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Model Testing of a 1-kg High-Explosive-Cell Maze

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MASTER

April 1, 1981

Lawrence Livermore National Laboratory

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Model Testing of a 1-kg High-Explosive-Cell Maze

ABSTRACT

The basement of the proposed High Explosives Applications Facility (Building 353) at the Lawrence Livermore National Laboratory includes several explosive test cells for the assembly and/or storage of up to 10 kg of high explosive (HE). This document reports 1/8-scale and 1/4-scale model tests conducted to confirm maze design criteria, to determine the cell explosive weight limit based on an allowable 10 psi reflected shock pressure at the hallway-maze doorway, and to specify permissible areas for handling HE within the cell. The integrity of cube-root scaling of the explosive charges detonated in the 1/8-scale model was verified by explosive testing in a comparable 1/4-scale model. Reflected shock pressures in the hallway adjacent to the maze and the effect of HE charge orientation were investigated and are also reported.

INTRODUCTION

The Lawrence Livermore National Laboratory (LLNL) has been funded by the Department of Energy (DOE) through the DOE San Francisco Operations Office (SAN) to design a High Explosives Applications Facility (HEAF) to conduct high explosives research at the Livermore site.

The purpose of this model testing was to obtain the information necessary (1) to confirm basic design criteria for the maze of a 12-ft-sq by 12.5-ft-high reinforced concrete cell that would structurally sustain an accidental 10-kg HE explosion; (2) to determine the cell explosive weight limit; and (3) to specify permissible HE handling areas within the cell. All these design criteria are based on the specified maximum allowable reflected shock pressure of 10 psi at the cell hallway-maze doorway.

Both 1/8-scale and 1/4-scale models of the proposed 1-kg cell were designed and constructed with the equivalent of 2-ft-4-in. by 6-ft-8-in. doorways. Doorways on a later 1/8-scale model were widened from 3.5 to 4.0 in. (2-ft-8-in. full scale) in compliance with a subsequently imposed National Fire Protection Association requirement. The effects of increasing doorway width and of random charge orientation are discussed. The 18-in.-sq by 18.75-in.-high 1/8-scale model was built of welded/bolted aluminum plate, and the 36-in.-sq by 37.5-in.-high 1/4-scale model was of welded steel plate. All test firings were conducted inside a steel 350-g firing tank in Building 345 at LLNL.

TEST SETUP

CELL MODELS

The cell models, which included the mazes and adjacent hallways, were 1/8-scale and 1/4-scale duplicates of the proposed explosive test cell. All dimensions below are inside dimensions unless otherwise indicated.

The 1/8-scale model was weld/bolt assembled from 0.5-in. aluminum plate. The cell section was 18-in. square, the maze 4.5-in. wide by 18-in. long, and the hallway 12-in. wide by 19-in. long. Figure 1 shows the 2-in.-thick walls of the maze. Doorways, initially 10-in. high by 3.5-in. wide, were later widened to 4 in. to model an increase of cell door

