CORRELATION ANOMALIES

BETWEEN

HELMET DROP-TEST SYSTEMS

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I. INTRODUCTION

During the latter half of 1974, a laboratory cross correlation of motorcycle helmet drop-test facilities was undertaken. This program, conducted by personnel from the Medina facilities of American Safety Equipment Corporation, involved the use of a MEP calibration device. Data obtained with this device, a modular elastromer programmer, or MEP, were then compared for absolute values as had been industry practice. Subsequent computer analysis along with high speed motion picture studies were performed and resulted in a more detailed understanding of response than possible from MEP data alone.

As a result of this analysis, it has been determined that major differences exist in the response characteristics of various test equipments which explain anomalies between test results obtained in helmet testing. The results indicate that calibration techniques historically used by test laboratories as well as industry need a continuing evaluation of procedures and updating where appropriate.

II. MEP TESTS

During August and September of 1974, Maurice Fox, Quality Assurance Manager of American Safety Equipment's Medina, Ohio plant performed a round-robin test program involving the test facilities of Southwestern Research Institute, U. S. Testing Labs, Dayton T. Brown, and the ASE Medina plant. These tests employed a modular elastomer programmer (MEP) which was purchased new. This device, a disc shaped block of elastic material having a major diameter of 5 inches and a thickness of 1 inch, was developed for quality and engineering testing of mechanical devices, and its use in the helmet industry goes back 5 to 7 years.

In use, the MEP replaces the rigid anvil of the drop test equipment and the drop assembly is allowed to fall against the MEP from given heights. An accelerometer, sensitive to shock spectra in the vertical plane, is mounted at the static center-of-gravity of the drop assembly. The resulting electrical signal from the accelerometer is an accurate histogram of the forces experienced by the test device during impact. These pulses are recorded electronically, or photographically, for later analysis of the shock characteristics.

During the round-robin tests, the MEP was substituted for the anvils on each laboratories' drop test system. Measurements were made to determine that all drop heights were consistant. In addition, where possible an optical gate was used to measure the velocity of each system, except that of SwRI, just prior to impact. (SwRI has a built-in velocity sensor).

Acceleration pulses were obtained from each series of tests after allowing calibration and "warm-up" drops. Table A details the observables from these tests. These results, discussed in more detail later, lead to some general characterizations. First, there is a normal spread in values of acceleration g's directly relateable to the values of impact velocities. Second, even though the set average of g's for the SwRI tests is less than other values on the table, the resultant dwell times of the shock pulse at the 150g and 200g levels are longer than any other set of dwell time data. This inverse nature in dwell time exists between data from SwRI and the other three test facilities.

The above inverse characteristic; i.e. longer dwell times for equal or smaller g values, was indirectly verified through an assessment of test data accumulated by several other manufacturers who had subjected similar helmets to tests at the test facilities.

TABLE A

SUMMARY OF MEP DATA

All data taken on one MEP.

Test	Laboratory	Drop	g's	ms/150	ms/200	V-1"	ms/base
#	DTB	48	368	2.31	1.89	186.92	5.06
	DTB	48	366	2.29	1.89	188.39	4.83
	DTB	48	363	2.31	1.89	190.69	4.81
#	MEDINA	48	400	2.0	1.65	190*	4.0
	MEDINA	48	400	2.1	1.7	190*	
	MEDINA	48	398	2.05	1.7	190*	
#	SwRI	48	395	2.45	1.9	190*	4.5
	SwRI	48	380	2.45	1.95	190*	4.6
	SwRI	48	370	2.45	1.95	190*	4.5
	SwRI	48	390	2.45	2.0	190*	4.5
#	UST	48	340	2.4	1.85	188.3	5.2
	UST	48	340	2.35	1.8	183.8	4.8
	UST	48	340	2.4	1.85	170.5	4.8

Footnotes

*Velocity assumed to be near theoretical because of adjustment.
#Data used for computer analysis.

III. COMPUTER DATA ANALYSIS

The generalizations of the basic MEP tests led to the use of computer analysis in order to isolate time varient phenomena not discernable from the peak (or instantaneous) values obtained in the MEP tests. A basic scheme was developed to allow use of the photographs of the shock pulses obtained from the MEP tests. This scheme called for the development of a computer program that would reconstruct the values of velocity change and displacement as functions of time from the acceleration pulse alone.

Given the basic relationships of velocity, motion and acceleration of a body, the differential equations of kinematics are derived. These well known relationships are:

$$v = \frac{ds}{dt} \qquad (1)$$

$$g = \frac{dv}{dt} = \frac{d^2 s}{dt} \qquad (2)$$

$$v \cdot dv = a \cdot ds \qquad (3)$$

where a = acceleration, s = displacement and v = velocity.

With these basic equations of kinematics, it is elementary to show that:

$$\Delta v = \int_0^t a \cdot dt \qquad (4)$$

$$\Delta s = \int_0^t v \cdot dt \qquad (5)$$

While care must be exercised in the use of these relationships (they are the relationships of <u>instantaneous</u> values of g, v, and s), they form the basis for reconstruction of values of velocity and displacement from measured values of acceleration vs. time. An important parameter that must be known is velocity at $t = 0$ in order to properly range the output of the integrations, but no other constant is required. Mass would appear to be a required input, but this was shown not to be the case by Galileo at a very early date. Knowing the instantaneous value of velocity at the time of impact, a computer integration routine can be developed using any one of several methods. Basically, these different methods deal with the treatment of the averaging or weighting of instantaneous values of the variable 'g' for summation. It is obvious from Equation 4 that the area under the acceleration vs. time curve is equal to velocity change and hence this integration must have a starting point (pre-impact velocity) in order to describe accurately the impact characteristics.

The computer program uses Equations 4 and 5 sequentially for each point of time between the limits desired. Normally, these limits include a short duration prior to impact and a short period after measured acceleration values return to -1g. This duration coincides with that period of time starting just prior to impact and ending when the helmet and test device have just left the contact pad on their way back up (rebound).

Input to the program is by line statement of conversion factors and data files. The data file is taken from linear dimensions of the shock pulse photograph record. Enough points are taken to provide reasonable integration accuracy. Each point is described by two numbers, such as, "2.4, 3.2," which give x and y dimensional values for many points along the curve. The data conversion statements provide the computer with the calibration values for the data set numbers.

Output of the program is in the form of plots, autoscaled, of acceleration, velocity and displacement as functions of time. The plot of acceleration serves to test for those human errors possible in data entry and to show time correlatables of this function with other test variables.

