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The Use of a Beryllium Hopkinson Bar to Characterize In-Axis and Cross-Axis Accelerometer Response in Shock Environments

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Abstract

The characteristics of a piezoresistive accelerometer in shock environments have been studied at Sandia National Laboratories in the Mechanical Shock Laboratory. A beryllium Hopkinson bar capability with diameters of 0.75 in. and 2.0 in has been developed to extend our understanding of the piezoresistive accelerometer, in two mechanical configurations, in the high frequency, high shock environments where measurements are being made. The in-axis performance of the piezoresistive accelerometer determined from measurements with a beryllium Hopkinson bar and a certified laser doppler vibrometer as the reference measurement is presented. The cross-axis performance of the accelerometer subjected to static compression on a beryllium cylinder, static strain on a steel beam, dynamic strain on a steel beam (ISA-RP 37.2, Paragraph 6.6), and compressive shocks in a split beryllium Hopkinson bar configuration is also presented. The performance of the accelerometer in a combined in-axis and cross-axis shock environment is shown for one configuration. Finally, a failure analysis conducted in cooperation with ENDEVCO gives a cause for the occasional unexplained failures that have occurred in some applications.

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The Use of a Beryllium Hopkinson Bar to Characterize In-Axis and Cross-Axis Accelerometer Response in Shock Environments

Introduction

Sandia National Laboratories (SNL) conduct impact experiments for a variety of structures. These impact experiments include earth and rock penetrator experiments in which a penetrator structure is propelled at velocities of 1000 fps (nominal) into earth or rock. During an impact experiment, metal to metal contact may occur within the structure and produce high frequency, high amplitude shocks. The piezoresistive accelerometer, which frequently measures the field experiment response of various high reliability structures, must withstand these severe shock environments. The piezoresistive accelerometer has several desirable characteristics: dc response, low power requirements, minimal zero shift, and high resonant frequency. A bandwidth of at least 10 kHz is needed for many applications because more sophisticated analyses are being performed with the experimental data. Additionally, requirements are being made to qualify components for frequency ranges of 10 kHz. For example, recent Army research has found that armored vehicle components can be damaged by the high frequency content of ballistic shock [1,2,3]. To enhance survivability of the new generation of combat vehicles, the Army has specified a minimum frequency range of 10 kHz for the design and qualification of components. Qualification to even higher frequencies is desired, if reasonably possible. Since there is no capability to calibrate or characterize accelerometers with shock inputs for frequencies above 10 kHz, the SNL Mechanical Shock Laboratory has been given the task of characterizing accelerometers for the conditions shown in Tables I and II. The two areas of high frequency performance and high amplitude shock (acceleration level) performance for the piezoresistive accelerometer are being pursued because measurements are being made in these environments.

The SNL Mechanical Shock Laboratory has a titanium Hopkinson bar capability to characterize accelerometers up to 200,000 g that has been used to determine the characteristics of a piezoresistive accelerometer at these high acceleration levels [4]. The SNL titanium Hopkinson bar with strain gages as the reference measurement has been calibrated for a bandwidth of dc to 10 kHz with an uncertainty of + 6% [5]. This capability was used to characterize the piezoresistive accelerometer initially.

The piezoresistive accelerometers are being characterized over the extended bandwidth of dc to 50 kHz to provide better interpretation of high frequency

Table I: Experiment Matrix for In-Axis Accelerometer Study.

	Low Amplitude (up to 20,000 g)	High Amplitude (up to 200,000 g)
Low Frequency (dc-10 kHz)	Titanium	Titanium
High Frequency (dc-50 kHz)	Beryllium	Beryllium

Table II: Environments for the Cross-Axis and Combined Shock Accelerometer Study.

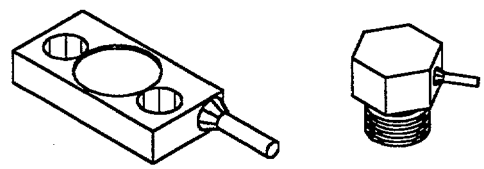
Environment	Experimental Configuration
Static Compression	Beryllium Cylinder
Static Strain	Steel Beam
Dynamic strain	Steel Beam
Compressive Mechanical Shock	Beryllium Cylinder in a Split Hopkinson Bar Configuration
Combined Shock	Titanium Hopkinson Bar with 45° Flats

measurements. To achieve this goal, a beryllium Hopkinson bar capability has been developed to extend the upper limit of the frequency range for Hopkinson bar calibration and characterization of accelerometers. The reference measurement for the beryllium Hopkinson bar in a single bar configuration is a commercial laser doppler vibrometer (LDV) that has been certified by the SNL Primary Electrical Standards Laboratory [6]. The LDV is the Polytec PI Model OFV-3000 controller and Model OFV-302 sensor head*. The in-axis performance of the piezoresistive accelerometer in two different mechanical packages has been determined from measurements with a beryllium Hopkinson bar [7].

The rectangular package that uses two #4-40 screws for mounting will be referred to as the flat package in this report. The cylindrical package that uses a single #1/4-28 mounting stud will be referred to as the can package. These accelerometers are the ENDEVCO* Model 7270A (flat package) and the ENDEVCO* Model 7270AM4 (can package) as shown in Fig. 1. Both configurations have been studied to determine if there are any differences in the performance characteristics between

*Reference to a commercial product implies no endorsement by SNL or the Department of Energy or lack of suitable substitute.

the two accelerometers. In some cases, it has been suspected that the flat package exhibited beam mode response (with fixed end conditions) in high frequency environments. It has been hypothesized that the can package might eliminate this beam response and the subsequent frequency content in the measured accelerometer response data.



Accelerometer, Flat Configuration   Accelerometer, Can Configuration

Figure 1: Two Mechanical Configurations for a Piezoresistive Accelerometer, ENDEVCO 7270A AND 7270AM4.

Others have tried to extend the frequency range of the Hopkinson bar by removing dispersion effects from the data [8,9] instead of using beryllium for the bar. The Hopkinson bar material for these experiments is typically titanium. However, this technique is not a valid approach to extend the bandwidth because there is no coherence in the data above ~15 kHz for the typical Hopkinson bar materials of aluminum, steel and titanium. A beryllium Hopkinson bar allows measurement of frequencies in the bandwidth of dc to 50 kHz with acceptable coherence because the beryllium's high stress wave speed can create a shorter pulse duration without dispersion than other Hopkinson bar materials that are used for the current accelerometer studies.

Results of characterizations of the accelerometers subjected to cross-axis static compression on a beryllium cylinder, static strain on a steel beam, dynamic strain on a steel beam, and compressive shocks in a split beryllium Hopkinson bar configuration are also presented. The static compression experiments have been performed in order to identify the mechanism that causes the cross-axis response in the accelerometers. The static deflection and dynamic strain experiments with a steel beam have been performed according to ISA-RP 37.2, Paragraph 6.6, because this recommended practice is the only established method for determining base strain response in accelerometers. Beryllium is used for the static compression and compressive mechanical shocks because of its low Poisson's ratio, 0.07. The result is that beryllium has negligible response in the accelerometer's sensitive axis, so these cross-axis experiments may be considered pure cross-axis environments.

The performance of the accelerometer in a combined in-axis and cross-axis shock environment is shown for one configuration. Finally, a failure analysis conducted in cooperation with ENDEVCO explains the occasional unexplained failures that make it unreliable for some applications.

Hopkinson Bar Configurations

The beryllium Hopkinson bar configuration for characterizing accelerometers for normal or in-axis input is shown in Figure 2. Normal input in this configuration

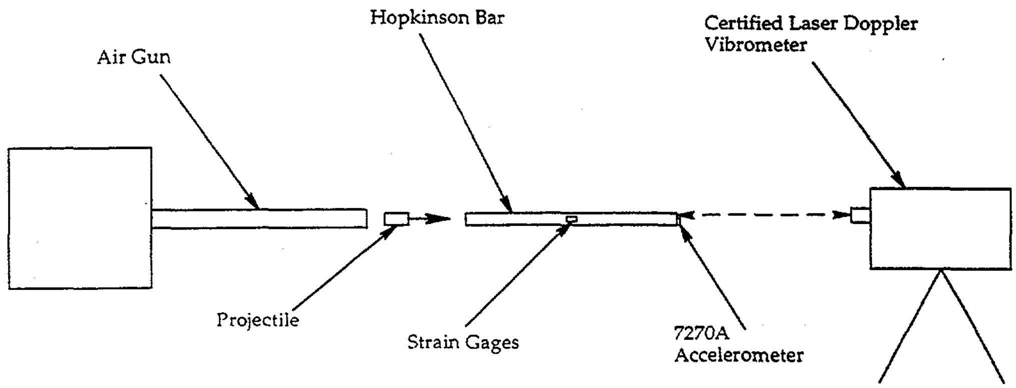
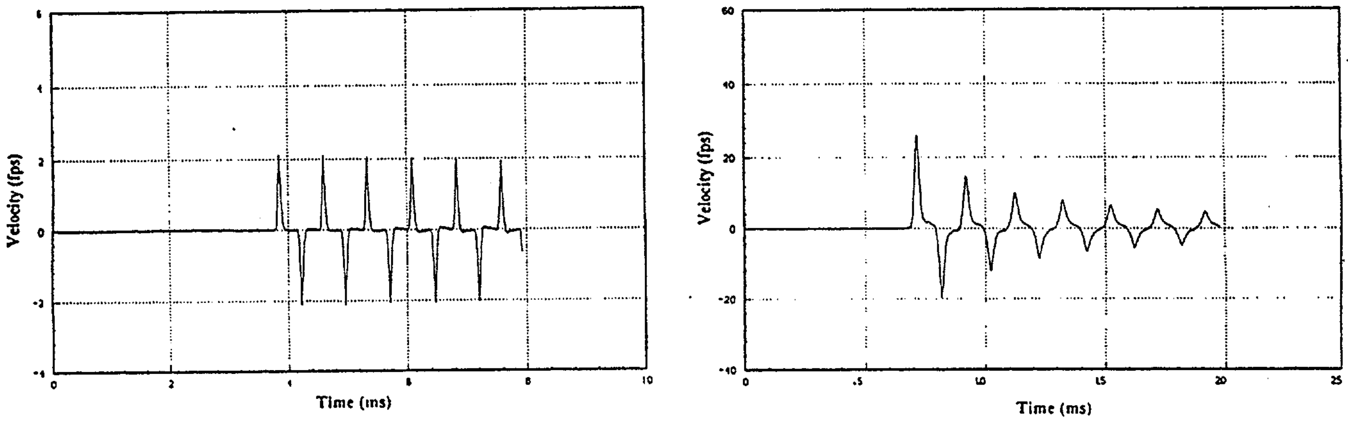


Figure 2: Beryllium Hopkinson Bar Configuration for Normal Input (0.75 in. and 2.0 in. Diameters).

is an input that is normal to the mounting surface or parallel to an integral mounting stud. A maximum shock magnitude of 70,000 g is used for the beryllium bar to insure that the beryllium will not yield because it is a health hazard in particle form. Both of the mechanical configurations for the piezoresistive accelerometer have been characterized with the normal input that is parallel to their sensitive axis. The reference measurement is the LDV as shown. Strain gages cannot be used as the reference measurement because the beryllium bar's response exhibits two anomalies that are shown in Figure 3: the high rate of damping and the non-return to zero of the stress time history. The SNL Mechanical Shock Laboratory has a titanium Hopkinson bar capability to characterize accelerometers up to 200,000 g that has been used to determine the characteristics of a piezoresistive accelerometer at these high acceleration levels [4]. The SNL titanium Hopkinson bar is the same configuration as Figure 2 but has strain gages as the reference measurement with an uncertainty of + 6% [5].

A configuration that uses a quartz crystal to directly measure the acceleration applied to an accelerometer mounted on a flyaway device at the end of the bar was investigated [10]. However, it was found that the Hopkinson bar material for this configuration is limited to aluminum that matches the impedance of the quartz crystal.



Titanium Bar

Beryllium Bar

Figure 3: Beryllium Hopkinson Bar Anomalies.

Cross-axis sensitivity of the piezoresistive accelerometers has been studied with the beryllium split Hopkinson bar configurations shown in Figures 4, 5, and 6. An in-axis response is the response of an accelerometer whose sensitive axis is in the direction of the shock. An out-of-axis or cross-axis response is the response of an accelerometer whose sensitive axis is not in the direction of the shock but is perpendicular to the to the direction of the shock. With beryllium's Poisson's ratio of 0.07, the cross-axis performance is obtained with negligible motion in the accelerometer's sensitive axis. A cross-axis configuration with the accelerometers mounted normal to the stress wave on the end of the bar was proposed previously [4] but was abandoned because the end-modes at 120 kHz in the Hopkinson bar caused the accelerometers to resonate and break.

Acceleration responses for the ENDEVCO 7270A and 7270AM4 mounted on titanium Hopkinson bars with two 45° flats on the end have been obtained with the configurations shown in Figures 7 and 8, respectively. A bar was machined to accommodate two accelerometers of the same model at the same time. The 45° flats provide a combined in-axis and cross-axis shock environment.

No special preparations of the beryllium Hopkinson bar interfaces with the inserts are made other than insuring that the surfaces are flat and polished. Careful alignment of the bars and the insert is required. All Hopkinson bars used for the results shown in this paper are freely supported. Both time domain calculations, as a percent difference from the reference measurement (LDV or strain gages), and frequency domain calculations, as frequency response functions, are made with the Hopkinson bar data.

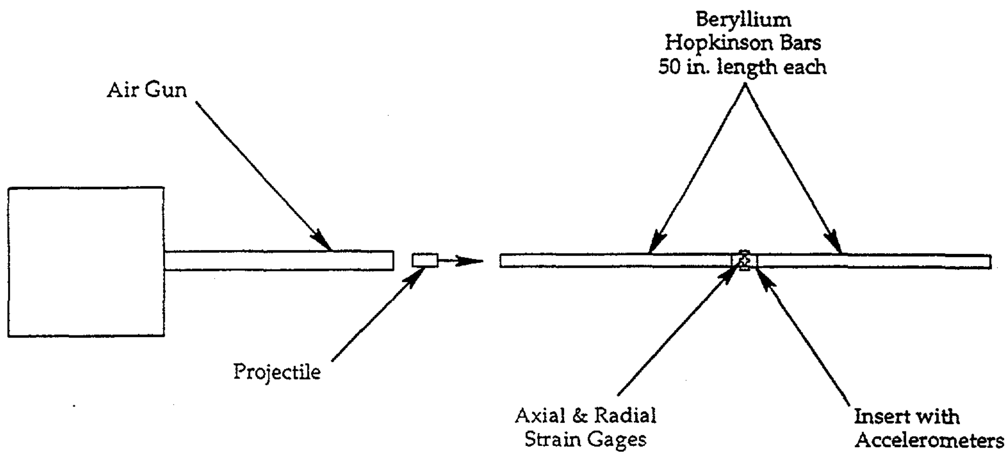


Figure 4: Split Beryllium Hopkinson Bar Configuration for Cross-Axis Input (0.75 in. and 2.0 in. Diameters).

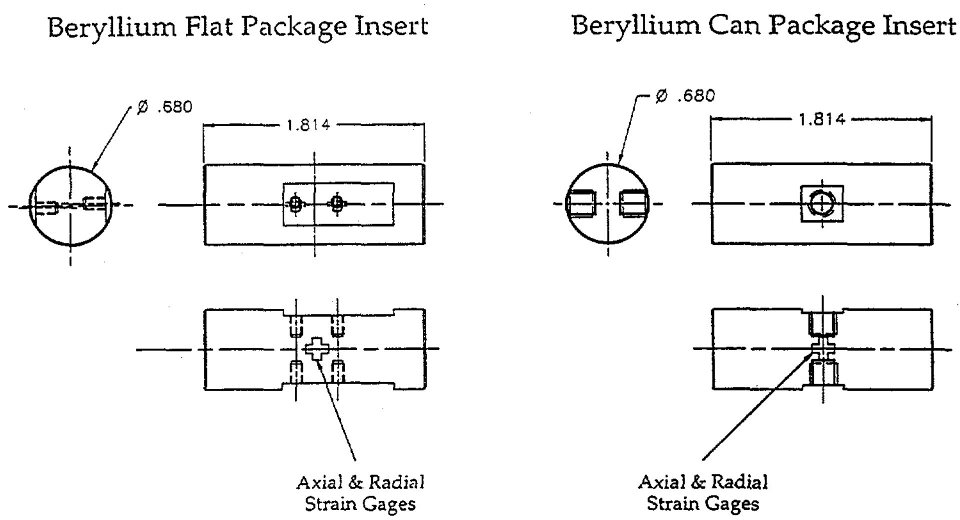


Figure 5: Insert for Split Beryllium Hopkinson Bar Configuration with 0.75 in. diameter.

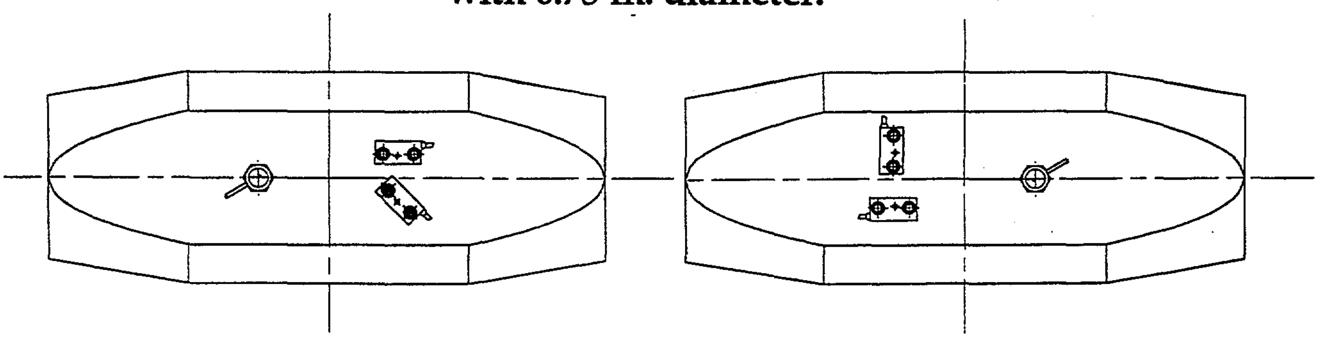


Figure 6: Two Flats on the Beryllium Insert for Static Compression and Mechanical Compressive Shock Cross-Axis Experiments (2 in. Diameter).

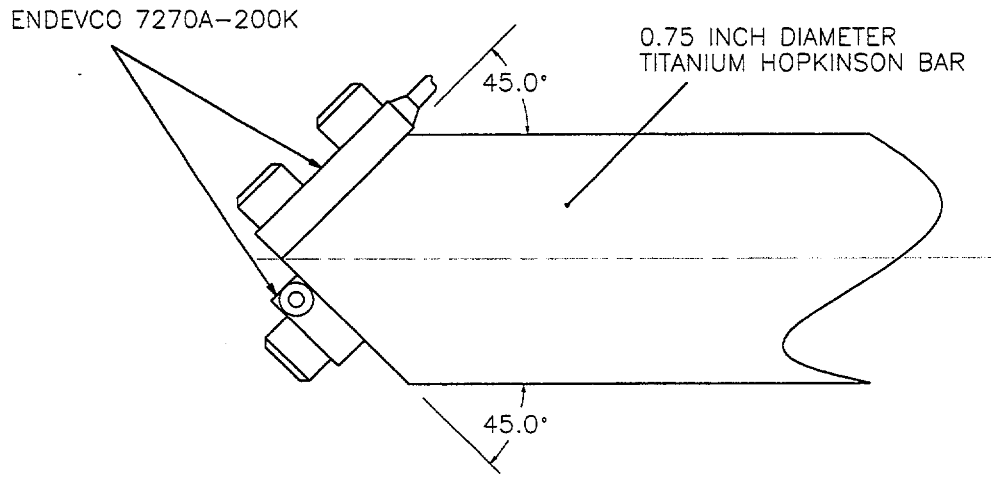


Figure 7: Titanium Hopkinson Bar with Two 45° Flats for the ENDEVCO 7270A.

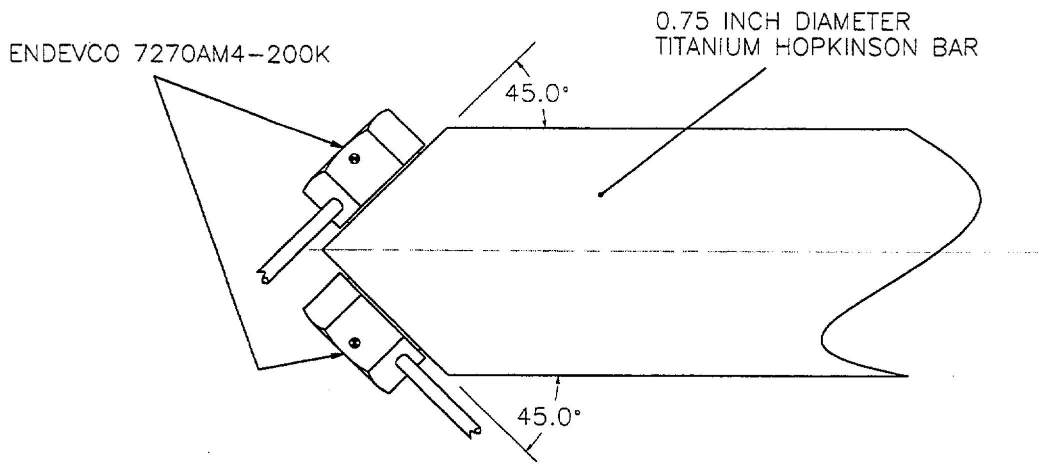


Figure 8: Titanium Hopkinson Bar with Two 45° Flats for the ENDEVCO 7270AM4.

Hopkinson Bar Analysis for In-Axis Response

The theory of stress wave propagation in a Hopkinson bar is well documented in the literature [11, 12]. The results of this theory are summarized as follows:

> A Hopkinson bar is defined as a perfectly elastic, homogeneous bar of constant cross-section.
>
> A stress wave will propagate in a Hopkinson bar as a one-dimensional elastic wave without attenuation or distortion if the wavelength, λ, is large relative to the diameter, D, or $10D \leq \lambda$.

For a one-dimensional stress wave propagating in a Hopkinson bar, the motion of a free end of the bar as a result of this wave is:

$$v = 2c\varepsilon \qquad (1)$$

or,

$$a = 2c\frac{d\varepsilon}{dt} \qquad (2)$$

where,

$$c = \sqrt{\frac{E}{\rho}} \qquad (3)$$

and v and a are the velocity and acceleration, respectively, of the end of the bar, c is the wave propagation speed in the bar, E is the modulus of elasticity, ρ is the density for the Hopkinson bar material, and ε is the strain measured in the bar at a location that is not affected by reflections during the measurement interval.

The motion of an accelerometer mounted on the end of the bar will be governed by equations (1) and (2) if the mechanical impedance of the accelerometer is much less than that of the bar or if the thickness of the accelerometer is much less than the wavelength. The requirement on the strain gage is that the gage length (g.l.) be much less than the wavelength or $\lambda \geq 10$ g.l.

The Mechanical Shock Laboratory Hopkinson bars, used for accelerometer characterizations, are made of either 6 AL, 4V titanium alloy (6% aluminum and 4% vanadium) or beryllium (99% pure) with a 0.76 inch diameter. The titanium bar is 72 in. long, and the beryllium bar is 50 in. long. The bar is supported in a way that allows it to move freely in the axial direction. A low pressure air gun is used to fire a 3 inch long hardened tool steel (for titanium) or magnesium (for beryllium) projectile at the end of the bar. This impact creates a stress pulse that propagates toward the opposite end of the Hopkinson bar. Regulating the air gun pressure that determines the impact speed controls the amplitude of the pulse. Placing a number of index cards on the impact surface controls the shape (approximately a half sine) and duration of the pulse. The LDV is located at the end of the beryllium bar on which the accelerometer is mounted and measures velocity at a point next to the accelerometer. This LDV with high frequency (up to 1.5 MHz) and high velocity (10 m/s) capability was purchased from a commercial source and has been certified by the Primary Electrical Standards Department at SNL. For the 1000 mm/s/V range (positive velocity), the total uncertainty with approximately a 95%

confidence level for the velocity is +5%. When the LDV is used over 90% of its range, this LDV has a +2-3% uncertainty for all specified frequencies and velocities. The uncertainty decreases for decreasing velocity scales. The LDV provides a reference velocity measurement for velocities up to 10 m/s and for frequencies up to 1.5 MHz. This reference measurement provides information in a bandwidth that is not available from strain gages that are generally considered to have a bandwidth of no greater than dc-40 kHz. Since these piezoresistive accelerometers and the Hopkinson bars have resonance at these high frequencies of 100's of kHz, the LDV is a useful diagnostic tool. Ref. [5] gives the details of the certification process.

All accelerometers in this study were calibrated in the SNL Calibration Laboratory using two methods: 1) shaker calibration and 2) dropball calibration. The two methods are traceable to the National Institute of Standards and Technology, NIST, formerly NBS as described elsewhere [13].

In-Axis Accelerometer Performance

To assess in-axis performance, the velocity (strain gages or LDV) and acceleration (accelerometer) records can be compared by converting to either velocity or acceleration as shown in (1) and (2). Hopkinson bar accelerometer calibration methods documented in the literature [14-17] generally use velocity, in which case the accelerometer record is integrated and compared directly to the strain record converted to velocity by the factor 2c. This provides smooth curves for comparison of time histories, however the higher frequency information is lost due to the integration process. Since it was desired to preserve the frequency response of the data, acceleration is used for the comparison of the data. Consequently, the time derivative of the strain records was required, and the resulting signal may be contaminated by high frequency noise created in the process of calculating the derivative. This problem was essentially eliminated by: 1) adequate sample rate of 500 kHz or higher; 2) low pass digital filtering with a cutoff frequency well above the frequency range of interest (10 kHz); and most importantly, 3) an accurate differentiation algorithm which was derived using the Fourier series reconstruction techniques in [17]. This algorithm results in an exact derivative of the digitized signal providing the Sampling Theorem has not been violated, that is, the data is not aliased [18]. With the reference acceleration and the accelerometer response, in-axis performance may be assessed in both the time-domain and the frequency domain.

Each mechanical configuration for the accelerometer was mounted directly to the end of a beryllium Hopkinson bar and subjected to shock pulses of about 40,000 g and 70,000 g with nominal pulse duration of about 15-20 μs in all cases. The magnitude of the accelerometer responses was compared to the acceleration magnitude derived from the LDV measurements. The results of these experiments are summarized in Table III. The percent deviations vary from 2% to 7% and no significant difference was observed in the two packages. Time history plots comparing the accelerometer response with the reference measurement, either strain gages or the LDV, are shown in Appendix A with their corresponding Fourier transforms. A resonance above 100 kHz for the can package is evident but not for the flat package. This resonance has been confirmed elsewhere in unpublished results. These results are similar to those obtained for the titanium Hopkinson bar in Table IV [4] and confirm the integrity of the beryllium Hopkinson bar configuration.

Table III: Percent Deviation Between Accelerometer and LDV Measurements with Beryllium Hopkinson Bar.

Accelerometer	40,000 g	70,000g
Can Package (1/4-28)	3%	2%
Flat Package (4-40)	4%	7%

Table IV: Percent Deviation Between Accelerometer and Strain Gage Measurements with Titanium Hopkinson Bar.

Accelerometer	10,000g	20,000g	50,000g
Can Package (1/4-28)	4%	6%	6%
Flat Package (4-40)	4%	3%	4%

Next, frequency response functions (frf's) were calculated for both accelerometer configurations for the shock levels of 40,000 g and 70,000 g with a nominal duration of 15 to 20 μs. The process of calculating these requires five consistent shocks at each level. The consistency of the time-domain domain data required for the frf calculation is demonstrated in Appendix A. The large deviations in the frf's beyond 10 kHz for titanium and 50 kHz for beryllium are caused by the loss of coherence and <u>not</u> an accelerometer response. Also, poor coherence, not the accelerometer, causes the low frequency deviations in the beryllium frf's. The frf's calculated for the ENDEVCO 7270A and 7270AM4 from data measured with both titanium and beryllium Hopkinson bars are shown in Appendix A.

The magnitude, phase and coherence of frequency response functions were calculated so that a quantitative evaluation could be made of the frequency response for the ENDEVCO 7270A and 7270AM4. The reference acceleration data, calculated from either strain gages or the LDV, and the accelerometer response data were used to calculate a frf, $H(j\omega)$, using the equations below [19].

$$H(j\omega) = \frac{H_1 + H_2}{2} \tag{4}$$

where,

$$H_1(j\omega) = \frac{\sum_{n=1}^{5} G_{xy}}{\sum_{n=1}^{5} G_{xx}} \tag{5}$$

and

$$H_2(j\omega) = \frac{\sum_{n=1}^{5} G_{yy}}{\sum_{n=1}^{5} G_{yx}} \tag{6}$$

and where G_{xy} is the cross-spectrum between the reference acceleration, x, and the accelerometer response, y; G_{yx} is the cross-spectrum between the accelerometer response, y, and the reference acceleration, x; G_{yy} is the auto-spectrum of the accelerometer response, y; and G_{xx} is the auto-spectrum of the reference acceleration, x. The frf, H_1 is biased by the error on the reference acceleration, and the frf, H_2 is biased by the error on the accelerometer response. The Hopkinson bar data for these frf calculations have noise on both the reference acceleration and the accelerometer response, so the average of the two frf's in (4) is used. The summations are performed for the ensemble of five reference accelerations and their corresponding accelerometer responses. The coherence, $\gamma^2_{xy}(j\omega)$, was also calculated for an ensemble of five data sets according to the equation [19],

$$\gamma^2_{xy}(j\omega) = \frac{H_1}{H_2} \tag{7}$$

as a measure of the linearity between the reference acceleration and the accelerometer response and of the noise in these data.

Hopkinson Bar Analysis for Cross-Axis Response

The axial motion, a, at a location in the Hopkinson bar other than the free end is

$$a = c\frac{d\varepsilon}{dt} \tag{8}$$

where ε is the axial strain. The radial motion, y, is

$$y = r\varepsilon_r \qquad (9)$$

where r is the radius of the Hopkinson bar and ε_r is the radial strain. Since the relationship between axial and radial strain is

$$\varepsilon_r = \mu\varepsilon \qquad (10)$$

where μ is Poisson's ratio, then the final expression for radial acceleration, a_y, is

$$a_y = \frac{\mu r}{c}\frac{da}{dt}. \qquad (11)$$

A prediction of the axial and radial acceleration for the beryllium Hopkinson bar using the equations above is shown in Figure 9. Strain measurements co-located with the accelerometers for the flat package insert of Figure 5 in the split Hopkinson bar configuration are shown in Figures 10 and 11 and indicate a Poisson's ratio of about 0.07.

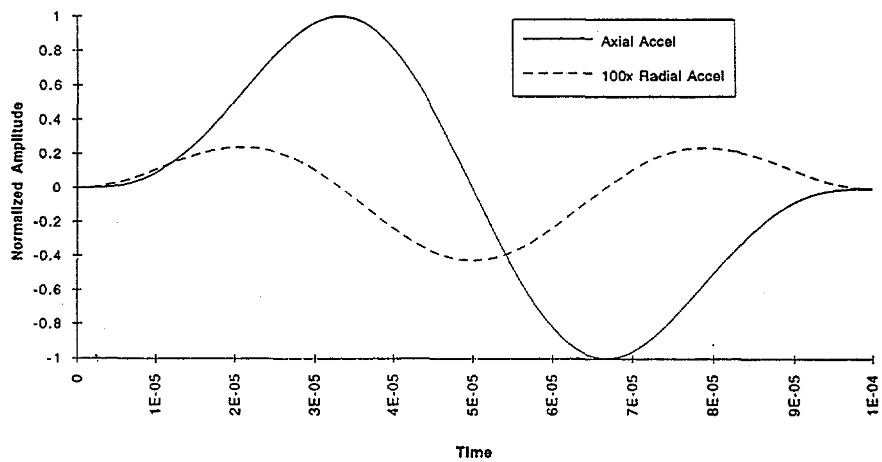


Figure 9: Theoretical Prediction of Axial and Lateral Accelerations for the Beryllium Hopkinson Bar.

Cross-Axis Accelerometer Performance

Two accelerometer responses measured on the insert are shown in Appendix B. This response is base strain dominated because it does not correspond to either of the curves in Fig. 9 but follows the general shape of the lateral strain response in

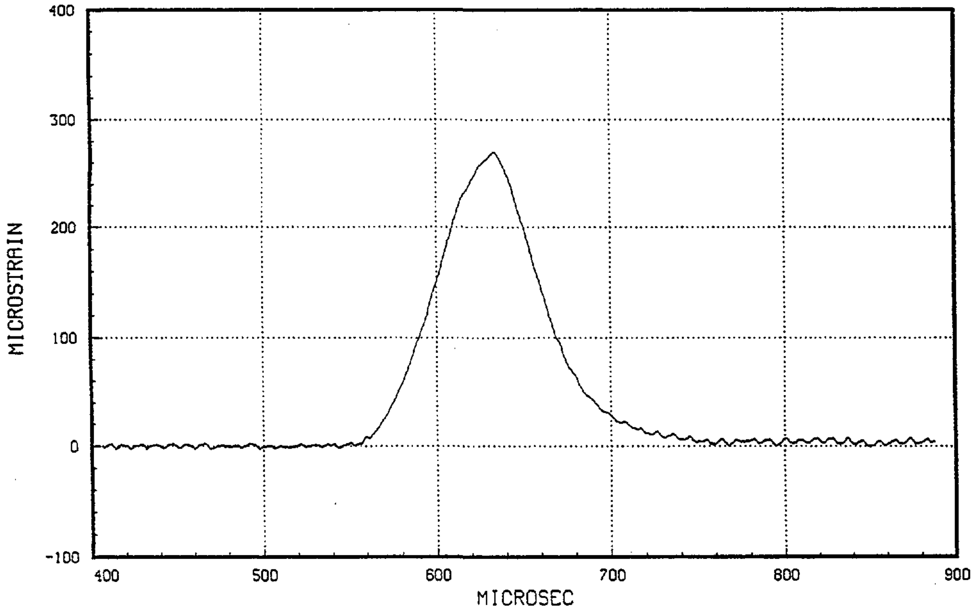


Figure 10: Axial Strain Response to Compressive Shock on the Beryllium Insert (0.75 in. Diameter).

