SAND--77-0199C
CONF-770397--1

# TECHNIQUE FOR MEASUREMENTS OF PLANE WAVES OF UNIAXIAL STRAIN

R. A. Graham
Sandia Laboratories, Albuquerque, New Mexico 87185

Edited transcript of an invited presentation at

The Workshop on Nonlinear Waves,

Sponsored by NSF and the University of Illinois, Chicago Circle.

March 21-23, 1977

To be published in

Proceedings, Workshop on Nonlinear Waves

GENERAL LECTURE III

Speaker: R. A. Graham
Session Chairman: J. R. Asay

## Techniques for Measurements of Plane Waves of Uniaxial Strain

Graham: I was asked to speak generally in the area of experimental aspects of nonlinear waves in solids. What I have put together is a look at the extent to which our knowledge of nonlinear waves in solids depends upon the characteristics of our measuring devices. I want to try to identify and quantify some of the most critical of these characteristics and then provide some quantitative evaluation of many of these detectors. It seems particularly appropriate at this conference to consider the characteristics of these detectors, since this has been an area which has remained vital, changed rapidly, and played a leading role in the directions that research has taken. The field continues to change very rapidly, but I think that at this time we can stop, look back into the past, and develop some perspective from the trends which we have seen affect us; hopefully, we will obtain some insights into the future.

Because of the time restrictions and because of my own background, I want to restrict the talk. First of all, I would like to talk only about measurement of plane waves in uniaxial strain--that is experiments in which large surface areas are loaded and the measurements are restricted to a central region that is not influenced by lateral boundaries. I will not consider the important area of loading methods, nor will I say much about the so-called in-situ pressure measurements in which the measurement is taken in the bulk of the solid. Dick Fowles will consider those areas in his talk.

Furthermore, I am only going to consider devices which actually provide a measurement of the wave profile--there are other important methods of probing the material properties but I want to concentrate on wave profile measurements.

Furthermore, there are some very important new developments in transverse motion measurements. This work is very new, and the people who are working in this area are here--Rod Clifton, Dick Fowles and Yogi Gupta. I hope that some time during the conference they will stand up and say a few words about these important measurements. For those of you who would like to do background reading on characteristics of instrumentation please see the reference list. The article by Jim Asay and I gives a comprehensive compilation of detectors and contains over 200 references. Previous reviews of technique include Fowles, 1972; Jones, et al., 1970; Karnes, 1968; McQueen, 1964; Doran, 1963; Duvall and Fowles, 1963; and Deal, 1962.

Before I move into the body of the talk, I'd like to bring the importance of our measurement techniques into perspective. To do that I would like you all to think for a moment about the images we have in our minds of waves propagating due to rapid impulsive loading and to emphasize that these images are influenced by experiment I'd like for you to think how much you would know strictly from your own human senses. I think it's clear that we would know very little about such high pressure events that persist for only a few nanoseconds or microseconds; hence, we are totally dependent on the images obtained from the various sensors that have been developed. We are going to obtain a clear view or a cloudy view, depending on the characteristics of these sensors.

The main question I would like to raise is, "does it matter which tool we use?" To answer that question we are going to have to be concerned with what tools are available, what characteristics they have, and how well their characteristics match those of the wave profiles that we are trying to measure. I will spend the bulk of the time developing data in this area. I would like to comment also on whether the characteristics of sensors appear to be sufficiently well known--calling attention to areas where our understanding is deficient. And finally, I think attention should be given to how well these experimental capabilities match our theoretical and numerical capabilities.

A road map of what will follow from here is the following: The bulk of the talk will be on the measurement of wave profiles. We will then skip to a new area--the first direct measurements of acceleration wave profiles. Toward the end of the talk I would like to answer some of the questions raised in the beginning.

Table I lists most of the detectors that have been widely used and summarizes the characteristics of these detectors. There are many reasons why experimentalists choose to perform an experiment using a particular detector. Many of these decisions are made objectively; others are made subjectively. We cannot quantify these decisions. But, we can begin to make quantitative comparisons once the experiment is done and we are faced with the interpretation of the data.

I find it helpful to break the various measuring instruments into two main categories: those that provide a measurement of the displacement as a function of time, and those that provide a measurement of the velocity or stress as a function of time. On the left in Table I are the years in which a particular device was first placed into significant service. Under the displacement-time measurements we can make a further breakdown into

TABLE I

DATES OF DEVELOPMENT OF DETECTORS
(Starred detectors are those most widely used today.)

| | Displacement vs. Time | | Velocity or Stress-Time |
|---|---|---|---|
| | Discrete | Continuous | |
| 1945 | pins | --- | --- |
| ~ | ~ | ~ | ~ |
| 1955 | flash gap | --- | --- |
| 1956 | --- | --- | --- |
| 1957 | pins | capacitor | --- |
| 1958 | --- | --- | --- |
| 1959 | --- | --- | --- |
| 1960 | --- | --- | *electromagnetic velocity capacitor |
| 1961 | --- | optical image | *quartz piezoelectric |
| 1962 | --- | --- | *Manganin piezoresistance |
| 1963 | --- | inclined mirror | optical lever |
| 1964 | pins | inclined resistor inclined prism | --- |
| 1965 | pins | displacement interferometer | --- |
| 1966 | --- | --- | --- |
| 1967 | --- | --- | velocity interferometer |
| 1968 | pins | --- | sapphire solid dielectric |
| 1969 | --- | --- | --- |
| 1970 | --- | electromagnetic stress integral | --- |
| 1971 | pins | --- | --- |
| 1972 | --- | --- | *VISAR |
| 1973 | --- | --- | $LiNbO_3$ piezoelectric axisymmetric magnetic |
| 1974 | --- | --- | --- |
| 1975 | --- | --- | --- |
| 1976 | pins | --- | --- |

discrete devices (a collection of them would provide us with points on the displacement-time history over a period of time) and into devices which provide continuous displacement time measurements. I think that it is particularly revealing to look historically at the trends that have developed as people have tried to obtain a picture of the world of very short duration, high stress events. This table shows people voting with their feet, so to speak, and some very interesting trends appear. The first measurements provided a discrete measurement of displacement vs. time. The devices used are pins that give an electrical signal when a specified displacement occurs. There are almost as many different types of pins as there are experimentalists. They continue to be developed to the present time. There are various self-generating pins, pins with different insulators, etc. Another discrete measurement technique is the flash gap technique, which is one of the oldest and most widely used techniques to obtain very high pressure equation of state data. This is a technique in which the fact that argon gas emits light when it is highly shocked is used to record gap closure times on film.

As noted in Table I, beginning in the early sixties, we began to see a whole range of developments for continuous displacement measurements and direct measurements of particle velocity or stress. We won't have time to describe how they all work. Those devices which are optical and write directly on film at high speeds are: the optical image, the inclined mirror, the inclined prism, and the optical lever devices. Those devices that are optical interferometers which convert the motion to an electrical signal are: the displacement interferometer, the velocity interferometer and the VISAR, which is a vastly improved interferometer technique that provides direct measurement of particle velocity. The electrical devices are: the displacement capacitor, the inclined resistance wire, the electromagnetic gauge, the electromagnetic velocity gauge, the velocity capacitor, the quartz piezoelectric gauge, the Manganin gauge, the sapphire solid dielectric gauge, the lithium niobate piezoelectric gauge and the axially symmetric gauge.

Following the early 1960s we began to develop many of these devices. Notice, however, that since 1965, almost 12 years ago, with one minor exception, we have not continued to develop the displacement devices. It's clear that preference has been given to the development of devices that provide direct measurements of particle velocity or stress. I think it's clear why this is so--any displacement device produces data that must be differentiated before the wave profiles of primary interest are obtained. Of course, data is taken directly as particle velocity or stress does not require differentiation in most applications.

Well, that is a fast look at the historical development! Now I would like to show a few measurements so that you can see why these trends have developed. I have collected a number of wave-profile measurements in which the same profile has been measured with a variety of techniques. I hope that these illustrations will give a feel for the capabilities of the various devices. In these experiments an impulsive loading is applied to a plane surface and then after some propagation distance, the free surface displacement or velocity or the interface velocity or stress is measured. The variables are typically the magnitude of the input stress and the propagation distance. I have been able to collect quite a number of different measurements. I will not be able to show you all of them, but I would like to indicate which measurements I have had available for examination.

The elastic wave in 4340 steel is particularly interesting for comparison purposes because the step profile places minimum demands on the instrumentation and measurements with six different techniques are available. The other measurements we have include elastic wave profiles in Armco iron. This is a particularly interesting situation. The profile has considerably more detail than the profile in 4340 steel; some interesting evolutionary behavior is going on. We also have wave profiles in 1060 aluminum that exhibit considerable detail. These measurements of Karnes are particularly interesting in that there are two almost identical experiments except that in one case a free surface measurement is made, whereas in the other case a quartz gauge measurement is made. Since the impedance of quartz matches that of aluminum very closely, the measurement is very close to an in-situ stress measurement. Other measurements which I have looked at, and I won't be able to show all these to you, include Karnes' measurements of elastic wave profiles in tungsten carbide using four different techniques. We also have Grady's measurements of elastic wave profiles in (100) directions in MgO, using three different techniques.

## Wave Profiles in 4340 Steel

Figure 1 shows the elastic wave profile for 4340 steel obtained by Minshall using a displacement capacitor. These timing marks are 100 nanoseconds apart; the voltage change is a measure of the displacement of the free surface. Differentiation of the trace shows an approximately constant velocity at early times--this is the elastic wave--followed by a transition region and a final plastic wave amplitude which is also constant.

Fig. 1

Figure 2 shows the same profile measured with a quartz gauge. In this case one obtains a direct measurement of interfacial stress as a function of time; the timing marks at the bottom are 40 ns apart. This figure shows a fast rising wave followed by a short period of constant stress and then a continuous increase through the plastic wave. Note the small, but definite change in stress approximately 640 ns after the arrival of the elastic wave. This change indicates the arrival of the elastic wave which has been reflected from the interface back into the sample, has interacted with the oncoming plastic wave and returned again to the detector.

Fig. 2

Figure 3 shows the measurement of the same profile with a velocity interferometer; the time works are 200 ns apart. Each fringe (i.e. peak-peak variation in amplitude) corresponds to a known change in particle velocity. Early in time there is a burst of fringes corresponding to the arrival of the elastic wave. There is then a slow increase in velocity with time followed by the main plastic wave. Again one can see the elastic wave reflected from the free surface and the incident plastic wave.

Fig. 3

Figure 4 shows an enlarged view of the velocity interferometer early time region of Fig. 3; the timing marks are again 200 ns apart. This figure shows a sharp burst of three fringes at the elastic wavefront.

Fig. 4

The wave profile at the back of a much thinner sample of 4340 steel is shown in Fig. 5. This wave profile was recorded with a sapphire gauge; the timing marks are 25 ns apart. Note that there is no evidence of a reflected wave in this case. This is because the acoustic impedance of sapphire matches that of the 4340 steel very well. Thus, the recorded stress profile is very close to the in-situ stress profile.

Fig. 5

Figure 6 shows some reduced data from the preceding figures. From Minshall's displacement capacitor measurements the solid line is the recorded displacement, in millimeters, as a function of time. The filled circles represent digitized data taken from the record. The open squares are pin data taken in a virtually identical experiment. The inset on the upper left is the velocity-time profile derived by numerical differentiation of the digitized data. Now it is clear that differentiation gives some indication of change in velocity which in this case is thought to experimental error. Minshall selected the value of 0.097 km/s for the magnitude of the elastic wave free surface velocity and noted that, as far as he could tell, the velocity was constant during the first 400 ns. Now if we attempted to differentiate the pin data in the same way we would find large scatter in the computed velocities. Of course, that is not what was done. Instead some smooth function is fit to the data and velocity is derived for the smooth function. However, when you choose such a function, you are essentially choosing the form of the velocity vs. time profile.