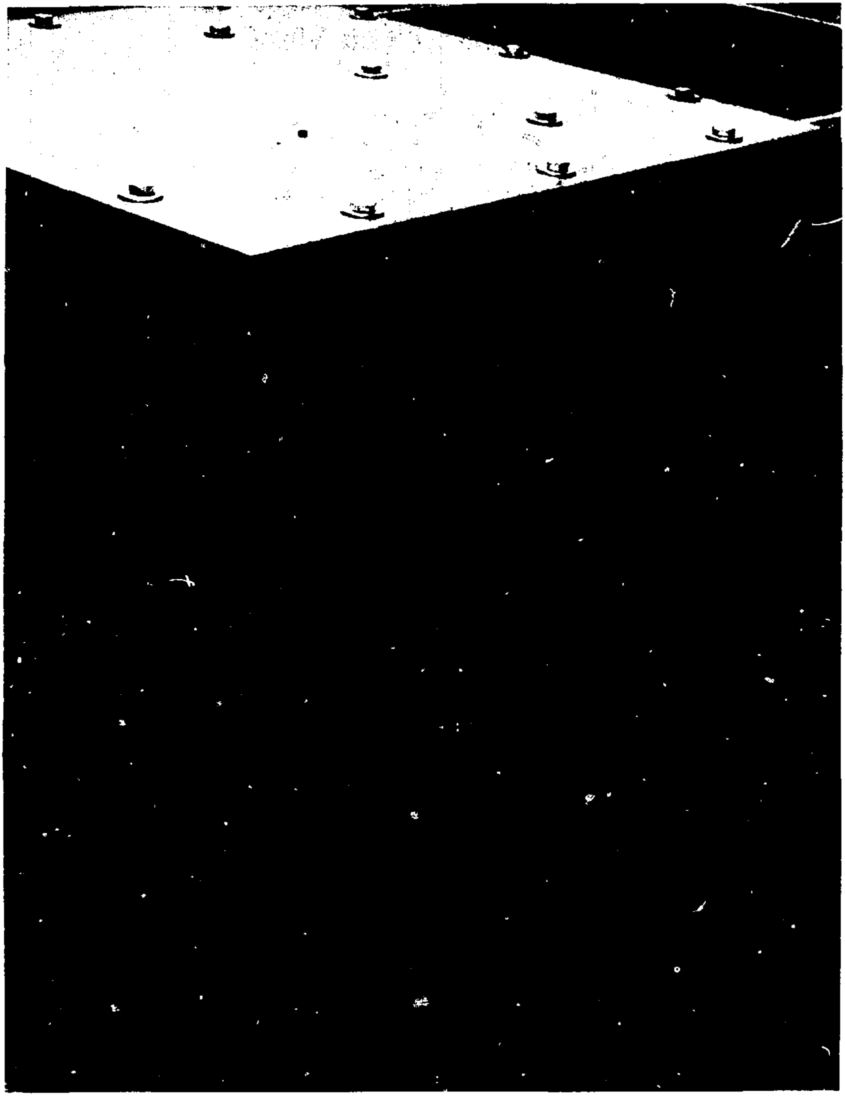


FIG. 1. One-eighth-scale model showing hallway-maze doorway (cell ceiling plate removed).

width from 2 ft 4 in. to 2 ft 8 in. The inside ceiling height of the entire model was 18.75 in. Figure 2 is the basic cell/maze layout of this model.

The 1/4-scale model was weld-assembled from 3/8-in. steel plate. The cell section was 36-in. sq, the maze 9-in. wide by 36-in. long, and the hallway 24-in. wide by 36-in. long. The 4-in.-thick maze walls were filled with concrete. Figure 3 shows the 7-in.-wide by 20-in.-high doorways. The inside ceiling height of the entire model was 37.5 in. The flat walls and ceiling of the cell section were stiffened by welding 2 by 6 steel channels to the outside surface.

FIRING TANK

All model testing was conducted inside a steel firing tank in Building 345. The firing tank, which is rated to safely contain an explosive charge of up to 350 g, is 8-ft diam by 8-ft long and is closed by a hydraulically rotated locking ring on an approximately 6-ft-diam forged steel door.

EXPLOSIVE CHARGES

Each HE charge consisted of a cylindrical pellet of PBX 9407 pressed to a density of 1.6 g/cm^3, to which was glued an MC 1957A detonator centered on the end of the pellet by a 0.0625-in.-thick Lucite washer. After the preassembled detonator/washer was glued to the pellet with Eastman 910, Hysol 615 Epoxy Patch was applied to support the detonator-washer bond. Charges for 1/8-scale testing were of 12.64-mm (approximately 0.5-in.) diam and weighed 1000 g/8^3 or 1.953 g, including the detonator weight of 0.021 g; nominal pellet weight was 1.932 g. Charges for 1/4-scale testing were of 25.34-mm (approximately 1.0-in.) diam and weighed 1000 g/4^3 or 15.625 g, including the detonator weight; nominal pellet weight was 15.604 g.