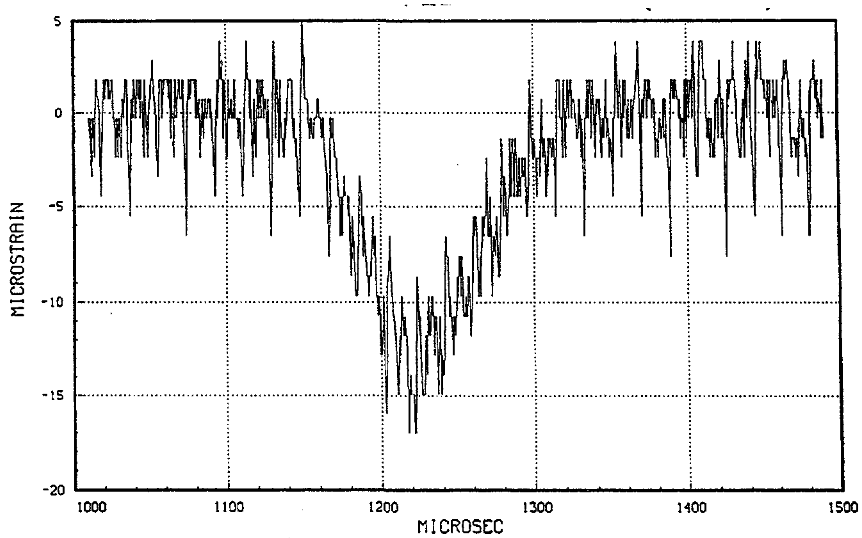


Figure 11: Lateral Strain Response to Compressive Shock on the Beryllium Insert (0.75 in. Diameter).

Fig. 10. A compressive static load was applied to the insert with the results shown in Fig. 12 (strain) and Appendix B (accelerometer response). Since the sensitivity of the accelerometer is approximately 1 μV/g and the applied strain was about 250 με, these results are consistent with the manufacturer's specifications of <0.5 mv output for a strain of 250 με. The orientations of the sensor in the two mechanical packages are shown in Figure 13. The precise orientation in the 7270AM4 allowed orientation of the sensor with the beams in line with the shock and oriented at 90° to the shock, and the results are shown in Appendix B.

The characterization of the cross-axis response of the ENDEVCO 7270A and 7270AM4 accelerometers continued in the four environments of static strain on a beam of 250 με; dynamic beam strain experiments at 250 με (as per ISA-RP 37.2, Paragraph 6.6); and static compression experiments up to 100 με and mechanical compressive shock with a 2 in. diameter split Hopkinson bar configuration. The larger diameter beryllium hardware allows the investigation of more orientations of the accelerometers. The orientation of the sensors for the static compression and mechanical compressive shock cross-axis experiments are shown in Figure 6. Radial strain measurements verified the performance of the beryllium. For the static and dynamic base strain experiments, a steel beam as specified in ISA-RP 37.2, Paragraph 6.6 was used. This recommended practice creates maximum surface strain at the fixed end of a cantilever beam. The transducers are mounted at this location and subjected to base strain. The base strain is one-dimensional surface strain because the beam has a very large radius of curvature that minimizes the motion at the transducer and the centrifugal acceleration, $r\omega^2$. The results of the static compression, static beam, and dynamic beam strain are shown in Tables V-VII, respectively. The response of the accelerometers in these three environments is a base strain response and is consistent with the manufacturer's specifications of <0.5 mv output for a strain of 250 με. Raw data for the static compression strain are shown in Appendix B.

The ENDEVCO 7270A (flat package) shows a base strain response when subjected to a compressive mechanical shock. The ENDEVCO 7270AM4 (can package) shows a base strain response when the beams are in line to the shock and an acceleration response when the beams are in other orientations to the shock. Time history plots of these responses are shown in Appendix B. These data have a 20 kHz frequency component that is the first axial mode of the insert. The data cannot be filtered to eliminate this resonant response without severely compromising the rise time of the initial response.

Table V: Static Base Strain Results.

Accelerometer Type	Orientation	Torque (in-lb)	Strain Sensitivity (g/με)	Voltage output at 250 με (mv)
7270AM4-200K	80°	75	0.5816	0.187
7270AM4-200K	25°	75	0.0612	0.019
7270A-60K	In Line	9	0.1531	0.064
7270A-60K	45°	9	0.4184	0.166
7270A-60K	90°	9	0.3061	0.124

Table VI: Static Beam Results.

Accelerometer Type	Orientation	Torque (in-lb)	Strain Sensitivity (g/με)	Voltage output at 250 με (mv)
7270AM4-200K	In Line*	75	3.2260	1.090
7270AM4-200K	15°	75	0.2368	0.080
7270A-60K	In Line	9	0.4232	0.175
7270A-60K	45°	9	0.6772	0.280
7270A-60K	90°	9	0.0943	0.039

* 0.009 in shim

Table VII: Dynamic Beam Strain Results.

Accelerometer Type	Orientation	Torque (in-lb)	Strain Sensitivity (g/με)	Voltage output at 250 με (mv)
7270AM4-200K	In Line*	75	3.1370	1.060
7270AM4-200K	15°	75	0.5387	0.182
7270AM4-200K	15°	30	0.1717	0.058
7270A-60K	In Line	9	0.3918	0.162
7270A-60K	90°	9	0.0435	0.018
7270A-60K	45°	9	0.5804	0.240

* 0.009 in shim

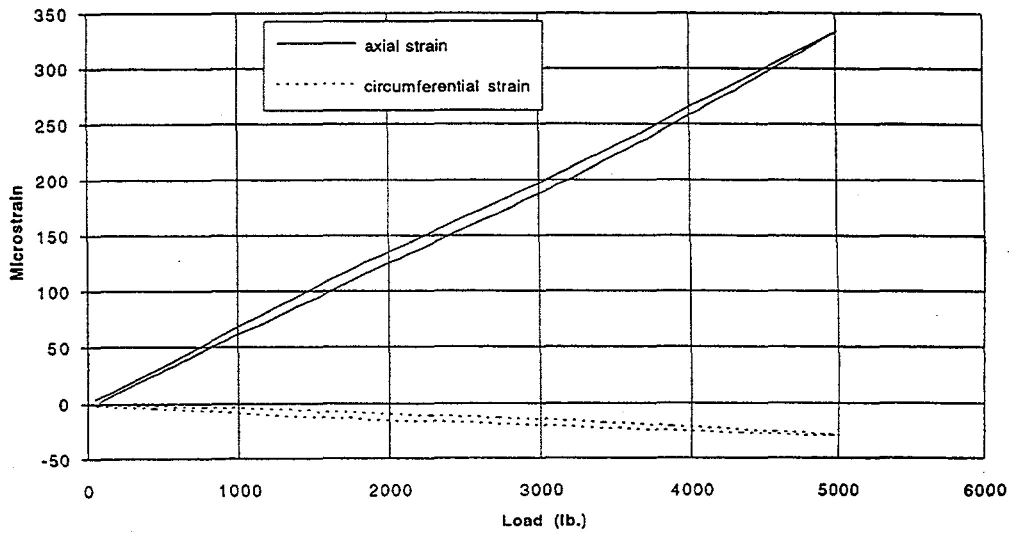
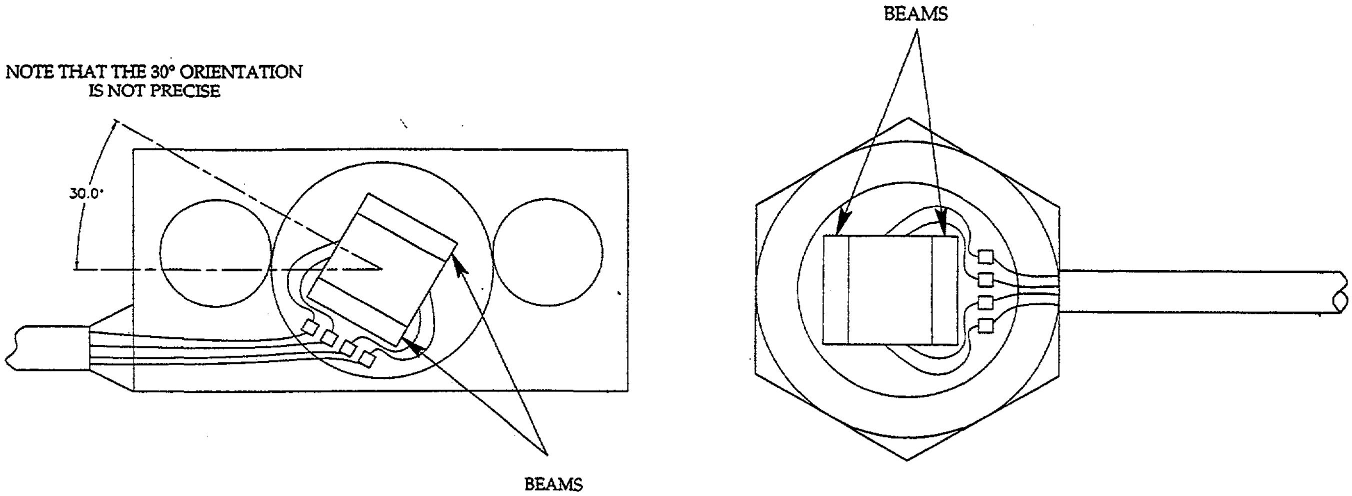


Figure 12: Strain Response for a Compressive Static Force Applied to the Beryllium Insert.



a) ENDEVCO 7270A **b) ENDEVCO 7270AM4**

Figure 13: Orientation of the Sensor in the ENDEVCO 7270A and the ENDEVCO 7270AM4.

Combined Shock Environment Performance

The ENDEVCO 7270A and 7270AM4 accelerometers were mounted on their respective titanium Hopkinson bar shown in Figures 7 and 8. The nominal amplitude of the applied shock pulse was measured with both the references of strain gages and the LDV and agreed within 1%. The results are shown in Table VIII, and time history plots are in Appendix B. Only one measurement from the 7270AM4 was obtained because the other accelerometer resonated and failed. Both the screws for the 7270A and the stud for the 7270AM4 had backed out after the shock pulse. The loose accelerometers chattered on their flats and caused the accelerometers to resonate. It is hypothesized that the ends modes of the bar caused the screws/stud to loosen. ENDEVCO has donated two accelerometers so that SNL can investigate this problem.

Table VIII: Summary of Accelerometer Performance in Combined Shock.

Nominal Amplitude	Accelerometer Model	In-Axis Ampltide	Accelerometer Response	Percentage Error
49,500 g	7270AM4	35,000 g	37,500 g	+ 7.1%
50,000 g	7270A	35,350 g	37,000 g	+ 4.7%
50,000 g	7270A	35,350 g	39,000 g	+10.3%

Failure Mode Analysis

On June 6, 1998, twenty-seven Model 7270A (flat package) accelerometers were given to ENDEVCO for failure analysis. Sixteen of the twenty-seven accelerometers had equal input/output resistances indicated that the sensors were intact; their failure mode is assumed to be cable failure. The remaining eleven accelerometers had specific complaints, including cable failure, as noted in Table IX. Three of the accelerometers showed evidence of exposure to high temperature or an electromagnetic environment because parts of the sensor were melted. These three accelerometers were purchased by Eglin AFB. The failure analyses performed in cooperation with ENDEVCO have provided a great insight as to the failure modes of the 7270A. ***The overwhelming majority of the failures are due to cable failure that is explained below.***

During a SNL program to develop a transducer with high input impedance, a response was measured that did not appear to originate with the sensor. The cable used with the transducer is the ENDEVCO 7270A cable. This cable is silverplated, 36 gage copper conductors with a silverplated-copper shield and fluorocarbon jacket. The cable was taped to a titanium Hopkinson bar with a 0.75 in. diameter and a 72 in. length as shown in Figure 14. All investigations were conducted at a nominal velocity of 10 fps magnitude and 90 μs duration (measured at 10% amplitude). An amplifier gain of 50 was used unless otherwise noted, and an excitation of 10 V. was provided on the black and red wires unless otherwise noted. The results of this investigation are summarized in Table X. These investigations show that the cable generates its own voltage output when it is subjected to a shock in line with the cable. This cable response can be as much as 10% of the transducer output. ***It is hypothesized that the movement of the wires inside their insulation causes the cable output. The movement of the wires eventually breaks the wires that can be misinterpreted as sensor failure***. The cable is subjected to shock in most applications because the cables are secured to a structure that undergoes a shock environment. These investigations explain not only the failure mode of the cable, but also mysterious transducer output without excitation from other shock experiments. It has been recommended to ENDEVCO that a methodology for isolating the cable from shock waves be developed in cooperation with SNL.

Table IX: Failure Analysis of Eleven ENDEVCO 7270A Accelerometers.

Model, S/N	Complaint	Action
7270A-20K AG5L3	Resonant frequency ringing during applied shock pulse.	Shocked unit at 4908 g; slight after pulse ringing present (typical output) Sens. 10.25 µV @ 0.171 mS, ZMO 41.8 mV
7270A-20K A19YF	No output: unit gauge resistance values change when tapped on bench. (i.e. R-W gage 17Ω before, 496Ω after)	Could not duplicate changing gage resistance. Shocked at 4850 g, output normal. Sens. 9.646 µV @ 0.174 mS, ZMO 22.6 mV; Zin/Zout = 605/604
7270A-20K AG502	dc offset shifts with cable movement	Verified complaint. Circuit open at G-B when cable is bent in a cross-axis direction, away from the serial number face. (otherwise output is 73.5 mV)
7270A-20K B91AF		All four gages intact. BW trace on ceramic open!!
7270A-20K B72CF	Purchased by Eglin AFB.	GB links all have tiny pimples at mid-length. Fused one downside gage.
7270A-60K A51KF	Displays ringing during dropball calibration.	Shocked 5 times between 4259 and 4880 g. Only showed typical after-pulse resonant frequency ringing. Sens. 1.738 µV @ 0.171 mS, ZMO -81.6 mV
7270A-200K AFFH2	Open - Purchased by Eglin AFB.	One link of GB fused. Adjacent links & aluminum have been melted.
7270A-200K AP693	Open	One link of WG broken, piece missing. Another edge flaked by shrapnel.
7270A-200K AD288	Open	Masses loose.
7270A-200K A44BF	No output	Failed glassbond. Gross die fracture, additional crack. INCLUSION IN GLASSBOND.
7270A-200K DN81F	No output - Purchased by Eglin AFB.	Severe ohmic heating to GB. 6 links vaporized, remaining 2 links shorted by fused Silicon. Traces leadwire to GB deeply melted.

Table X: Hopkinson Bar Cable Investigation Summary.

No.	Description	Results
1	Cable taped to the bar. Cable shield also tied to the bar. Cable conductors connected to amplifier as shown.	Oscillatory output with a period of about 500 μs (2kHz) and peak magnitude of 8.3 V.
2	Same as No. 1 but no excitation voltage.	Oscillatory output with a period of about 350 μs (3 kHz) and peak magnitude of 10.1 V. **This means the output is self-generated.**
3	Same as No. 1 with green and white wires disconnected from the amplifier input. (Excitation voltage is still applied.)	Oscillatory output with a period of about 350 μs (3 kHz) and peak magnitude of 2.0 V. **Output is capacitive coupling through remaining wires.**
4	Same as No. 1 but all conductors disconnected from the amplifier. Cable shield is still connected as shown.	Oscillatory output with a period of about 350 μs (3 kHz) and peak magnitude of 0.1 V.
5	Same as No. 4 but cable shield is also disconnected.	Output is amplifier drift only - magnitude is about 40 mV or 0.8 mV peak before gain. **This is the open circuit, baseline noise.**
6	A low impedance transducer (350Ω bridge) is connected to the end cable and powered. The cable is taped to the bar as before. Transducer is just hanging in the air. Shield is connected as shown.	Oscillatory output with an irregular period and a peak magnitude of 125 mV peak-to-peak. Baseline noise has dropped to 3 mV. **The 125 mV represents about 10% of the transducer response for this stress wave.**
7	Same as No. 2 with the shield disconnected.	Oscillatory output with a period of about 1200 μs (833 Hz) and peak magnitude of ±2 V.
8	Repeat of No. 2.	Oscillatory output with a period of about 350 μs (3 kHz) and peak magnitude of 16.3 V.
9	Same as No. 8 but cable removed from the bar and hangs by the bar in the air.	Output is amplifier drift only - magnitude is about 100 mV per 1 ms.
10	Same as No. 9 with no bar impact (baseline noise plots).	Output is amplifier drift only - magnitude is about 40 mV or 0.8 mV prior to amplifier gain.
11	Repeat of No. 2 with a longer duration pulse (169 μs) created by the use of 0.0625 in. thick felt instead of the index cards used for the previous	Oscillatory output with a period of about 350 μs (3 kHz) and peak magnitude of 14.8 V.

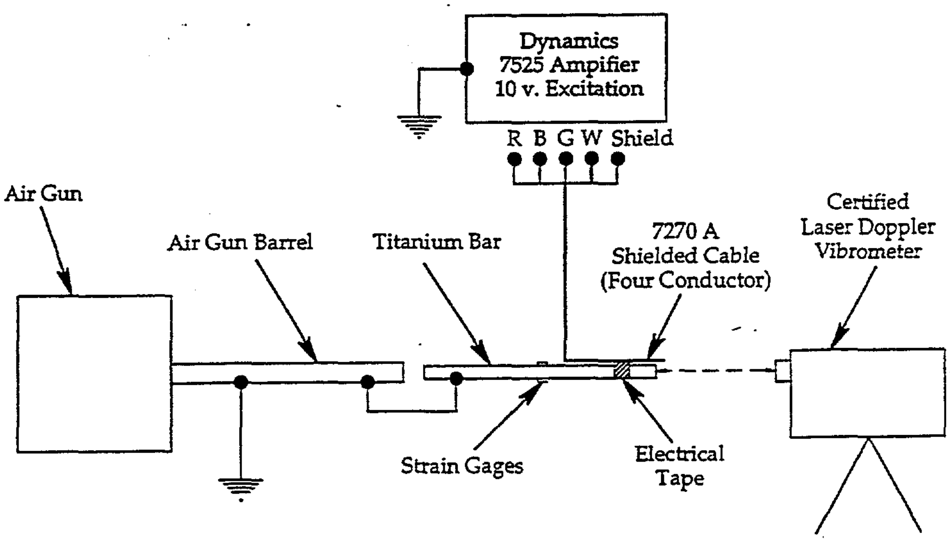


Figure 14: Hopkinson Bar Configuration for Cable Response Investigations.

Conclusions and Future Work

Results in this report show the ENDEVCO 7270A and 7270AM4 are similar in response for in-axis shocks with the exception of a resonance noted in the can package at about 100 kHz that is not apparent in the flat package. The in-axis characterizations include both time-domain results with a bandwidth of from dc to 100 kHz and frequency-domain results with a bandwidth of from dc to 50 kHz. The results of the in-axis studies for these two accelerometers confirm the manufacturer's performance specifications for the accelerometers that were previously unconfirmed.

The characterization of the cross-axis response of the ENDEVCO 7270A and 7270AM4 accelerometers in the four environments of static compression experiments up to 100 $\mu\varepsilon$; static strain on a beam of 250 $\mu\varepsilon$, dynamic beam strain experiments at 250 $\mu\varepsilon$ (as per ISA-RP 37.2, Paragraph 6.6), and mechanical compressive shock with split beryllium Hopkinson bar configuration have been completed. The cross axis response of the ENDEVCO 7270A is base strain sensitive, but the cross-axis response of the ENDEVCO 7270AM4 may be either base strain or acceleration. The accelerometer meets the manufacturer's specifications for base strain and cross axis sensitivity.

The characterization of the ENDEVCO 7270A and 7270AM4 accelerometers in a combined shock environment at 45° has been completed. In every case, the accelerometer response was amplified by 4% to 10% in comparison to the reference measurement. The amount of amplification depends on both the mechanical package and orientation of the sensor to the shock. Since the accelerometers resonated and some failed in this environment, ENDEVCO has donated two accelerometers so that SNL can continue this part of the study.

Finally, a failure analysis conducted in cooperation with ENDEVCO gives a cause for the occasional unexplained failures that make this piezoresistive accelerometer questionable for some applications. When this analysis is combined with SNL measurements of the cable response in shock environments, a scenario emerges that explains mysterious unpowered accelerometer outputs and accelerometer failures. A configuration to apply simultaneous, perpendicular shocks is being constructed at the SNL Mechanical Shock Laboratory and will be used to continue the investigation of the failure modes for this accelerometer. These characterizations, accomplished at the high frequencies and high shock levels, will permit better interpretation of data measured in the presence of high frequency, high shock environments.

References

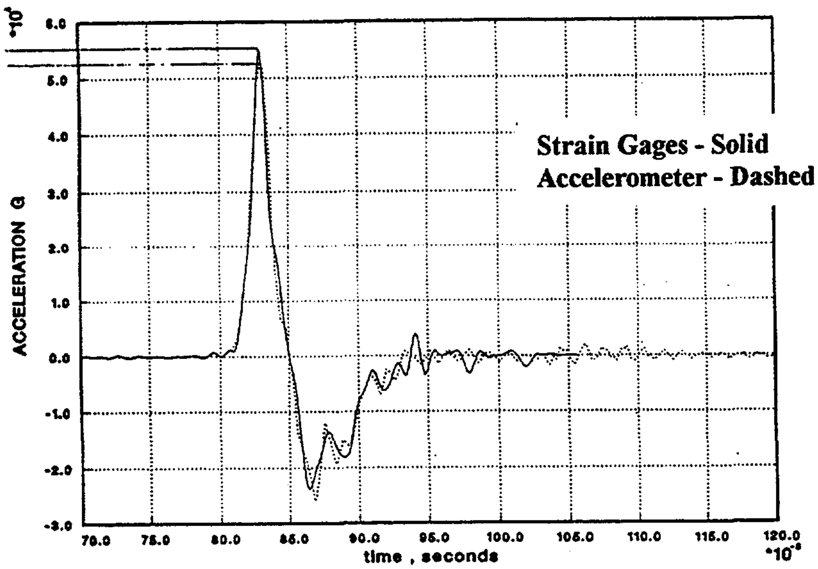
1. Walton, Scott W., "New Ballistic Shock Protection Requirement for Armored Combat Vehicles," 60th Shock and Vibration Symposium, Vol. 1, November 1989.
2. Walton, Scott W., "The Significance of Shock Content Above 10kHz on Equipment," 63rd Shock and Vibration Symposium, Vol. 1, November 1992.
3. Walton, Scott W., "Methodology Investigation Final Report of Correlation of Component Damage to Ballistic Shock II," U.S. Army Combat Systems Activity, Aberdeen Proving Ground, MD, TECOM Report No. 7-CO-M91-CSD-004, Report No. CSTA-7241.
4. Bateman, V. I., N. T. Davie, and F. A. Brown, "Characteristics of a Piezoresistive Accelerometer in Shock Environments up to 150,000 G," Proceedings of the 41st Annual Technical Meeting, Anaheim, CA, April 30-May 5, 1995, DT&E Volume, pp. 217-224.
5. Bateman, V. I., W. B. Leisher, F. A. Brown, and N. T. Davie, "Calibration of a Hopkinson Bar With a Transfer Standard," Journal of Shock and Vibration, Vol. 1, No. 2, November-December, 1993, pp. 145-152.
6. Bateman, V. I., B. D. Hansche, and O. M. Solomon, "Use of a Laser Doppler Vibrometer for High Frequency Accelerometer Characterizations," Proceedings of the 66th Shock and Vibration Symposium, Vol. II, October 30 -November 3, 1995, pp. 203-216.
7. Bateman, V. I., F. A. Brown, and N. T. Davie, "Use of a Beryllium Hopkinson Bar to Characterize a Piezoresistive Accelerometer in Shock Environments," Journal of the Institute of Environmental Sciences, Volume XXXIX, No. 6, November/December 1996, pp. 33-39.
8. Umeda, Akira and Kazunaga Ueda, "Study on the Dynamic Force/Acceleration Measurements," Sensors and Actuators, A21-A23, 1990, pp. 285-288.
9. Ueda, K., and A. Umeda, "Characterization of Shock Accelerometers Using Davies Bar and Strain Gages," Experimental Mechanics, September 1993, pp. 228-233.
10. Togami, T. C., V. I. Bateman, and F. A. Brown, "Evaluation of a Hopkinson Bar Flyaway Technique for High Amplitude Shock Accelerometer Calibration," Proceedings of the 68th Shock and Vibration Symposium, Vol. II, November 3-7, 1997.
11. Davies, R., "A Critical Study of the Hopkinson Pressure Bar," Philosophical Transactions, Series A, Royal Society of London, Vol. 240, pp. 352-375, January 8, 1948.
12. Kolsky, H., Stress Waves in Solids, Oxford University Press, 1953.
13. Bateman, V. I., R. G. Bell, and N. T. Davie, "Evaluation of Shock Isolation Techniques for a Piezoresistive Accelerometer," Proceedings of the 60th Shock and Vibration Symposium, David Taylor Research Center, Portsmouth, VA, November 1989.

References (cont.)

14. Cannon, J. and D. Rimbey, "Transient Method of Calibrating a Piezoelectric Accelerometer for the High g-level Range," American Society of Mechanical Engineers No. 71-Vibr-43, ASME Vibrations Conference and the International Design Automation Conference, September 1971, Toronto, Canada.
15. Brown, G., "Accelerometer Calibration with the Hopkinson Pressure Bar," Instrument Society of America preprint No. 49.3.63, 18th Annual ISA Conference and Exhibit, September 1963, Chicago, Illinois.
16. Sill, R. D., "Shock Calibration of Accelerometers at Amplitudes to 100,000 g Using Compression Waves," Proceedings of the 29th International Instrument Symposium, Albuquerque, NM, May 2-6, 1983, pp. 503-516.
17. Stearns, S. D., "Integration and Interpolation of Sampled Waveforms," SAND77-1643, Sandia National Laboratories, January 1978.
18. Stearns, S. D., Digital Signal Analysis, Hayden Book Company Inc., 1975, pp. 37-40.
19. Bendat, J. S. and A.G. Piersol, Random Data, 2nd Edition, John Wiley and Sons, 1986, pp.164-185.

Appendix A

In-Axis Performance of the Piezoresistive Accelerometer



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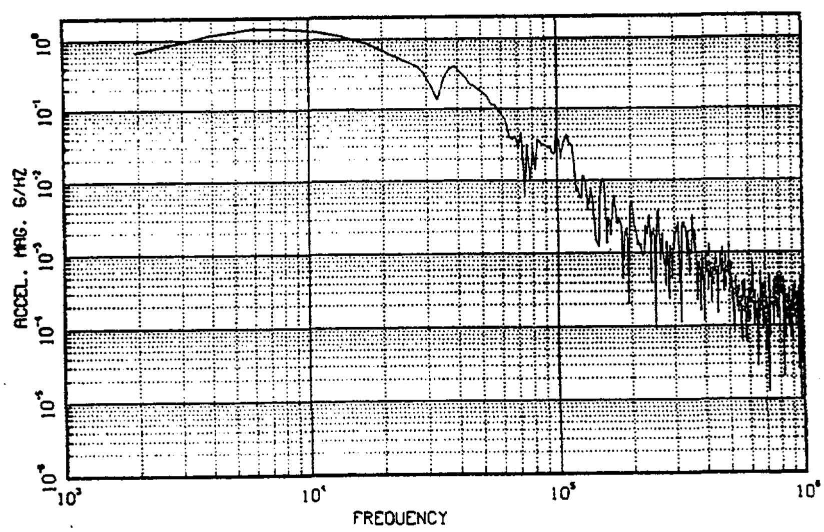
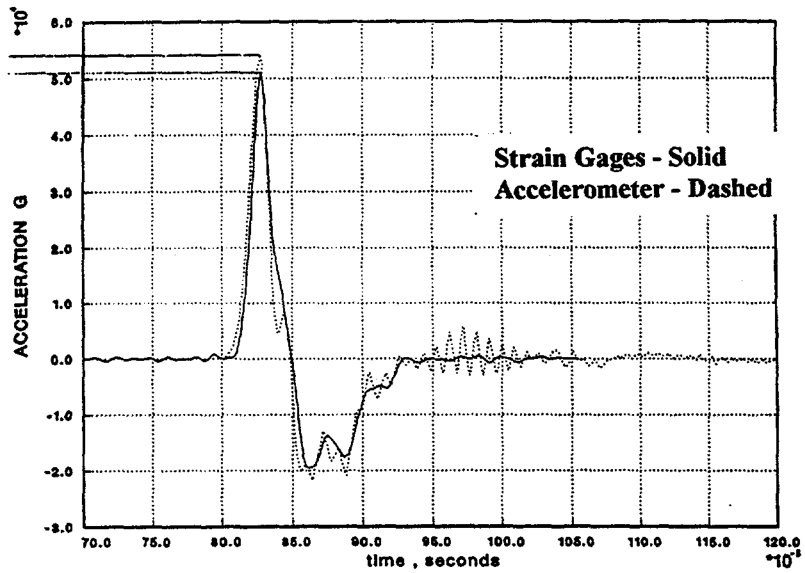


b) Fourier Transform

Time History and Fourier Transform for the ENDEVCO 7270A Mounted on a 0.75 in. Diameter Titanium Hopkinson Bar.



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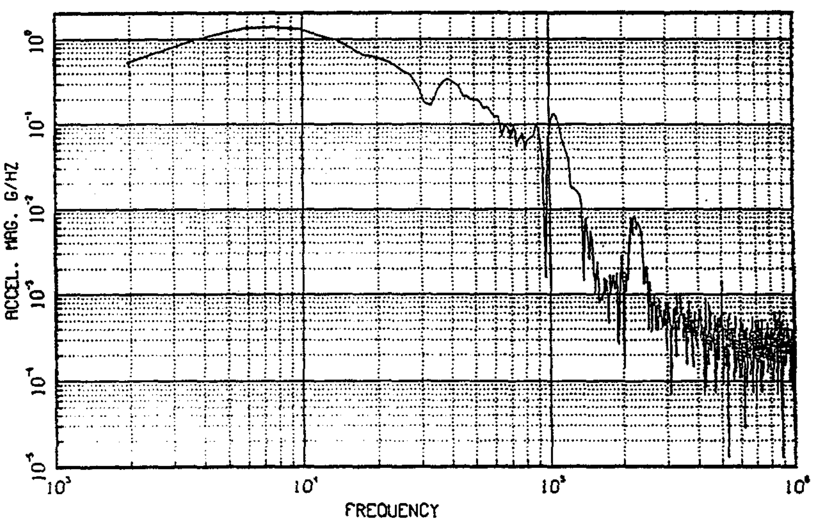
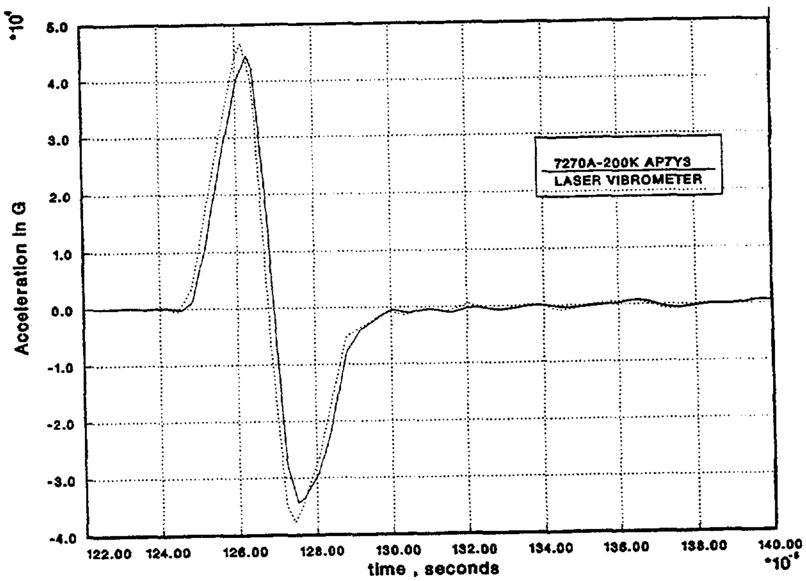
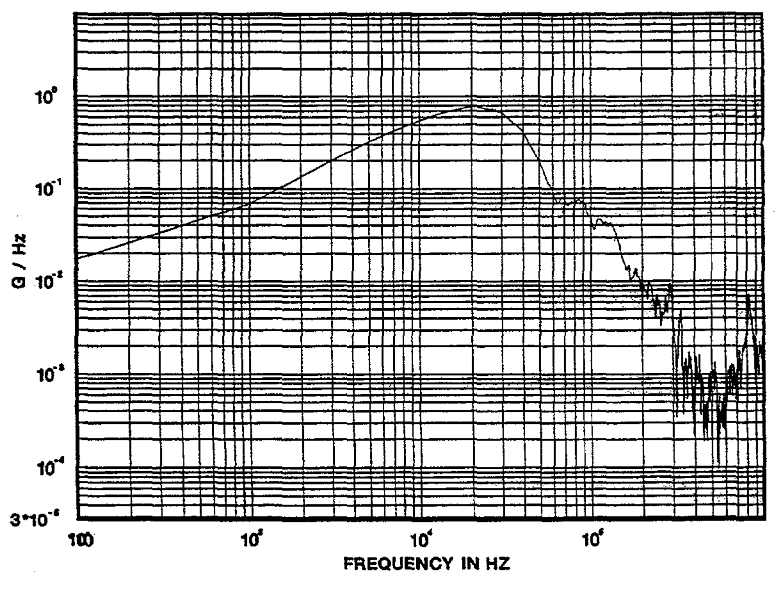


b) Fourier Transform

Time History and Fourier Transform for the ENDEVCO 7270AM4 Mounted on a 0.75 in. Diameter Titanium Hopkinson Bar.