Figure 7 shows a similar profile obtained from a velocity interferometer record. In this case we have direct measurement of velocity as a function of time. The values derived from Minshall's experiment are also shown in this figure. The velocity interferometer data show a very rapid increase in the particle velocity at the wavefront, a constant interval for approximately 100 ns, an increase through the plastic wave and a late time plateau. Again I would like to call your attention to the reflected elastic wave. The recording of this reflection is a very good indication of the time resolution and sensitivity of devices.

Fig. 6

Fig. 7

## Wave Profiles in Armco Iron

I would now like to turn our attention to some wave profiles in Armco iron. Figure 8 shows the oscilloscope trace from the velocity capacitor gauge used by Taylor and Rice. The timing marks are at one microsecond intervals. Figure 8 shows a fairly slowly rising elastic wave, followed by a reversal in acceleration corresponding to a decrease in velocity. Again, the reflected elastic wave is shown clearly. At late times the nonlinear gauge response which is taken out by the data reduction is evident.

Fig. 8

Figure 9 shows a similar wave profile measured with a quartz gauge. This is one of Benedick's measurements. The timing marks are 40 ns apart. I want to call your attention to the detailed structure of the reflected wave. This structure presumably is evidence of interesting rate dependent behavior which, as far as I know, has never been fully described.

**Fig. 9**

Figure 10 shows an oscilloscope trace of a similar wave profile in Armco iron recorded by Barker with a VISAR. The fringe count is again proportional to the particle velocity. The small timing intervals are 200 ns apart. Immediately following the arrival of the elastic wave there is a fringe reversal corresponding to a reduction in the particle velocity. The profile shows the reflected elastic wave, the main plastic wave, and a second wave corresponding to a phase transition.

Fig. 10

Figure 11 shows the reduced data from Barker's work on iron using the VISAR. Two velocity-time profiles are shown for two different thicknesses of Armco iron targets: the arrival times in the two cases are made the same in order to facilitate comparison. This figure shows very interesting phenomena with considerable detail. The profiles show finite risetime, a reversal of acceleration behind the elastic wavefront, and considerable detail in the reflected wave. And, as the wave propagates further, one sees an evolutionary behavior that includes decreases in accelerations (both in the risetime of the elastic precursor and following the elastic precursor) and a decrease in the amplitude of the reflected elastic wave. Before setting out to examine this evolutionary behavior in too much detail one should keep in mind that other records in this same series show substantial variations. This is presumably due to the fact that the velocity interferometer records the motion of an area on the surface that is small compared to the grain size. As a result the measured wave profile may depend on the particular location for which the motion is being recorded.

Wave Profiles in MgO

Figure 12 shows the measurements of wave profiles in MgO by Dennis Grady using a VISAR to obtain velocity-time profiles. For three different input levels the amplitude of the elastic precursor is shown to decrease with decreasing impact velocity. Figure 12 shows in considerable detail the very fast relaxation behind the precursor, the dependence of the valley behind the precursor on driving stress, and the unloading from the high pressure state.

Fig. 11

Fig. 12

Figure 13 shows wave profiles in MgO under similar loading conditions but recorded with the Manganin gauge and the quartz gauge. The timing marks are 200 nanoseconds apart in each case. The quartz gauge follows the detail of the rise and relaxation of the precursor very well, whereas these details are not followed so faithfully by the Manganin gauge. Now to a certain extent this is an unfair comparison with Manganin gauges because electrical signals are self-generated in this material and it was necessary to use a gauge about twice as thick as one would ordinarily use in order to obtain the required sensitivity. Nevertheless, I think that it is clear that the Manganin gauge has a more limited capacity to follow the kind of detail shown in Fig. 13.

Wave Profiles in Tungsten Carbide (Measurements of Karnes)

Figure 14 is a quartz gauge record that shows the main features of wave profiles in a tungsten carbide, Kennametal 68. The profile consists of a sharp shock followed by a more slowly increasing stress or velocity.

Figure 15 shows the reduced data from the quartz gauge compared to the same measurement with a displacement interferometer. The same profile is shown as determined by the inclined resistance wire and velocity interferometer in Figure 16. This series of measurements permits us to give a fairly quantitative measure of the errors associated with time resolution for this particular wave profile. In this case the Hugoniot elastic limit determinations are: inclined resistance wire, 5.0 GPa; displacement interferometer, 4.0 GPa; quartz gauge, 3.65 GPa; and velocity interferometer, 3.49 GPa.

Fig. 13

Fig. 14

Fig. 15

Fig 16

I've tried to show what the different profiles look like when measured with different techniques. In so doing one raises questions about how to quantify the difference between the different techniques. It's clear that they have different capabilities for following wave details. I would like now to try to quantify that difference. I don't suggest that my definitions are unique. Instead, they should be viewed as one attempt to address the question.

Consider for a moment the problem of detecting a wave profile consisting of a shock wave followed by a state of constant velocity. Such a profile puts minimal requirements on the detector. If one is not concerned with details during the risetime all one has to do is measure the time at which the wave arrives, which is less difficult to follow than the velocity-time profile, and then accumulate sufficient data in time to determine the final velocity. These are the conditions under which the discrete displacement-time measuring devices have been used very effectively. For very high pressures, some excellent measurements have been made. The difficulty with these measurements is that they do not allow one to determine whether or not the particle velocity is constant; that is, the data used to compute the velocity are not sufficiently accurate to allow further differencing to obtain the acceleration.

It seems to me that in characterizing detectors a critical measure of their capability for recording a wave profile is tested by a wave profile consisting of a sharp jump followed by a fast decay. This corresponds, for example, to determining their suitability for measuring wave profiles in MgO and LiF. I'd like to describe how well different detectors measure such wave profiles. If we had somehow measured response characteristics for these detectors, then there would be no problem. The difficulty is that these characteristics have not been measured. Under these conditions I find it helpful to consider the following kind of experiment. Assume that we have a machine that will somehow apply a step loading followed by decay at various rates. We can then generate a set of response functions for a given detector by applying a series of loadings, all with steps followed by exponential decay at different rates. For example, Fig. 17 illustrates such a set of response functions. Since we do not have such a loading machine and have to estimate responses from known physical characteristics of our detectors and from measurements of wave profiles in the literature, it is sufficient for our present purposes to characterize our detector resolution in terms of its capabilities to determine the peak input stress to an accuracy of 3 to 5%. On this basis we call the time resolution the time at which the peak response of the detector equals 95 to 97% of the peak input. For a given detector this will be a unique value. I have compared the time resolution characteristics of various devices on the basis of their ability to follow the input curve--particularly the amplitude of the peak. The time resolution of a device will be characterized as the characteristic time of the sharpest decay for which the response curve lies within 3-5 percent of the input curve.

In order to estimate time resolutions I have gone through the literature and looked at the reported wave profiles, including those shown herein. I have, I believe, looked at almost all the measurements in the literature in trying to make this comparison. The results are shown in Table II. I expect they'll be subject to some opposition and refinement, but I don't believe the overall picture will change a great deal. I believe discrete

Fig. 17

displacement-time devices have a time resolution of no better than 200 ns. The continuous displacement-time devices have a time resolution of approximately 100 nanoseconds; the electromagnetic velocity gauge and the optical lever gauge have time resolution capabilities of 50-100 nanoseconds. Other time resolutions are: The Manganin, velocity capacitor, 25-50 nanoseconds; the displacement interferometer, 10-25 nanoseconds. Note that the latter is a real exception. In this case measurement of displacement provides better time resolution than some direct velocity measurements. This is because of the accuracy with which the displacement interferometer can measure displacement. A time resolution of approximately 1-5 nanoseconds is obtained for the piezoelectric gauge, the velocity interferometer, the VISAR, and the sapphire dielectric gauge.

This table indicates that over the past 15 or 20 years we have seen an improvement in time resolution of approximately two orders of magnitude. We have seen a distinct revolution take place in our capabilities of examining the details of wave profiles. These new capabilities have had a particularly pronounced effect on theory of dynamic plasticity, fracture and the kinetics of melt and polymorphic phase transitions. As far as I can tell, experiments can resolve detail not fully explained by theory. An exception to this situation in which the experiment leads the theory is in the characterization of material response in terms of higher-order motion--acceleration and jerk.

TABLE II

STRESS/VELOCITY TIME RESOLUTION
OF VARIOUS GROUPS OF DETECTORS

| Detectors | Resolution |
|---|---|
| Discrete Displacement-Time Detectors | ~ 200 ns |
| Continuous Displacement-Time Detectors | ~ 100 ns |
| Optical Lever, Electromagnetic Velocity Gauge | 50 - 100 ns |
| Manganin Gauge, Velocity Capacitor | 25 - 50 ns |
| Displacement Interferometer | 10 - 25 ns |
| Piezoelectric Current-Mode Gauge, Velocity Interferometer, VISAR, Sapphire Gauge | 1 - 5 ns |

Next, I'd like to describe some current work--the first direct measurements of accelerations associated with a wave profile. We have been able to accomplish these measurements rather easily. The particular device we've used has a number of interesting and convenient features. First of all, this device will measure the velocities and accelerations simultaneously without compromising either measurement. The active element for the device is the conventional current-mode piezoelectric gauge--quartz or lithium niobate. This device is used in a configuration which provides large signals, and easy variability of experimental parameters to cover acceleration measurements over approximately five orders of magnitude. The principle of the device is to directly obtain a finite difference measurement of $\frac{di}{dt}$, the rate of change of current in the gauge. From previous work we know that the current is proportional to the piezoelectric polarization. (This is correct to such a good approximation that deviations from proportionality are so small as to be negligible for applications considered here.) The governing equations are given below.

Let $\Delta$ be defined as the finite difference of current, i, with time, t. Then

$$\Delta \equiv \Delta i/\Delta t \approx \frac{di}{du}\frac{du}{dt} \quad , \tag{1}$$

where u is the particle velocity. From the linearized theory of a piezoelectric gauge, the current is related to properties and dimensions of the gauge by the relation

$$i = (AU/\ell)P = (AU/\ell)\left[e_{11}\frac{u}{U} + \frac{1}{2}b_{111}\left(\frac{u}{U}\right)^2\right] \quad , \tag{2}$$

where A and $\ell$ are the area and thickness of the gauge respectively, U is the wave speed in the gauge, P the piezoelectric polarization and $e_{11}$ and $b_{111}$ are the second- and third-order piezoelectric stress constants. Upon taking the derivative of Eq. 2 and substituting into Eq. 1, the desired relation between $\Delta$ and the acceleration, a, is

$$\frac{\ell\Delta}{A} = \left(e_{11} + \left(\frac{u}{U}\right)b_{111}\right)a \quad , \tag{3}$$

where $u = \int a dt$. Two special cases are of interest: if the strain is low, such as happens at the beginning of many acceleration wave pulses, or if the material is linearly piezoelectric so the third-order piezoelectric constant is zero, then the acceleration is proportional to the rate of change of current, with a proportionality constant that depends on geometric factors and the second-order piezoelectric constant. If the acceleration is constant, then the relation between acceleration and rate of change of current can be integrated explicitly to give a quadratic relationship. For arbitrarily shaped acceleration pulses, it is necessary to integrate Eq. 3 numerically to obtain the acceleration-time profile; however, this is not a serious inconvenience.