The results of each test calculation is returned to computer memory after plots are made. A second section of the program now calls any two test sets and performs a set subtraction and plots differential graphs. In simple terms, these curves allow a correlation of how one test compares in magnitude and time with any other test. In this way, the true time dependent differences between two tests conducted on two different equipments can be found.

Figures 1 through 4 are single test calculation plots for the separate test laboratories. Figures 5 through 8 show the differential values between various single laboratory tests. Each figure is identified as to the equipment involved.

When viewing the single test plots, it will be helpful to note that instantaneous values of the three variables are indicated by capital letters, V., A., and D, which represent velocity, acceleration and displacement.

IV. DISCUSSION OF COMPUTER ANALYSIS

As previously mentioned, a first look at peak value data can lead one to the erroneous conclusion that different test equipments correlate fairly well.

Computer analysis yields values for time dependent acceleration, velocity and displacement and it is seen that while systems may be made to correlate for peak values, at other times the units are very much out of correlation.

From the single test calculation plots, Figures 1 through 4, it can be determined that peak values of acceleration occur near 2.4 ms after anvil contact for 48" flat anvil tests using the sample MEP. The shapes of the curves from one test to another are similar to the eye. However, at the point of maximum MEP compression where the velocity direction reverses, (near 2.4 ms) there are large differences in the ratio of precontact velocity to past contact velocity. Table B gives values and differences for pre-impact and post-impact velocities. It also gives " ΔV" values (total magnitude of velocity change), and the ratio between the two velocities. This latter number serves as a figure-of-merit to gauge system performance.

TABLE B

TEST FACILITY	PREIMPACT VELOCITY "/sec	POSTIMPACT VELOCITY "/sec	ΔV "/sec	RATIO
DTB	189	119.422	308.422	.632
ASE-MEDINA	190	83.674	273.674	.44
SwRI	190	123.164	313.164	.65
U.S. TESTING	183.8	102.535	286.335	.56

The values of ΔV indicated no correlation between precontact velocity and total velocity change. This is due to fundamental differences in test equipment discussed later. The ratios of post to pre-impact velocity magnitudes offer a striking measure of system performance. Again there is no correlation between initial velocity and velocity ratios. This also is indicative of the same basic system differences.

The foregoing differences and ratios are important but do not identify the causes of the differences. Analysis of the differential plots begins to give an indication of where the differences come from. Using the differential curve of SwRI vs. Medina as an example, Figure 6, this can be shown.

Referring to Figure 6: If both systems were in perfect correlation at each instant of time, all data points would be on the "0" difference line from T=0.0ms to 6.0 ms. These are obviously not. In addition, there is a "waist" in the data at 2.4 ms, the time of maximum compression of the MEP, or the time the head form has come to rest prior to rebounding upward. This "pinch" or "waist" indicates that only at this instant (except at T=0) are the two systems correlatable.

Before and after 2.4 ms there are major excursions of the A curve. It is seen that the SwRI equipment is experiencing 63.549 g's more force at 0.8 ms than the Medina system. Further, it is seeing 43 g's <u>less</u> force at 1.6 ms. Again at 3.2 ms the SwRI system is 60 g's higher. This is a 107.549 g excursion in a test that generates 400 g's total. The area under these acceleration deviations is reflected in the magnitude of the V curve. This curve is seen to remain at or on one side of the 0 difference line for all time values. At T=0, it is at 0 difference, but reaches a peak at 1.6 ms and another at 4.4 ms, the instant the test device left contact with the MEP on its way upward (rebound). The magnitudes of the velocity changes tend to agree with areas under the A curve.

These observations lead one to a generalized conclusion: The Medina system is losing velocity as compared to the SwRI system just prior to maximum MEP compression and again right after. Loss after appears to be greatest by a large factor.

While the analysis now gives a reason for observed differences, it does not yield the physical cause. This finding required the use of high speed film analysis.

V. HIGH SPEED FILM ANALYSIS

After the computer analysis yielded the above conclusion, high speed films were made of several tests at Medina and at Bell Helmets. In addition, films of tests at SwRI were made available to this writer for analysis.

Upon viewing of these 2000 frame/sec. films, it became obvious that the drop test assembly known as the "Grant Cross Arm," and used by a preponderance of test facilities (excluding SwRI, Snell and Bell) suffers from mechanical design problems associated with a center-of-percussion phenomena. While the unit is in static balance on a line through the center of gravity, it is not in dynamic balance about this point and distorts on impact. The result of this is that the bearing guides of the Grant arm bend from parallel by as much as 6 to 7 degrees near the moment of maximum test object compression. This causes the teflon guide bearings to bind on the drop guide wires and lose energy through friction. These losses begin to occur just prior to maximum compression of the test device with the maximum angle and friction occurring after 2.4 ms when the headform reverses direction upward while the bearing holder is still moving downward. This agrees with the computer analysis. Figure 9 shows the geometry of the drop arm assembly before contact and at 3 ms.

Films of the SwRI system show no visible distortion or binding during impact. This explains the higher rebound characteristics of this system as compared to others, as well as the higher values of ΔV and ratio values in Table B.

VI. CONCLUSION

While meeting equipment requirements of various associations and Federal standards, results from one test facility are very difficult to correlate with those of another facility even though pains are taken in attempting basic calibrations, cross-correlations, round-robins, etc. Many in the field have felt that this inconsistancy results from the inability to produce two helmets alike. As a result of this analysis, it is possible that helmets are more consistant than appreciated and that the inconsistancy is in the test equipment.

From a mathematical point of view, this test inconsistancy results principally in differences in measured g forces and pulse dwell times. Using only readings at peak values, it would appear possible to alter drop heights to set two helmet tests alike. However, in doing so, the dwell times will never correlate consistantly because of the basic difference in the integral of g's vs. time. This is due to the fact that while the peak g's may be the same when comparing two separate tests, the total ΔV, or area under the g vs. time curve, will not be the same and the difference must result in a change in the shape of the acceleration pulse. For otherwise identical systems, those producing larger ΔV's produce longer dwell times for the identical tests. Individual test devices -MEPs, helmets, etc., may alter the magnitude of these differences, but not the direct relationship.

While the amount of data used for this analysis was not exhaustive, they appear adequate in light of the conclusive findings of the film studies which complement the computer study. Also, in the data, small differences in pulse phase after T=0 can yield differences in the differential plots. Care was exercised to identify

T=0 and in future tests, a T=0 time will be measured.

For product engineering reasons alone, it would appear prudent to update drop-test facilities which presently use certain types of guided wire equipment. There is additional reason for such change in light of Federal standards. It is most desirable to rule out inconsistancies now appearing in test result data. This is not a total indictment of all such systems, as there are several which can produce moderately good results. These latter systems could be improved, but this may be more expensive to accomplish than change-over to newer designs, and then one would never be in total correlation with equipment used for Federal compliance.