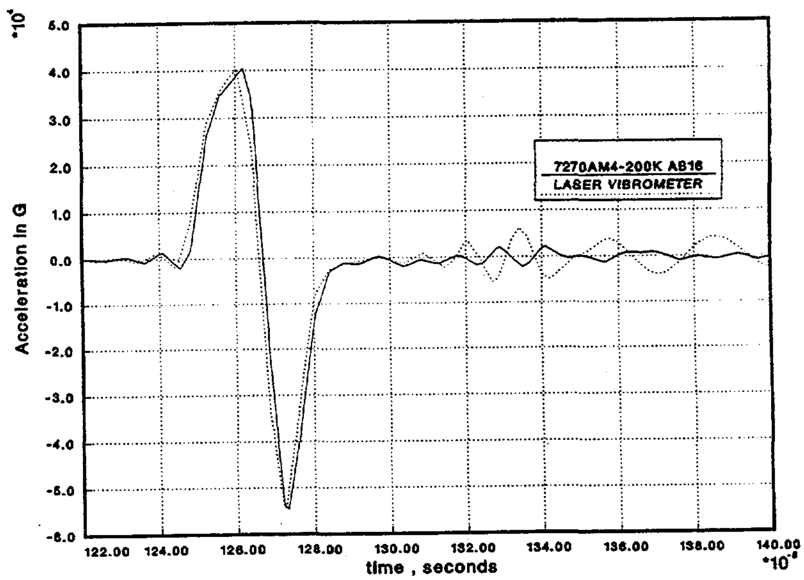


a) Time History

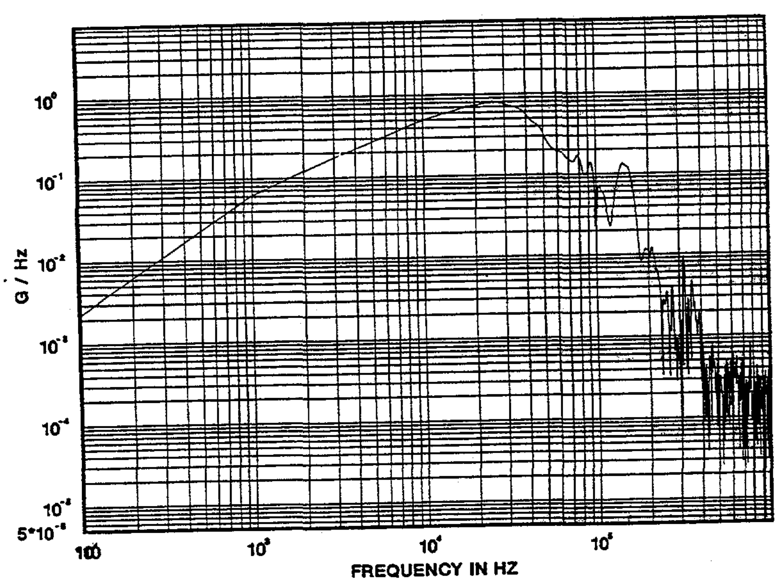


b) Fourier Transform

Time History and Fourier Transform for the ENDEVCO 7270A Mounted on a 0.75 in. Diameter Beryllium Hopkinson Bar.

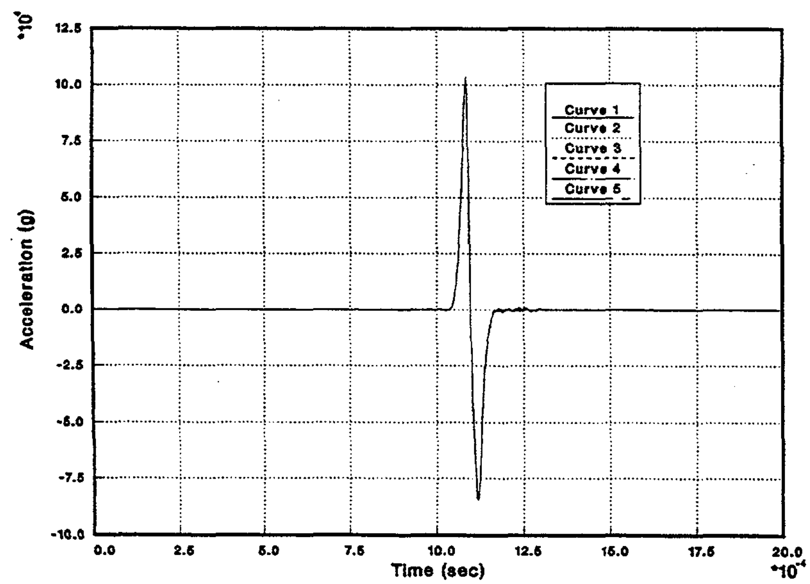


a) Time History

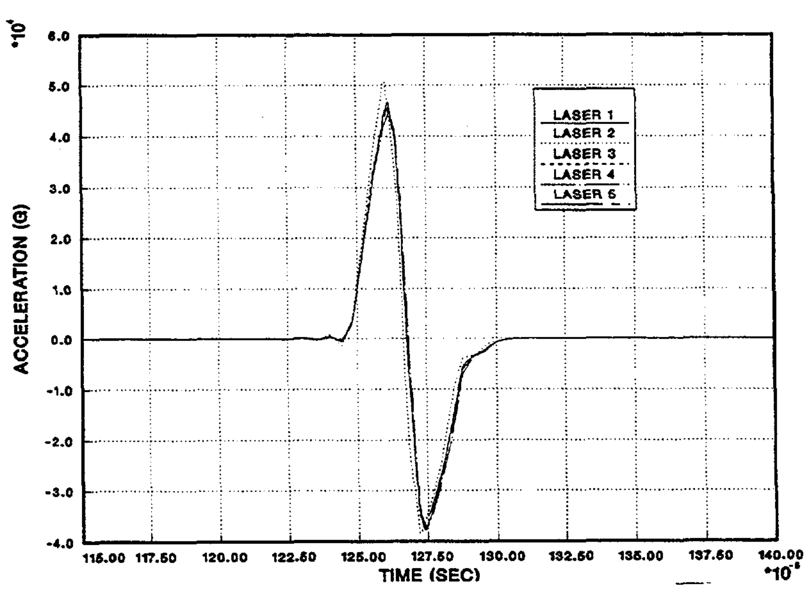


b) Fourier Transform

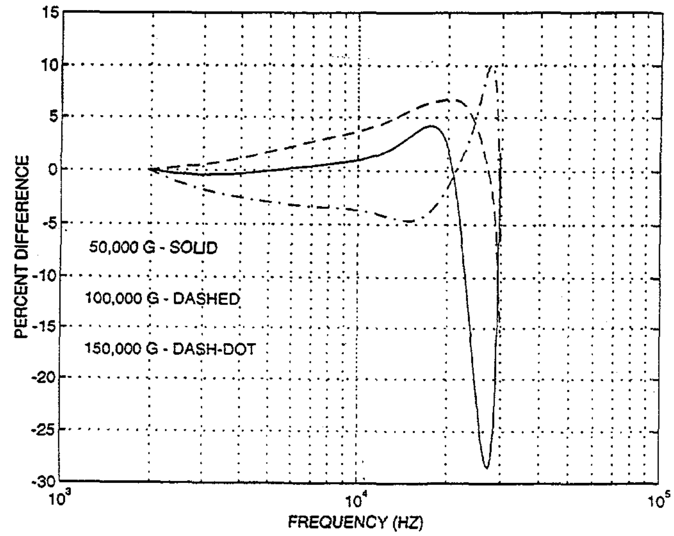
Time History and Fourier Transform for the ENDEVCO 7270AM4 Mounted on a 0.75 in. Diameter Beryllium Hopkinson Bar.



Five Accelerometer Responses Measured on the Titanium Hopkinson Bar at 100,000 g.



Five Laser Doppler Vibrometer Accelerations Calculated from Responses Measured on the Beryllium Hopkinson Bar at 40,000 g.



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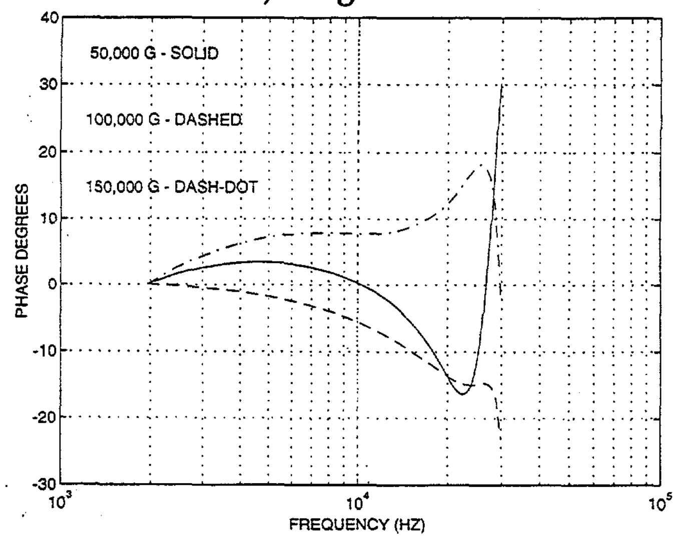
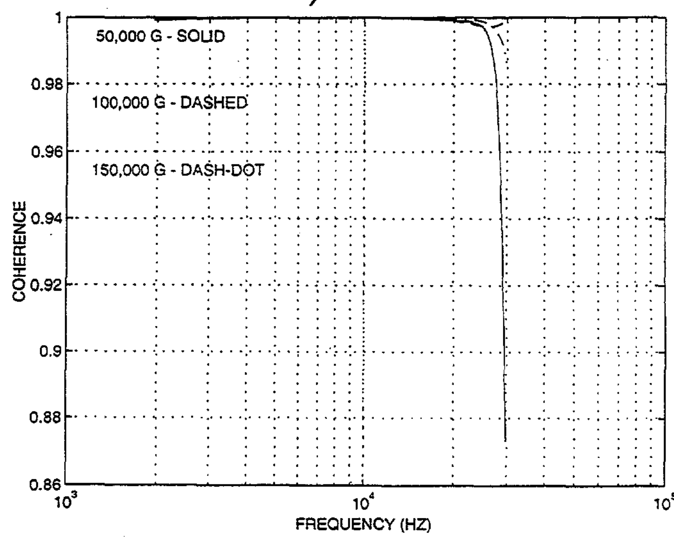
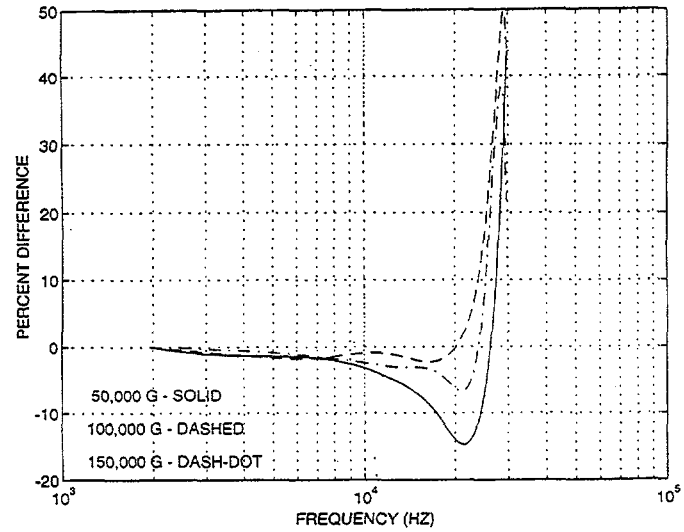


b) Phase

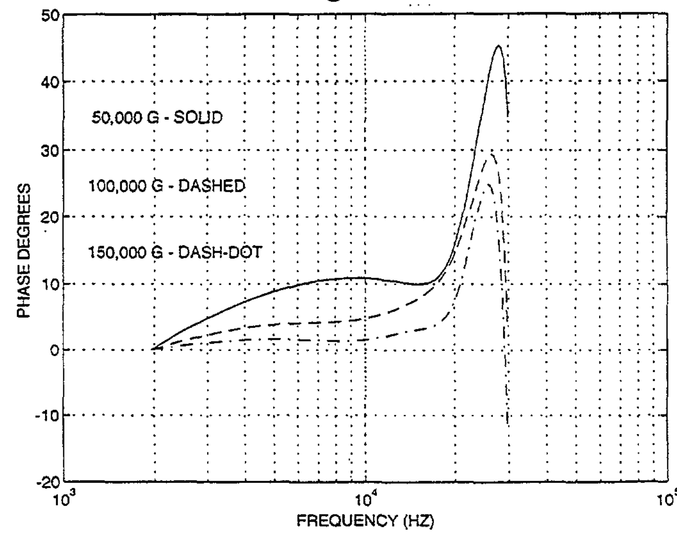


c) Coherence

Frequency Response Functions for the ENDEVCO 7270A Mounted on a 0.75 in. Diameter Titanium Hopkinson Bar.



a) Magnitude



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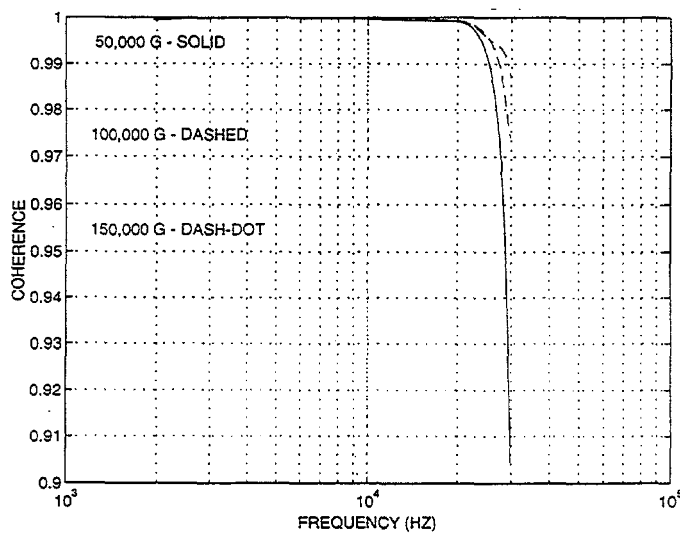
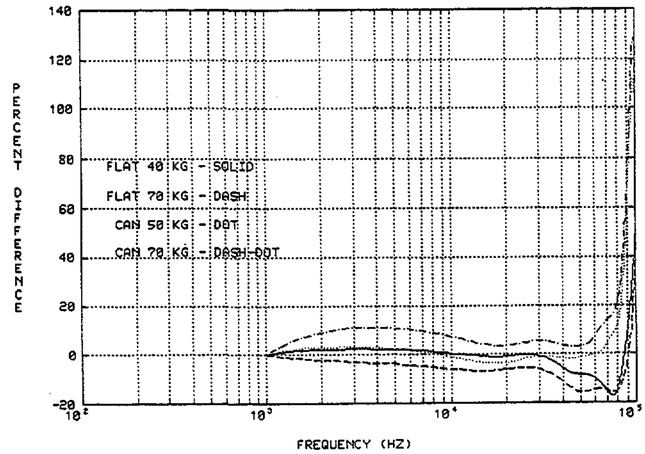
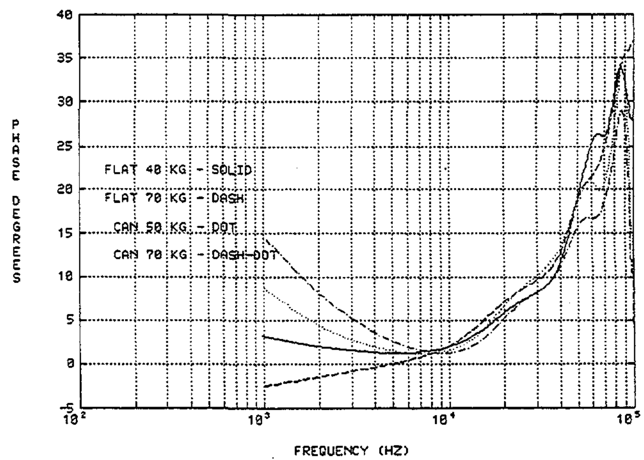


c) Coherence

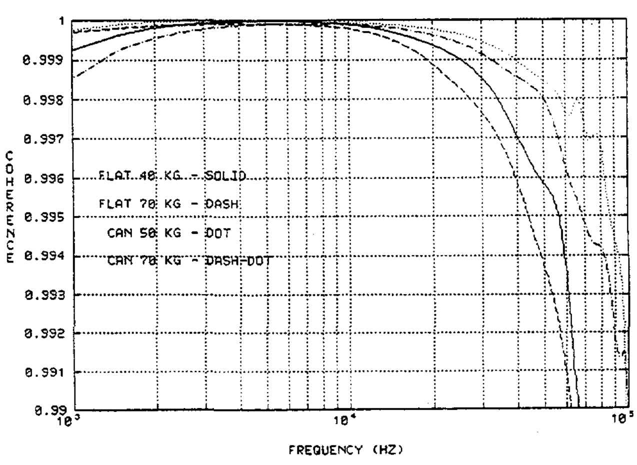
Frequency Response Functions for the ENDEVCO 7270AM4 Mounted on a 0.75 in. Diameter Titanium Hopkinson Bar.



a) Magnitude



b) Phase

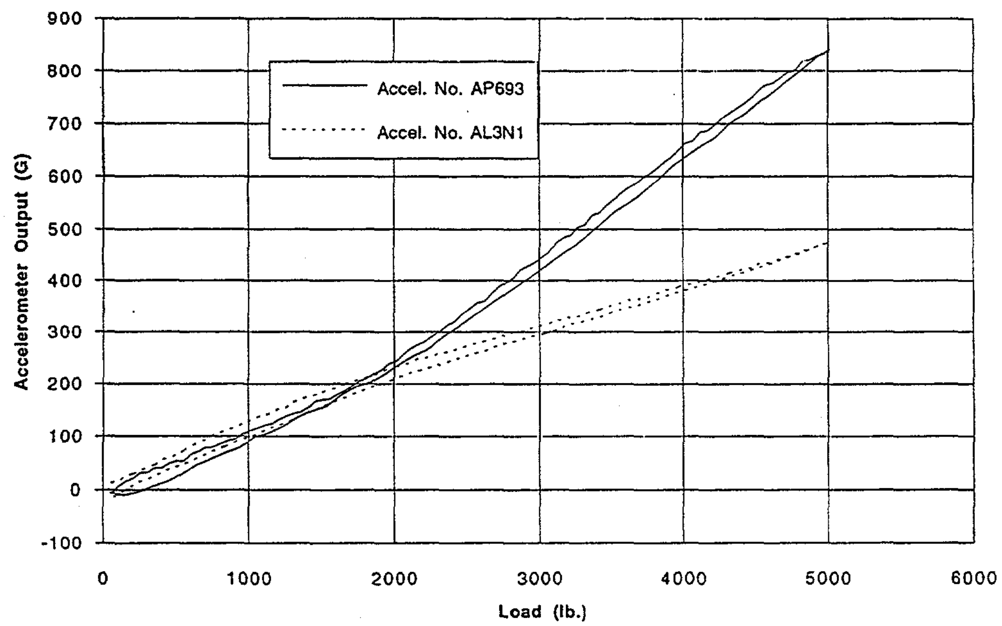


c) Coherence

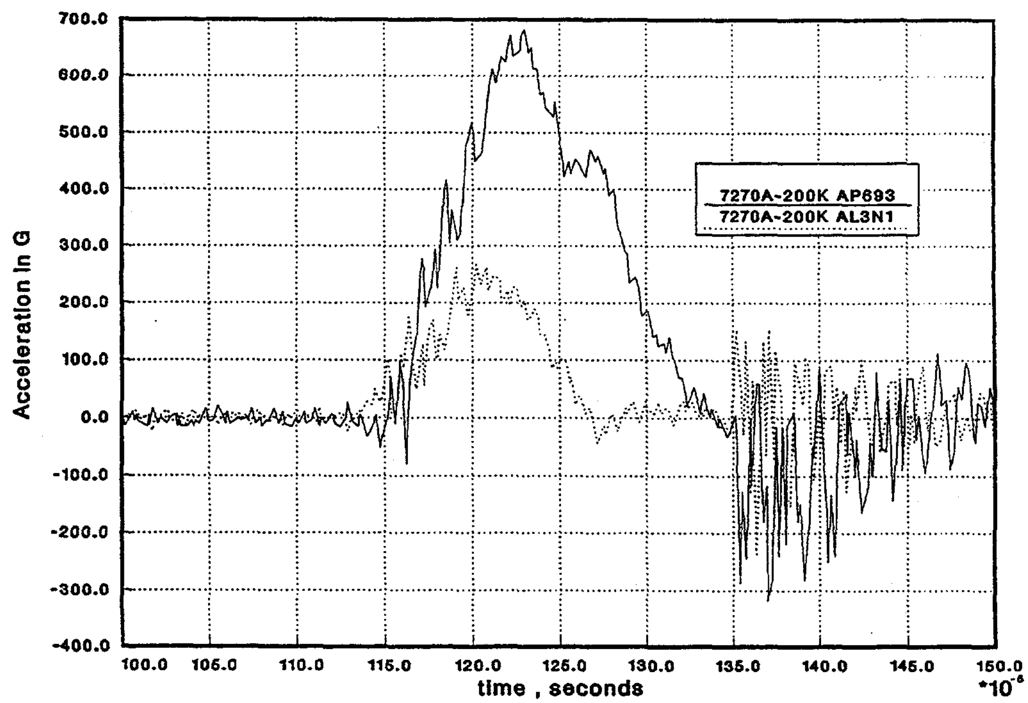
Frequency Response Functions for the ENDEVCO 7270AM4 and the ENDEVCO 7270A Mounted on a 0.75 in. Diameter Beryllium Hopkinson Bar.

Appendix B

Cross-Axis Performance of the Piezoresistive Accelerometer

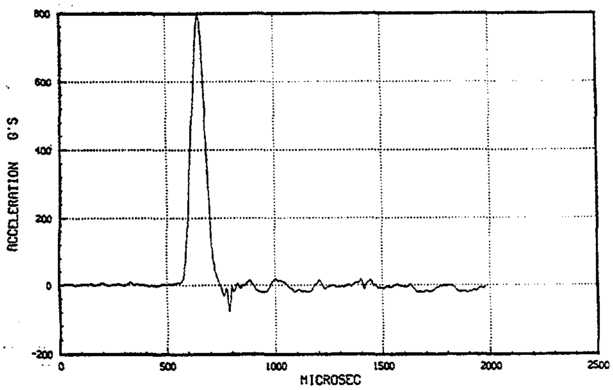


ENDEVCO 7270A Response for a Static Strain (250 με Amplitude) Applied to the Beryllium Insert (0.75 in. Diameter).



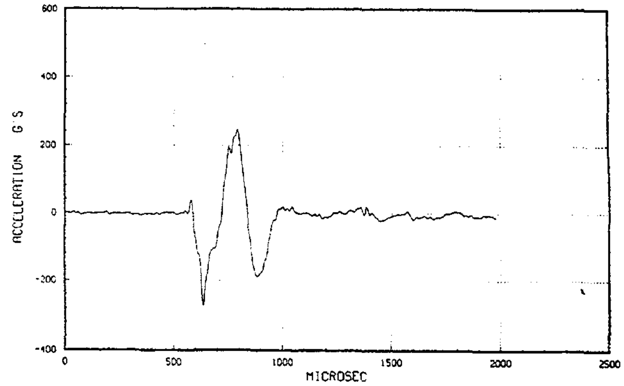
ENDEVCO 7270A Response for a Compressive Shock Applied to the Beryllium Insert (0.75 in. Diameter).

BEAMS IN LINE TO SHOCK



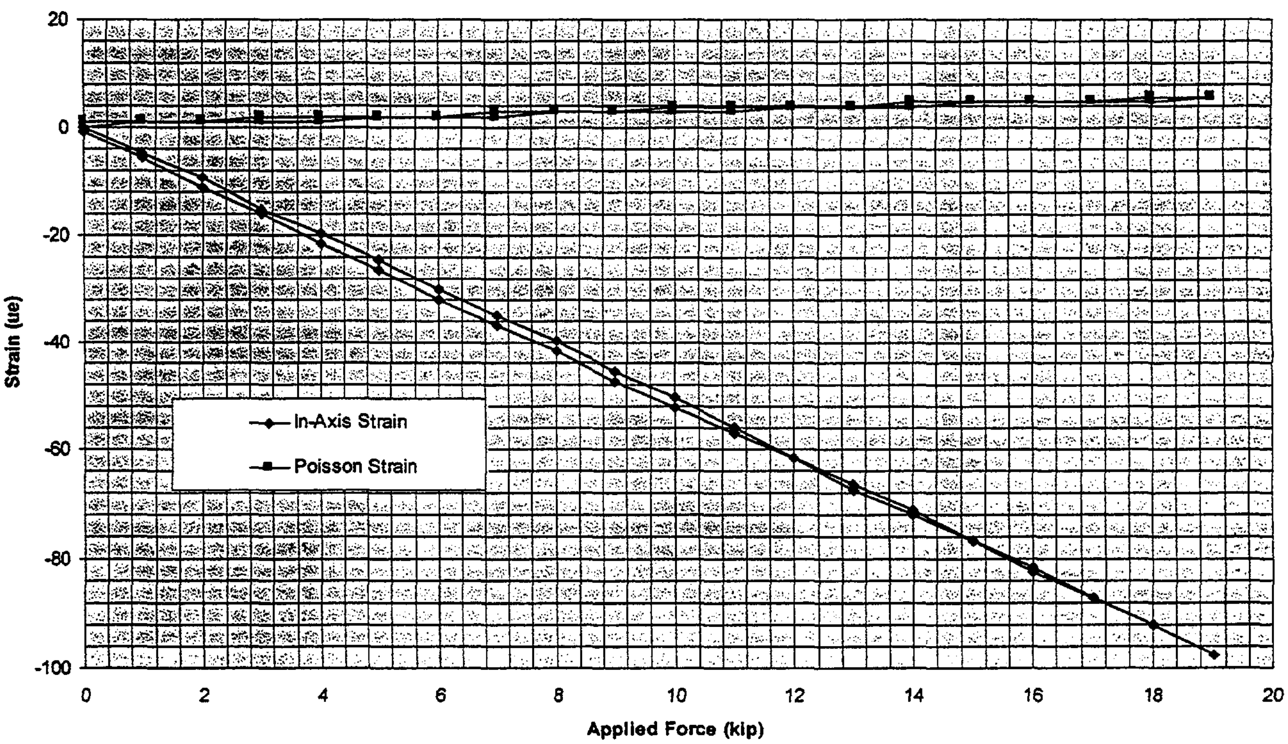
RESPONSE IS BASE STRAIN

BEAMS AT 90 DEGREES TO SHOCK

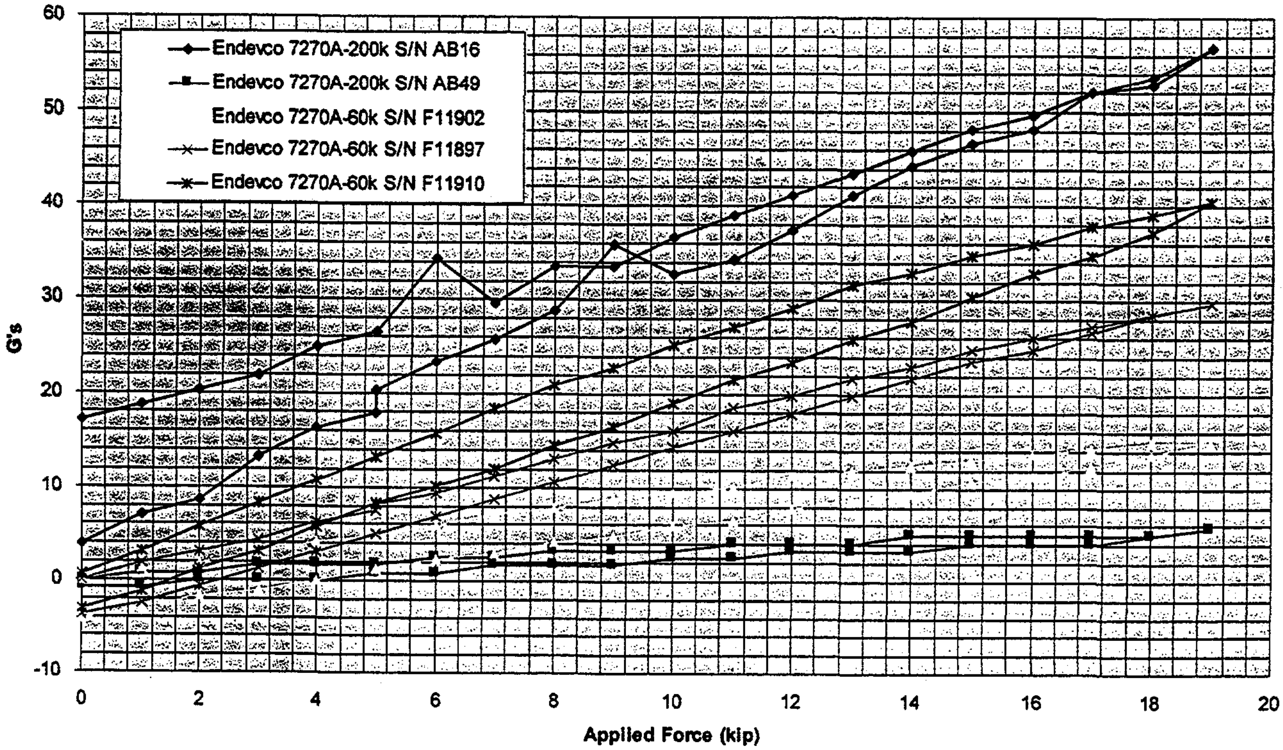


RESPONSE IS ACCELERATION

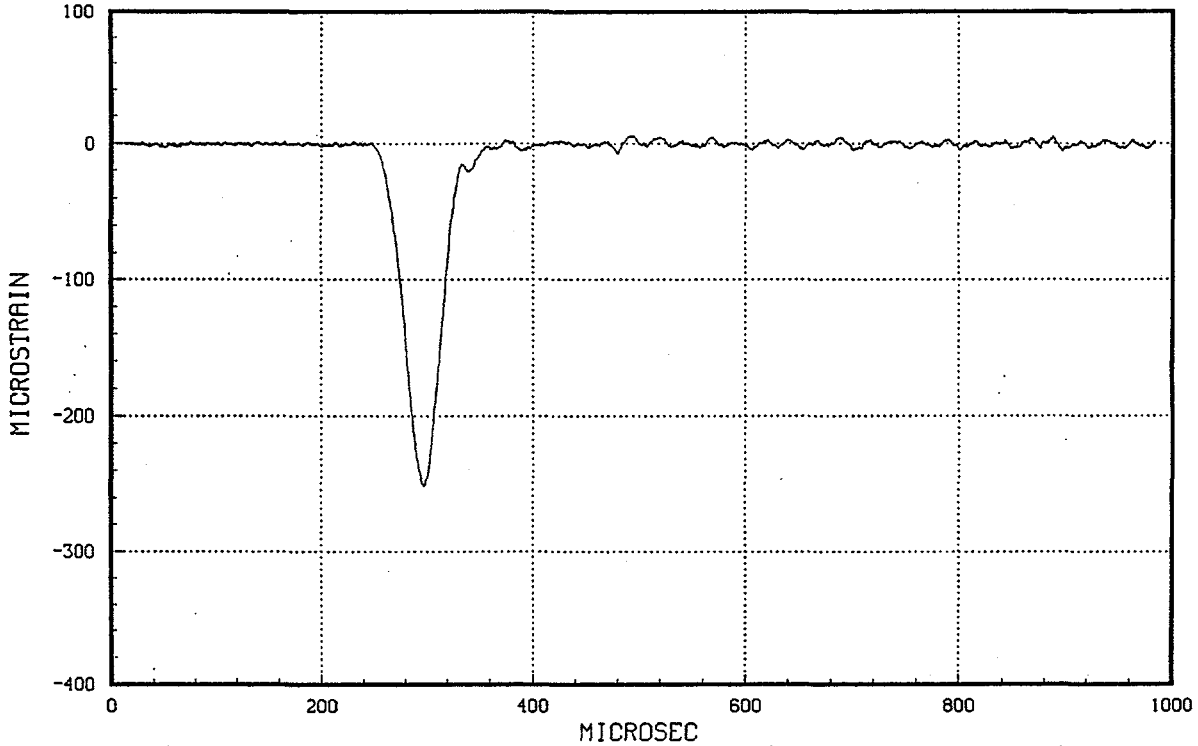
ENDEVCO 7270AM4 Response for a Compressive Shock Applied to the Beryllium Insert (0.75 in. Diameter).