The configuration used in such measurements of acceleration waves is shown in Fig. 18. As in conventional quartz gauge applications, a low loss coaxial cable, suitably terminated, is connected to the electrode of the sensor. The current in this cable is directly proportional to the particle velocity at the specimen-gauge interface to a close approximation. In order to directly obtain the acceleration of the interface two additional cables are connected to the sensor electrode. These two cables differ in length by a pre-selected amount, resulting in a prescribed time difference between the delayed and direct signals. By using these two signals as inputs to a differential pre-amplifier one obtained directly a signal that is proportional to the rate of change of current. Combined, the conventional quartz gauge technique and the present extension of that technique provide for simultaneous measurement of particle velocity and acceleration.

An example of an experimental record using these combined techniques is shown in Fig. 19 for the case of the ramp-wave in fused silica. On the left is the output from the cable used for monitoring particle velocity. On the right is the world's first direct measurement of acceleration on this time scale. The rate of change of current is shown to rise, in a finite time, to a steady value which is the first value of acceleration; the rate of change of current then increases with time. The latter increase will be subsequently shown to be due to the nonlinearity associated with the third-order piezoelectric constant. The risetime of the ramp-wave in Fig. 19 is approximately 200 nanoseconds.

Fig. 18

Fig. 19

Comparison of measured accelerations in vitreous silica, such as those shown in Fig. 19, with accelerations deduced from measured velocities are shown in Fig. 20. The differences in acceleration are due to different distances of propagation. The early work of Barker was for fused quartz called GE 151; more recent work has been for Dynasil 1000. Data from these two materials are distinguished in Fig. 20 by means of different symbols. Accelerations obtained from Fig. 19, both by differentiation of the velocity-time profile and directly by monitoring the rate of change in current are compared in Fig. 20. Overall, the new technique appears to provide a reasonable measurement of acceleration. Problems associated with bonding the sensors to the specimens have been overcome and quite a number of direct measurements of acceleration have now been made. Reduction of the data to eliminate the nonlinearity associated with the term involving the third-order piezoelectric constant is shown in Fig. 21. The acceleration-time profile shown in Fig. 21 is for the same experiment reported in Fig. 19. Note that in Fig. 21 one has not only the initial value for acceleration, but also the world's first measurement of jerk--the derivative of acceleration--in this time regime. In this case the value of the jerk is zero; nevertheless, the experimental result gives some indication of how well the jerk could be measured. Thus, the extensions of the quartz gauge technique allow for the study of both acceleration and jerk. I believe that similar improvements in this area are necessary if we are to learn how to characterize material properties in terms of higher-order motional parameters.

In closing I would like to try to answer some of the questions that are posed in the Introduction.

Fig. 20

Fig. 21

Does it matter which experimental tool we use? I think I've shown that the detector characteristics vary quite widely. The time resolution of velocity or stress varies several orders of magnitude. With some exception, the detectors that provide the best time resolution have come from direct measurements of velocity or stress. Analogously, I believe that the best acceleration measurements will come from direct measurements of acceleration. I believe that the choice of detector used in studying materials is of critical importance. What we see depends on how we look! My own feeling is that many of the differences we discuss at meetings have less to do with different details of physics or mechanics than they do with different details which are available for study depending on the detectors that are used.

With regard to the deficient areas in detector development I raise the question of whether the response characteristics of currently used detectors are sufficiently well-known. Many of the detectors have been studied in considerable detail, whereas others have been examined in much less detail. Given the importance of detector response I believe that we need to spend more time on that aspect of our work. I can appreciate why more of this is not done. Most of us who are working with these devices feel that we are not in the business of developing detectors, but are interested in the phenomena we are trying to measure. Furthermore, it is more difficult to get financial support to study instrumentation than it is to take measurements. Thus, we often tend to be satisfied when our voltage signal appears on the oscilloscope, but this is really the first step. We need to be concerned about explicit characterization of the time resolution capability of the measuring system. As I was reading papers in preparation for this presentation I found that in most cases the time resolution of the measuring system is not addressed.

There are other deficiencies in our understanding of gauge responses. If we have a device which is going to be used in different configurations and/or in different host materials, and the theory says that the output should be independent of these configurations, then let's verify that this is indeed the case; if it is not let's understand why there are differences. In my view, it is more important to understand anomalies in gauge response than normal gauge response. What are the limiting conditions which, when exceeded, result in substantial changes in the response characteristics? I believe that we must understand in detail the physical mechanisms that lead to particular gauge responses. There are many examples where fairly small effects observed under well-controlled step loading conditions lead to quite substantial effects when extrapolated to other loading conditions.

A nagging question that has been around for a long time deals with the evaluation of differences between in-situ and back-surface measurements. I believe that this question needs explicit attention--both discussion and specific experiments to evaluate these differences. As far as I am aware, we are not able to perform ideal measurements in the bulk. All measurements attempt to approach these ideal conditions, but we don't have the perfect in-situ gauge. What is the degree of approximation in the various measurements? I believe that the closest we have come to in-situ measurements are the measurements of particle velocity in optically transparent materials, such as fused quartz and PMMA, which have been reported by Nunziato, Walsh, Schuler and Barker. Of course, the technique employed is applicable only to optically transparent materials.

In the future I believe that one of the new directions which will be important is the acceleration measurements which I have indicated. I believe that we can now begin to work routinely to design experiments involving acceleration pulse generators for probing material properties. This approach, being independent of the shock loading situation, should either confirm or change some of our previous notions regarding material behavior. I believe that the transverse motion measurements will be very important and I would like to see some attention in the future on determining the stress vs. particle velocity relations for solids in the stress range from 0.5 to 5.0 GPa so that we can perform more accurate experiments without using symmetric impact.

I promised to say a few words about the comparison of our experimental, theoretical, and numerical capabilities. I haven't collected any data on this matter, but can give my general impression. I'm not as concerned about the differences of these capabilities as I am about deficiencies in the area of understanding of physical mechanisms, the mechanics of what is happening in the wave and the determination of the response characteristics of the materials being studied. Every problem I have encountered has revealed a depth of understanding that I have felt to be unsatisfactory. We have not yet taken full use of our experimental theoretical and numerical capabilities to develop detailed understanding of material responses. For example, one outstanding question which we have been aware of for a long time, but which has not been resolved, is that of the shear strength of materials in a high pressure state.

I am very pleased to acknowledge the cooperation of numerous individuals who provided me with original data on the various wave profile measurements. These people include W. B. Benedick, J. W. Taylor, C. H. Karnes, L. M. Barker, D. E. Grady and F. Tuler.

Asay: Thank you, Bob. We have time for a few brief questions.

Gupta: I'd like to make two points: (i) your slide about time resolution is not wrong, but it's not correct either; (ii) the important question to ask is "what are you trying to do?". One must take the best approach for solving a given problem--I think Bob tried to say that. I believe that the time resolution capability of in-situ gauges is better than Bob indicated, but, I agree, not as good as that of a velocity interferometer. Jim Asay and I must have taken 75 to 100 records of precursor decay in LiF, with time resolution of the order of 2-5 nanoseconds; however, these measurements have provided information on material behavior only at the precursor. The later part of the recorded profiles has, so far, been unused even though this part of the profile contains a wealth of information. This situation exists because one must assume a material model and employ computer codes for comparison of material behavior with observed wave profiles. On the other hand, if we had used in situ gauges we would have lost the top 3 percent of the precursor, but we could have deduced stress-strain curves from the data directly. Thus, time resolution, in itself, is not necessarily the most important consideration in selecting gauges.

Dick: I would like to make two comments:

First, with regard to the determination of accelerations I think it may be preferable to use a particle velocity gauge, either piezoelectric or interferometric. Numerical processing of these records is required anyway (because of nonlinearities in the case of piezoelectric gauges) so that numerical differentiation can be carried out with little additional work. Such numerical differentiation is essentially what is being done electronically in the technique you have described.

The other point which I'd like to have you respond to is whether the quartz gauge measures stres or particle velocity at the interface. As Dick Fowles has pointed out, stress-time and velocity-time profiles do not have to be proportional to each other. How can the quartz gauge be both a stress gauge and a velocity gauge?

Graham: Which do you think the quartz gauge is? When we first reported on the gauge we expr ssed coefficients in terms of stress; however, I believe that I can justif its interpretation as a particle-velocity gauge more satisfactorily than it interpretation as a stress gauge. The material is elastic so that stress and particle velocity are proportional within the gauge. The problem is at the interface. If stress and particle velocity are not coincident there, the coupling problem between the sample and the gauge is the problem. This problem is not inherent to quartz gauges. I think the same question arises in connection with in-situ gauges.

I doubt that accelerations obtained from differentiating velocity-time profiles are as accurate as those obtained from the technique that I have described. I can't imagine determining the jerk from a measured velocity-time profile!

Taylor: The point is that you differentiate electronically. You can differentiate any signal electronically. Thanks to electrical engineers one can use a differential pre-amplifier to differentiate the signal from any gauge. I tried to do this 15 years ago but could not obtain a differential pre-amp that was fast enough. That is the trick.

Graham: That's true, in principle. However, the reason that the piezoelectric gauge works so well for this purpose is that the input signal is so large. I end up with 300 millivolts output after differentiation. In fact, I have had output signals as large as 7 volts. In principle you can apply the same finite differencing scheme to the output signal from any gauge, but from other gauges you will generally be at such low signal levels that noise will be a limiting factor.

Reference List

Barker, L. M. and R. E. Hollenback, 1974, J. Appl. Phys., Vol. 45, pp. 4872-4887.

Deal, W. E., Jr., 1962 in Modern Very High Pressure Techniques, edited by R. H. Wentorf, Butterworths, Washington, pp. 200-227.

Doran, D. G., 1963, in High Pressure Measurement, edited by A. A. Giardini and E. C. Lloyd, Butterworths, Washington, pp. 59-86.

Duvall, G. E. and G. R. Fowles, in High Pressure Physics and Chemistry, Vol. 2, edited by R. S. Bradley, Academic Press, New York, pp. 209-291.

Fowles, G. R., 1972, in Dynamic Response of Materials to Intense Impulsive Loading, edited by P. C. Chou and A. K. Hopkins, Air Force Materials Lab, Wright-Patterson AFB, Ohio, pp. 405-480.

Grady, D. E., 1977, in High Pressure Research: Applications in Geophysics, edited by M. H. Manghnani and S. Akimoto, Academic Press, New York, pp. 389-438.

Graham, R. A. and J. R. Asay, 1977, High Temperatures-High Pressures, accepted.

Jones, A. H., C. J. Maiden and W. M. Isbell, 1970, in Mechanical Behavior of Materials Under Pressure, edited by H. L. D. Pugh, Elsevier Publishing Co., Ltd., London, pp. 680-747.

Karnes, C. H., 1968, in Mechanical Behavior of Materials Under Dynamic Loads, edited by U. S. Lindholm, Springer-Verlag, New York, pp. 270-293.

McQueen, R. G., 1964, in Metallurgy at High Pressures and High Temperatures, edited by K. A. Gschneider, Jr., M. F. Hepworth and N. A. D. Parlee, Gordon and Breach, New York, pp. 44-132.

Nunziato, J. W., E. K. Walsh, K. W. Schuler and L. M. Barker, in Encyclopedia of Physics, Vol VIa/4, Mechanics of Solids IV, edited by C. Truesdell, Springer-Verlag, New York, 1974, pp. 1-108.