Unless otherwise noted, explosive charges were oriented with their cylindrical axes perpendicular to the plane of the cell-maze doorway (N-S) and the detonator was glued to the maze doorway end of the pellet.

INSTRUMENTATION

Reflected pressures were sensed by model XTM-1-190-50 Kulite pressure transducers having a calibrated pressure range of 50 psi and a maximum rated pressure of 100 psi. The transducer used to sense pressures at the maze doorways was threaded into a 0.750-in.-diam by 0.875-in.-long cylindrical aluminum adapter. The 0.156-in.-diam face of the transducer diaphragm was flush with the end of the cylinder. Although this approximately 5:1 diameter ratio is sufficient for reliable sensing of shock pressures, it is inappropriate for accurately detecting impulse. A laboratory clamp assembly, isolated from the model (and from the firing tank) by a rubber pad under its base, was used to center the transducer face in the hallway plane of the maze doorway (see Fig. 4). The transducer used to sense pressures along the hallway centerline was mounted in a 2.750-in.-diam sharp-edged tapered disk that assured reliable sensing of reflected shock pressures, free air pressures, and impulse. This transducer assembly was similarly mounted in a shock-isolated laboratory clamp assembly (see Fig. 5, which also shows another transducer that was used to obtain pressure readings for structural design).

Amplified millivolt pressure signals from each transducer were sampled every 0.01 ms by individual Biomation data receivers during the 20-ms recording period. A Tektronics computer display terminal in the control room was used to direct all data processing. Pressure-time information from the data receivers was processed by a Modular Computer System model 11/221, displayed on the terminal screen, printed out on a Versatek Matrix printer-plotter, and stored on magnetic tape for subsequent data analysis and future reference.

DATA ACQUISITION

The data was stored on magnetic tape by the computer. A Tektronics computer display terminal in the computer room was used to reprint the original graphs, to print new graphs of selectively filtered data, and to obtain integrated impulses, as required for data analysis.

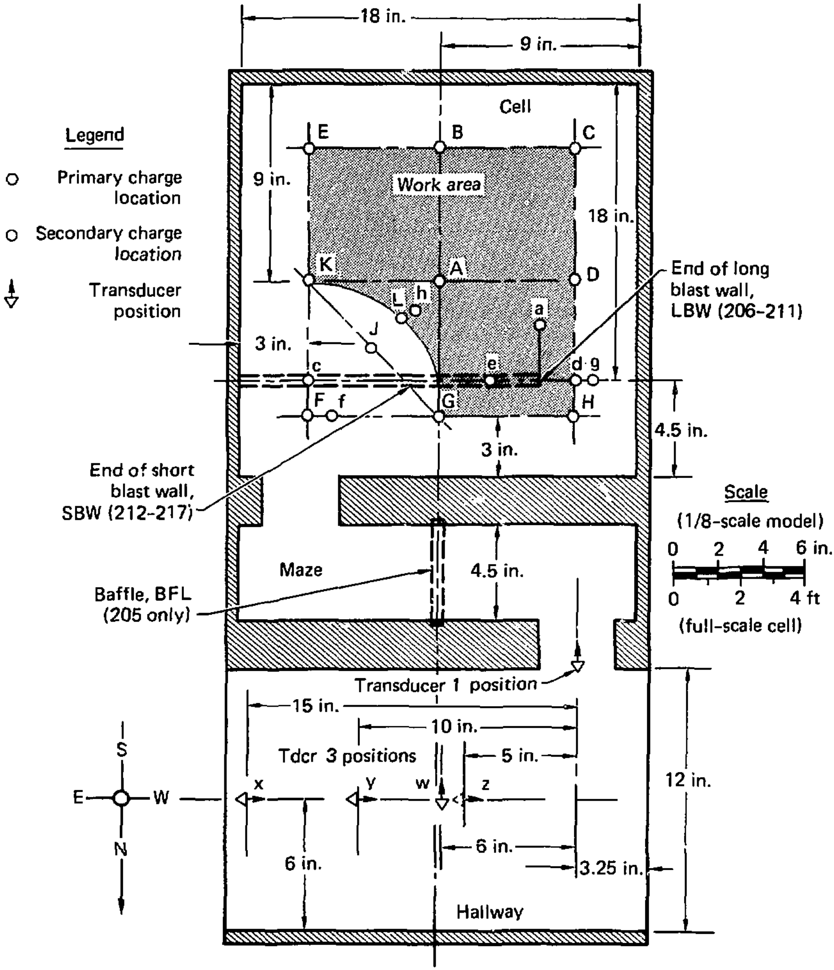


FIG. 2. Basic cell-maze layout, 1/8-scale shown.

