  for manganese foils.

mean stress vs. strain for pmma

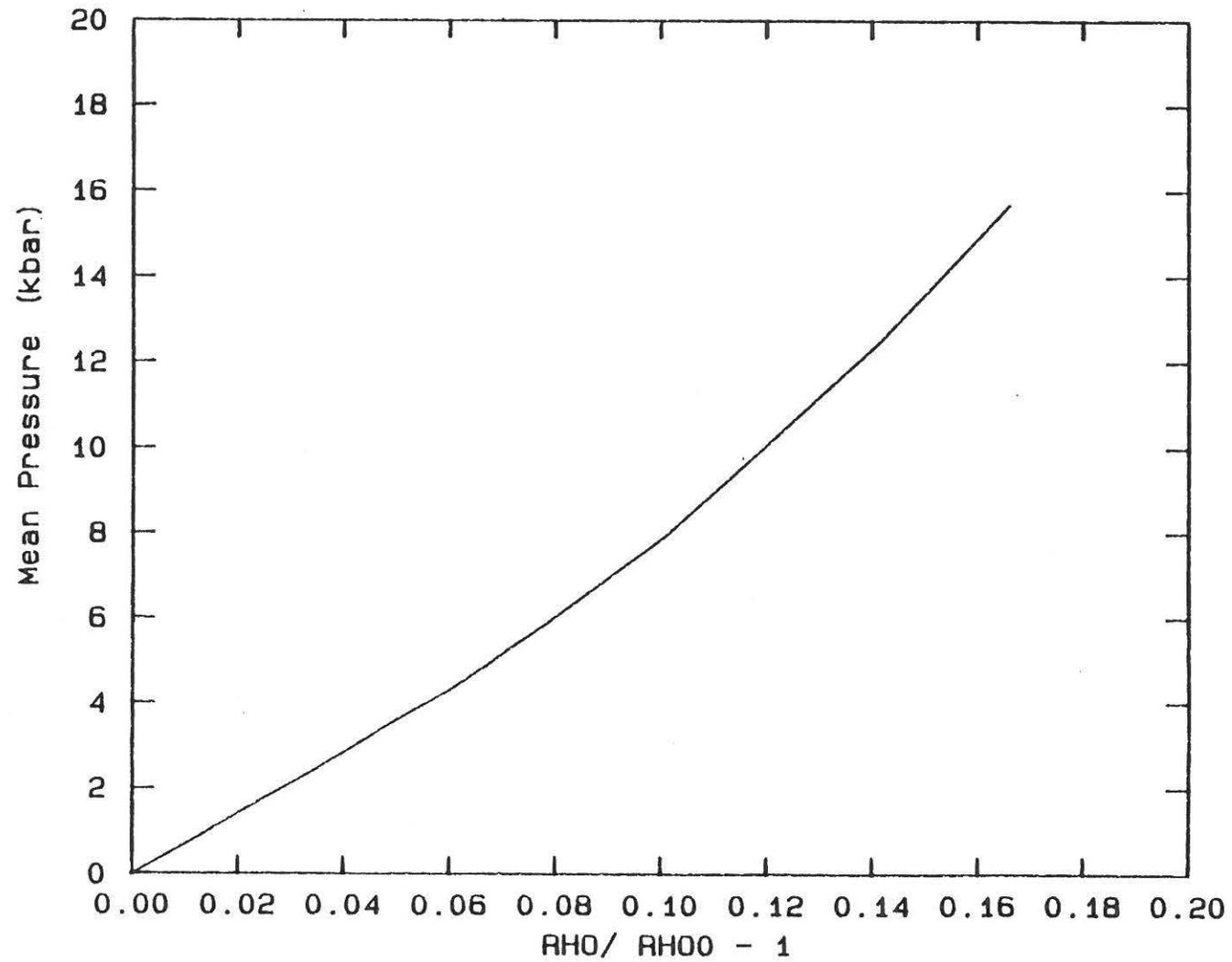


Fig b.3 Mean stress versus strain for PMMA