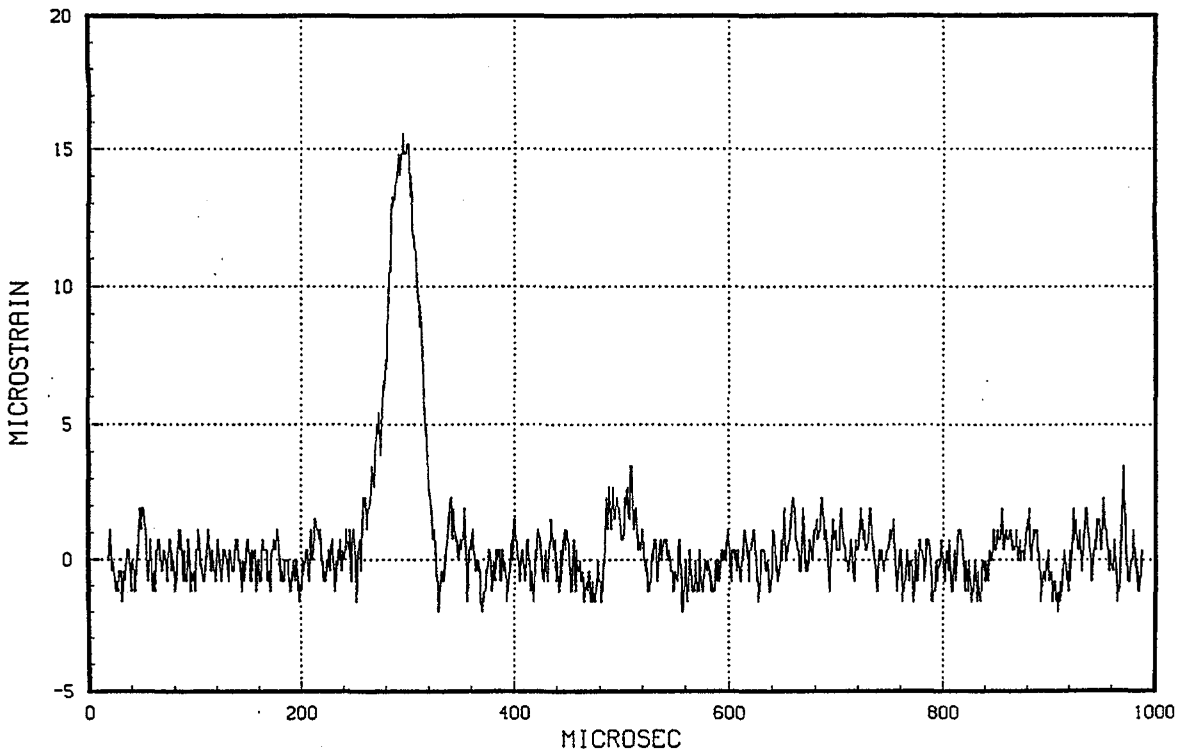
Strain Response for the Beryllium Insert (2.0 in. Diameter).



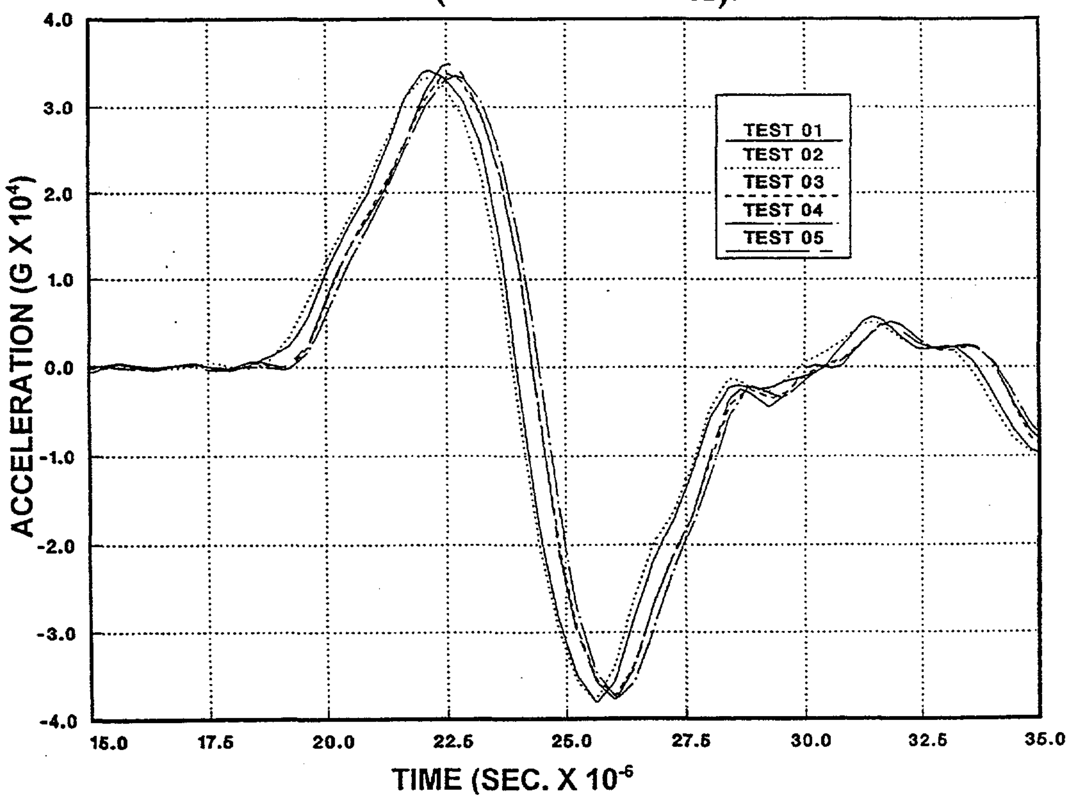
ENDEVCO 7270A-60K and 7270AM4-200K Response for a Static Strain (100 $\mu\varepsilon$ Amplitude) Applied to the Beryllium Insert (2.0 in. Diameter).



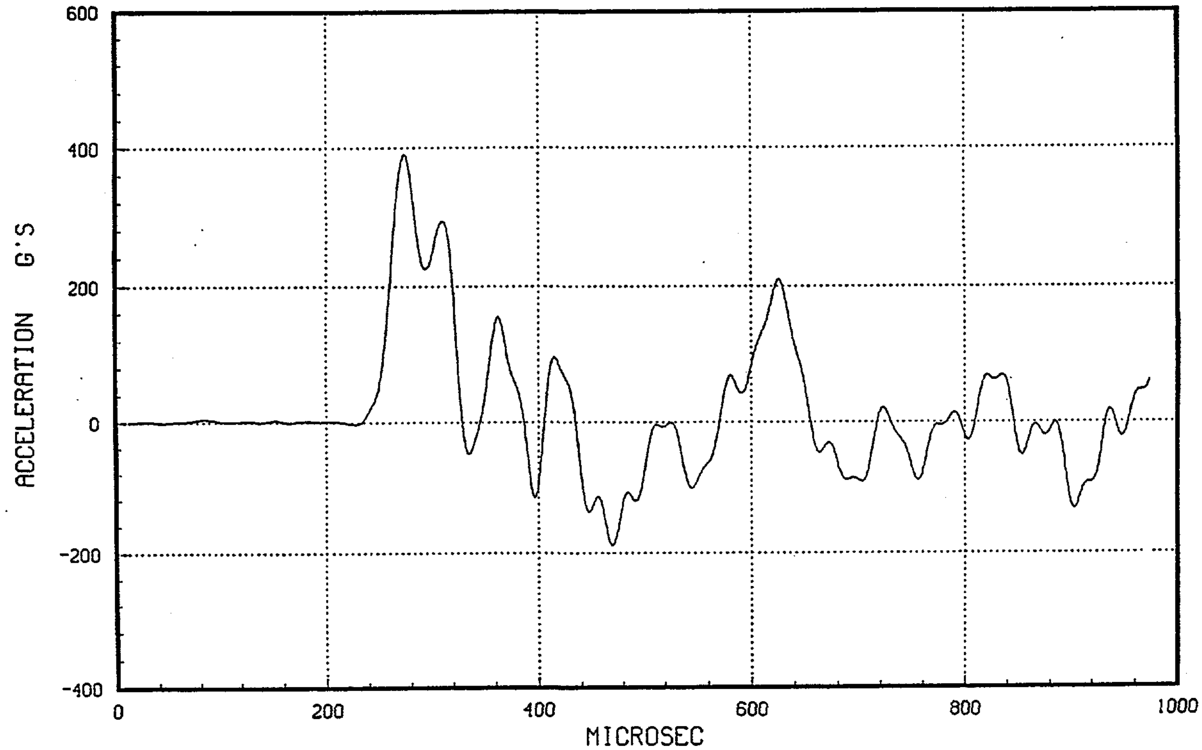
Axial Strain Response to Compressive Shock on the Beryllium Insert (2.0 in. Diameter).



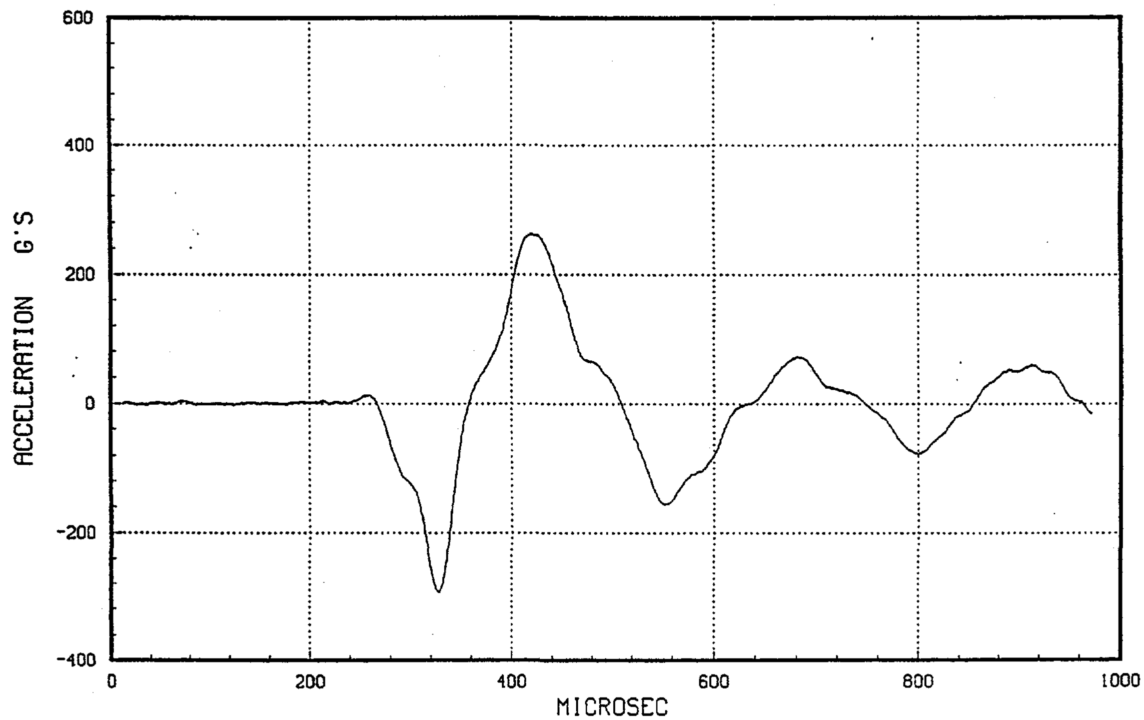
Lateral Strain Response to Compressive Shock on the Beryllium Insert (2.0 in. Diameter).



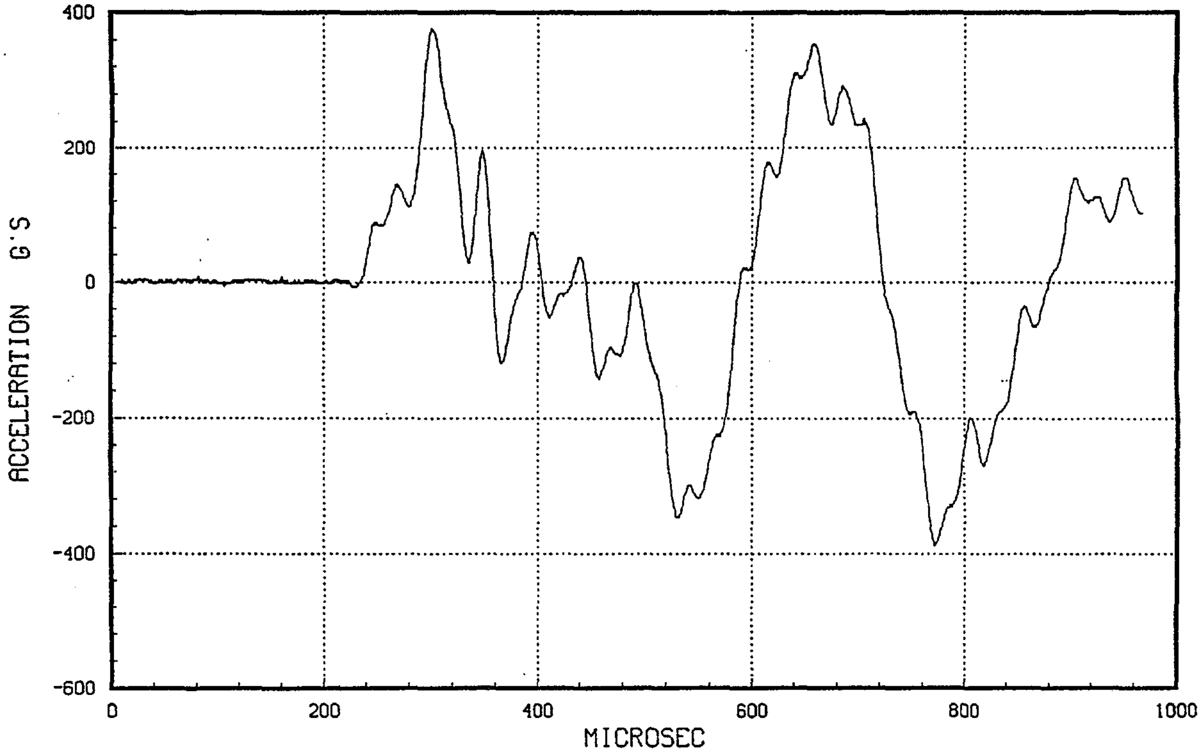
Consistent Axial Acceleration Measured on the Beryllium Insert (2 in. Diameter).



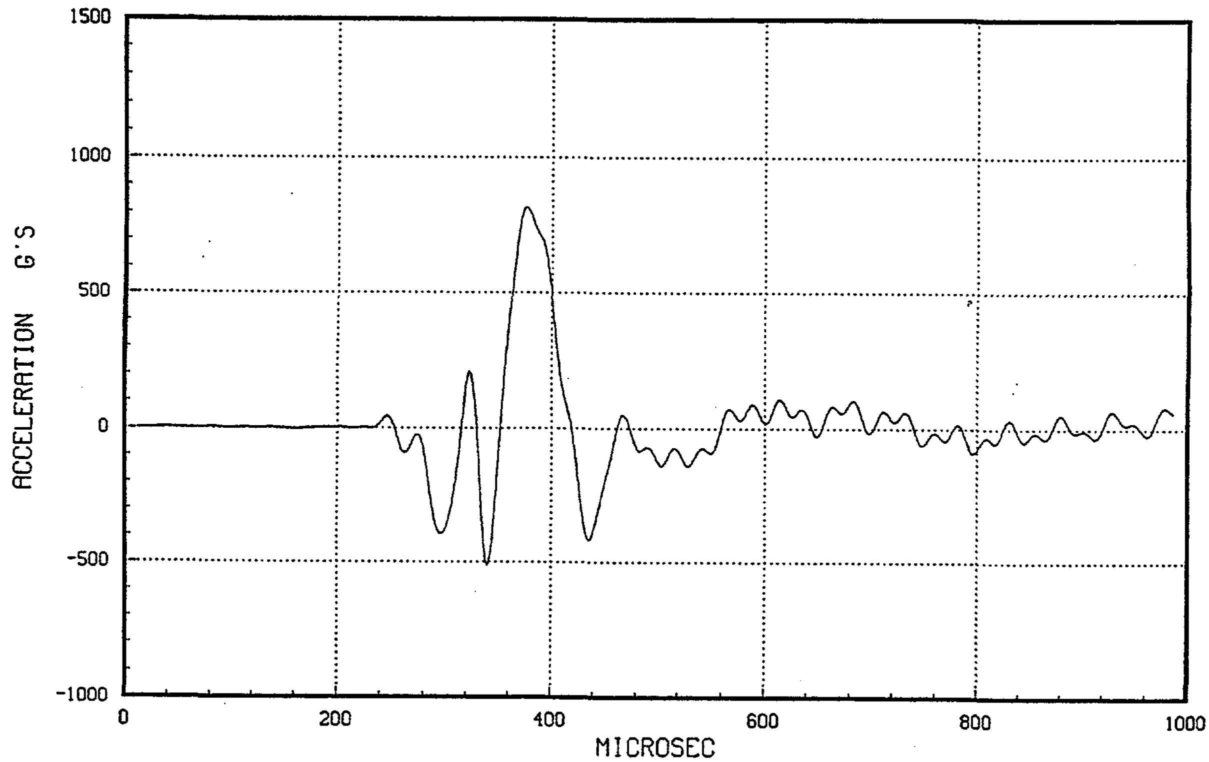
ENDEVCO 7270A-60K Base Strain Response to Cross-Axis Compressive Shock (250 με Amplitude) with 0° Angle and 30 kHz Analog Filter (2 in. Diameter Beryllium Insert).



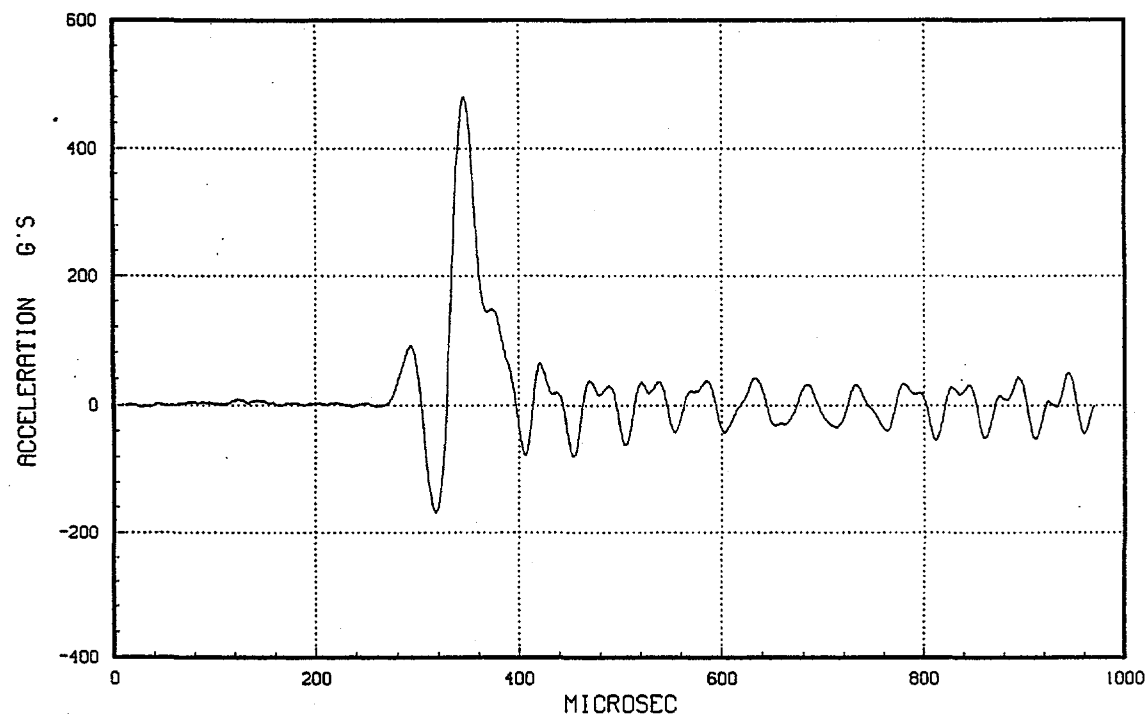
ENDEVCO 7270A-60K Base Strain Response to Cross-Axis Compressive Shock (250 με Amplitude) with 45° Angle and 30 kHz Analog Filter (2 in. Diameter Beryllium Insert).



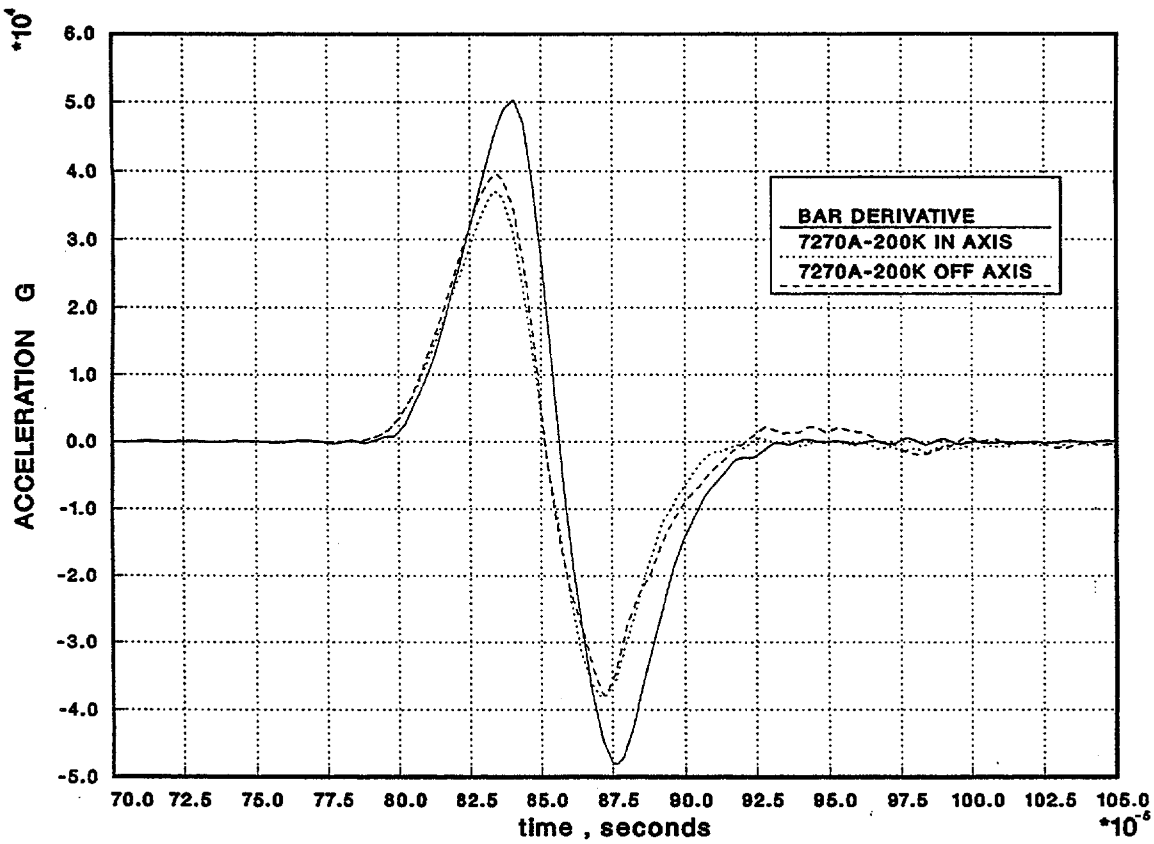
ENDEVCO 7270A-60K Base Strain Response to Cross-Axis Compressive Shock (250 με Amplitude) with 90° Angle and 30 kHz Analog Filter (2 in. Diameter Beryllium Insert).



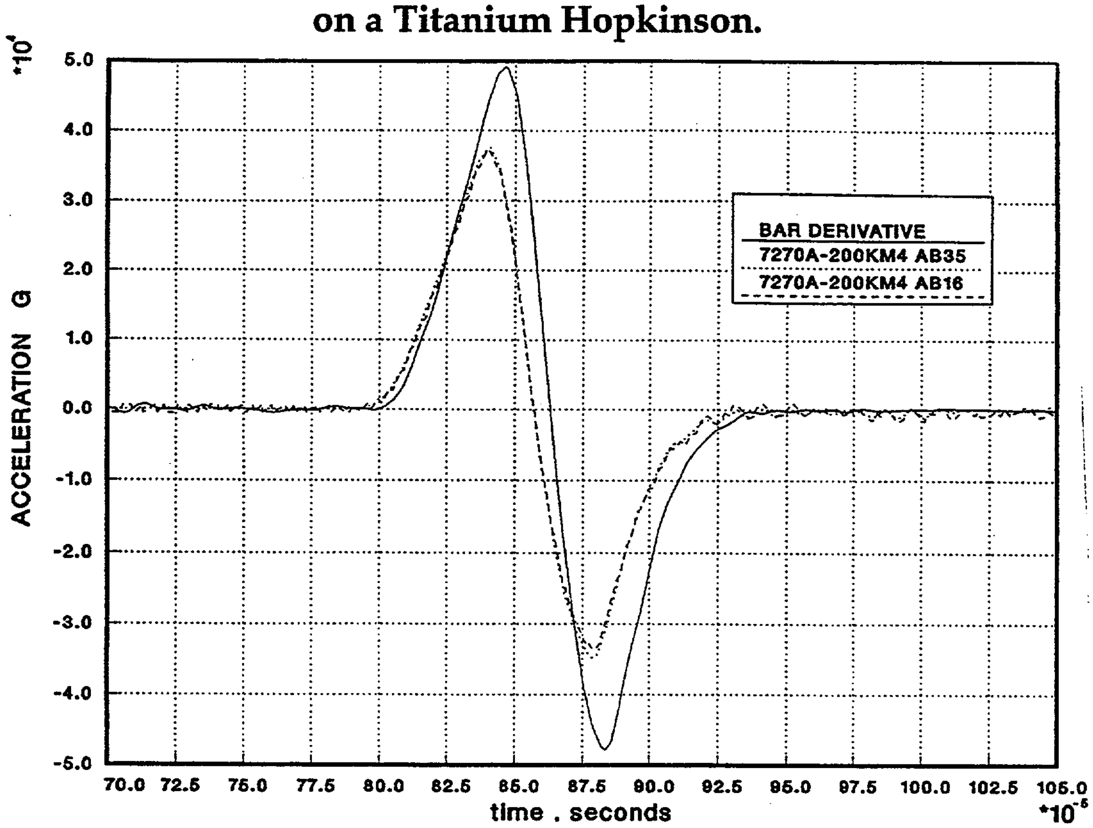
ENDEVCO 7270AM4-200K Acceleration Response to Cross-Axis Compressive Shock (250 με Amplitude) with 15° Angle and 30 kHz Analog Filter (2 in. Diameter Beryllium Insert).



ENDEVCO 7270AM4-200K Acceleration Response to Cross-Axis Compressive Shock (250 με Amplitude) with 65° Angle and 30 kHz Analog Filter (2 in. Diameter Beryllium Insert).



ENDEVCO 7270A-200K Response to Combined Shock at 45° on a Titanium Hopkinson.



ENDEVCO 7270AM4-200K Response to Combined Shock at 45° on a Titanium Hopkinson.

Appendix C

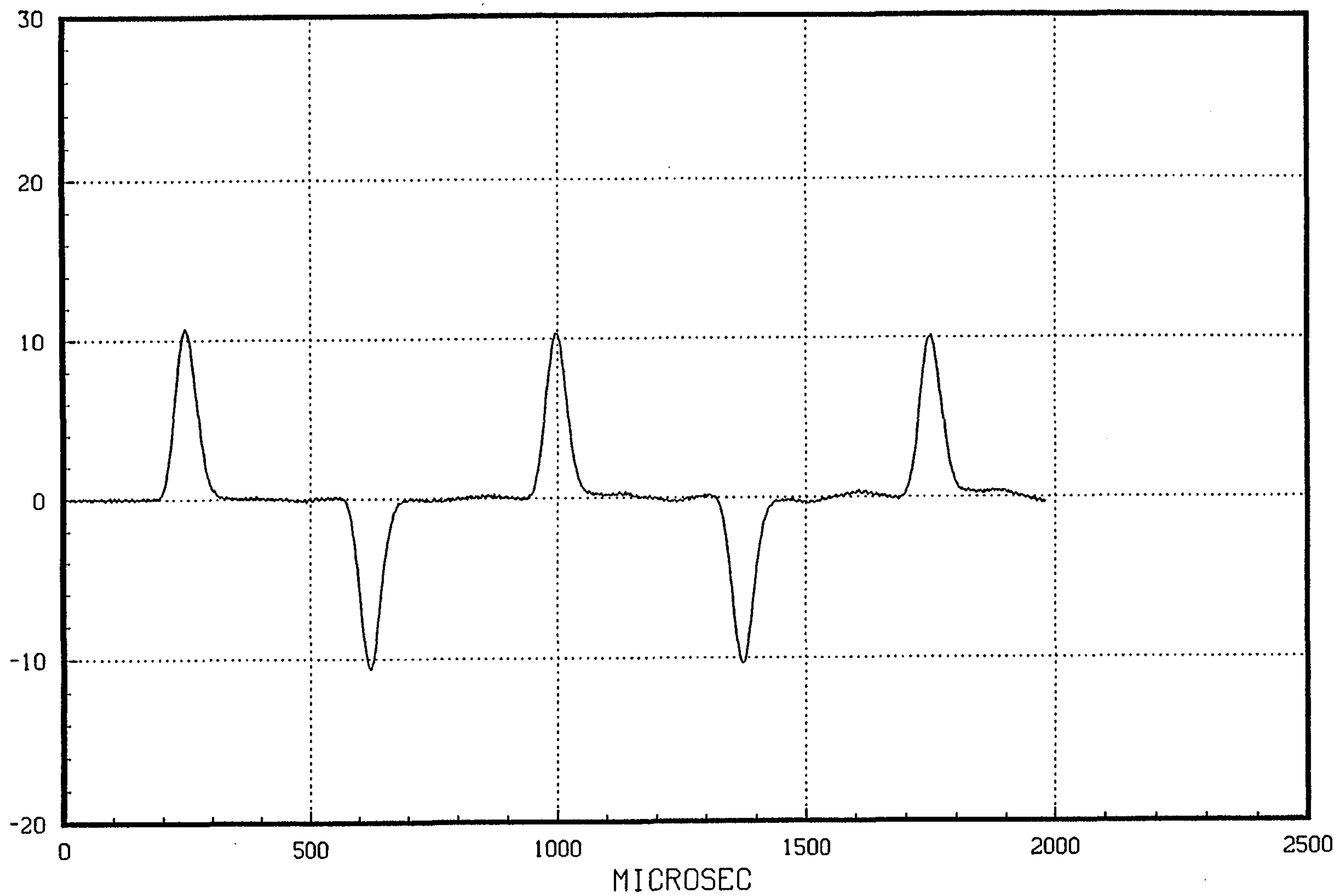
Piezoresistive Accelerometer Cable Response

data verified by
date

7270 WIRE CHECK

08/06/96
CALIBRATION TEST

AK4258
FILTER 0.00HZ



TEST 01

M.F.A. 10.681 BAR INPUT

TT= 0.088 MS. TR= 0.032 MS.
TF= 0.038 MS. TP= 0.041 MS.