A more thorough laboratory correlation should be undertaken to develop numerical values for present differences in an attempt to restructure previous history. In addition, as other types of drop-tests are used in this industry (penetration), as well as other safety related industries, the procedures and computer programs developed in this study could be used to shed light on other related problems.

Appendix A contains numerical values used for data plots.

Acknowledgements

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Figure 1

MEP AT DAYTON T BROWN - #7 - VO=189 IN/SEC

FUNCTION	SYMBOL	LEFT	INCREMENTS	RIGHT
ACCELERATION(G)	A	Ø	6.32263	379.358
VELOCITY(IN/SEC.)	V	-119.422	5.14037	189
DISPLACEMENT(IN.)	D	Ø	4.56452E-3	Ø.273871

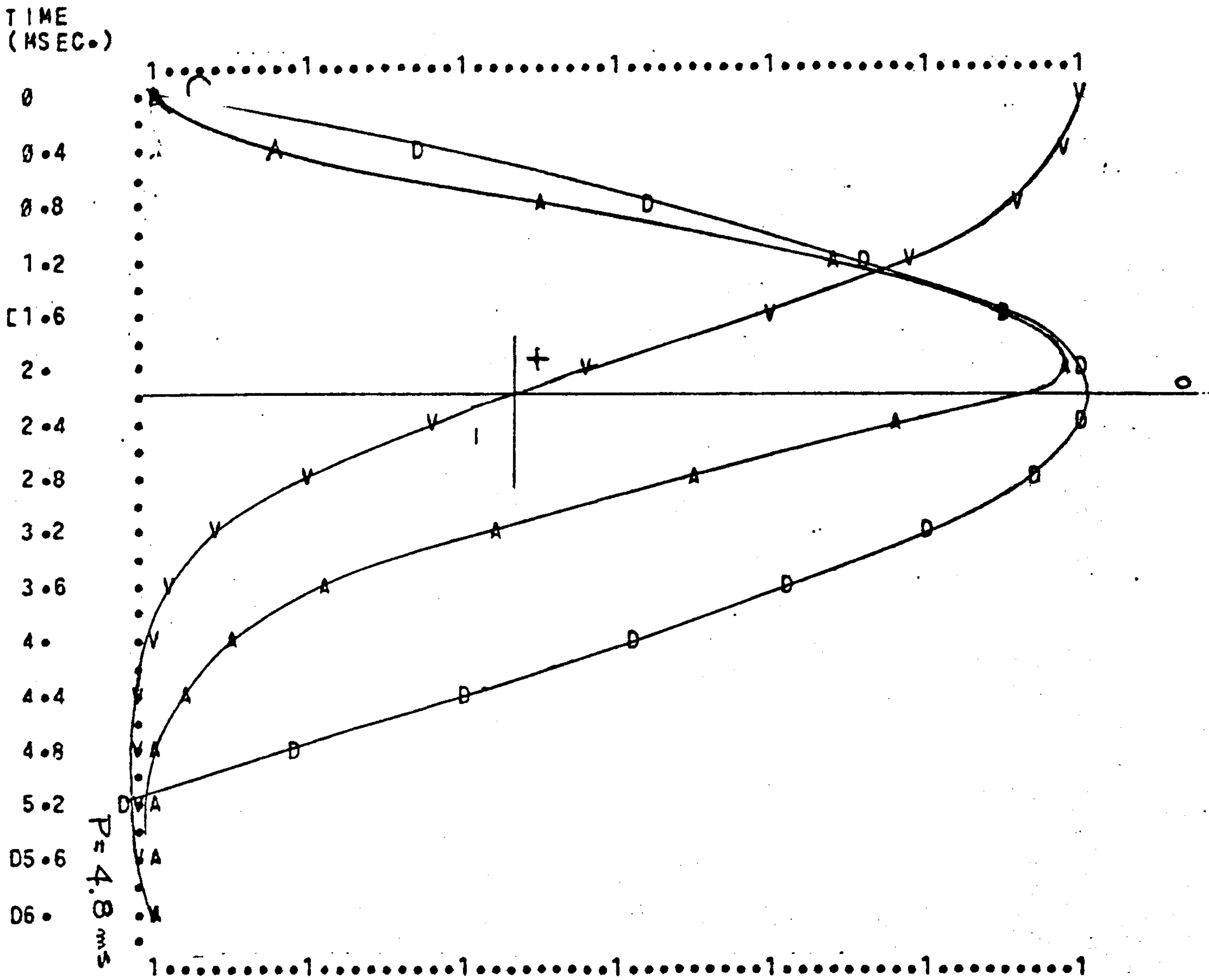


Figure 2

MEP AT SWRI/ V=190.0/ H=48 IN/ RECORD #

FUNCTION	SYMBOL	LEFT	INCREMENTS	RIGHT
ACCELERATION(G)	A	0	6.43264	385.959
VELOCITY(IN/SEC.)	V	-123.164	5.21939	190
DISPLACEMENT(IN.)	D	0	4.98737E-3	0.299242