Figure Captions

Figure 1. Displacement vs. time record obtained by F. S. Minshall with a displacement capacitor gauge on the free surface on a 6.4 mm thick 4340 steel sample hardened to RC54 and explosively loaded with baratol. Time increases from left to right; each of the time marks shown on the lower trace are 100 ns apart. "A" is a fiducial. A velocity vs. time plot from such a record is shown in Fig. 6. (Experiment 1011C, private communication, F. S. Minshall.)

Figure 2. Stress vs. time record obtained by W. B. Benedick with a piezoelectric gauge on a 25 mm thick 4340 steel sample hardened to RC30 and explosively loaded with baratol. Time increases from left to right; the timing wave has a period of 40 ns. The record shows a jump in stress corresponding to an elastic wave and later in time the arrival of a wave reflected from the oncoming plastic wave. (Experiment 532B-660, private communication, W. B. Benedick)

Figure 3. Velocity interferometer record obtained by F. Tuler on a 25 mm thick 4340 steel sample hardened to RC34 and symmetrically impacted at a velocity of 480 m/s. Time increases from left to right; each of the timing marks are 200 ns apart. With this device a change in velocity is indicated by a change in optical intensity; i.e., a fringe. The record shows the arrival of a sharp elastic wave by a burst of fringes about 120 ns from the beginning of the trace followed by a slowly changing velocity. The second burst of fringes is the reflected

elastic wave and the final burst of fringes corresponds to the plastic wave. See Fig. 7 for the reduced data. (Experiment 1351, private communication, F. Tuler.)

Figure 4. The record shown in Figure 3 is here shown on an expanded time scale to show detail of the elastic wave. The time marks are 200 ns apart.

Figure 5. Stress vs. time record from a solid dielectric gauge (sapphire) on a 3.3 mm thick 4340 steel sample hardened to RB87 symmetrically impacted at 377 m/s). Time increases from right to left. The smaller timing wave below the main trace has a period of 20 ns. Following the fiducial a sharply rising elastic wave is followed by a plastic wave. (Experiment 332).

Figure 6. Reduced velocity vs. time data from a displacement capacitor record on a 25 mm thick 4340 steel sample hardened to RC35 and explosively loaded with baratol. The horizontal lines in the velocity plot correspond to individual differentiation between the digitized continuous displacement record. The filled circles on the velocity plot are the constant velocity level selected by Minshall to describe the record. (Private communication, F. S. Minshall.)

Figure 7. Velocity time record from a velocity interferometer experiment similar to that shown in Figures 3 and 4. The constant velocity indicated by the displacement vs. time record in Fig. 6 is shown as a filled circle. Note the reflected elastic wave. (Private communication, F. Tuler.)

Figure 8. Free surface velocity vs. time record obtained on a 127 mm thick Armco iron sample impact loaded at 77 m/s. Time increases from left to right; the timing intervals shown below the trace are 1,000 ns apart. Late time nonlinearity of the gauge record is removed in data reduction. (Taylor and Rice, J. Appl. Phys. Vol. 34, 1963, pp. 364-371.)

Figure 9. Stress vs. time record obtained on a 19 mm thick Armco iron sample explosively loaded with baratol. Time increases from right to left; the timing wave has a period of 40 ns. The slowly rising elastic wave is followed later in time by a sharply relaxing reflected elastic wave!

Figure 10. A VISAR (an optical velocity interferometer) record of a 6.3 mm thick Armco iron sample impact loaded at 1.9 km/s. Time increases from left to right; time marks are 200 ns apart. The record shows a slowly rising elastic wave and the plastic wave. The reduced record is shown in Figure 11. (Barker and Hollenback, J. Appl. Phys., Vol. 45, 1974, pp. 4872-4887.)

Figure 11. Free surface velocity vs. time for the VISAR record shown in Figure 10 and a similar record obtained from an Armco iron sample 19 mm thick. Note the detail on the reflected elastic wave.

Figure 12. Wave profiles in 3.3 mm thick [100] MgO crystals impact loaded at 4.8, 8.2 and 11.2 GPa. Note the detail of the relaxation behind the elastic wave. (Grady, in High Pressure Research: Applications in Geophysics, Academic Press, New York (1977), p. 421.)

Figure 13. Elastic-plastic waves in impact-loaded [100] MgO crystals as detected with an in-situ Manganin gauge, top and a quartz gauge, bottom. Timing marks are 200 ns apart. (Grady, loc. cit.)

Figure 14. Stress vs. time record--obtained by C. H. Karnes with a quartz gauge on a 6.3 mm thick tungsten carbide sample impacted symmetrically at 700 m/s. Time increases from left to right; timing marks are 200 ns apart. (Experiment WC-3, C. H. Karnes, private communication.)

Figure 15. Comparison of tungsten carbide wave profile of Figure 14 with a similar measurement with a displacement interferometer by C. H. Karnes. (Experiment WC-9, private communication, C. H. Karnes.)

Figure 16. Measurements by C. H. Karnes as in Figures 14 and 15 with the inclined resistance wire and a velocity interferometer. (Experiments WC-4 and WC-7, private communication, C. H. Karnes.)

Figure 17. Response functions of a detector subjected to a step loading followed by experimental decays at various rates.

Figure 18. Experimental configuration for the delay cable technique for obtaining simultaneous velocity and acceleration measurements with a piezoelectric current-mode gauge such as quartz or lithium niobate.

Figure 19. Experimental record of velocity (left) and acceleration (right) and a wave propagating through 12 mm thick fused quartz (Dynasil 1000) sample. Time increases from left to right. Timing marks are 20 ns apart.

Figure 20. A summary of acceleration measurements on fused quartz (either GE151 or Dynasil 1000.) Accelerations are produced because the third-order elastic constant of fused quartz is of opposite sign to that in most materials. The Barker experiments are previously reported (Barker and Hollenbach, J. Appl. Phys., Vol. 41, 1970, pp. 4208-4226.) The other experiments are not previously reported.

Figure 21. The entire acceleration pulse from the record of Figure 19 is obtained by using data reduction which incorporates nonlinear effects in the quartz gauge due to the third-order piezoelectric constant. The ability to determine jerk is shown. In this case the jerk is zero.