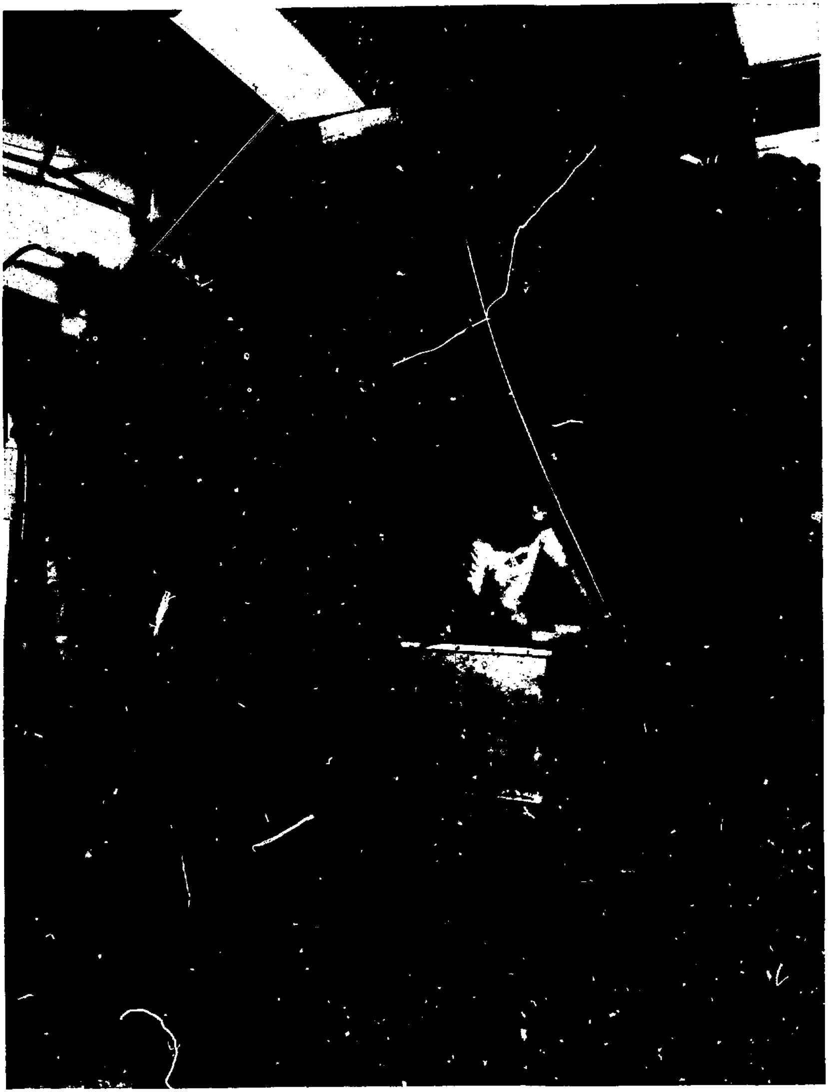


FIG. 3. Firing tank in Building 345 at LLNL, Livermore, California.