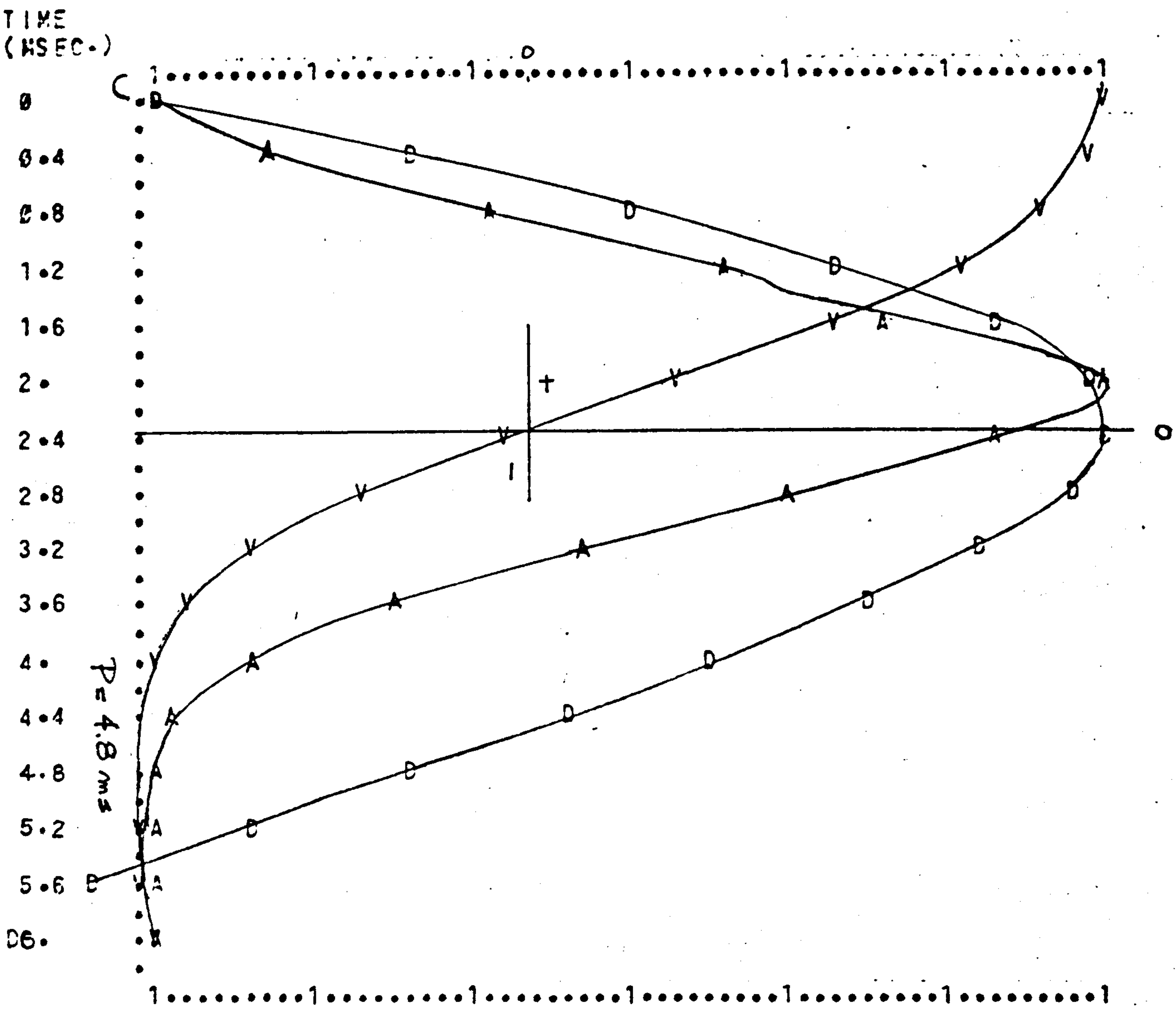


Figure 3

MEP AT US TESTING LABS - V0=183 IN/SEC - 48IN

FUNCTION	SYMBOL	LEFT	INCREMENTS	RIGHT
ACCELERATION(G)	A	0	5.5	330
VELOCITY(IN/SEC.)	V	-102.535	4.77225	183.8
DISPLACEMENT(IN.)	D	0	4.79282E-3	0.287569

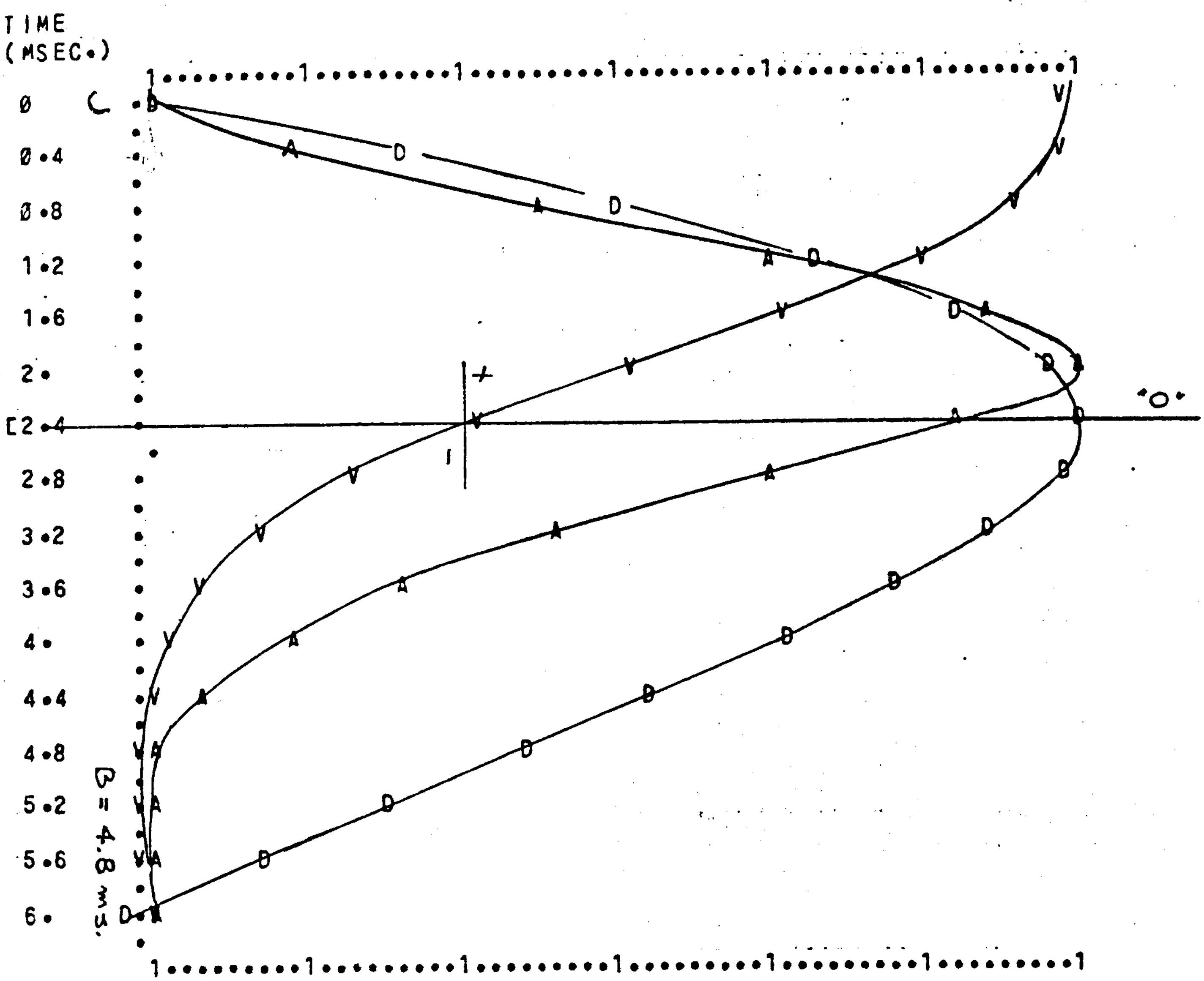


Figure 4

MEP TEST - #1 - 48 IN - V0=190 IN/SEC

MEDINA

FUNCTION	SYMBOL	LEFT	INCREMENTS	RIGHT
ACCELERATION(G)	A	0	6.58333	395
VELOCITY(IN/SEC.)	V	-83.674	4.56123	190
DISPLACEMENT(IN.)	D	0	5.37381E-3	0.322429