top

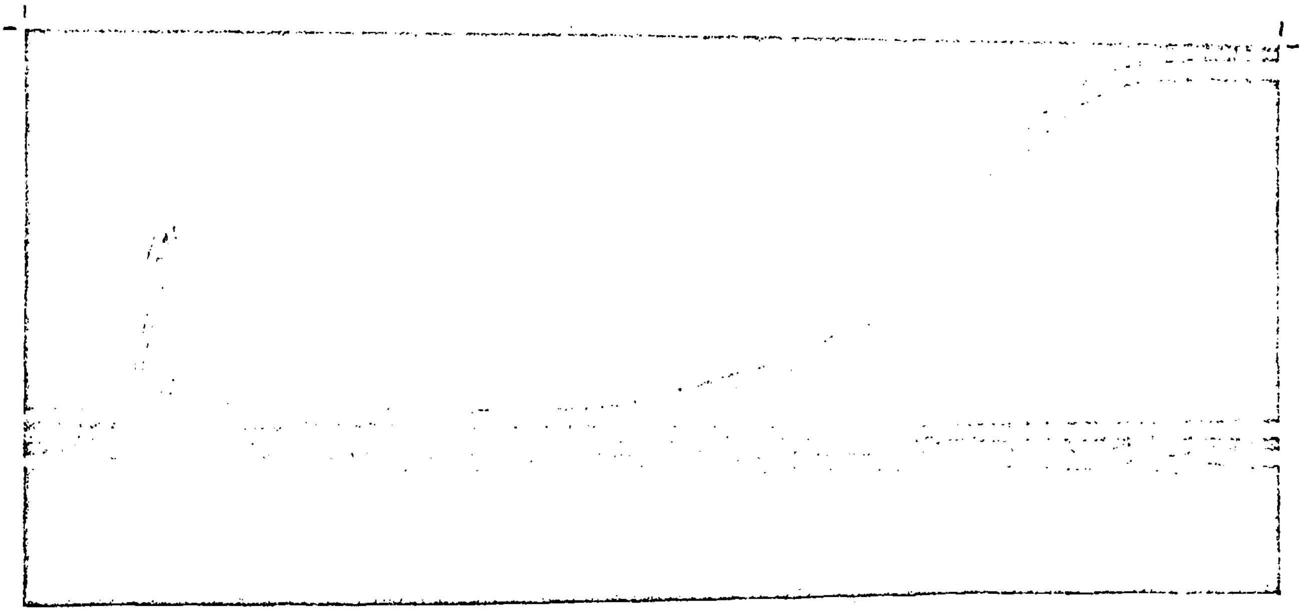

Figure 1
Graham

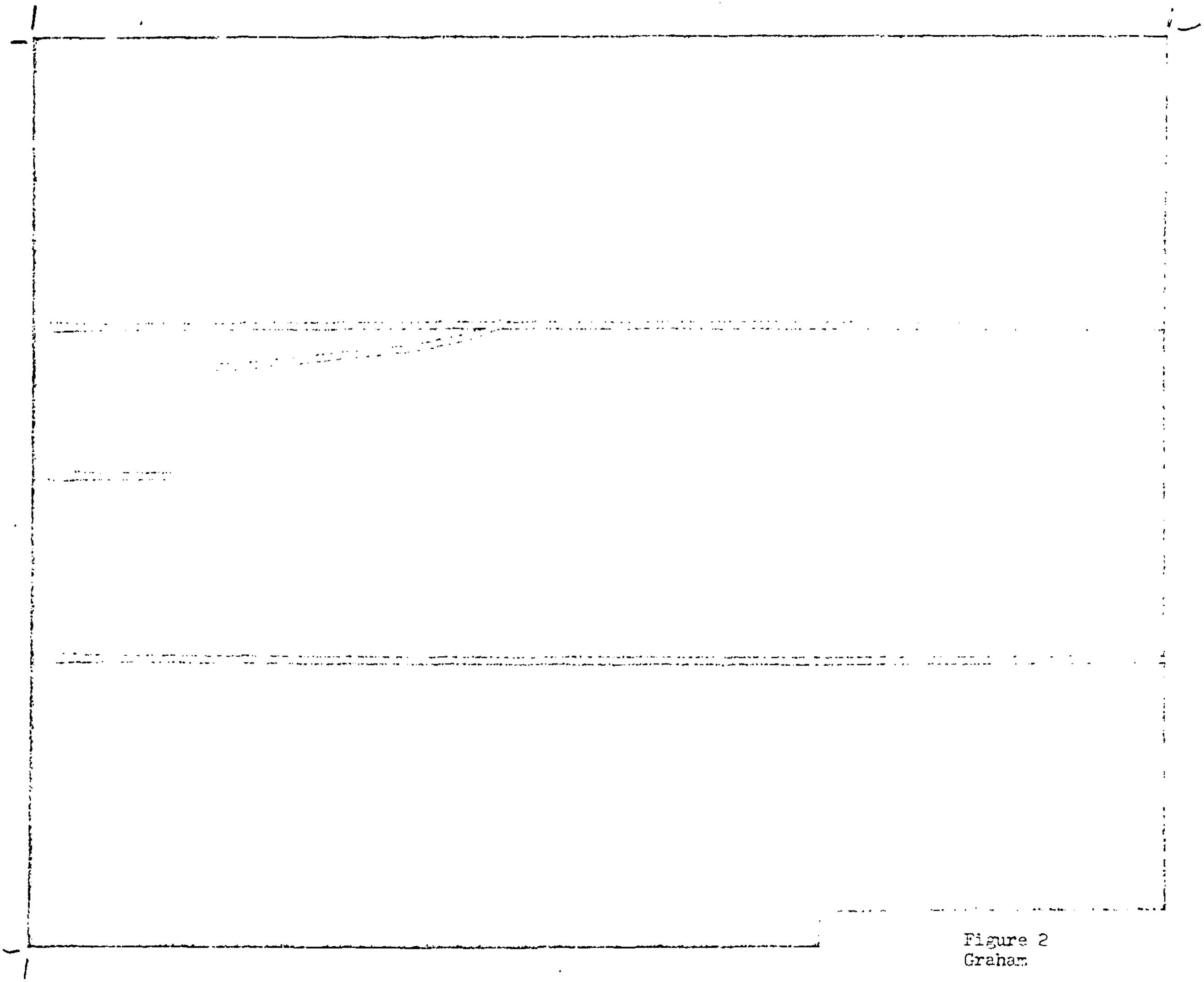


Figure 2
Graham

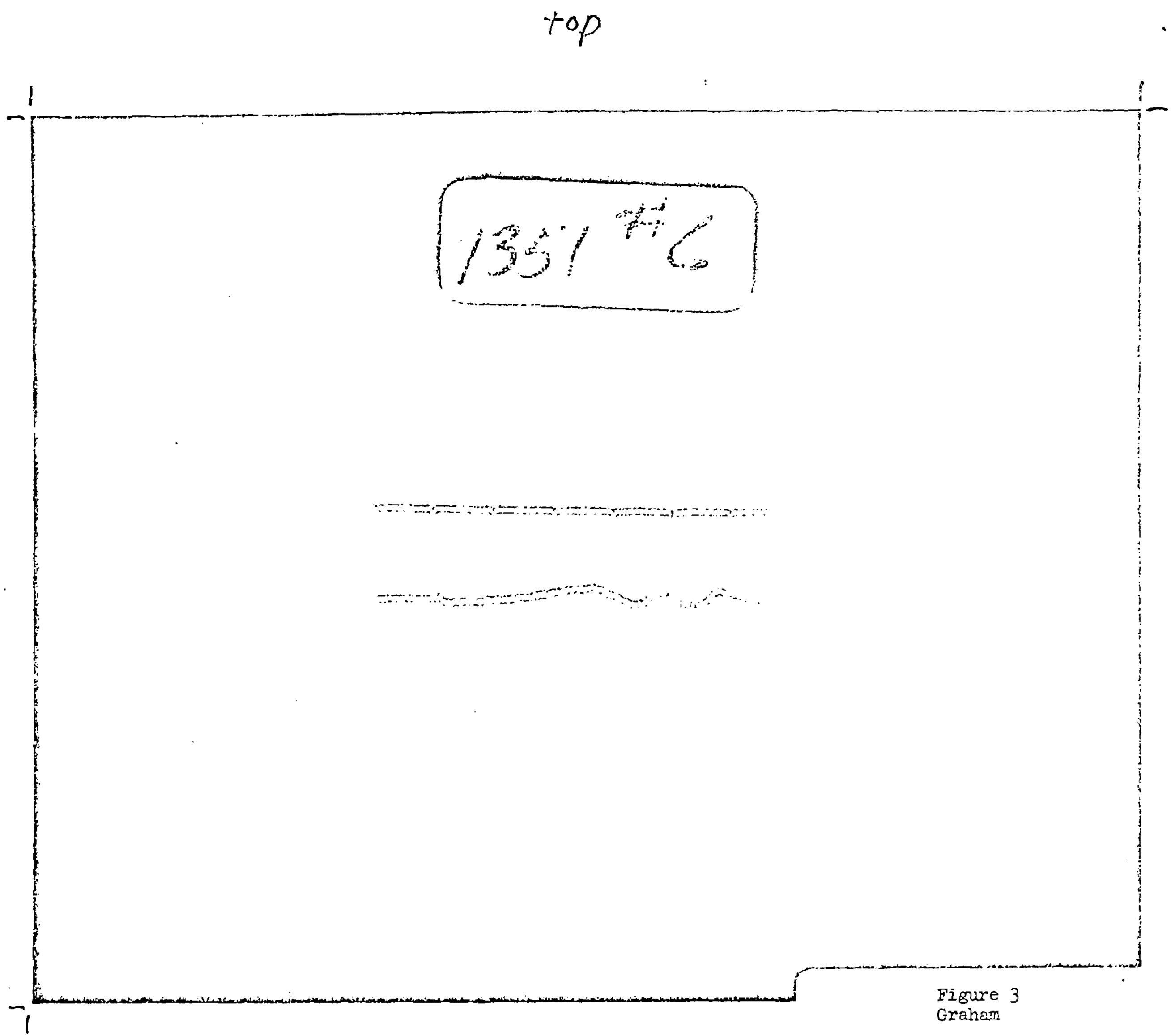


Figure 3
Graham

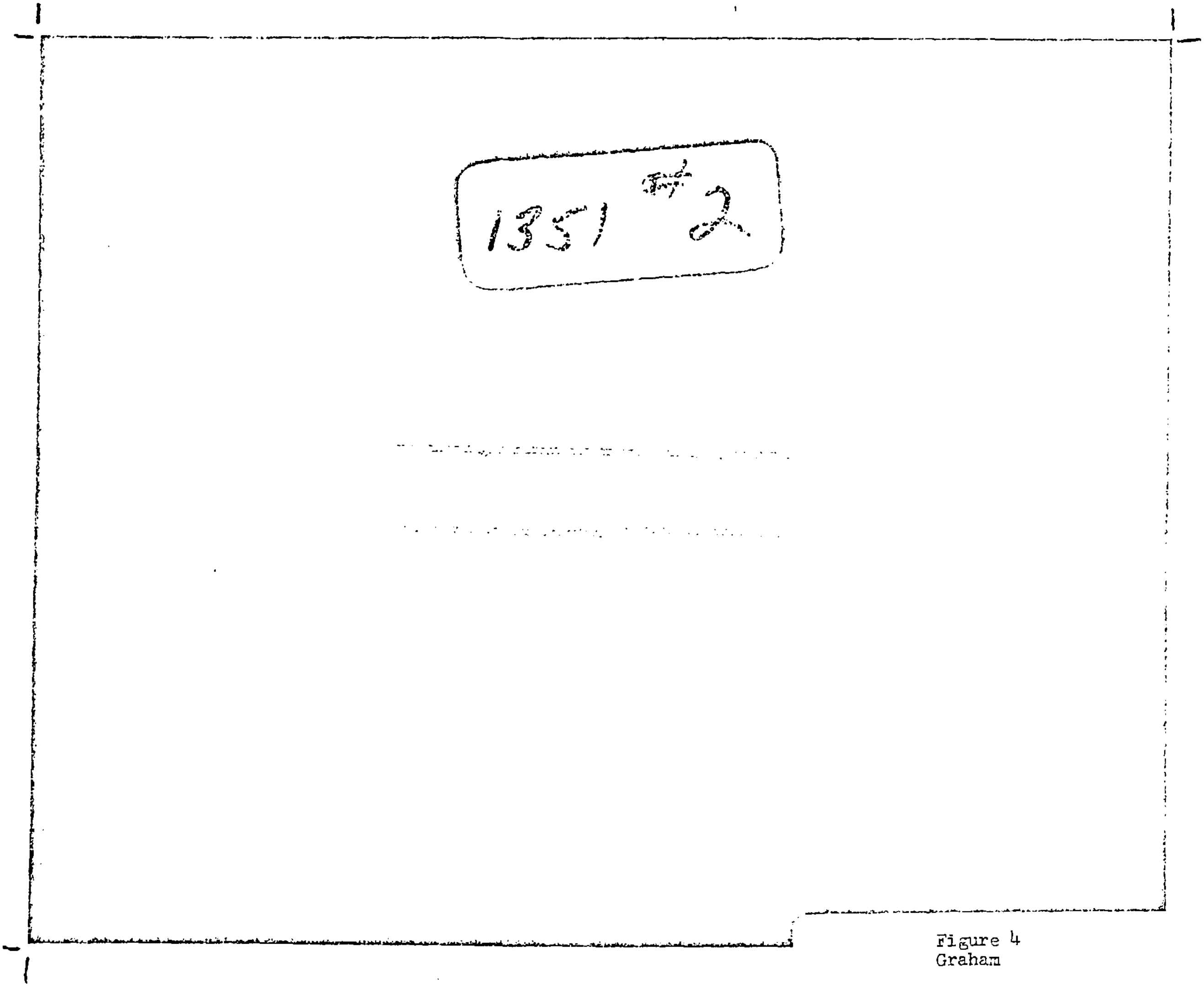


Figure 4
Graham

TOP

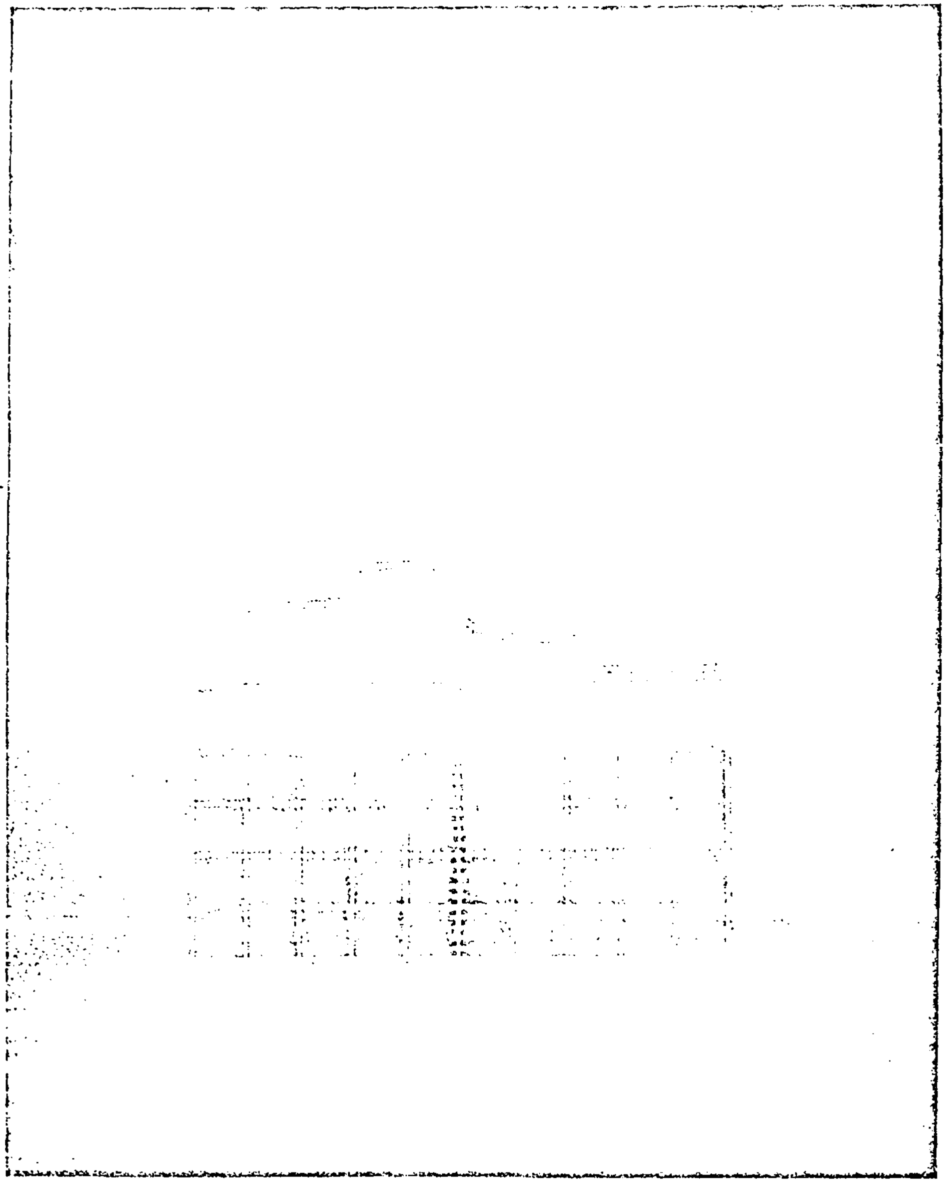

Figure 5
Graham