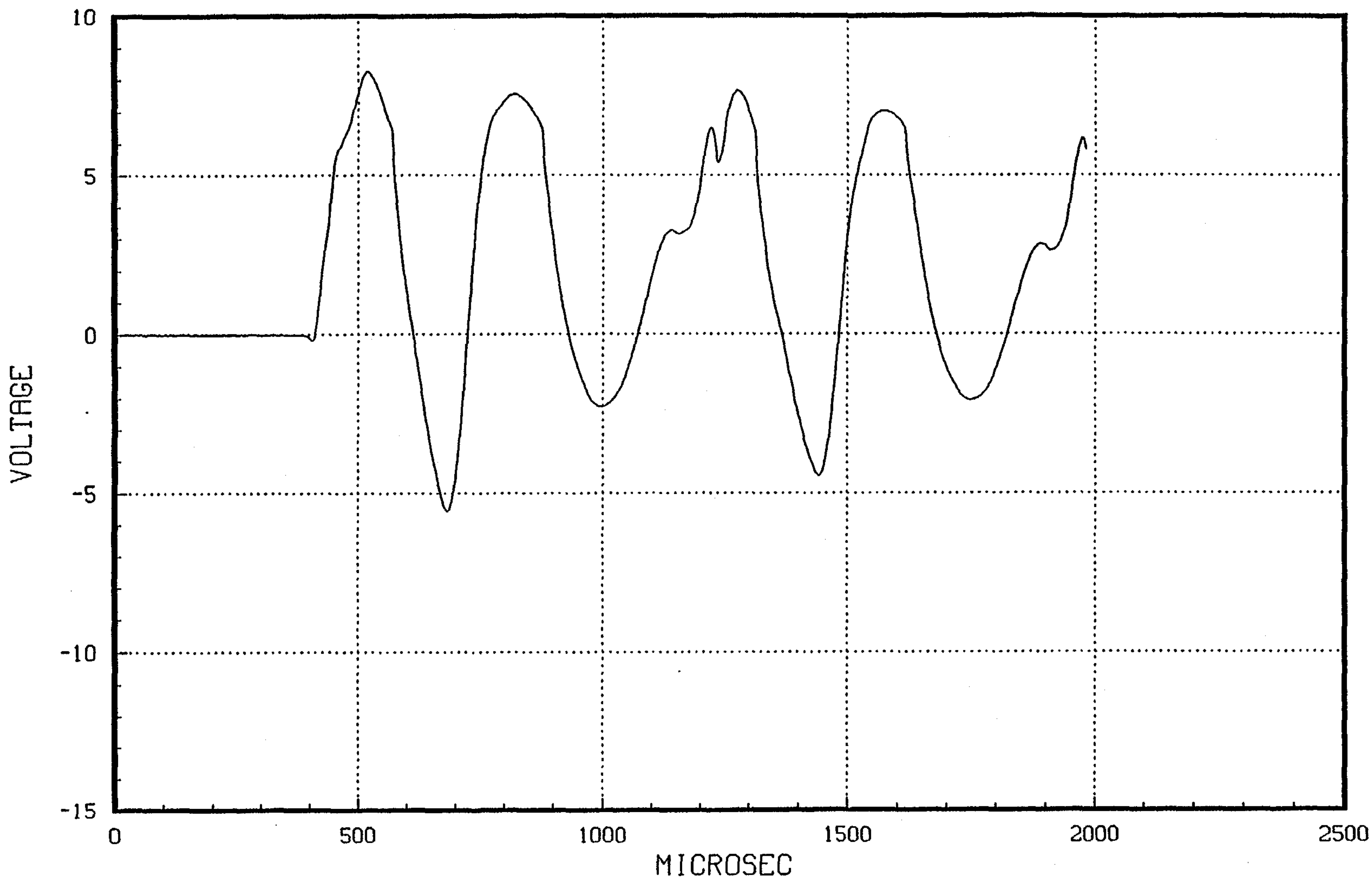
PLOT 1 13.55.27 TUES 6 AUG, 1996 JOB-BATCH7321 Sandia National Laboratory DISSPLA 11.0

data verified by
date

7270 WIRE CHECK

08/06/96
TAPED TO BAR

AK4258
FILTER 0.00HZ



TEST 01 1.0uv/g M.F.A. 8.267 7270 WIRE

TT= 0.186 MS. TR= 0.078 MS.
TF= 0.057 MS. TP= 0.102 MS.

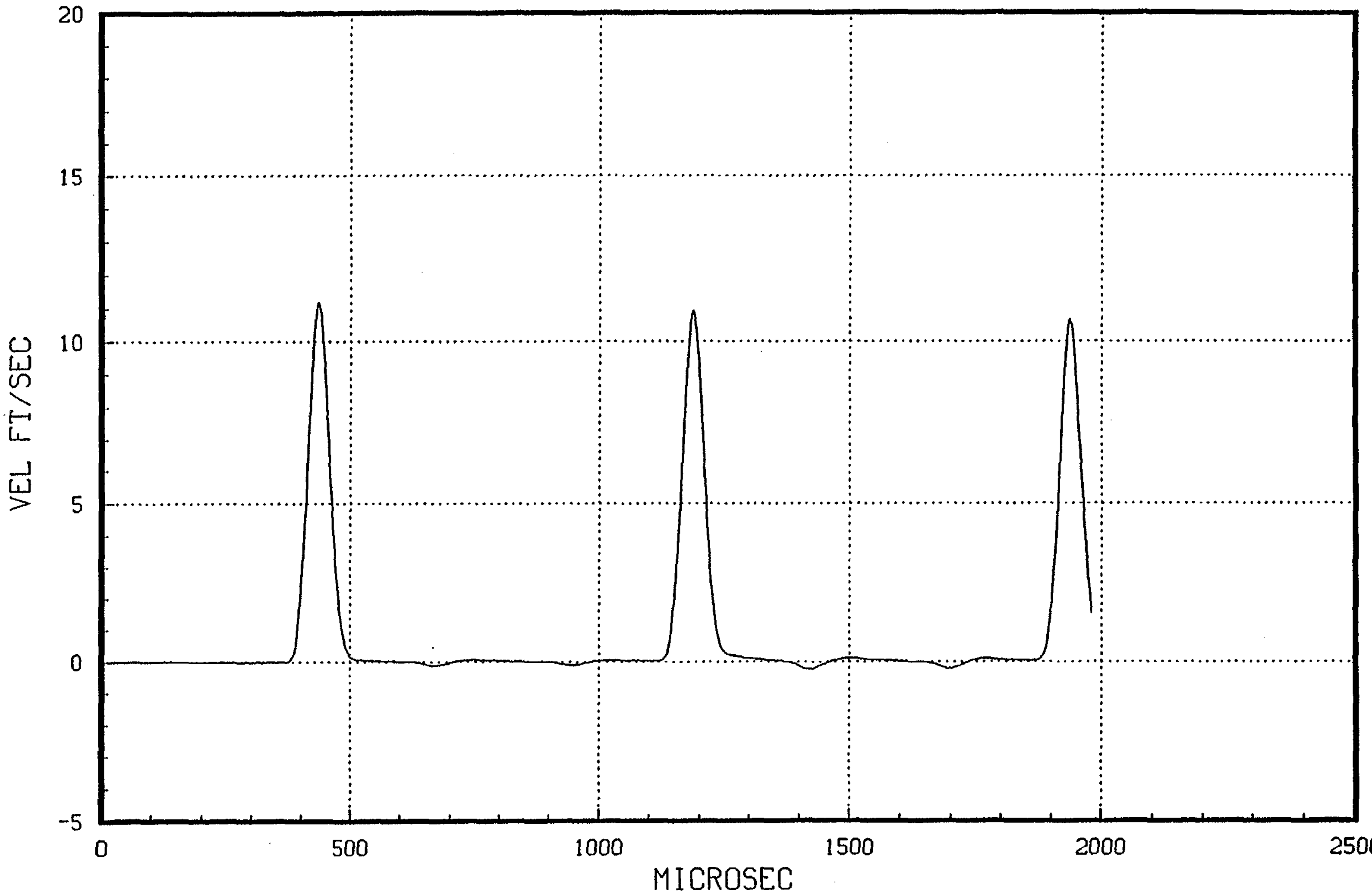
PLOT 1 13.58.23 TUES 6 AUG, 1996 JOB-BATCH7321 Sandia National Laboratory DISSPLA 11.r

data verified by
date

7270 WIRE CHECK

08/06/96
CALIBRATION TEST

AK4258
FILTER 0.00HZ



TEST 01

M.F.A. 11.175

LASER VIBROMETER

TT= 0.089 MS. TR= 0.032 MS.
TF= 0.038 MS. TP= 0.041 MS.

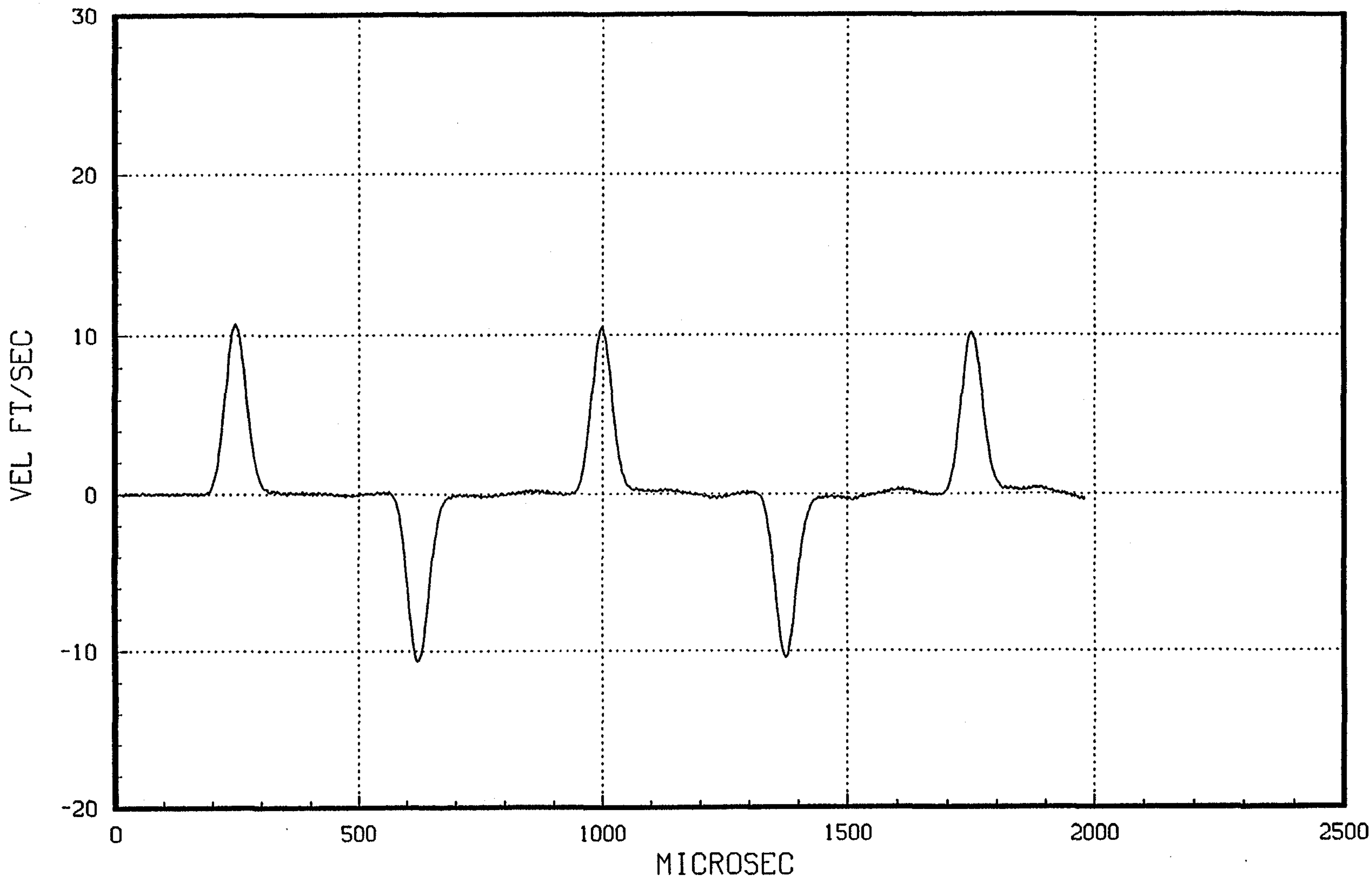
PLOT 1 13.59.00 TUES 6 AUG, 1996 JOB-BATCH7331 Sandia National Laboratory DISSPLA 11.r

data verified by
date

7270 WIRE CHECK

08/06/96
CALIBRATION TEST

AK4258
FILTER 0.00HZ



TEST 02

M.F.A. 10.679 BAR INPUT

TT= 0.089 MS. TR= 0.033 MS.
TF= 0.037 MS. TP= 0.043 MS.

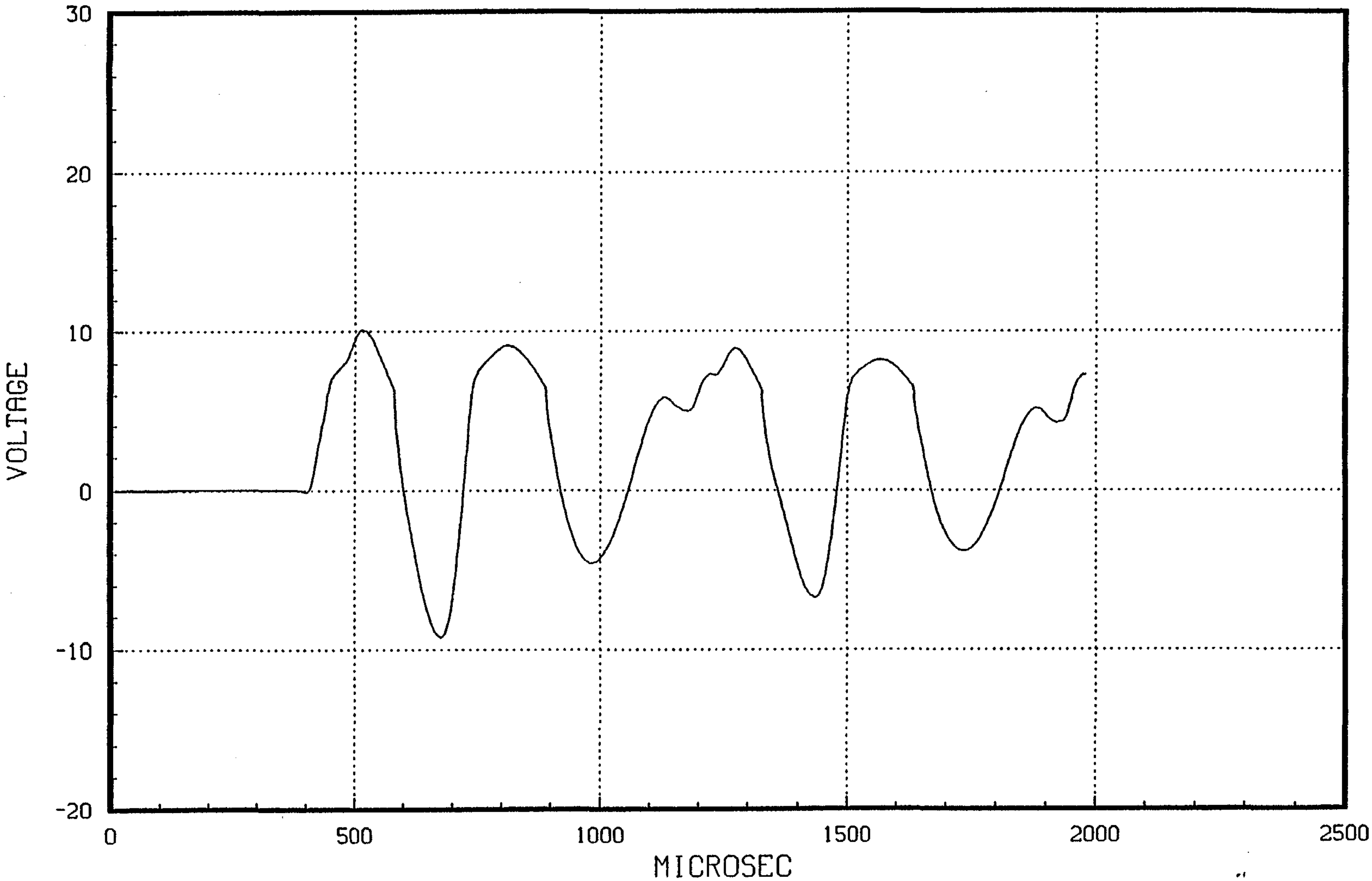
PLOT 1 14.05.19 TUES 6 AUG, 1996 JOB-BATCH7331 Sandia National Laboratory DISSPLA 11.0

data verified by
date

7270 WIRE CHECK

08/06/96
TAPED TO BAR

AK4258
FILTER 0.00HZ



TEST 02 1.0uv/g

M.F.A. 10.124

7270 WIRE

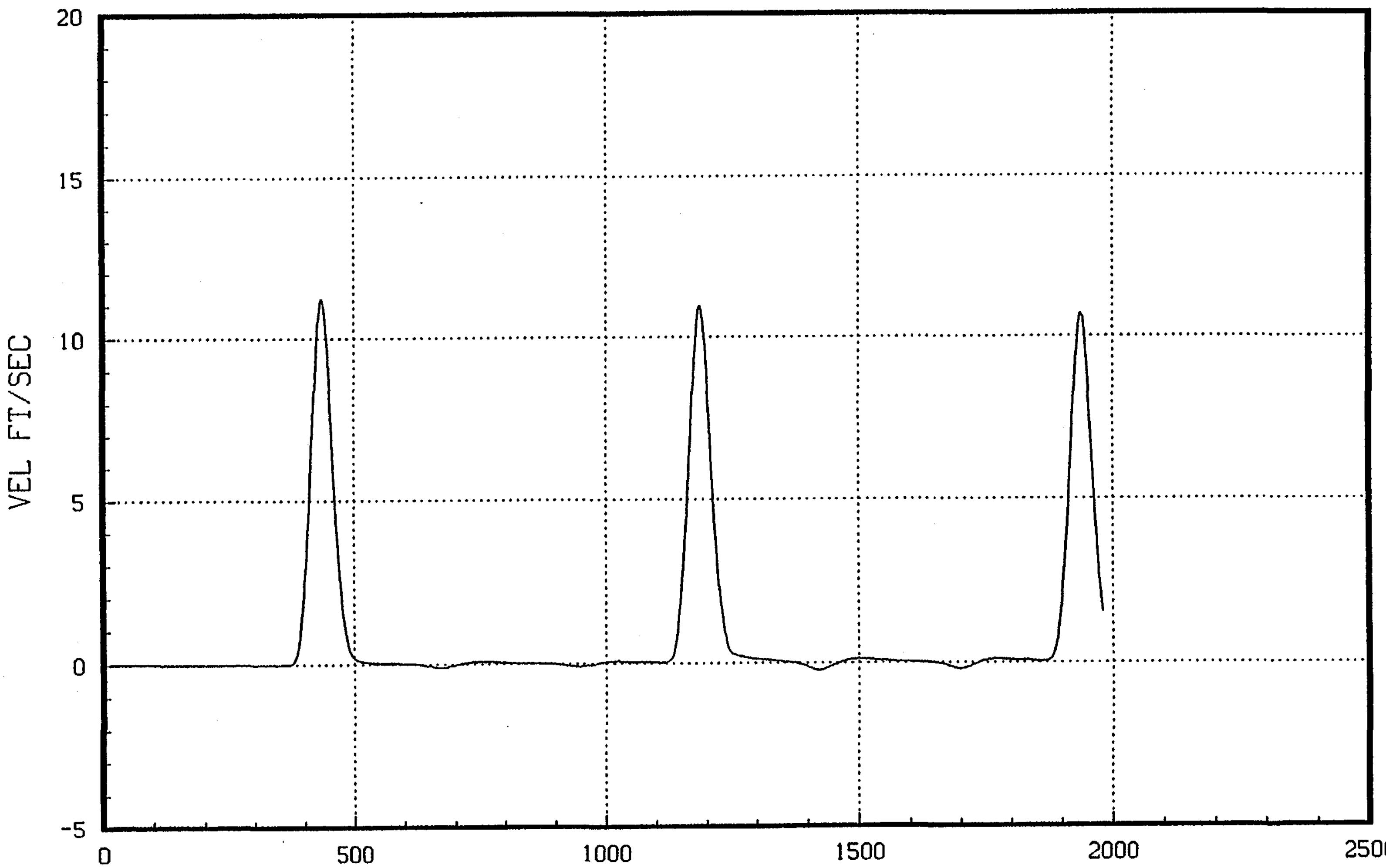
TT= 0.178 MS. TR= 0.079 MS.
TF= 0.054 MS. TP= 0.100 MS.

data verified by
date

7270 WIRE CHECK

08/06/96
CALIBRATION TEST

AK4258
FILTER 0.00HZ



TEST 02

M.F.A. 11.222

LASER VIBROMETER

TT= 0.089 MS. TR= 0.033 MS.
TF= 0.037 MS. TP= 0.043 MS.

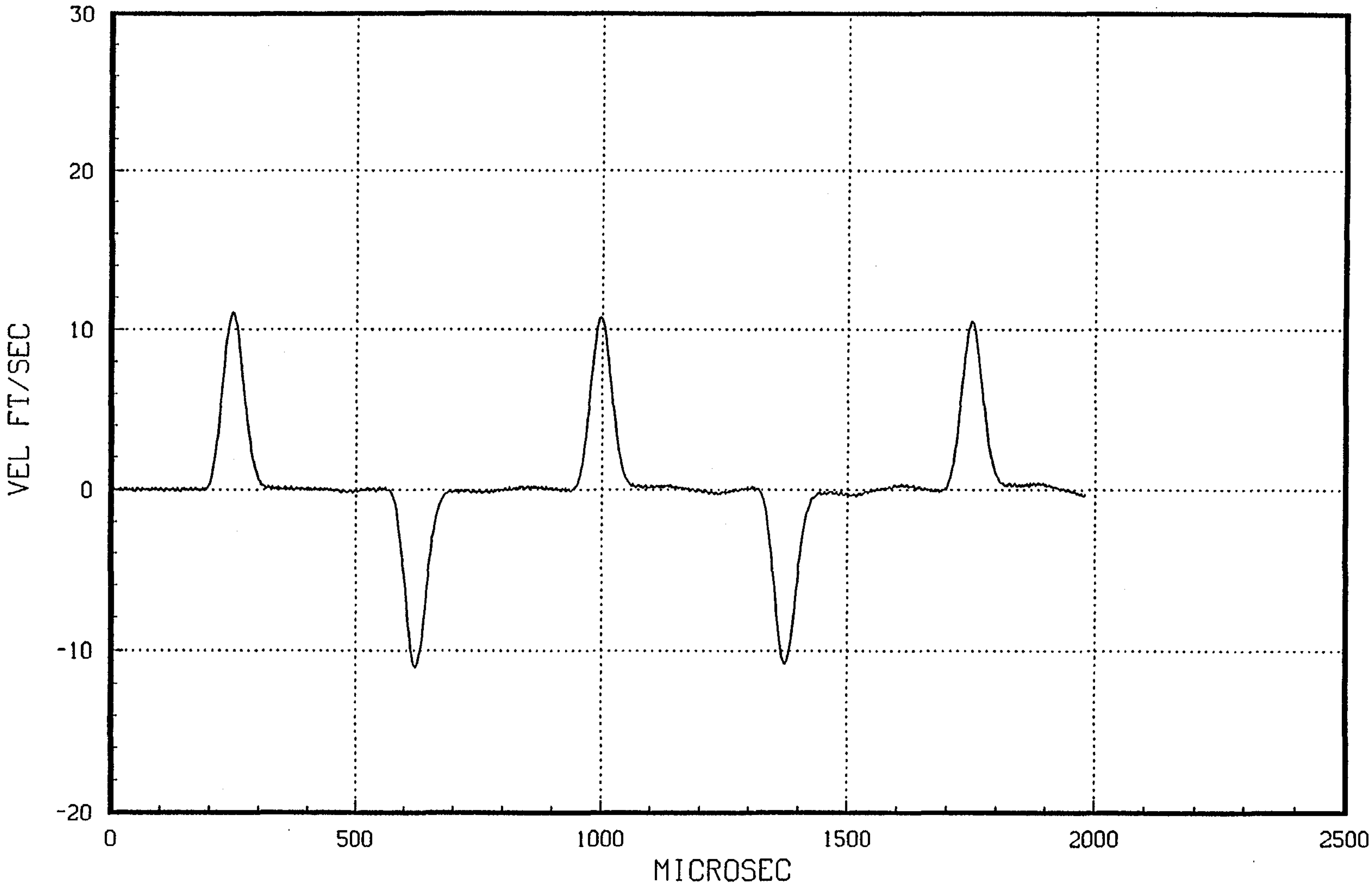
PLOT 1 14.06.01 TUES 6 AUG, 1996 JOB-BATCH7331 Sandia National Laboratory DISSPLA 11.

data verified by
date

7270 WIRE CHECK

08/06/96
CALIBRATION TEST

AK4258
FILTER 0.00HZ



TEST 03

M.F.A. 11.052 BAR INPUT

TT= 0.089 MS. TR= 0.032 MS.
TF= 0.038 MS. TP= 0.041 MS.

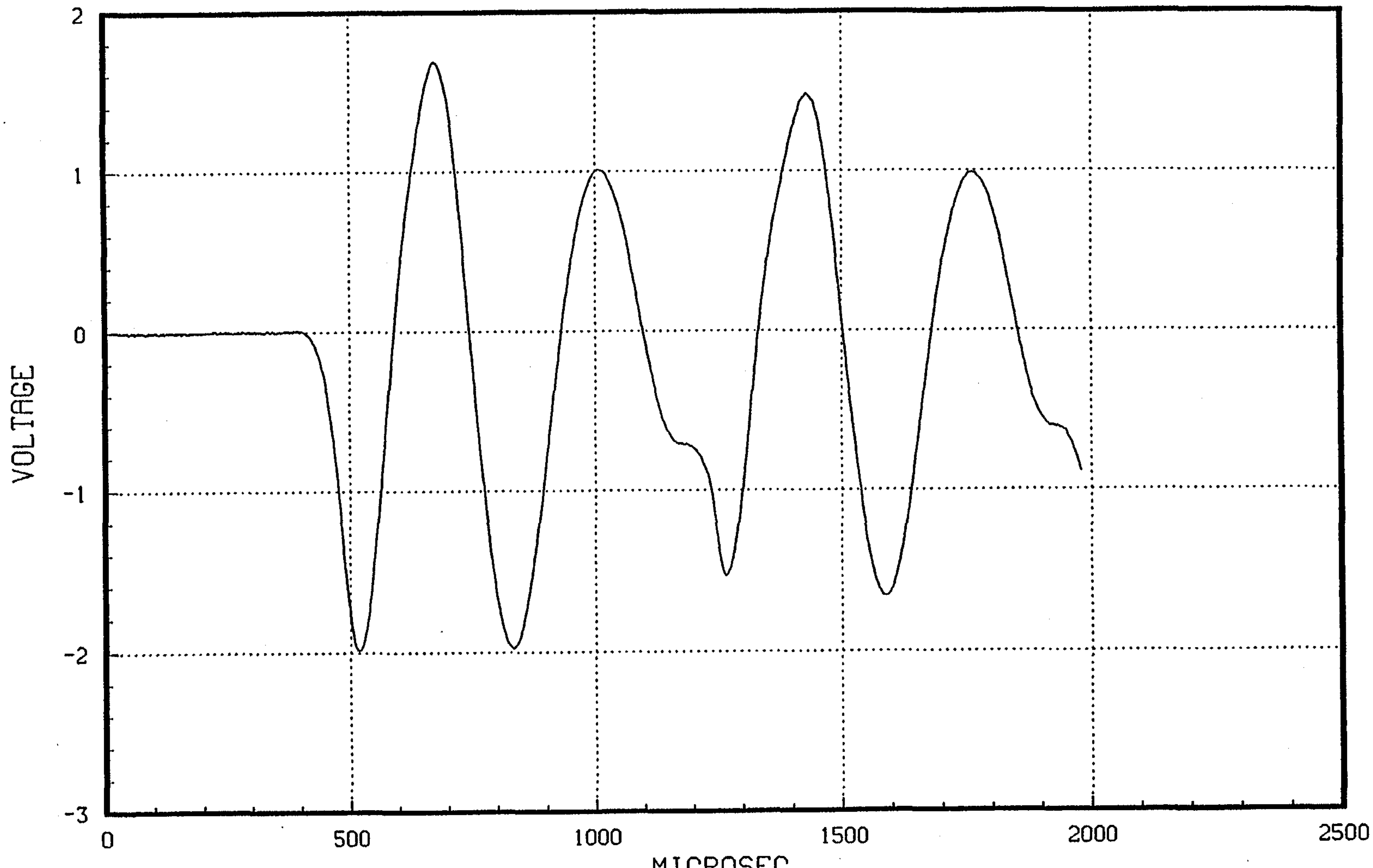
PLOT 1 14.15.03 TUES 6 AUG, 1996 JOB=BATCH7341 Sandia National Laboratory DISSPLA 11.1

data verified by
date

7270 WIRE CHECK

08/06/96
TAPED TO BAR

AK4258
FILTER 0.00HZ



TEST 03 1.0uv/g M.F.A. -1.984 7270 WIRE

TT= 0.143 MS. TR= 0.060 MS.
TF= 0.048 MS. TP= 0.076 MS.

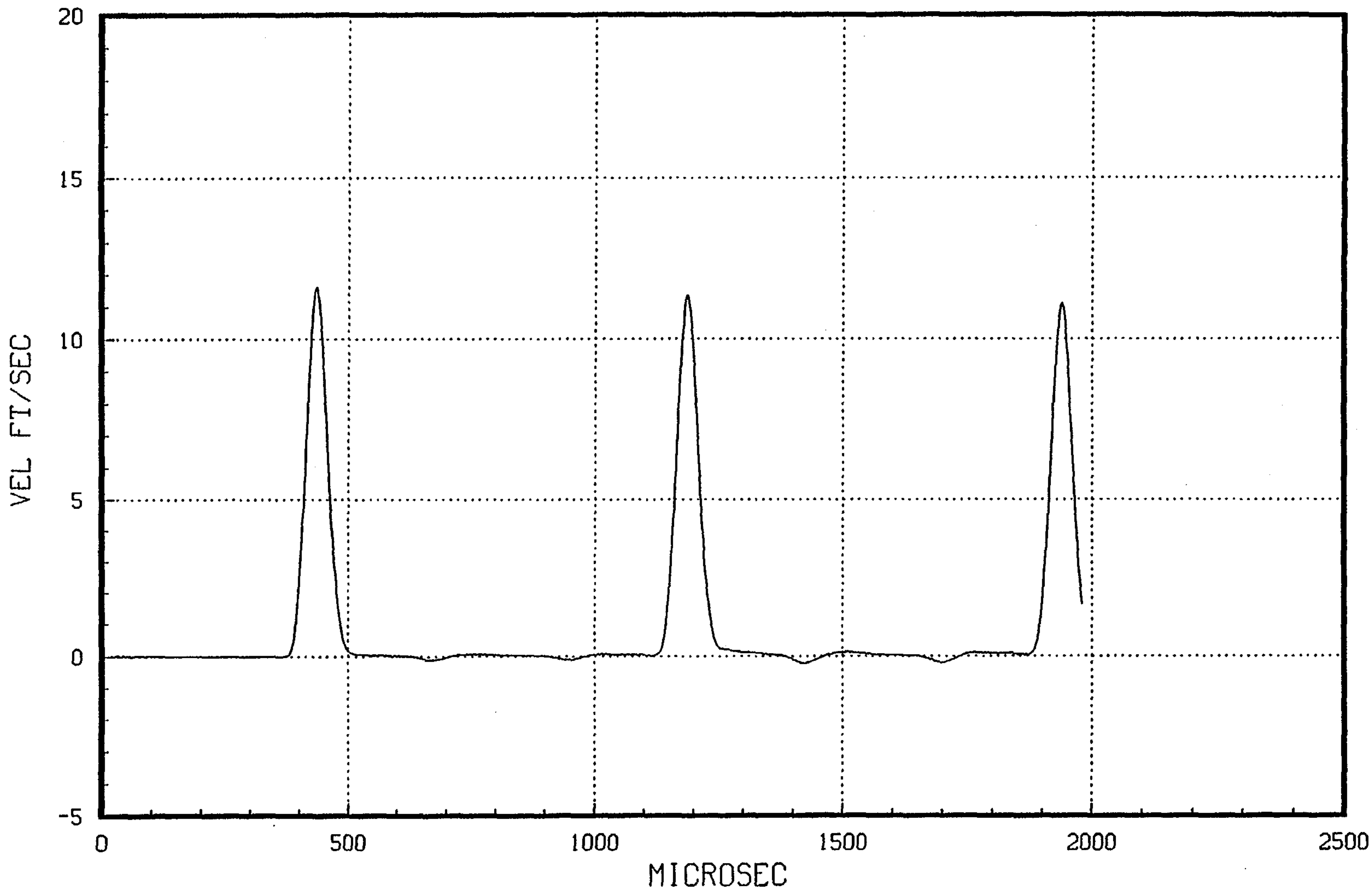
PLOT 1 14.15.22 TUES 6 AUG, 1996 JOB-BATCH7341 Sandia National Laboratory DISSPLA 11.0

data verified by
date

7270 WIRE CHECK

08/06/96
CALIBRATION TEST

AK4258
FILTER 0.00HZ



TEST 03

M.F.A. 11.613 LASER VIBROMETER

TT= 0.089 MS. TR= 0.032 MS.
TF= 0.038 MS. TP= 0.041 MS.