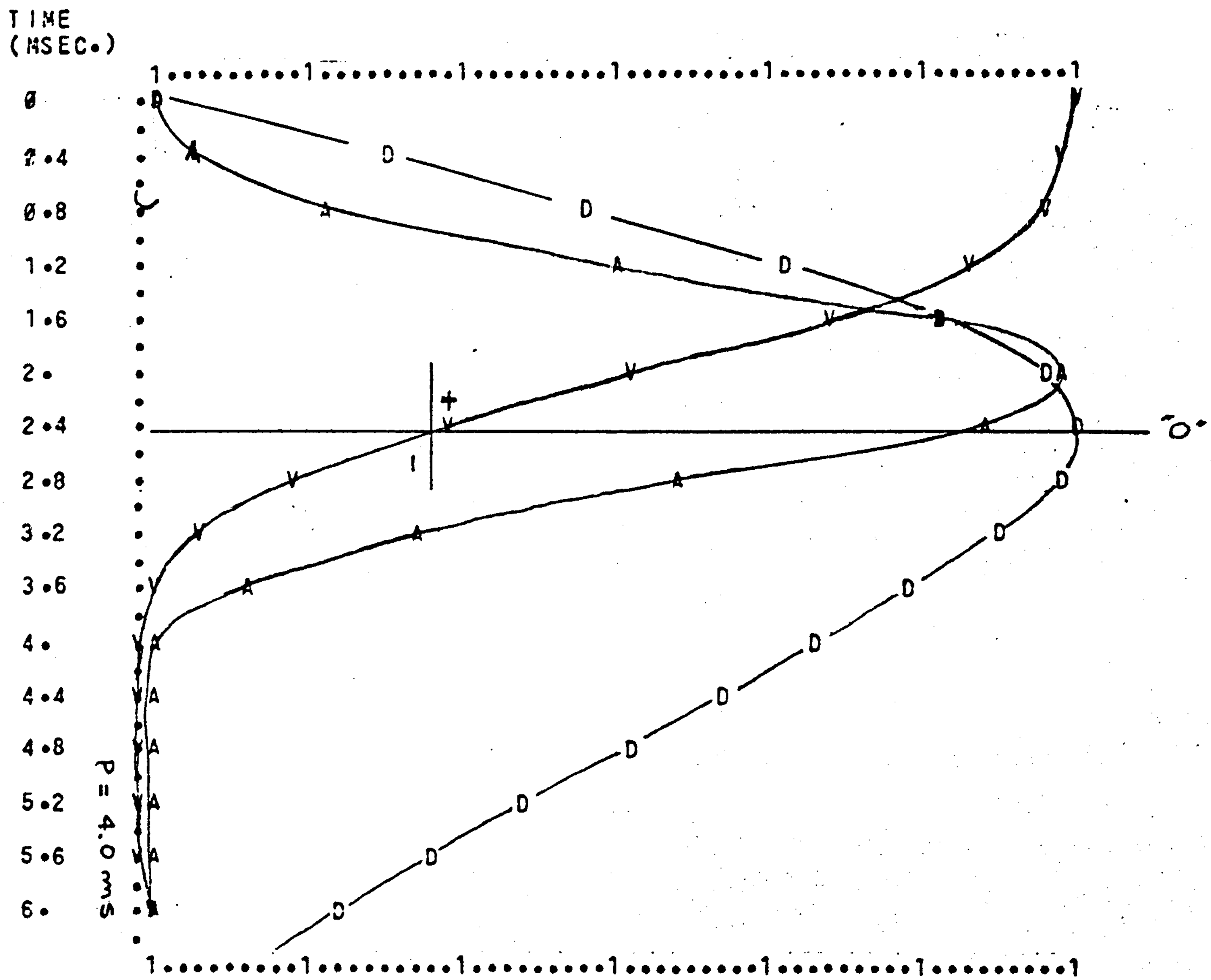


Figure 5

PLOTTED RESULTS OF FILE 1 MINUS FILE 2

SwRI Test less Dayton T. Brown Test

FUNCTION	SYMBOL	LEFT	INCREMENTS	RIGHT
ACCELERATION(G)	A	-56.601	1.8867	56.601
VELOCITY(IN/SEC)	V	-21.258	0.7086	21.258
DISPLACEMENT(IN)	D	-0.036947	1.23157E-3	0.036947