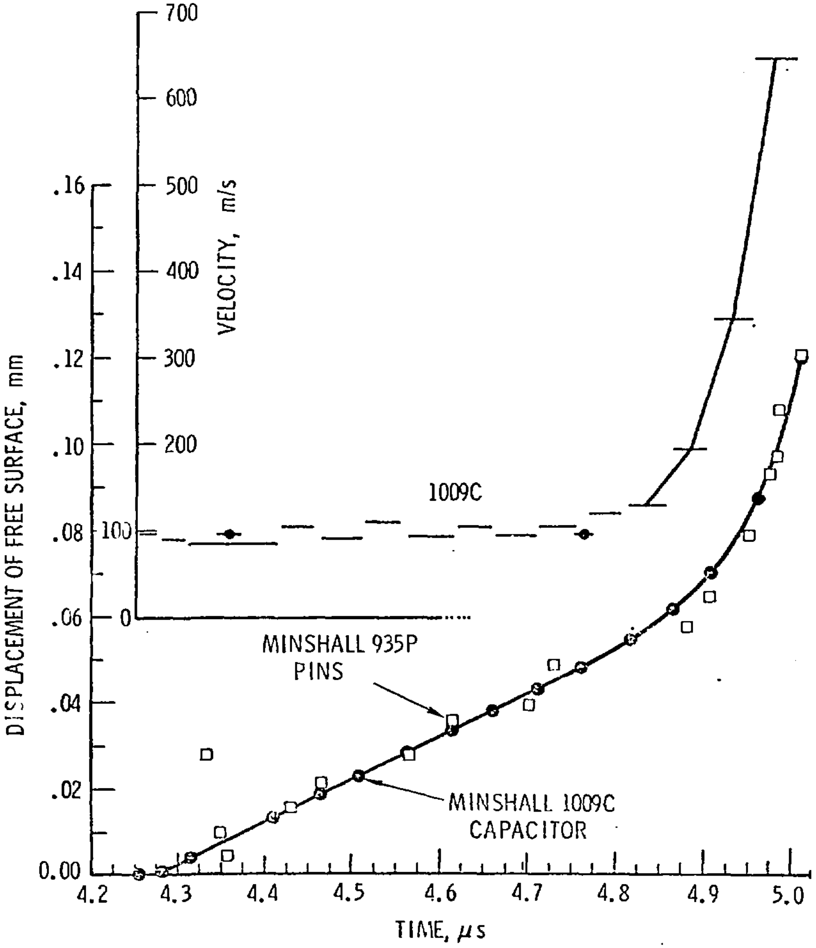


Figure 6
Graham

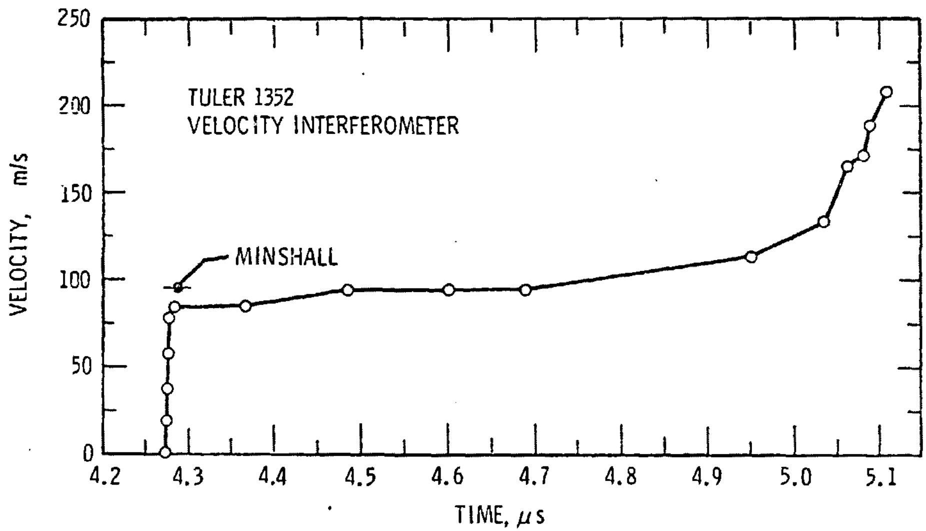


Figure 7
Graham

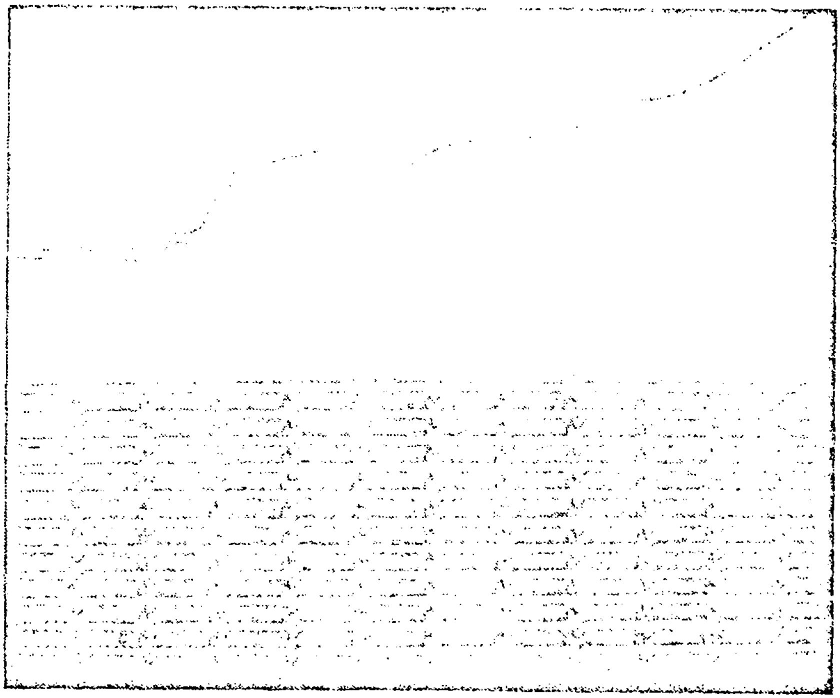

Figure 8
Graham

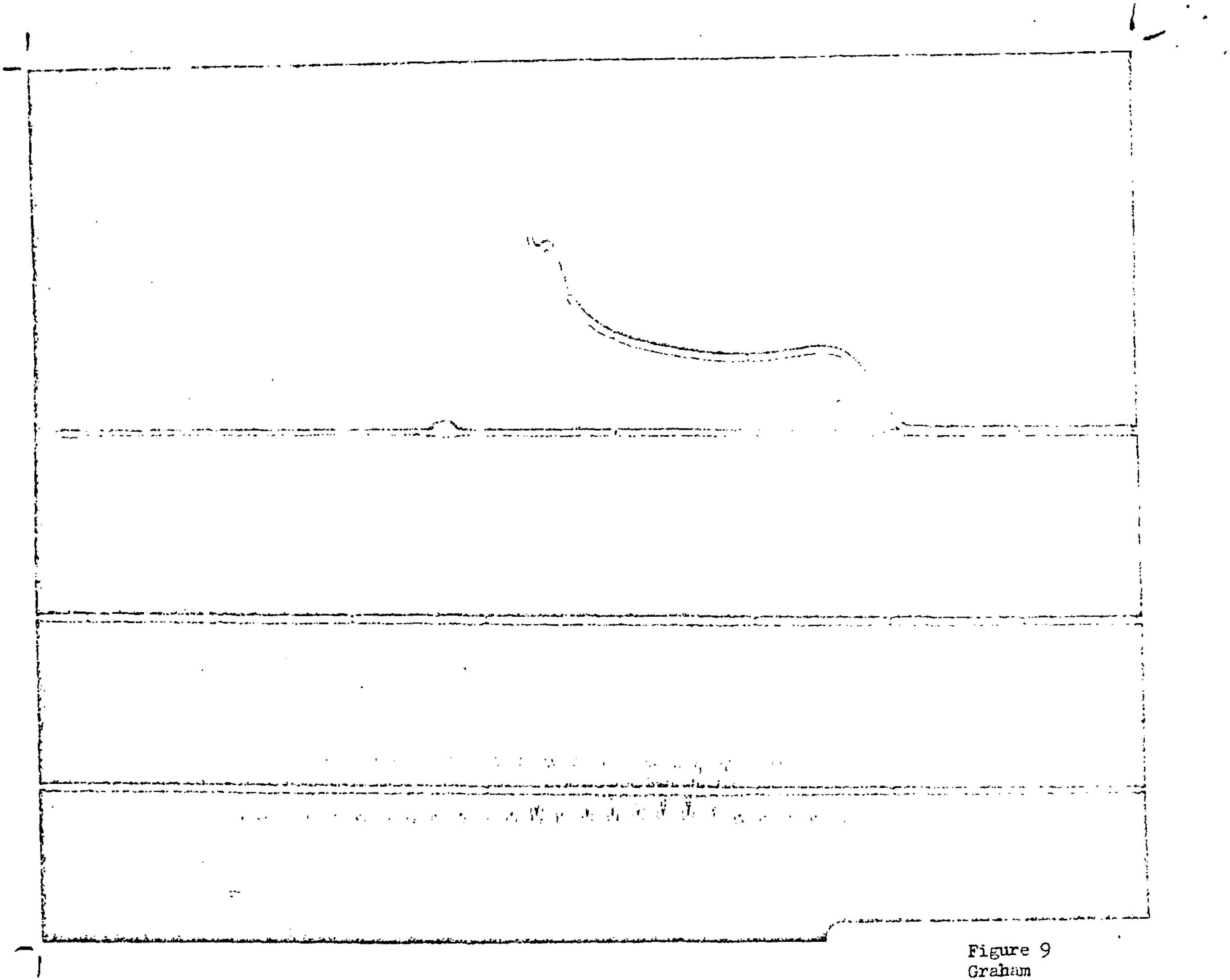

Figure 9
Graham

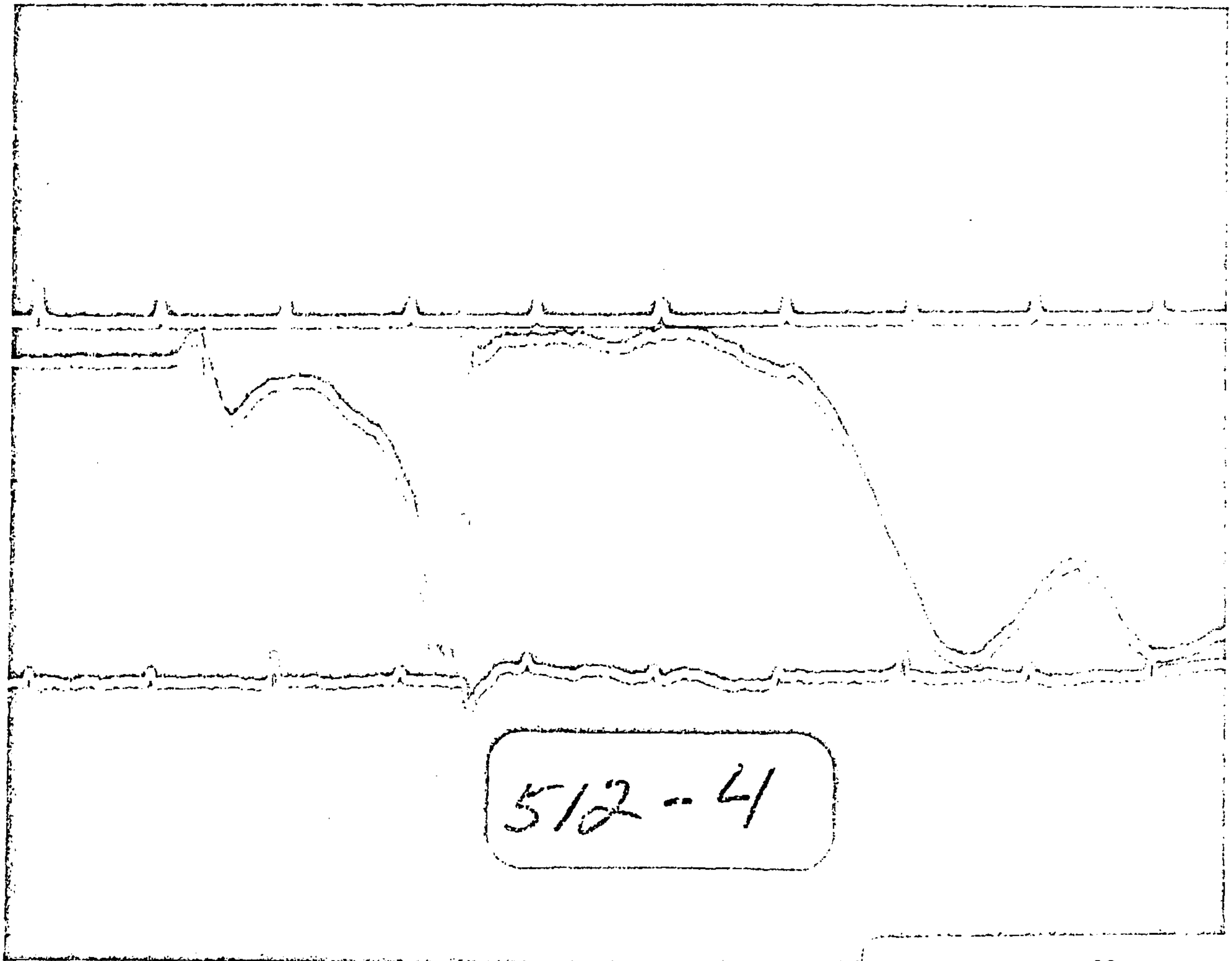


Figure 10
Graham

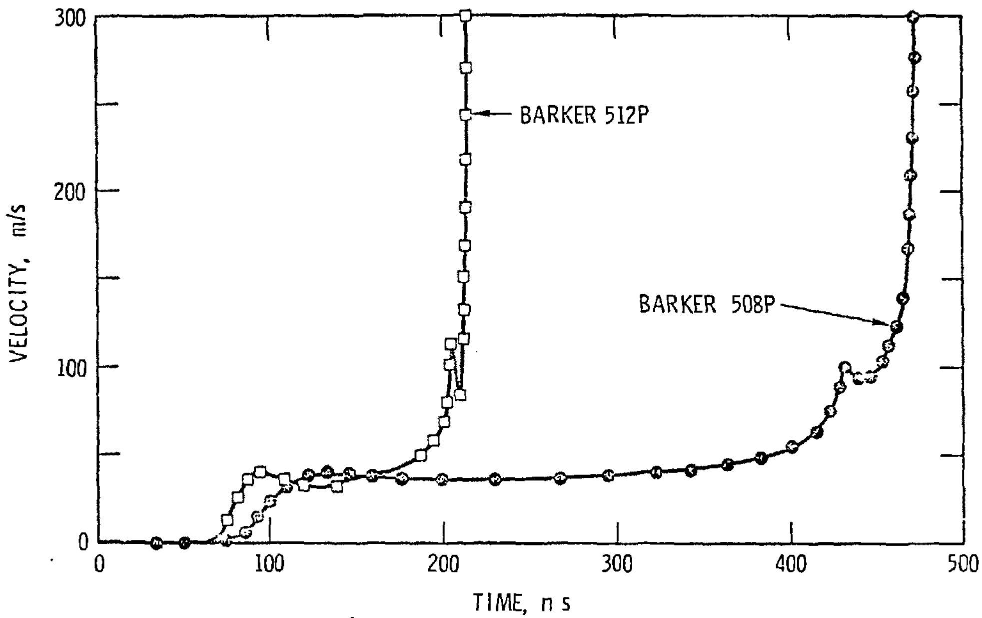