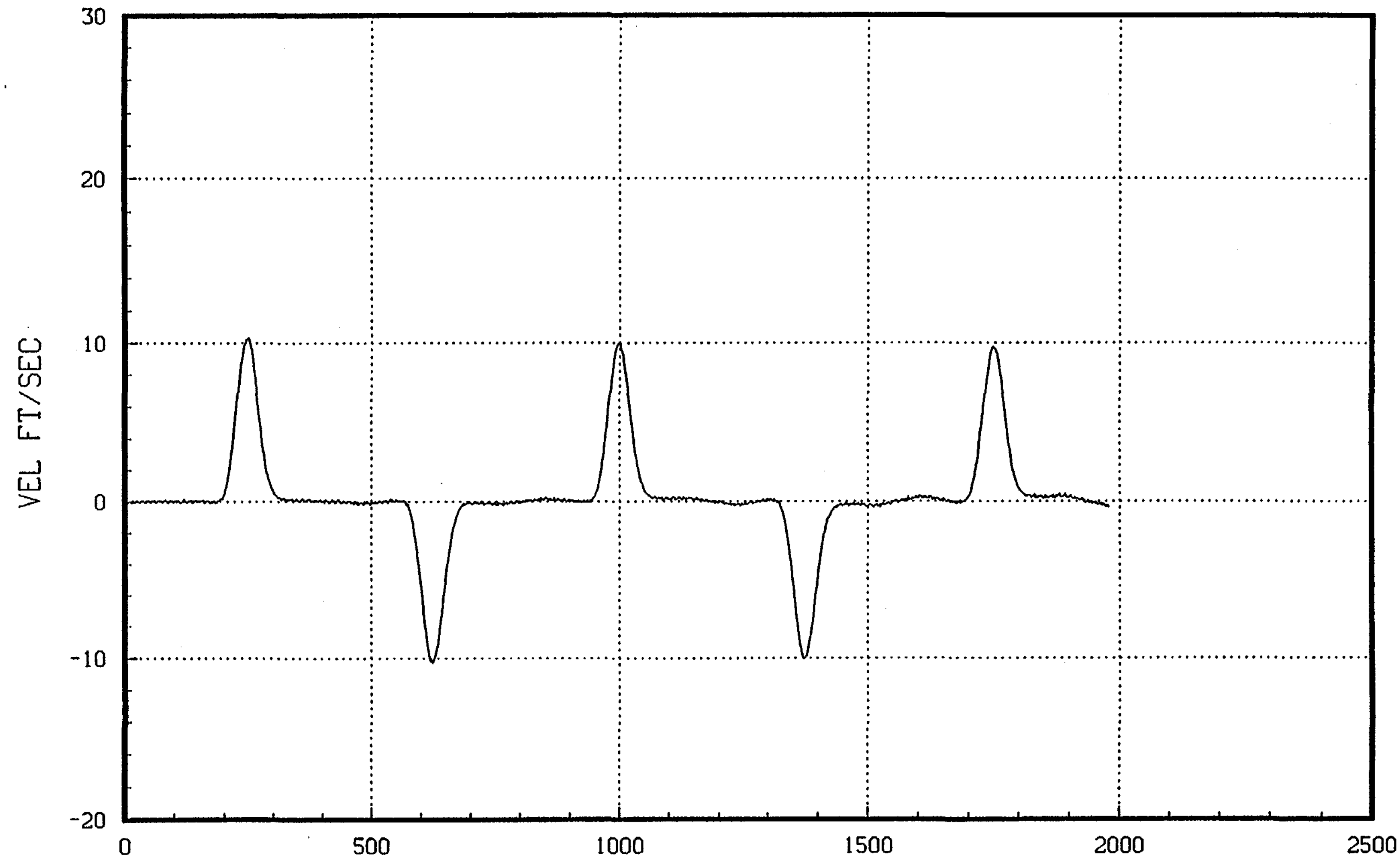
PLOT 1 14.15.44 TUES 6 AUG, 1996 JOB=BATCH7341 Sandia National Laboratory DISSPLA 11.

data verified by
date

7270 WIRE CHECK

08/06/96
CALIBRATION TEST

AK4258
FILTER 0.00HZ



TEST 04 M.F.A. 10.263 BAR INPUT

TT= 0.090 MS. TR= 0.032 MS.
TF= 0.038 MS. TP= 0.043 MS.

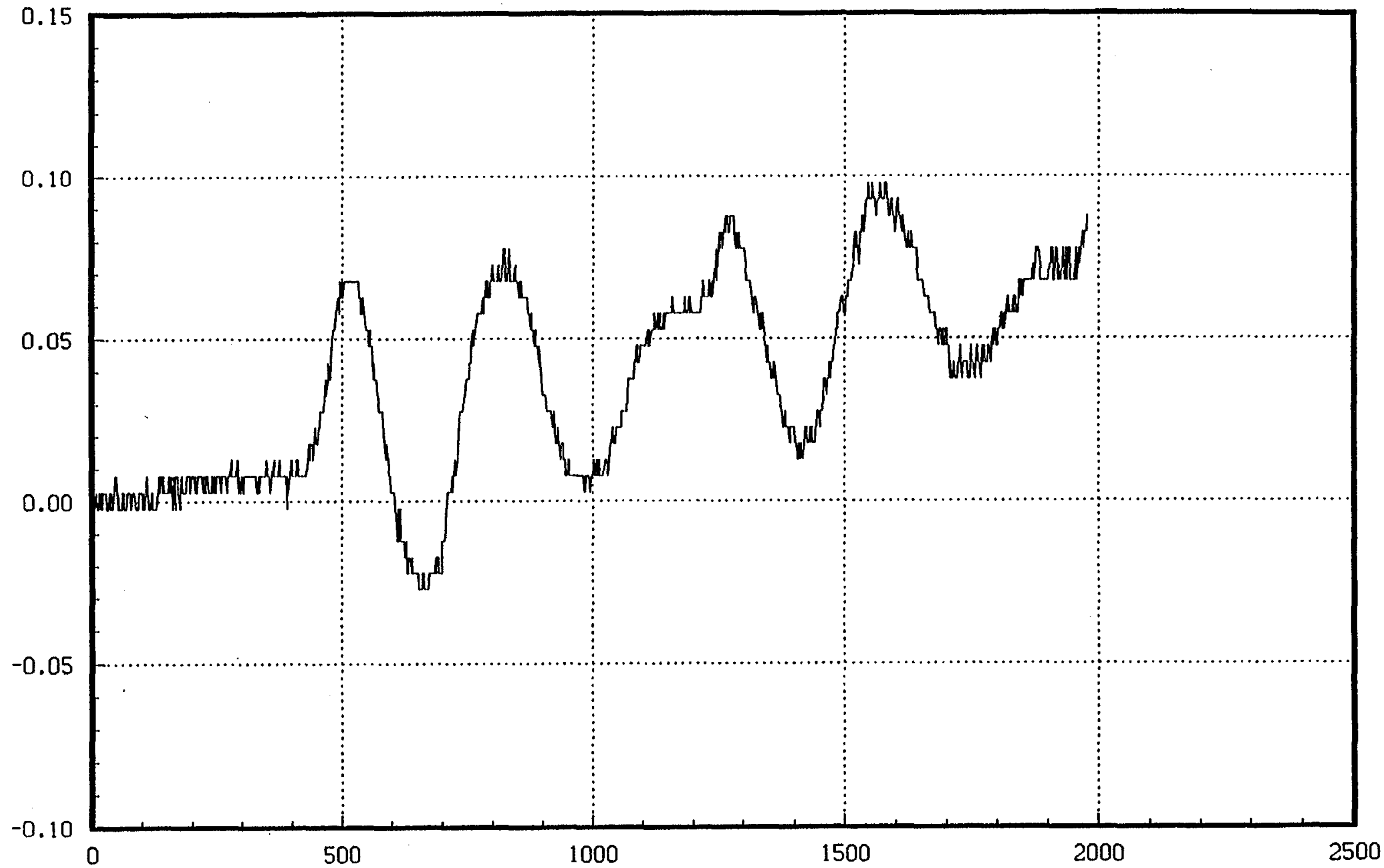
PLOT 1 14.18.25 TUES 6 AUG, 1996 JOB-BATCH7341 Sandia National Laboratory DISSPLA 11]

data verified by
date

7270 WIRE CHECK

08/06/96
TAPED TO BAR

AK4258
FILTER 0.00HZ



TEST 04 1.0uv/g M.F.A. 0.097 7270 WIRE

TT= 0.000 MS. TR= 0.243 MS.
TF= 0.000 MS. TP= 0.557 MS.

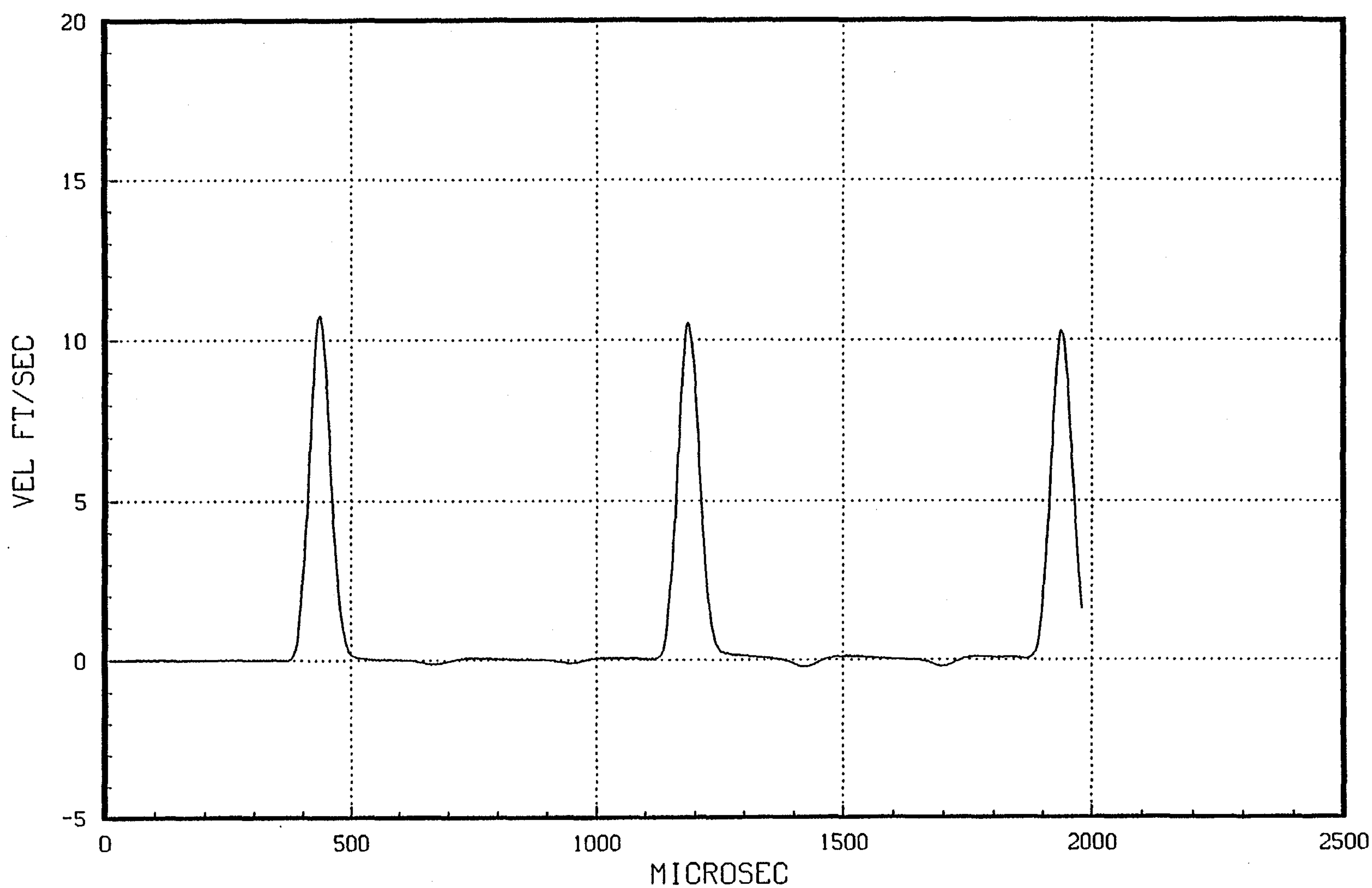
PLOT 1 14.18.46 TUES 6 AUG, 1996 JOB-BATCH7351 Sandia National Laboratory DISSPLA 11

data verified by
date

7270 WIRE CHECK

08/06/96
CALIBRATION TEST

AK4258
FILTER 0.00HZ



TEST 04 M.F.A. 10.760 LASER VIBROMETER

TT= 0.090 MS. TR= 0.033 MS.
TF= 0.039 MS. TP= 0.042 MS.

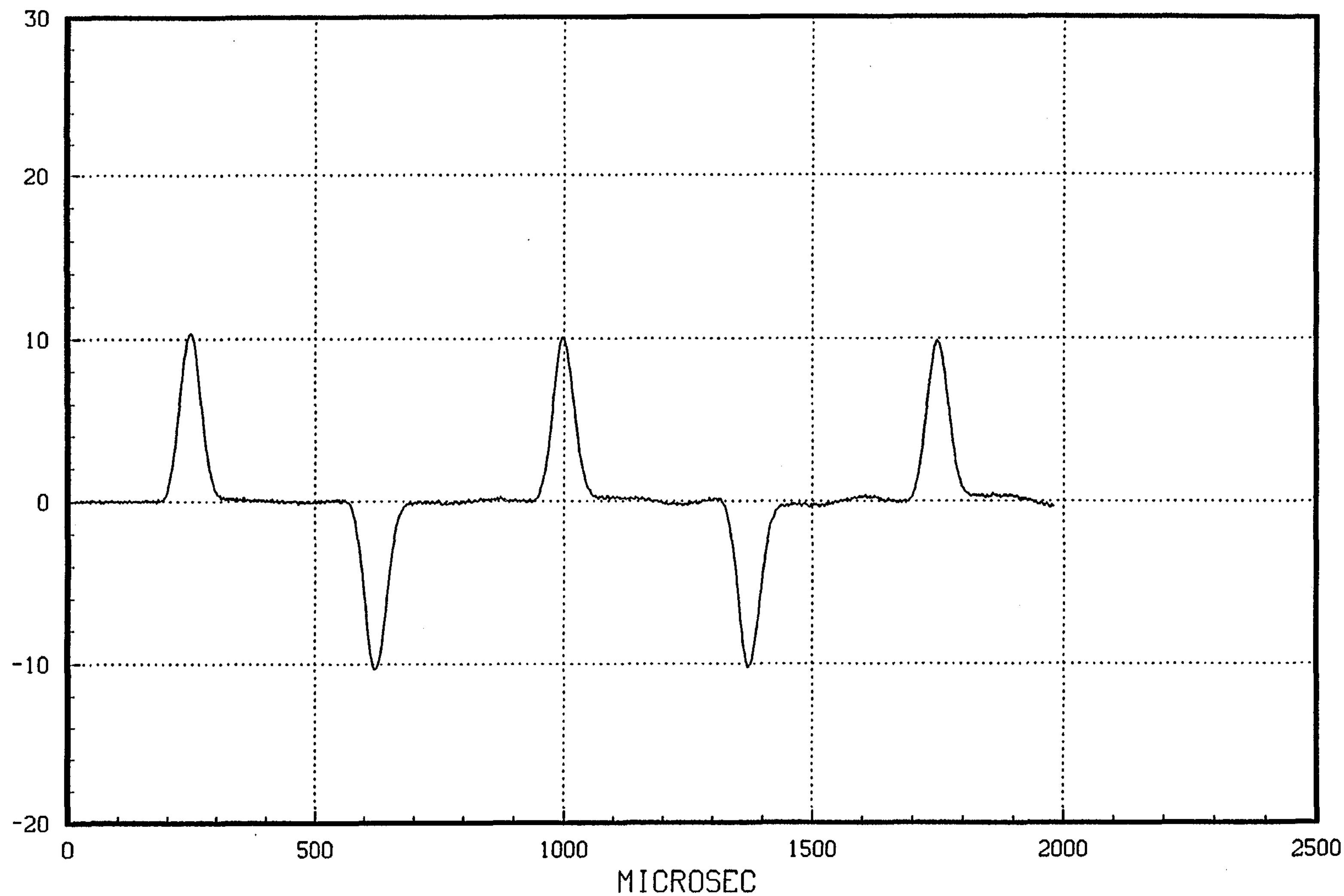
PLOT 1 14.19.37 TUES 6 AUG, 1996 JOB-BATCH7351 Sandia National Laboratory DISSPLA 11.

data verified by
date

7270 WIRE CHECK

08/06/96
CALIBRATION TEST

AK4258
FILTER 0.00HZ



TEST 05

M.F.A. 10.351 BAR INPUT

TT= 0.090 MS. TR= 0.033 MS.
TF= 0.038 MS. TP= 0.043 MS.

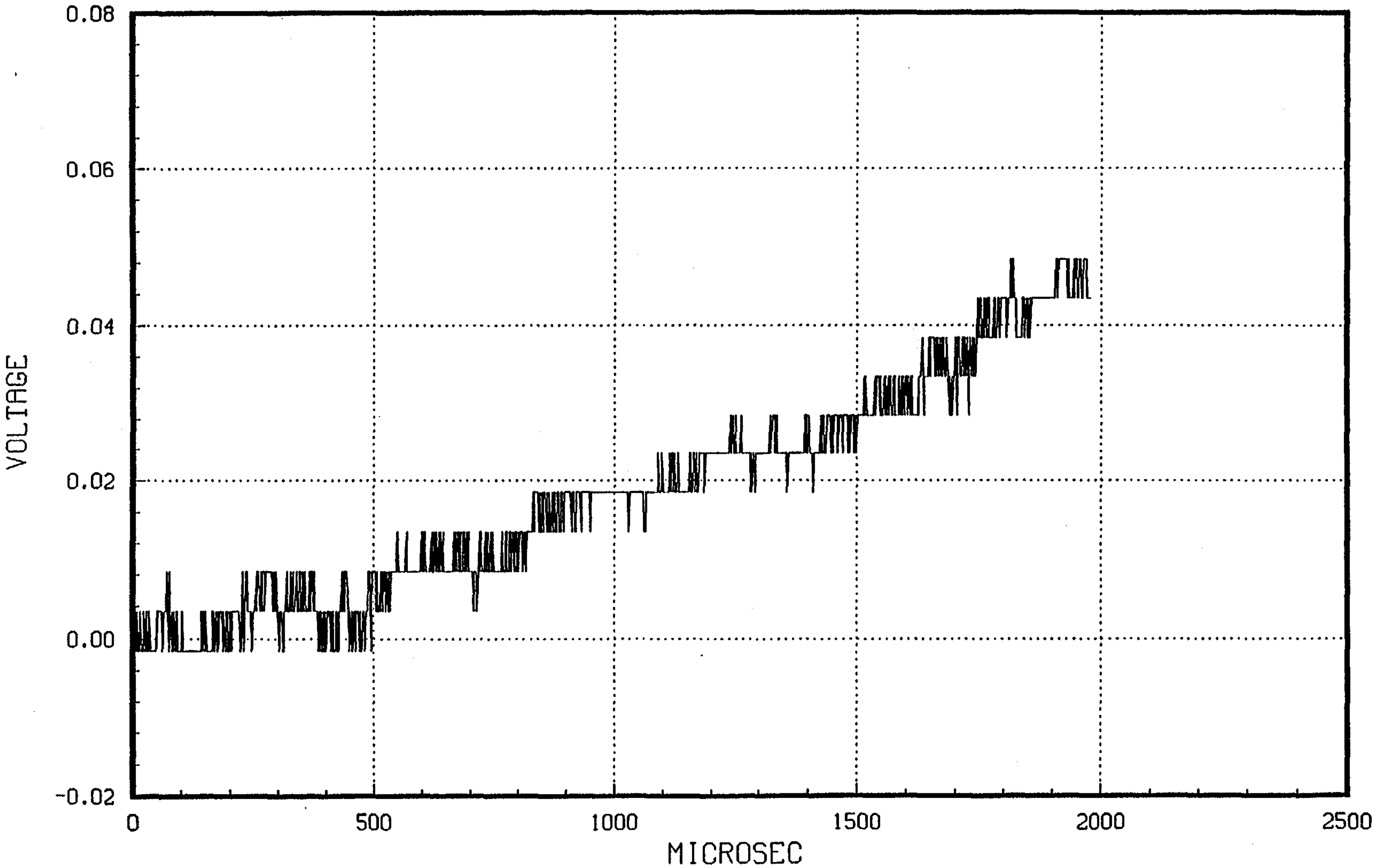
PLOT 1 14.22.14 TUES 6 AUG, 1996 JOB-BATCH2351 Sandia National Laboratory DISSPLA 11.

data verified by
date

7270 WIRE CHECK

08/06/96
TAPED TO BAR

AK4258
FILTER 0.00HZ



TEST 05 1.0uv/g M.F.A. 0.049 7270 WIRE

TT= 0.000 MS. TR= 1.273 MS.
TF= 0.000 MS. TP= 1.393 MS.

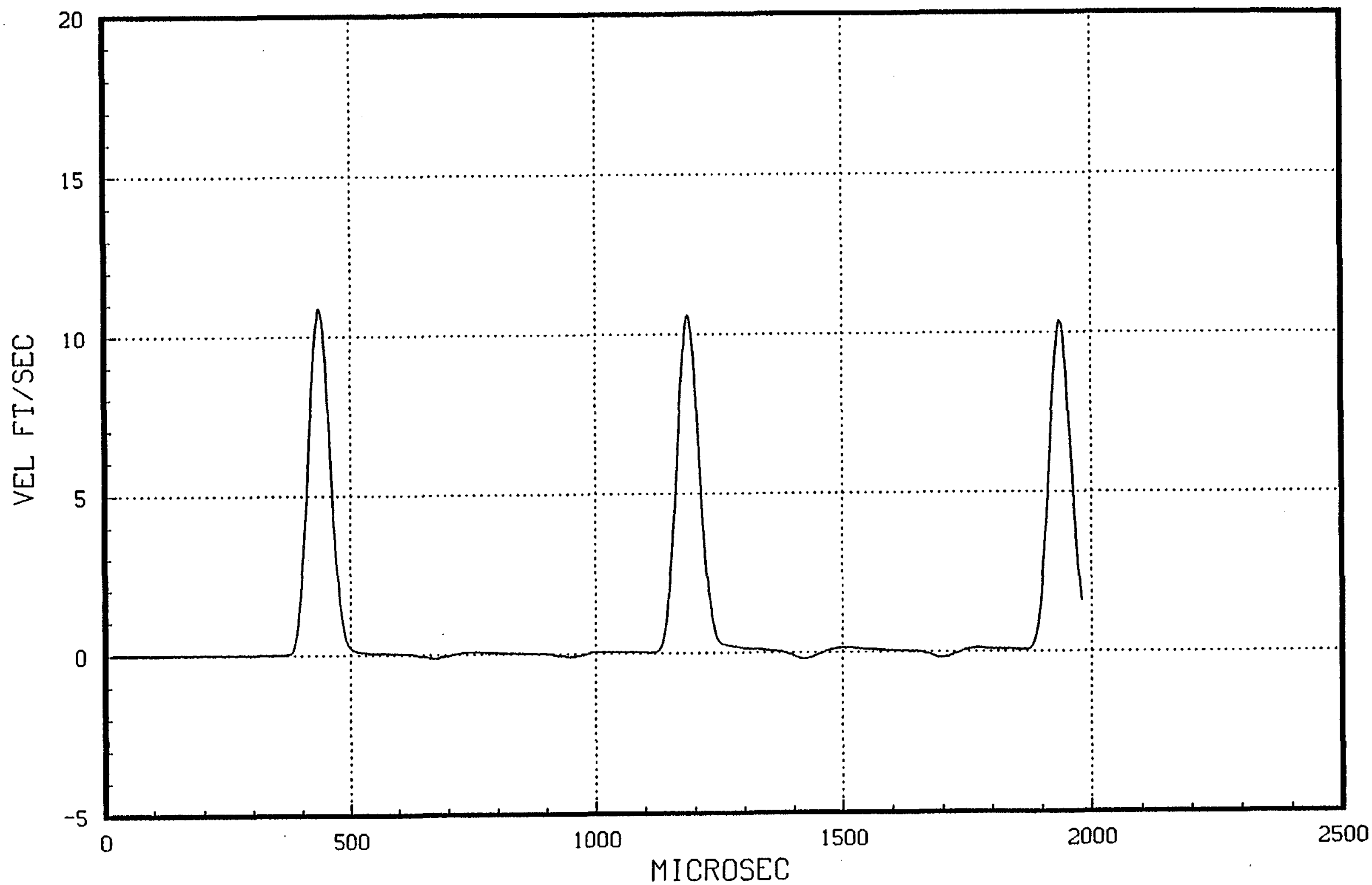
PLOT 1 14.22.34 TUES 6 AUG, 1996 JOB-BATCH7351 Sandia National Laboratory DISSPLA 11.

data verified by
date

7270 WIRE CHECK

08/06/96
CALIBRATION TEST

AK4258
FILTER 0.00HZ



TEST 05

M.F.A. 10.880 LASER VIBROMETER

TT= 0.091 MS. TR= 0.033 MS.
TF= 0.039 MS. TP= 0.043 MS.

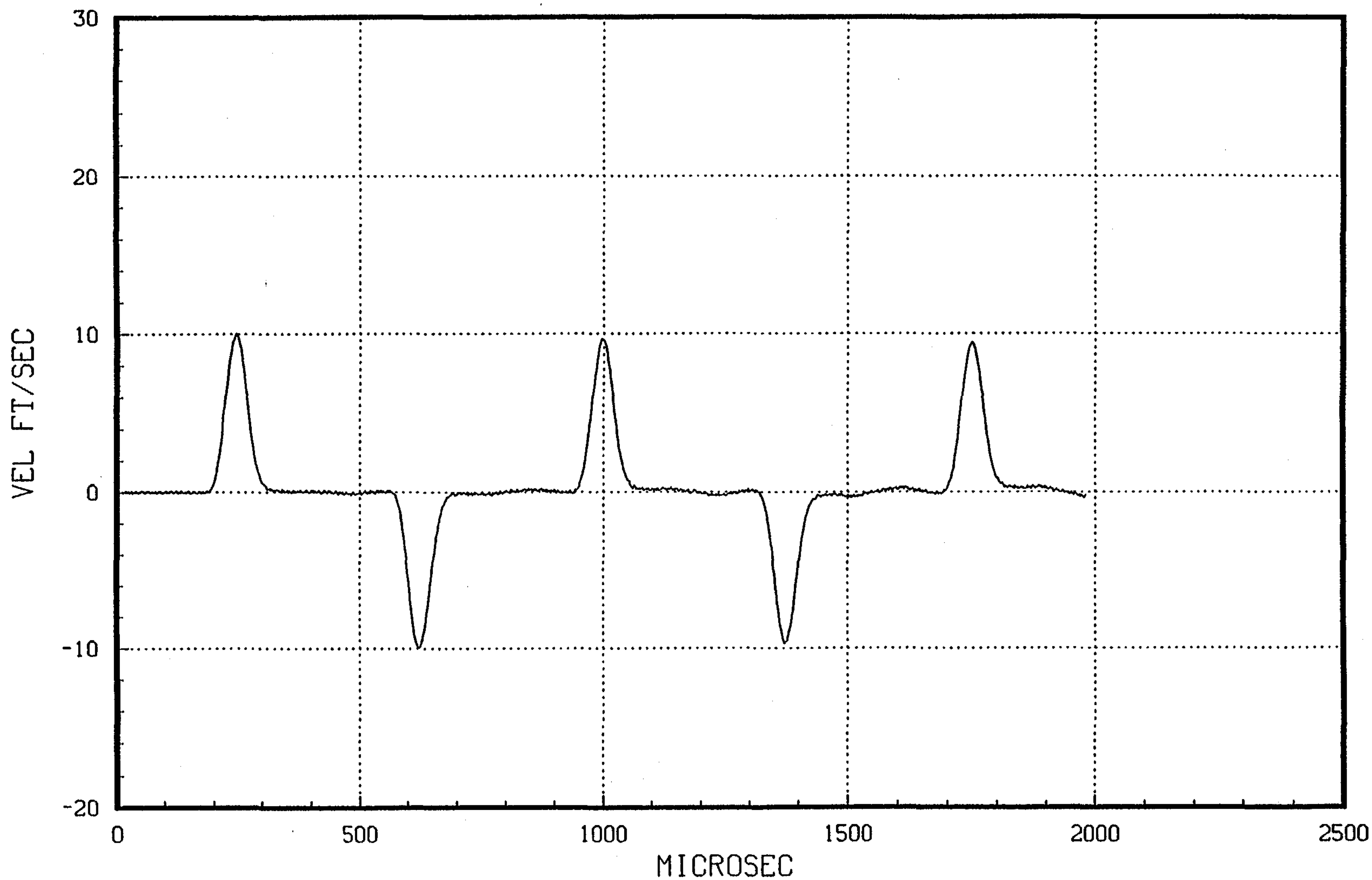
PLOT 1 14.22.53 TUES 6 AUG, 1996 JOB-BATCH7351 Sandia National Laboratory DISSPLA 11.0

data verified by
date

7270 WIRE CHECK

08/06/96
CALIBRATION TEST

AK4258
FILTER 0.00HZ

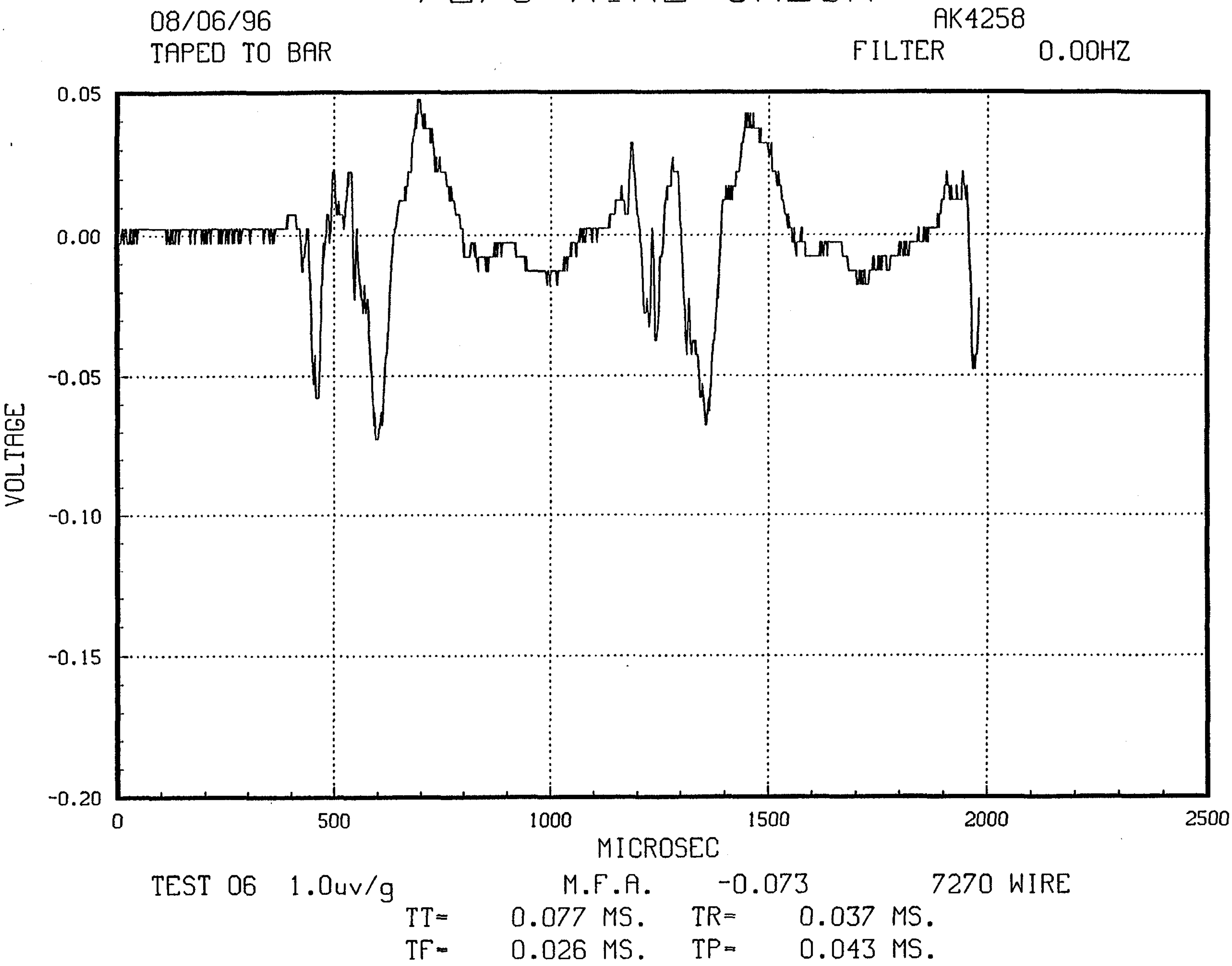


TEST 06 M.F.A. 9.975 BAR INPUT

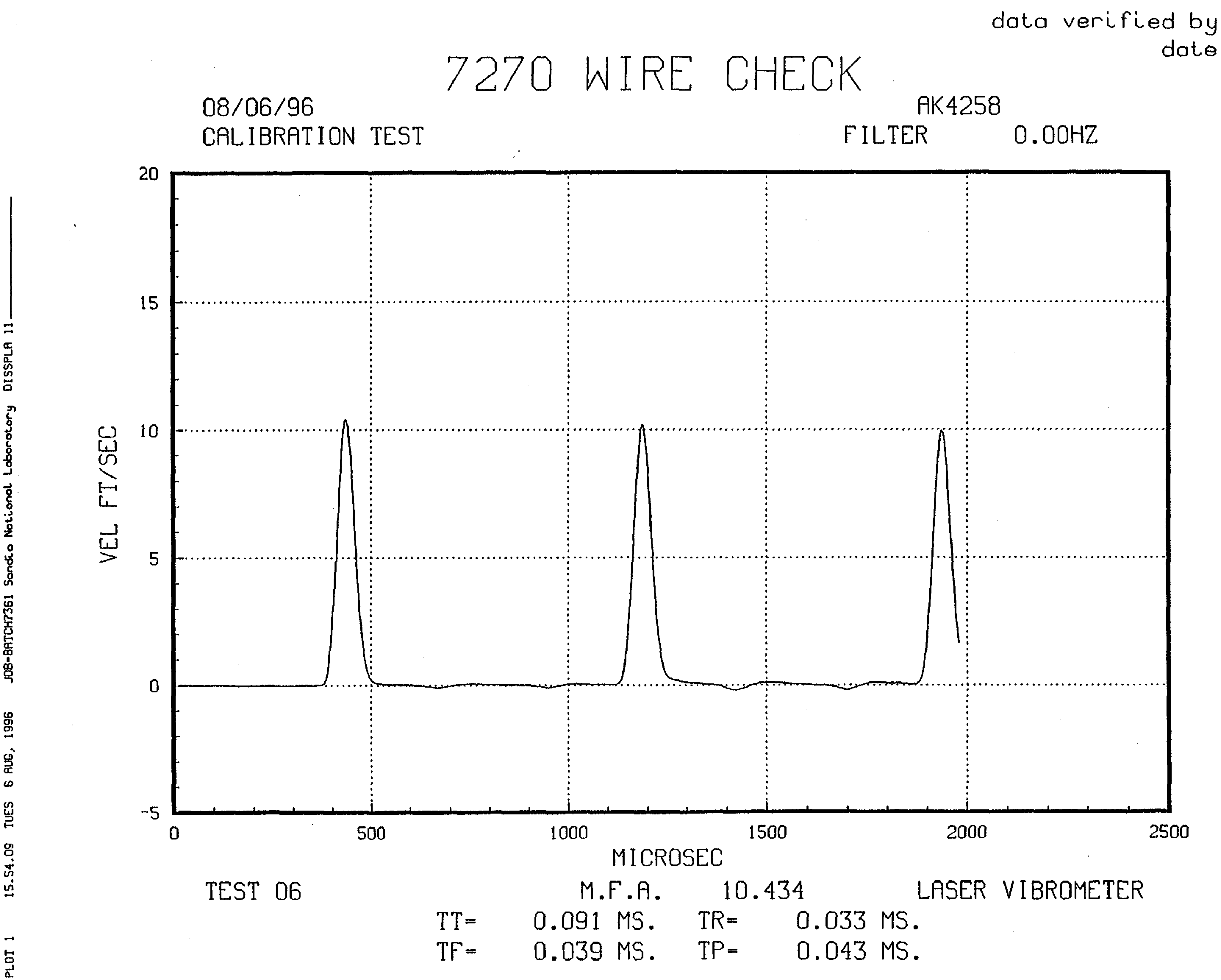
TT= 0.091 MS. TR= 0.033 MS.
TF= 0.040 MS. TP= 0.043 MS.

data verified by
date

7270 WIRE CHECK



PLOT 1 15.53.50 TUES 6 AUG, 1996 JOB-BATCH7361 Sandia National Laboratory DISSPLA 11.