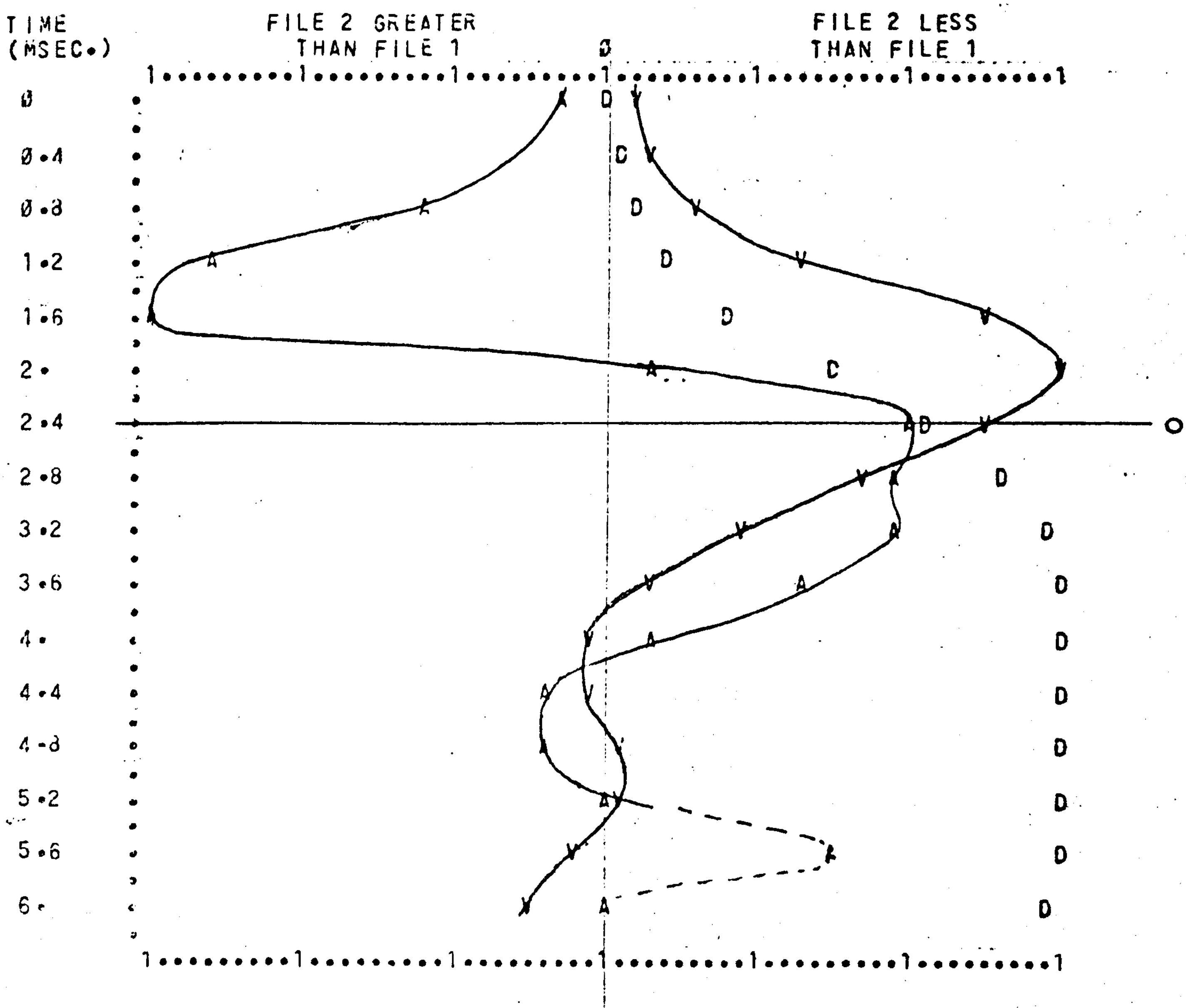


Figure 6

PLOTTED RESULTS OF FILE 1 MINUS FILE 2

SwRI Test less Medina Test

FUNCTION	SYMBOL	LEFT	INCREMENTS	RIGHT
ACCELERATION(G)	A	-63.549	2.1183	63.549
VELOCITY(IN/SEC)	V	-39.49	1.31633	39.49
DISPLACEMENT(IN)	D	-Ø.132421	4.41404E-3	Ø.132421

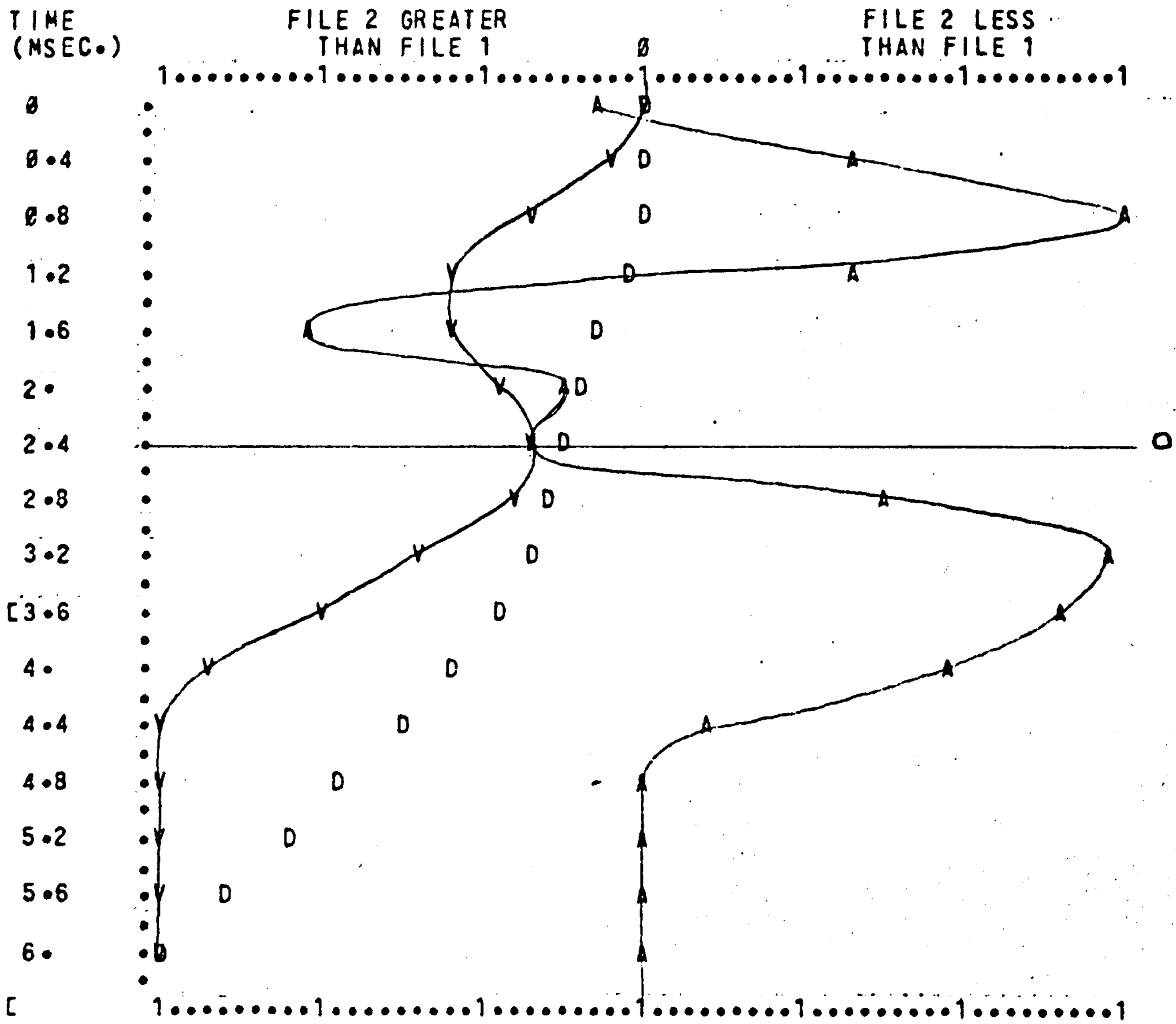


Figure 7

PLOTTED RESULTS OF FILE 1 MINUS FILE 2

SWRI Test less U.S. Testing Laboratories Test

FUNCTION	SYMBOL	LEFT	INCREMENTS	RIGHT
ACCELERATION(G)	A	-56.373	1.8791	56.373
VELOCITY(IN/SEC)	V	-23.406	0.7802	23.406
DISPLACEMENT(IN)	D	-5.96473E-2	1.98824E-3	5.96473E-2