Figure 11
Graham

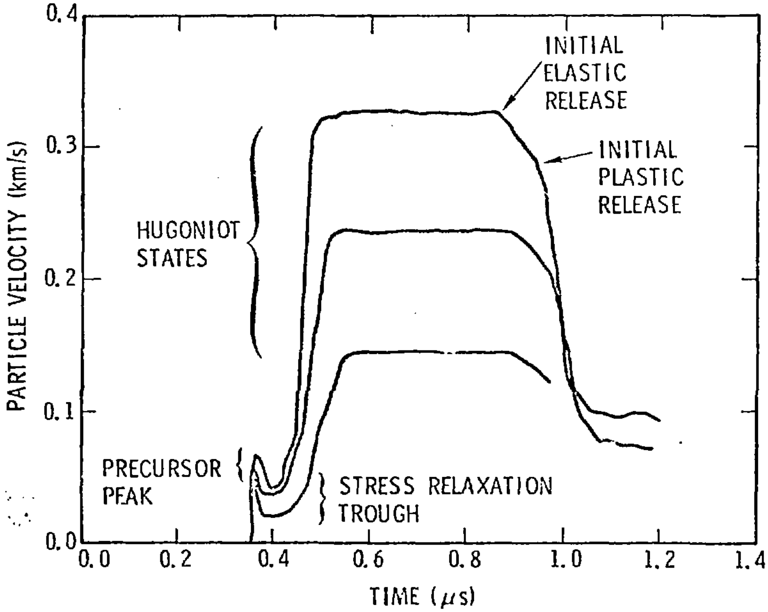


Figure 12
Graham

top

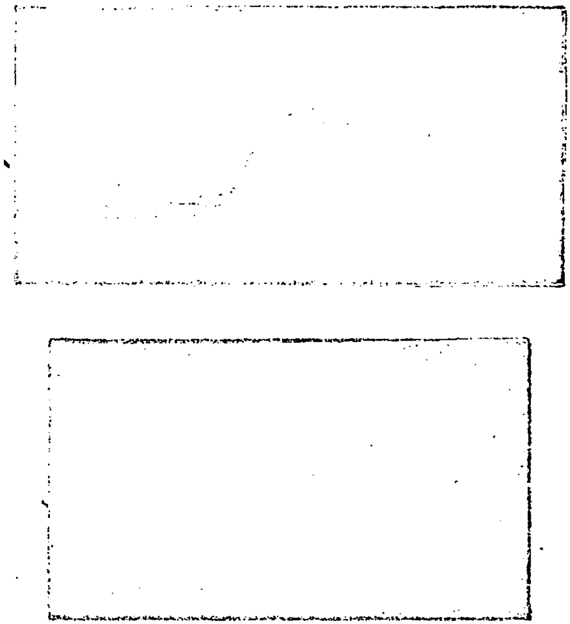

Figure 13
Graham

top

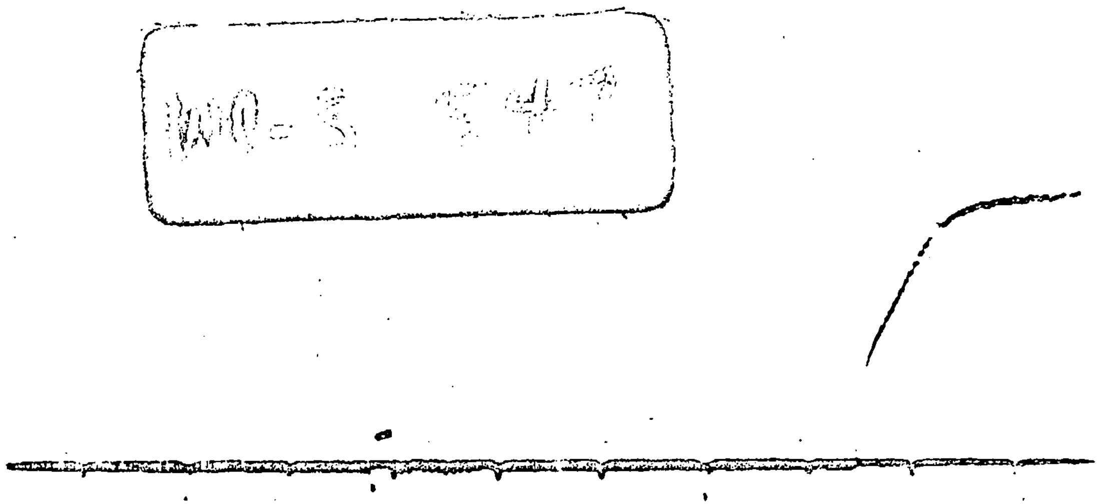

Figure 14
Graham

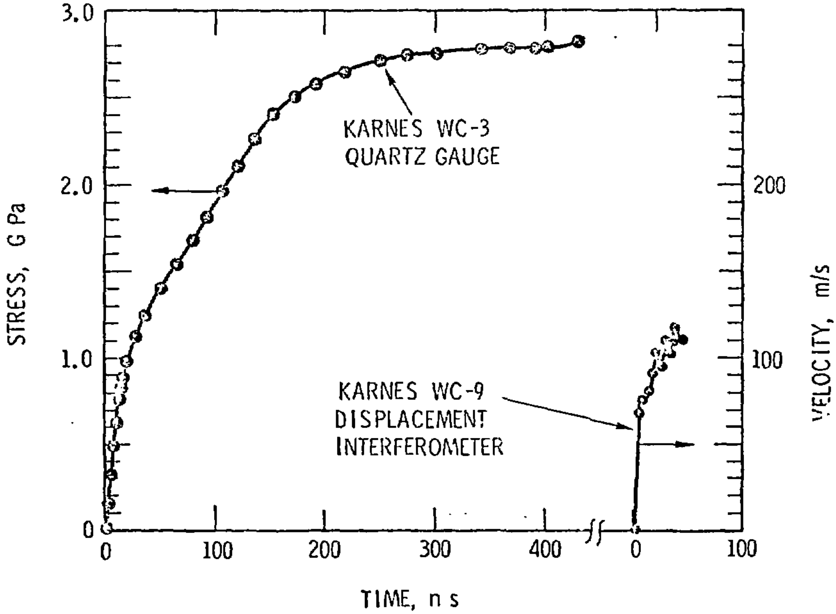


Figure 15
Graham

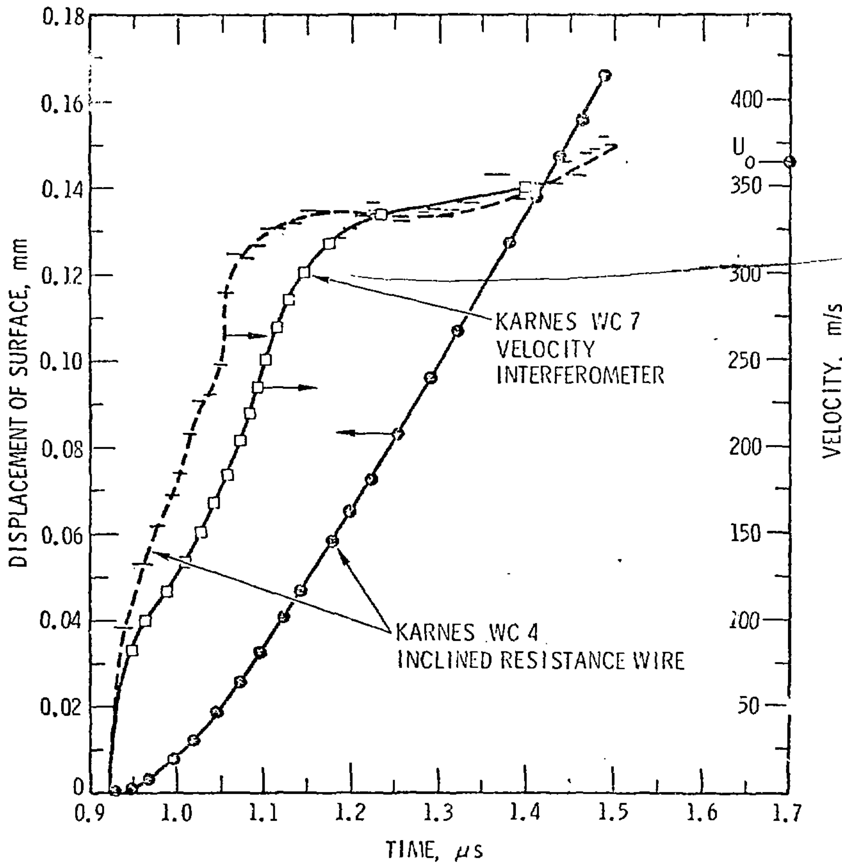