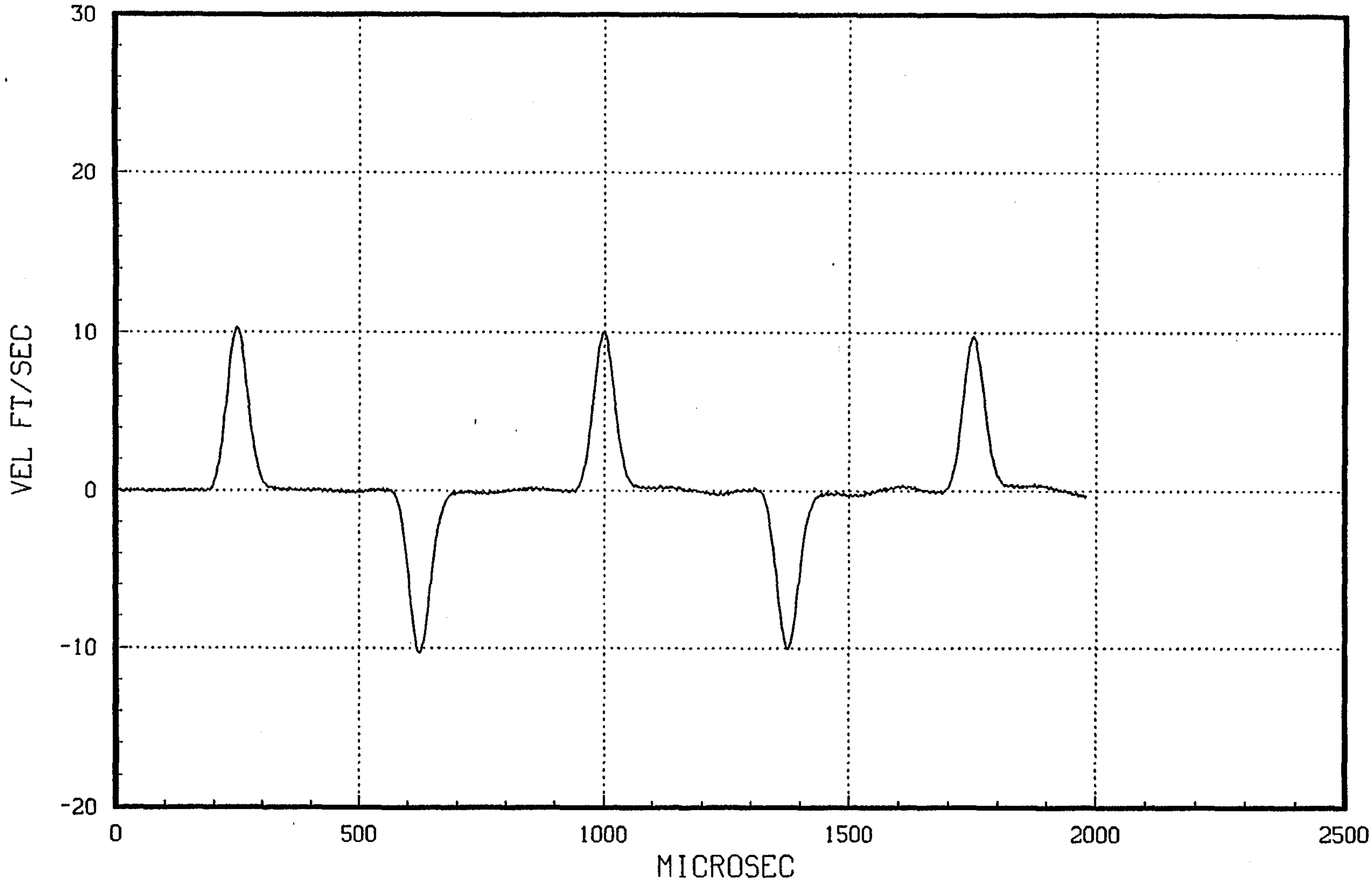

data verified by
date
7270 WIRE CHECK
08/06/96
CALIBRATION TEST
AK4258
FILTER 0.00HZ
VEL FT/SEC
20
15
10
5
0
-5
0
500
1000
1500
2000
2500
MICROSEC
TEST 06
M.F.A. 10.434
LASER VIBROMETER
TT= 0.091 MS. TR= 0.033 MS.
TF= 0.039 MS. TP= 0.043 MS.
PLOT 1 15.54.09 TUES 6 AUG, 1996 JOB-BATCH7361 Sandia National Laboratory DISSPLA 11

data verified by
date

7270 WIRE CHECK

08/08/96
CALIBRATION TEST

AK4258
FILTER 0.00HZ



TEST 07

M.F.A. 10.310 BAR INPUT

TT= 0.091 MS. TR= 0.033 MS.
TF= 0.039 MS. TP= 0.043 MS.

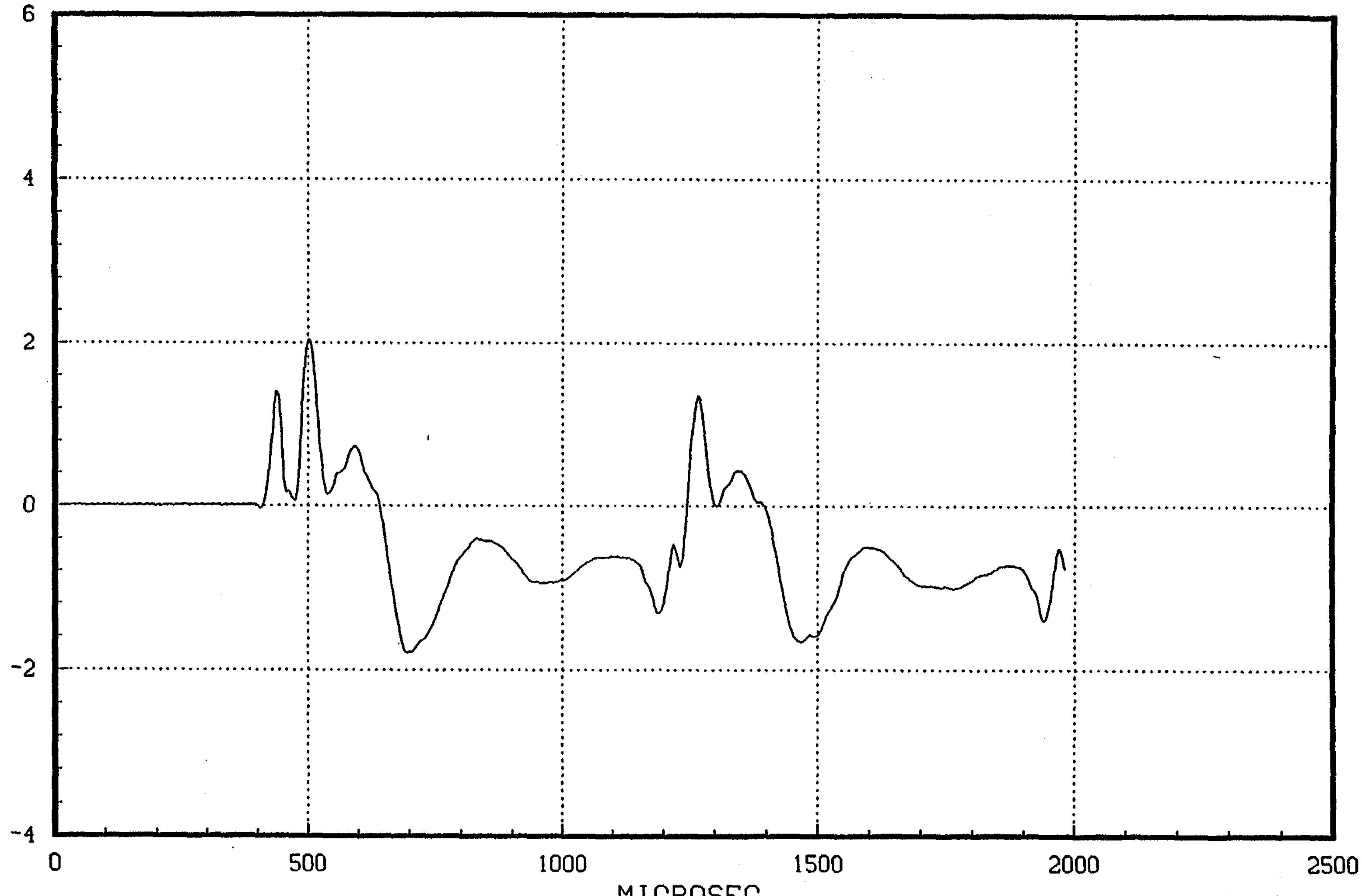
PLOT 1 13.23.46 THUR 8 AUG, 1996 JOB-BATCH7371 Sandia National Laboratory DISSPLA 11.0

data verified by
date

7270 WIRE CHECK

08/08/96
TAPED TO BAR

AK4258
FILTER 0.00HZ



TEST 07 1.0uv/g M.F.A. 2.043 7270 WIRE

TT= 0.055 MS. TR= 0.016 MS.

TF= 0.025 MS. TP= 0.023 MS.

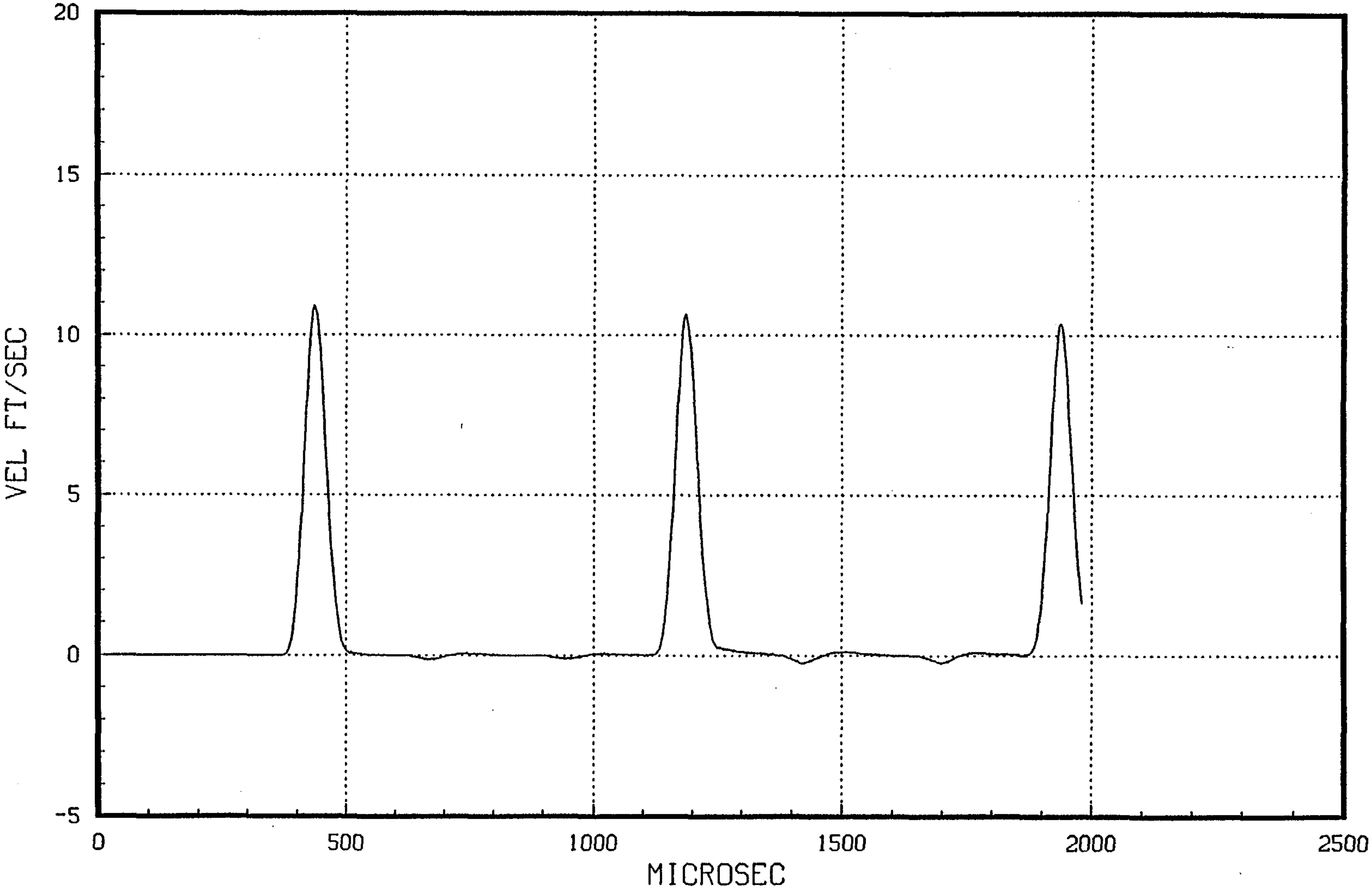
PLOT 1 13.24.12 THUR 8 AUG, 1996 JOB-BATCH7381 Sandia National Laboratory DISSPLA 11.

data verified by
date

7270 WIRE CHECK

08/08/96
CALIBRATION TEST

AK4258
FILTER 0.00HZ



TEST 07 M.F.A. 10.892 LASER VIBROMETER

TT= 0.090 MS. TR= 0.033 MS.
TF= 0.038 MS. TP= 0.043 MS.

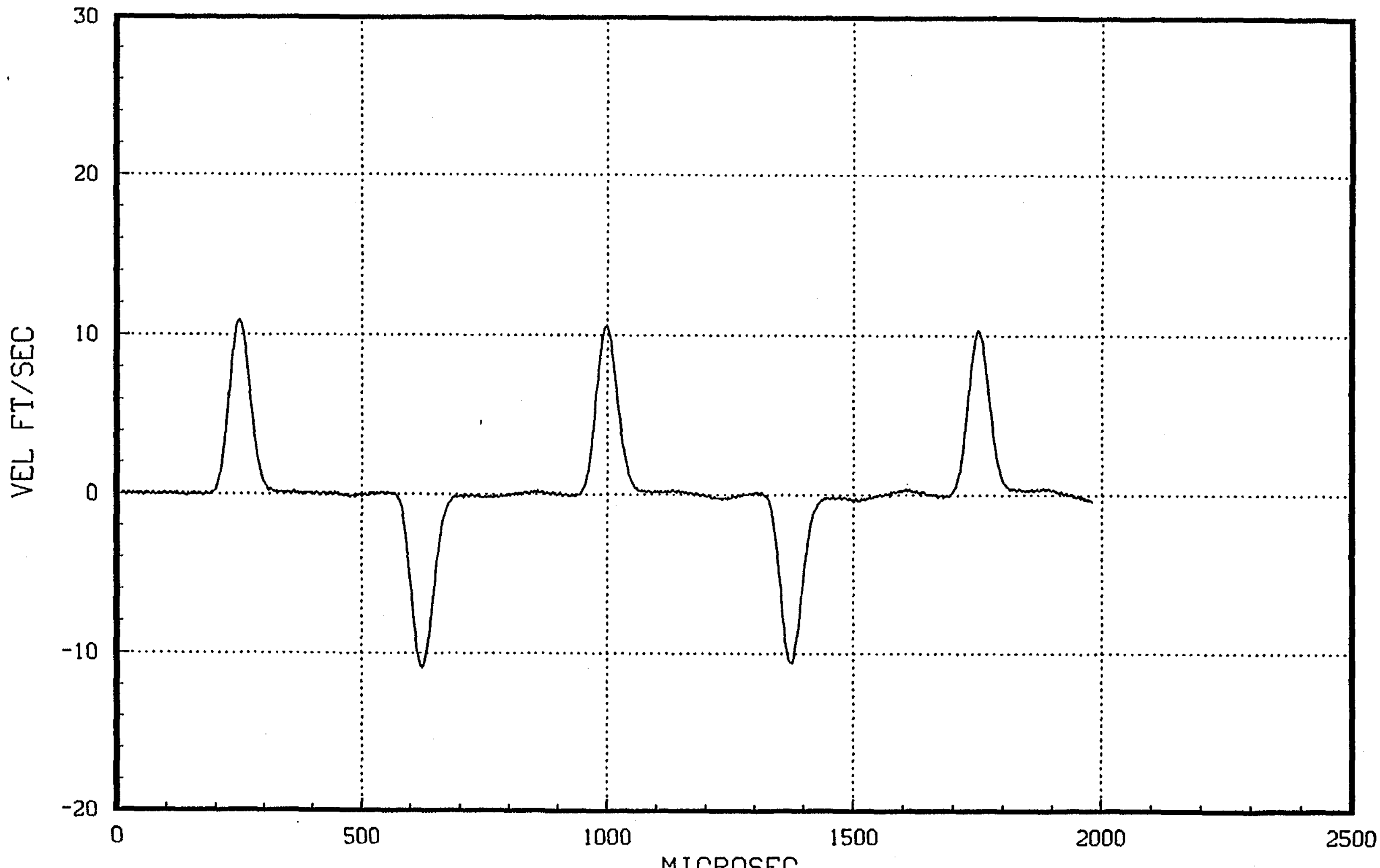
PLOT 1 13.24.33 THUR 8 AUG, 1996 JOB-BATCH7381 Sandia National Laboratory DISSPLA 11.0

data verified by
date

7270 WIRE CHECK

08/08/96
CALIBRATION TEST

AK4258
FILTER 0.00HZ



TEST 08

M.F.A. -10.881

BAR INPUT

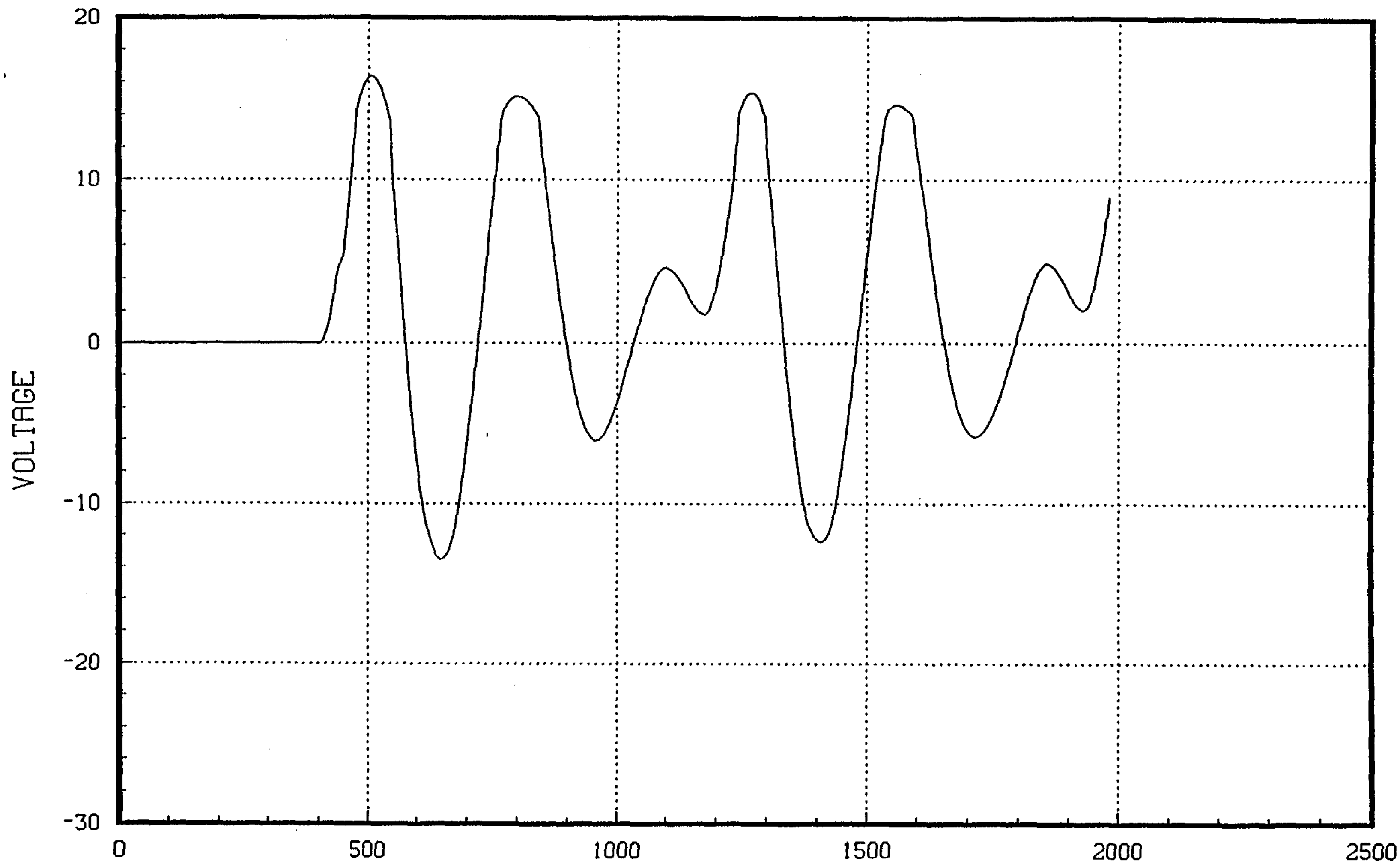
TT= 0.088 MS. TR= 0.031 MS.
TF= 0.039 MS. TP= 0.040 MS.

data verified by
date

7270 WIRE CHECK

08/08/96
TAPED TO BAR

AK4258
FILTER 0.00HZ



TEST 08 1.0uv/g M.F.A. 16.367 7270 WIRE

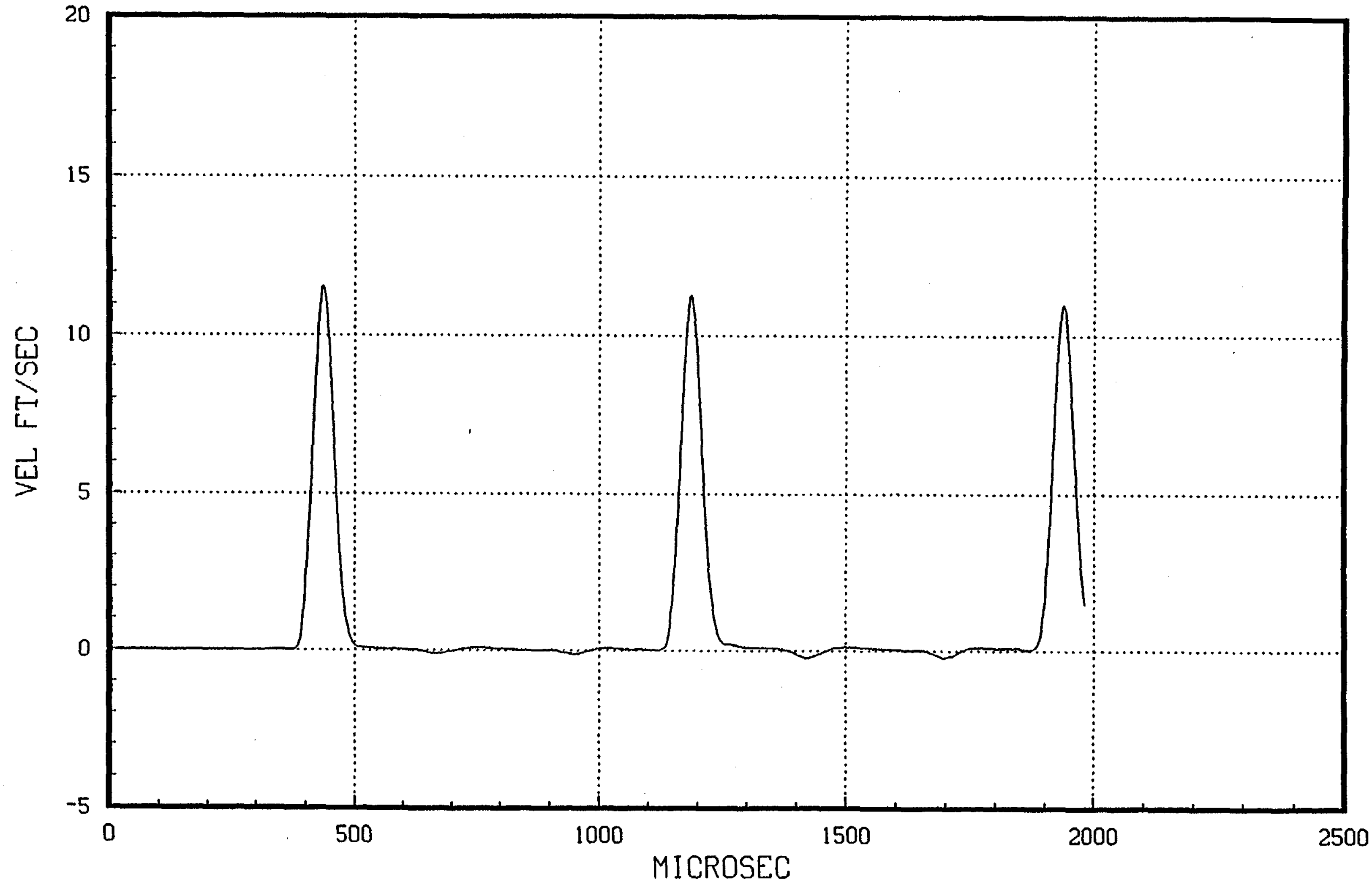
TT= 0.151 MS. TR= 0.058 MS.
TF= 0.039 MS. TP= 0.086 MS.

data verified by
date

7270 WIRE CHECK

08/08/96
CALIBRATION TEST

AK4258
FILTER 0.00HZ



TEST 08

M.F.A. 11.564 LASER VIBROMETER

TT= 0.087 MS. TR= 0.031 MS.
TF= 0.037 MS. TP= 0.040 MS.

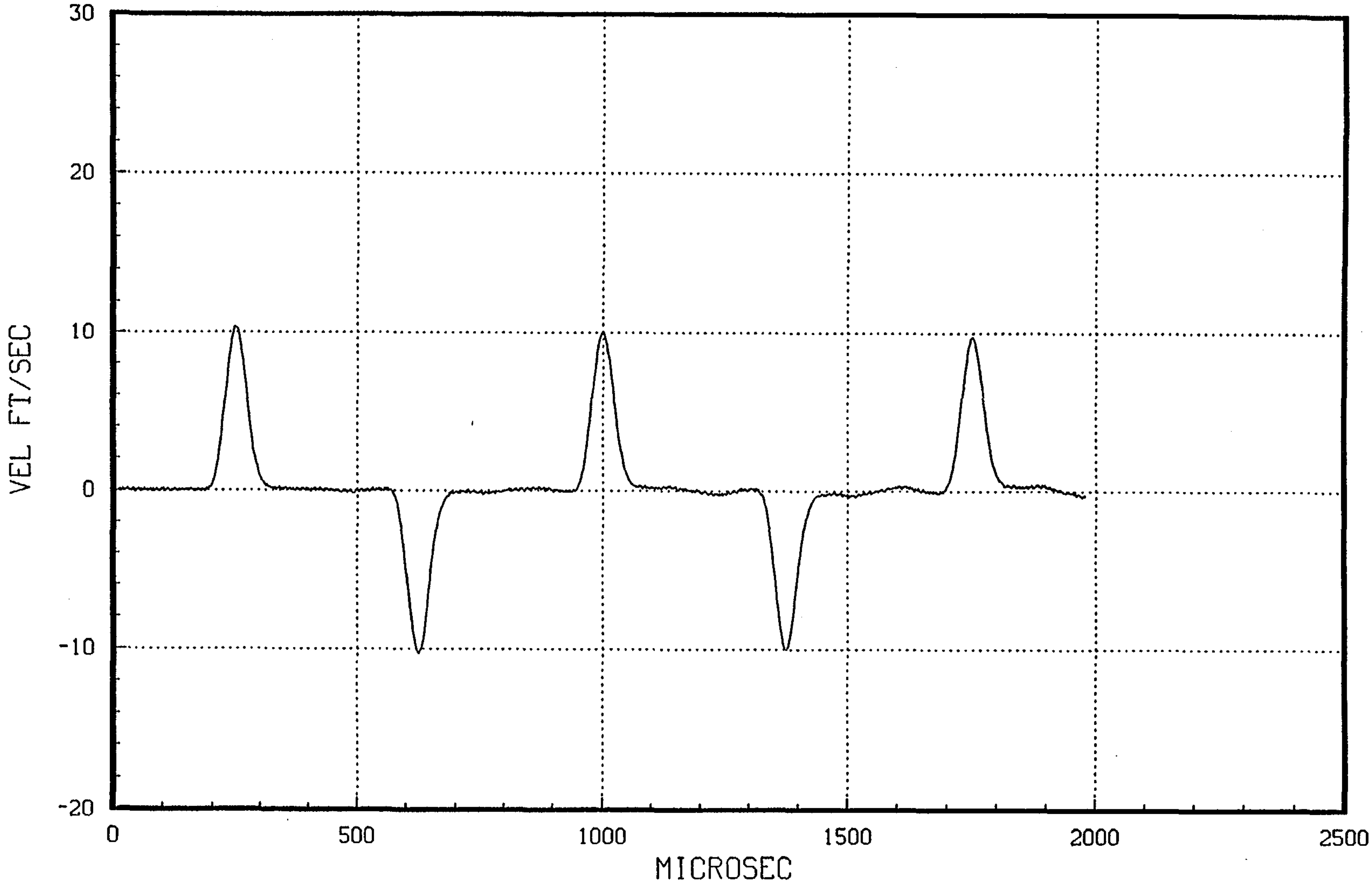
PLOT 1 13.33.46 THUR 8 AUG, 1996 JOB-BATCH7391 Sandia National Laboratory DISSPLA 11.0

data verified by
date

7270 WIRE CHECK

08/08/96
CALIBRATION TEST

AK4258
FILTER 0.00HZ



TEST 09

M.F.A. 10.302 BAR INPUT

TT= 0.092 MS. TR= 0.034 MS.
TF= 0.039 MS. TP= 0.042 MS.