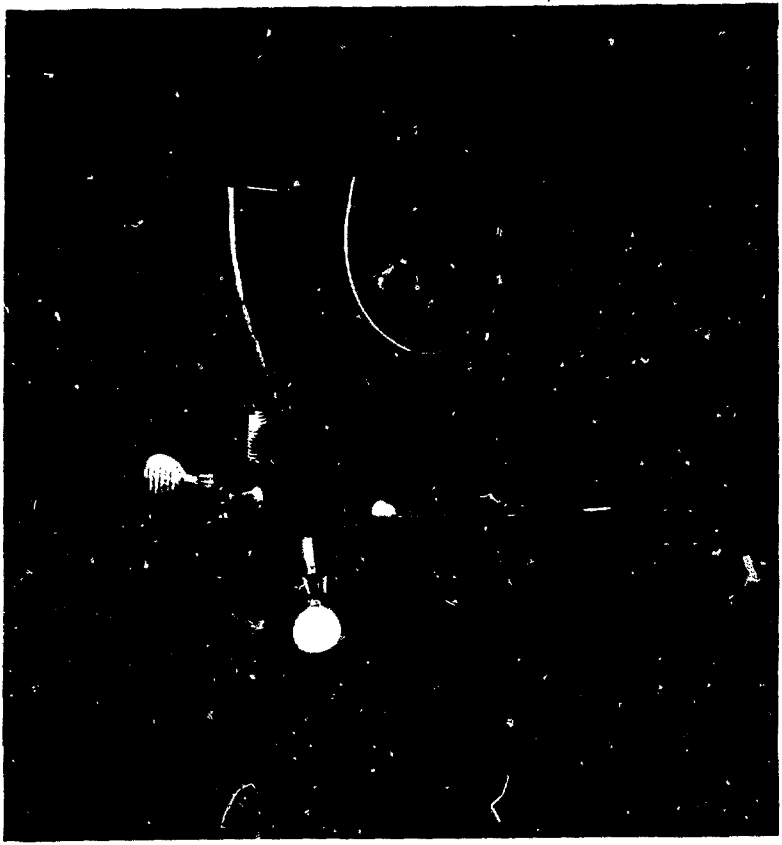


FIG. 4. Transducer stand (foreground) for hallway pressure sensing.