Figure 16
Graham

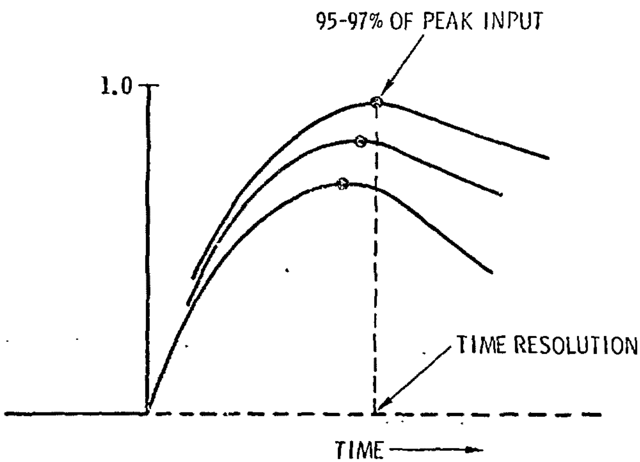


Figure 17
Graham

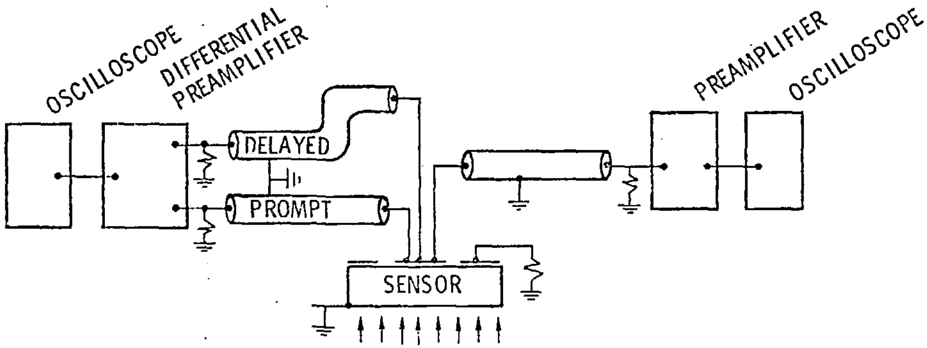


Figure 18
Graham

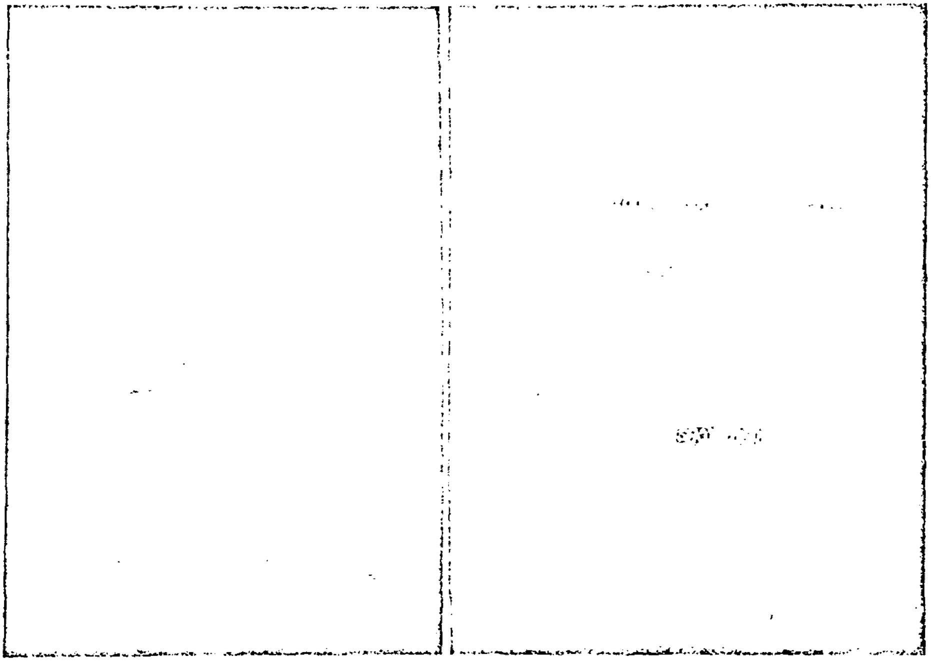

Figure 19
Graham

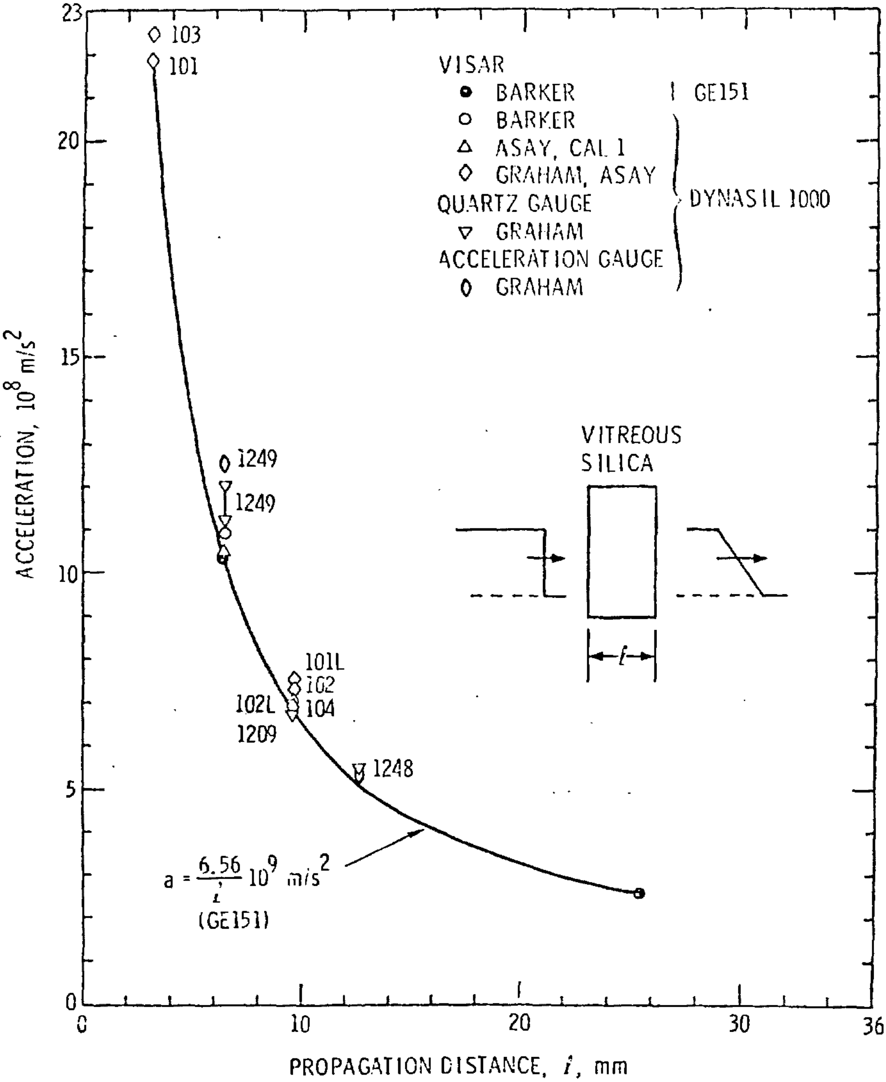


Figure 20
Graham

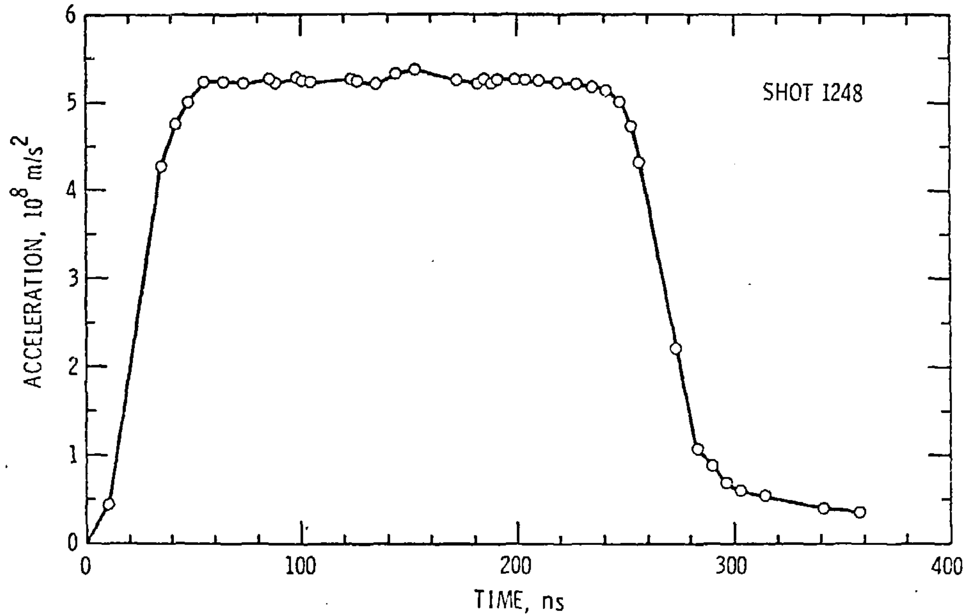


Figure 21
Graham