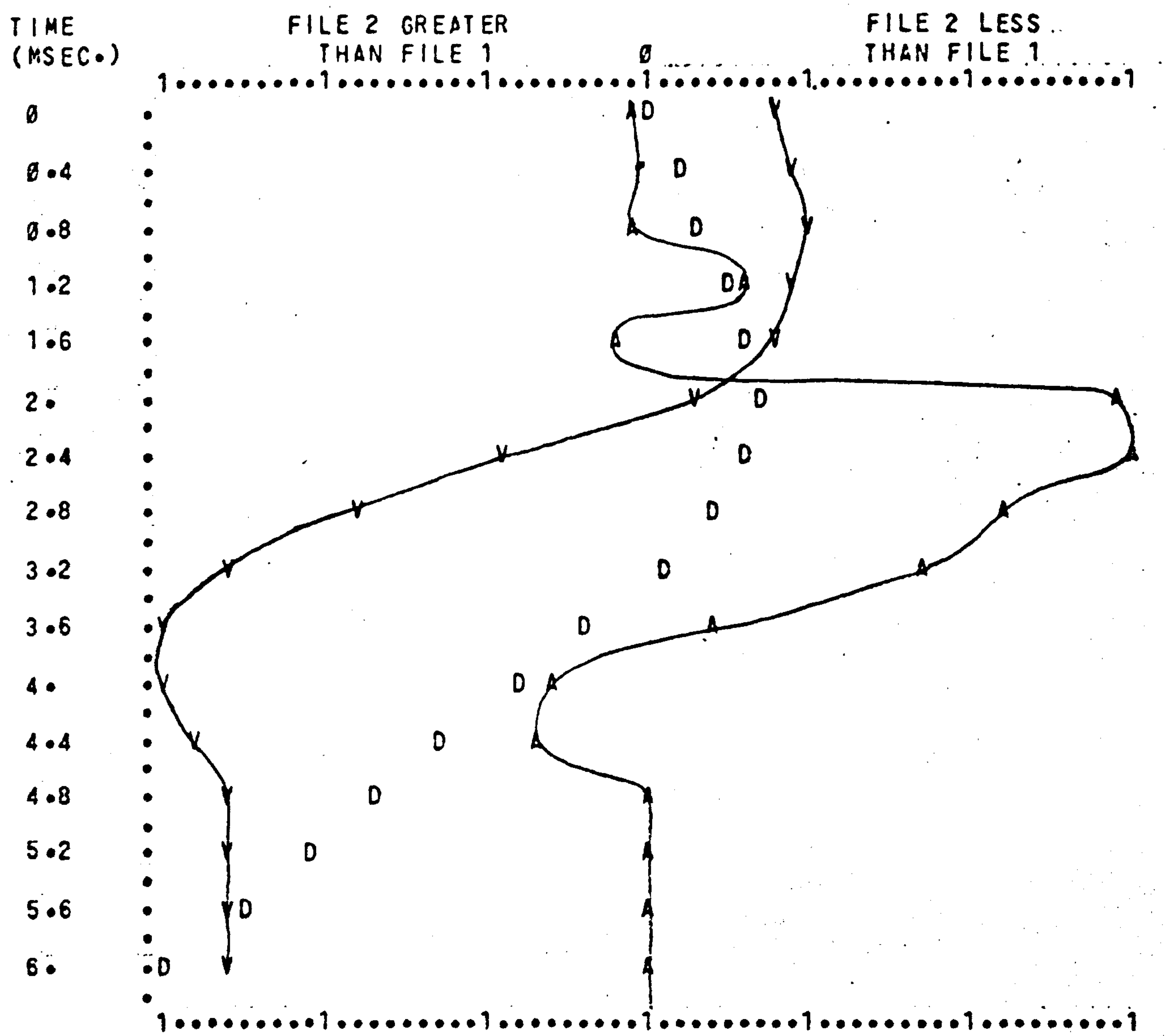
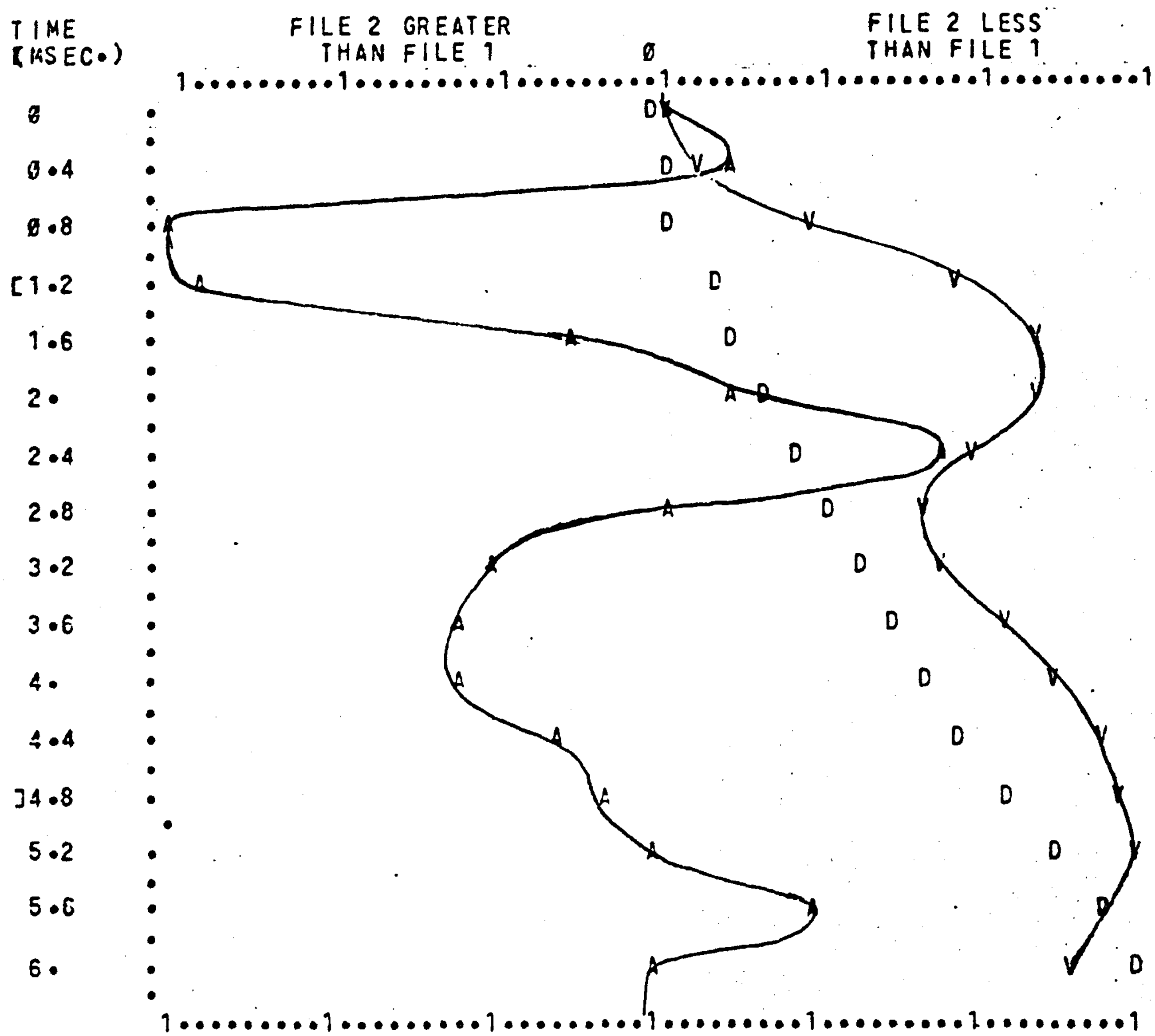