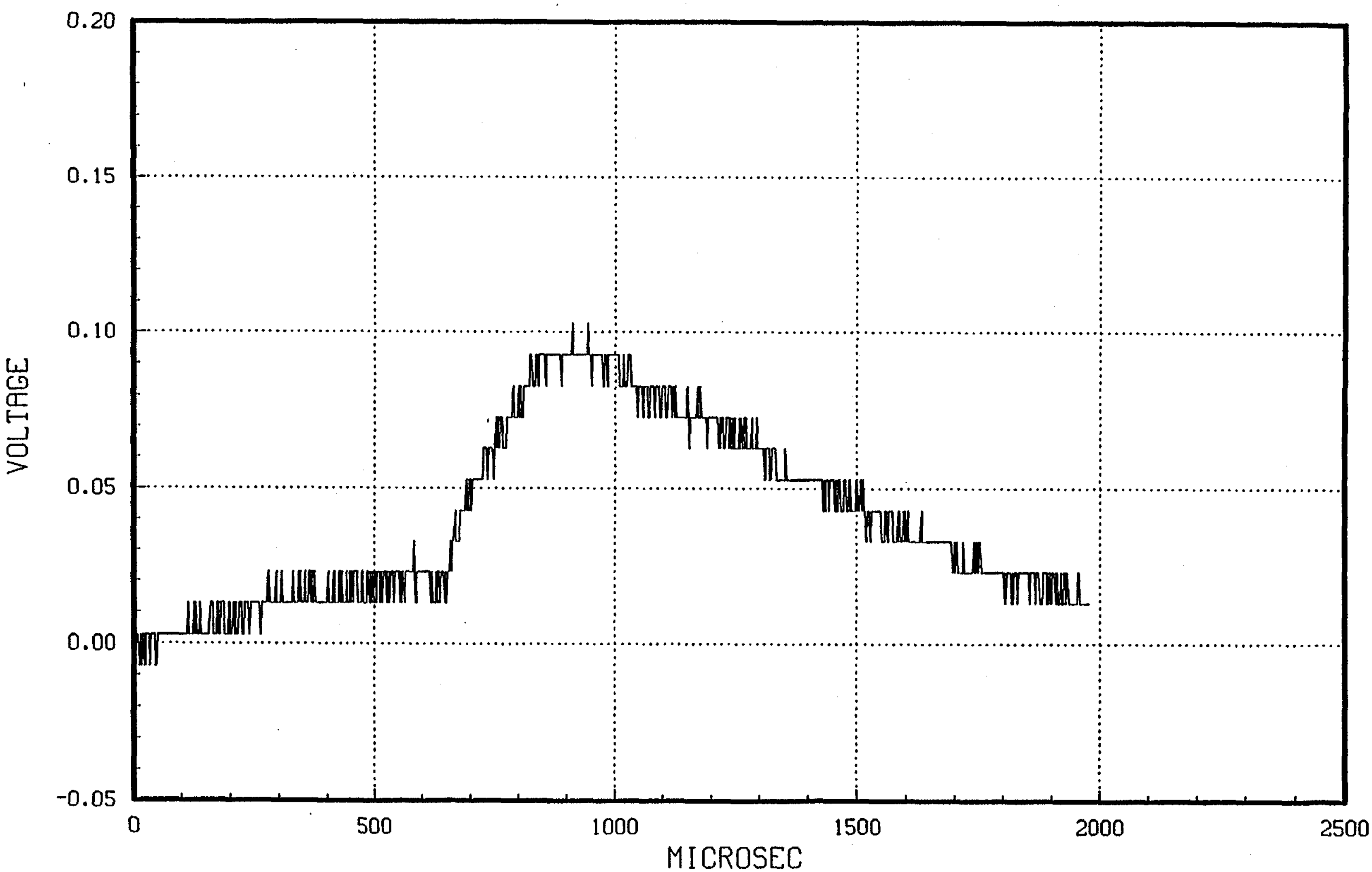
PLOT 1 13.42.01 THUR 8 AUG, 1996 JOB-BATCH7391 Sandia National Laboratory DISSPLA 11.

data verified by
date

7270 WIRE CHECK

08/08/96
REMOVED FROM BAR

AK4258
FILTER 0.00HZ



TEST 09 1.0uv/g M.F.A. 0.096 7270 WIRE

TT= 0.031 MS. TR= 0.556 MS.

TF= 0.000 MS. TP= 0.678 MS.

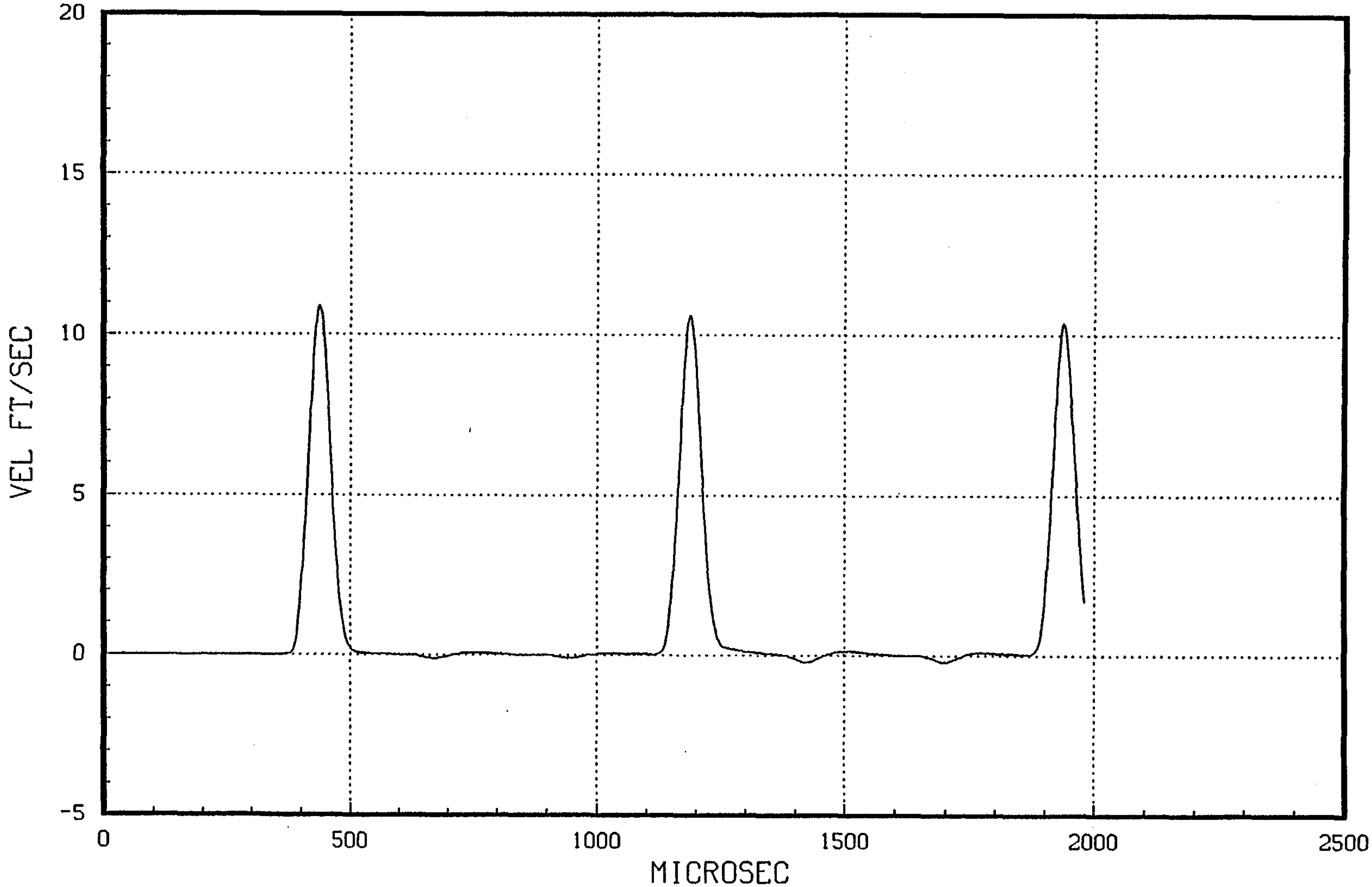
PLOT 1 13.42.22 THUR 8 AUG, 1996 JOB-BATCH2391 Sandia National Laboratory DISSPLA 11.1

data verified by
date

7270 WIRE CHECK

08/08/96
CALIBRATION TEST

AK4258
FILTER 0.00HZ



TEST 09 M.F.A. 10.885 LASER VIBROMETER

TT= 0.091 MS. TR= 0.033 MS.
TF= 0.039 MS. TP= 0.043 MS.

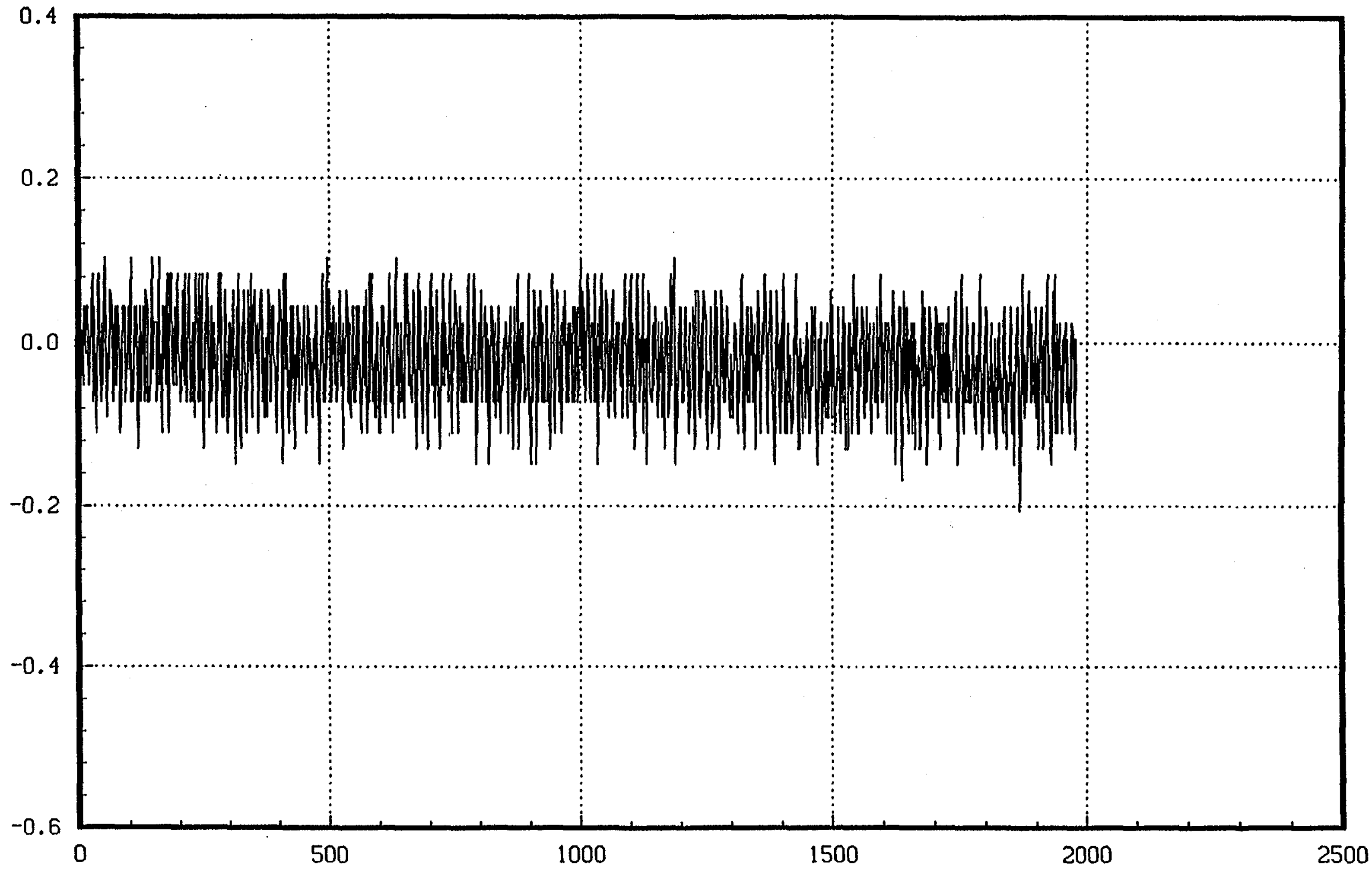
PLOT 1 13.42.41 THUR 8 AUG, 1996 JOB=BATCH7391 Sandia National Laboratory DISSPLA 11.

data verified by
date

7270 WIRE CHECK

08/08/96
CALIBRATION TEST

AK4258
FILTER 0.00HZ



TEST 10 M.F.A. -0.103 BAR INPUT

TT= 0.008 MS. TR= 0.003 MS.
TF= 0.003 MS. TP= 0.004 MS.

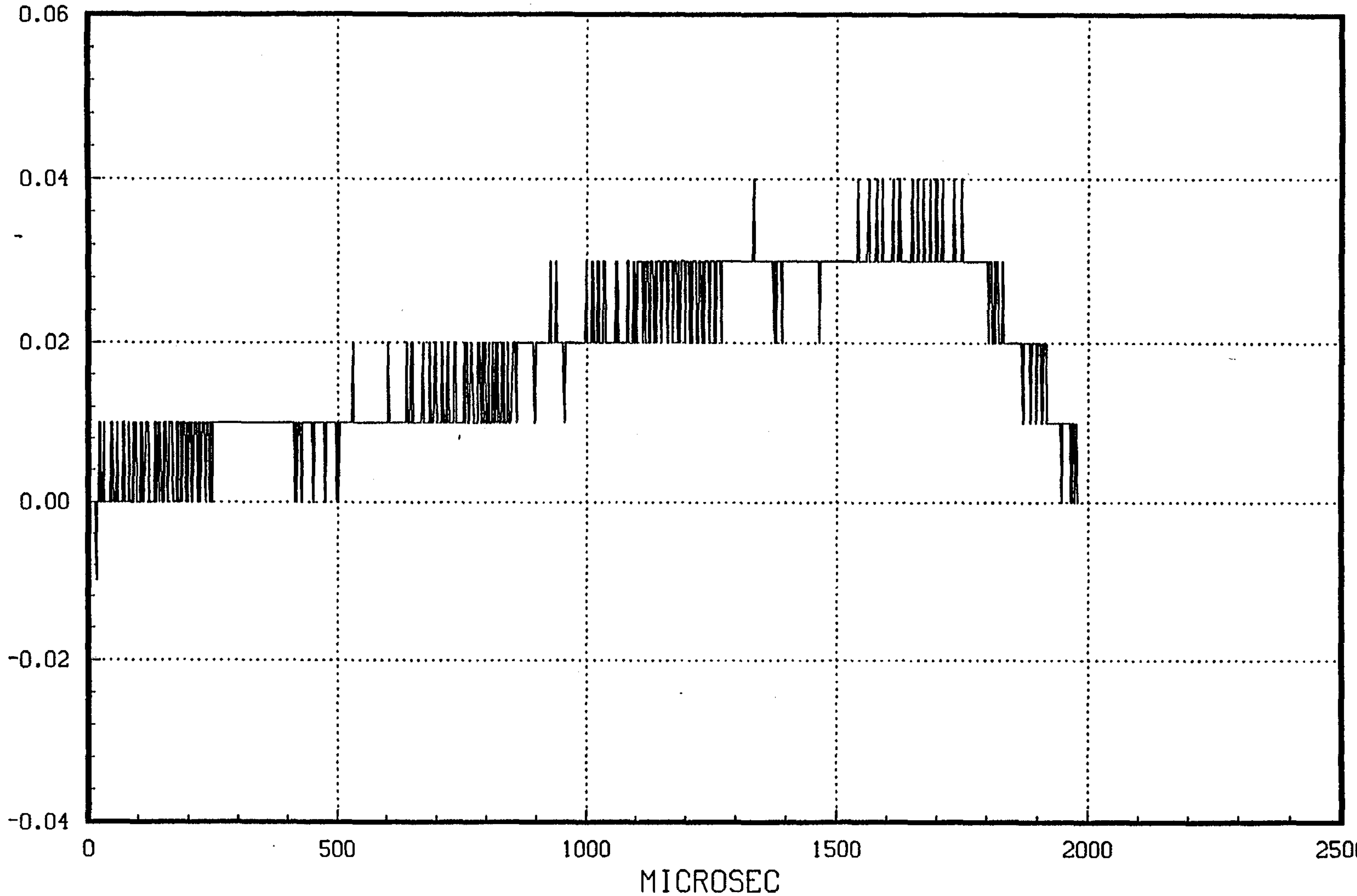
PLOT 1 13.45.43 THUR 8 AUG, 1996 JOB-BATCH7401 Sandia National Laboratory DISSPLA 11.1

data verified by
date

7270 WIRE CHECK

08/08/96
REMOVED FROM BAR

AK4258
FILTER 0.00HZ



TEST 10 1.0uv/g M.F.A. 0.036 7270 WIRE

TT= 1.395 MS. TR= 1.364 MS.

TF= 0.000 MS. TP= 1.379 MS.

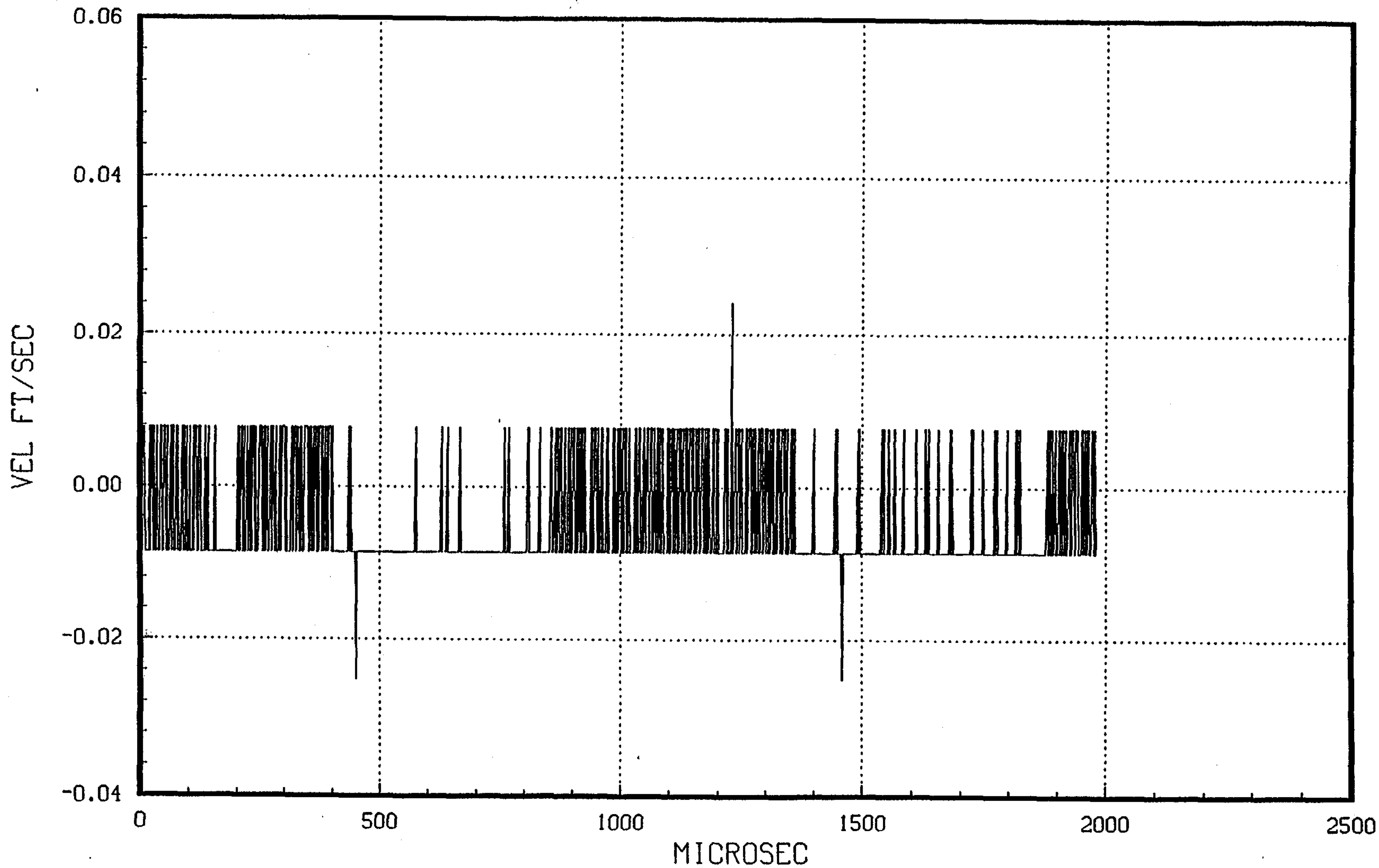
PLOT 1 13.46.02 THUR 8 AUG, 1996 JOB-BATCH7401 Sandia National Laboratory DISSPLA 11.0

data verified by
date

7270 WIRE CHECK

08/08/96
CALIBRATION TEST

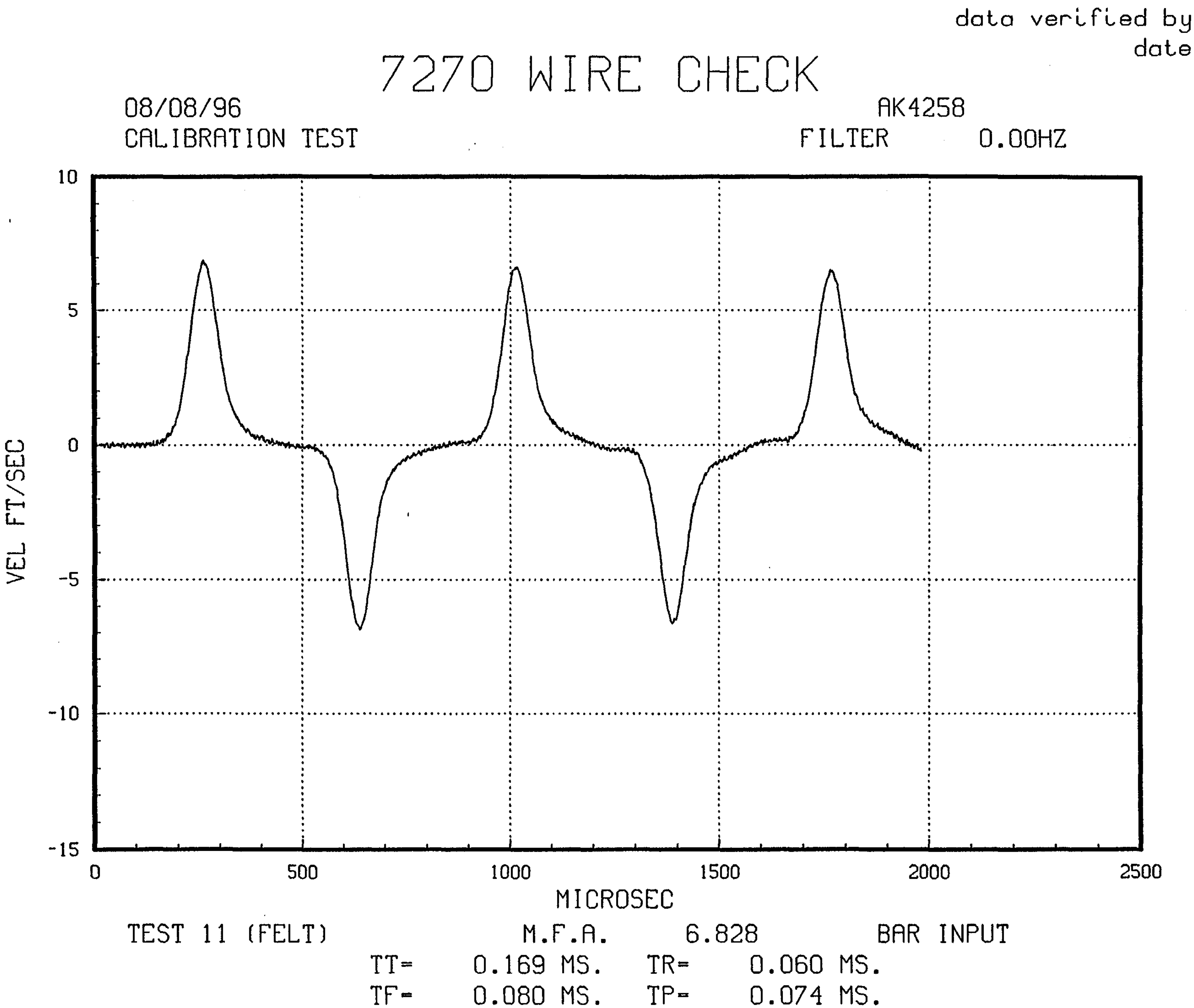
AK4258
FILTER 0.00HZ



TEST 10

M.F.A. -0.011 LASER VIBROMETER

TT= 0.022 MS. TR= 0.007 MS.
TF= 0.013 MS. TP= 0.009 MS.



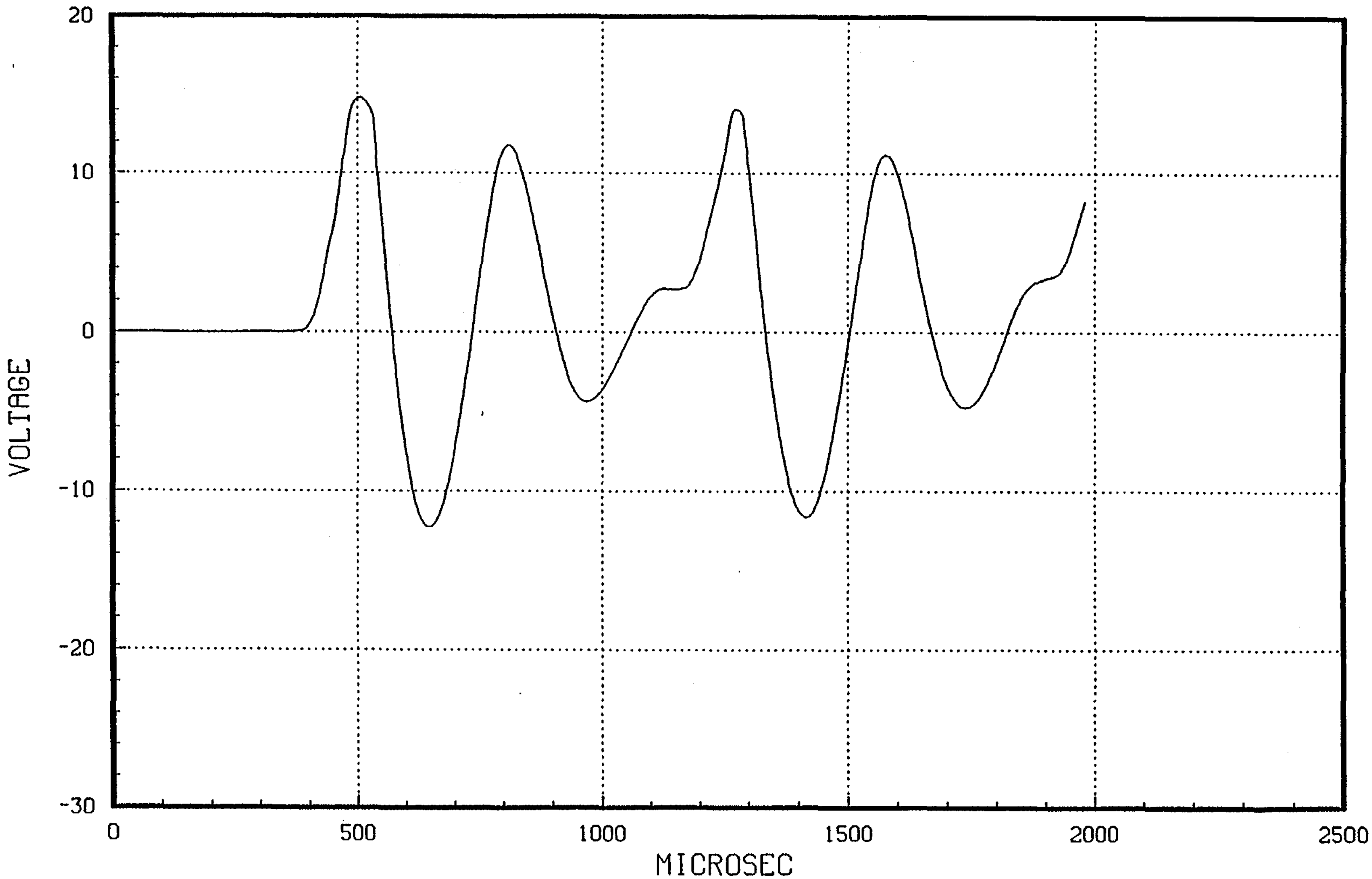
data verified by
date
7270 WIRE CHECK
08/08/96
CALIBRATION TEST
AK4258
FILTER 0.00HZ
10
5
0
-5
-10
-15
VEL FT/SEC
0
500
1000
1500
2000
2500
MICROSEC
TEST 11 (FELT)
M.F.A. 6.828
BAR INPUT
TT= 0.169 MS. TR= 0.060 MS.
TF= 0.080 MS. TP= 0.074 MS.

data verified by
date

7270 WIRE CHECK

08/08/96
TAPED TO BAR

AK4258
FILTER 0.00HZ



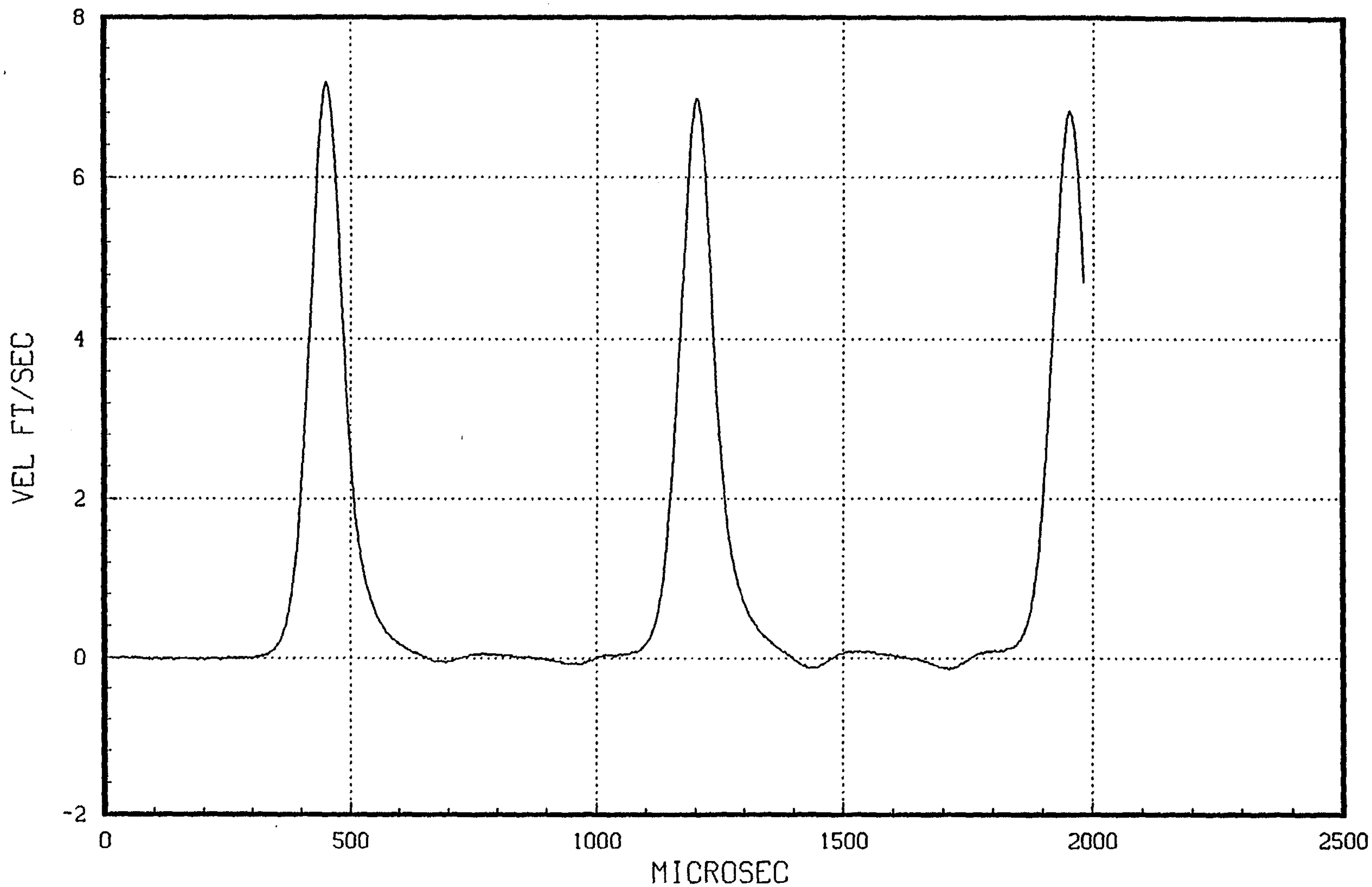
TEST 11 1.0uv/g M.F.A. 14.812 7270 WIRE
TT= 0.152 MS. TR= 0.068 MS.
TF= 0.032 MS. TP= 0.093 MS.

data verified by
date

7270 WIRE CHECK

08/08/96
CALIBRATION TEST

AK4258
FILTER 0.00HZ



TEST 11 M.F.A. 7.168 LASER VIBROMETER

TT= 0.166 MS. TR= 0.060 MS.
TF= 0.077 MS. TP= 0.075 MS.

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