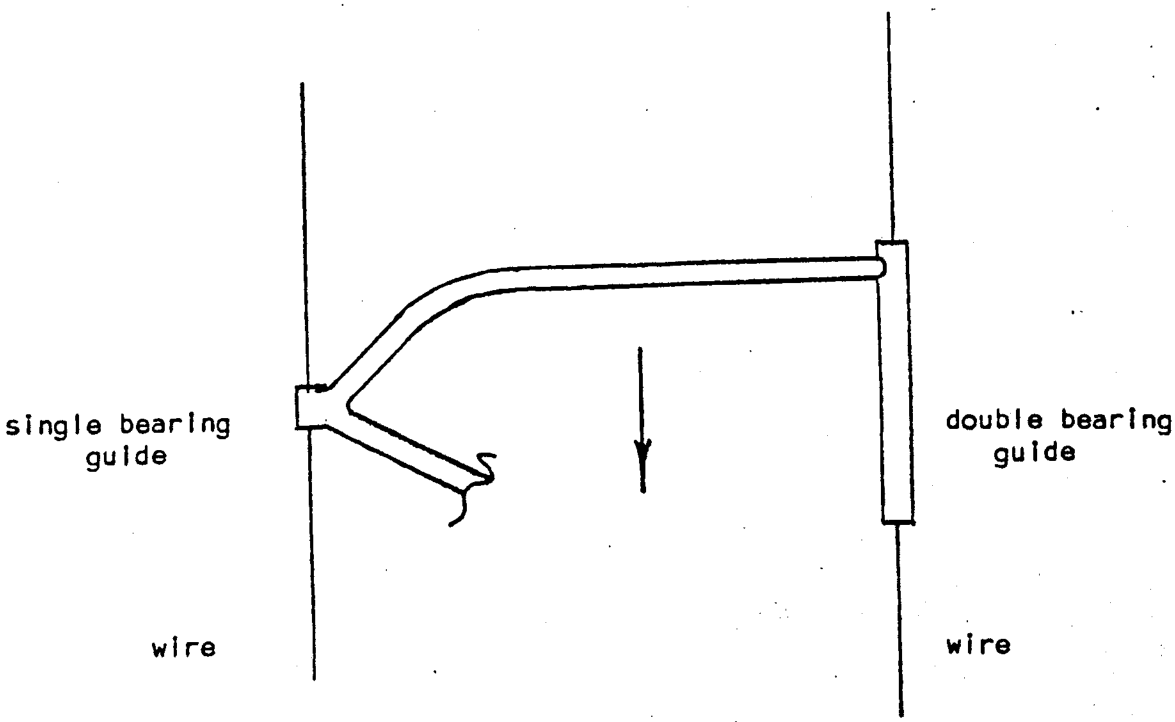
Figure 8

PLOTTED RESULTS OF FILE 1 MINUS FILE 2

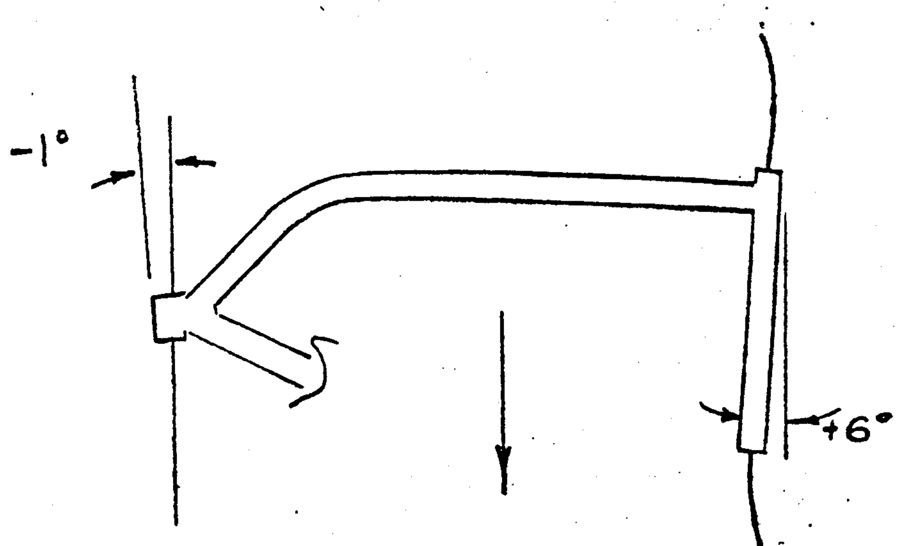
Medinal Test less DTB Test

FUNCTION	SYMBOL	LEFT	INCREMENTS	RIGHT
ACCELERATION(G)	A	-84.5Ø3	2.81677	84.5Ø3
VELOCITY(IN/SEC)	V	-4Ø.2594	1.34198	4Ø.2594
DISPLACEMENT(IN)	D	-Ø.167994	5.5998E-3	Ø.167994





a. Prior to impact



b. At T = 3.0 ms during impact. Distortion is between bearing guides.

Figure 9. High speed film analysis of drop assembly.