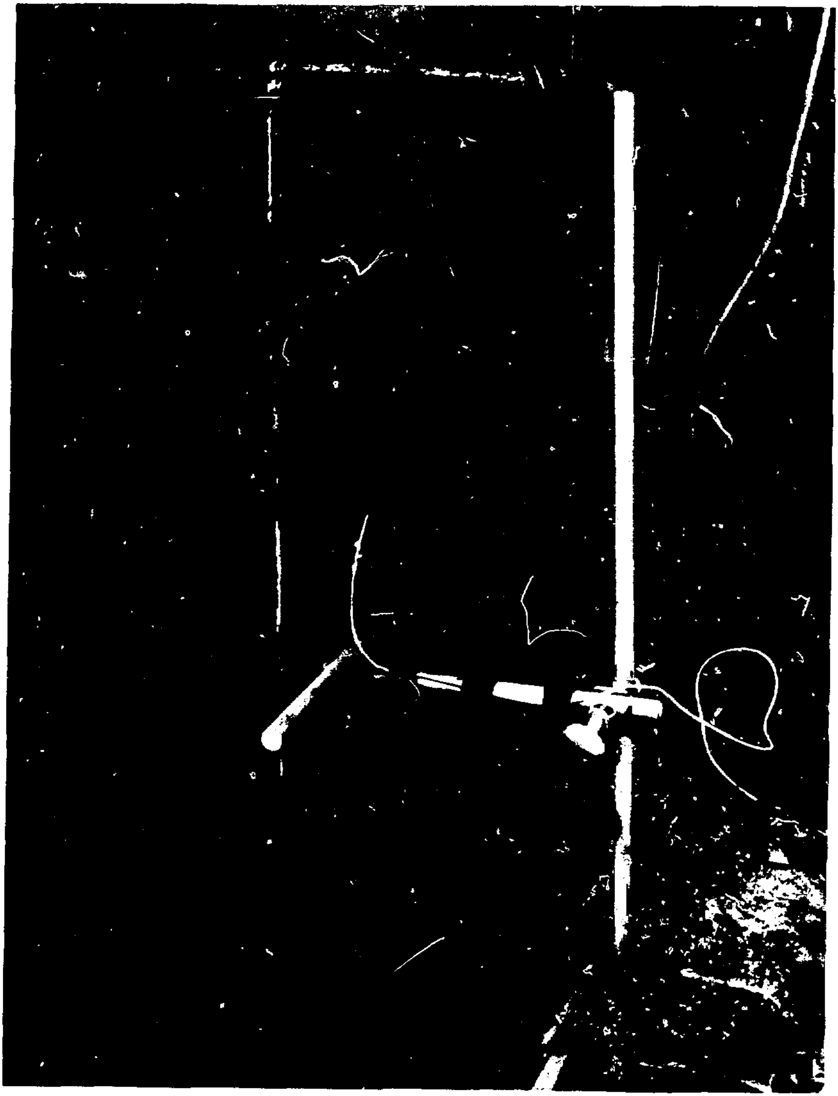


FIG. 5. Hallway-maze doorway of 1/4-scale model showing centered transducer.

REFLECTED PRESSURE AT HALLWAY-MAZE DOORWAY

NARROW DOORWAY MODELS

One-Eighth-Scale Series

Procedure. The 1/8-scale model with 3.5-in. by 10.0-in. doorways (Fig. 6) was placed in the firing tank and the transducers were installed at the appropriate locations. The cell ceiling panel (with the HE charge) was bolted in place and the detonator cable was connected. The tank door was then closed and secured and the explosive charge was detonated from the adjacent control room.

Results and Discussion. The peak pressures sensed by the transducer at the maze doorway in position 1 (see Fig. 2) and the times after detonation at which the peak pressures were recorded and are listed in Table 1. The average peak pressure for the four detonations at K was 14.0 psi at the average arrival time of 2.9 ms after detonation. Pressure-versus-time graphs for these experiments (258 through 261) are in Appendix B.

The standard deviation of the peak pressures for experiments 258 through 261 is ±0.6 psi. All pressure data falls within the range of 1.3 standard deviations from the average. The most probable error of the average peak pressure, as calculated by Bessel's formulas,[1] is ±0.2 psi. The standard deviation of the time of arrival of the peak pressure for experiments 258 through 261 is ±0.1 ms. All time data fall within the range of 2.0 standard deviations from the average. The most probable error of the average time is ±0.0 ms.

Conclusions and Recommendations. The recorded data appeared to be sufficiently consistent for comparison with the results of subsequent 1/4-scale testing, to determine preliminary cell explosive limits, and to prove scaling.

One-Quarter-Scale Series

Procedure. The test procedure was identical to that for the 1/8-scale series, except that the HE charge was positioned (at K) through a flanged hole in the center of the cell ceiling instead of being attached to the removable ceiling plate. Figure 7 is the narrow doorway 1/4-scale model used for this series.

Results and Discussion. The peak pressures sensed by transducer 1 (hallway-maze doorway) and the times at which they were recorded are listed in Table 2. The average peak pressure for the three shots at location K was 14.0 psi at the average time of 5.9 ms after detonation. Several high, single-pressure peaks and one very narrow high peak complicated rational analysis of the computer-plotted graphs of experiments 225 and 229. Their source was reasonably attributed to projected Lucite particles from the unavoidably shattered HE charge holder striking the exposed diaphragm of the pressure transducer at the precise time when a signal was being transmitted to the Biomation data receiver. Considering the extremely low impulse represented by these spurious pressure escalations occurring at typically lower-impulse times, they were disregarded as inappropriate for comparative data analysis. Pressure-versus-time graphs for these experiments are included in Appendix A.

TABLE 1. One-eighth-scale experiments at location K south, narrow doorway.

Experiment number	Peak reflected pressure at position 1 (psi)	Time after detonation (ms)	Weight of HE charge, including detonator (g)
258	13.7	2.8	1.948
259	14.5	3.0	1.948
260	14.7	3.0	1.953
261	13.2	2.9	1.950
Average:	14.0	2.9	1.950

FIG. 6. One-eighth-scale model with cell ceiling plate removed.

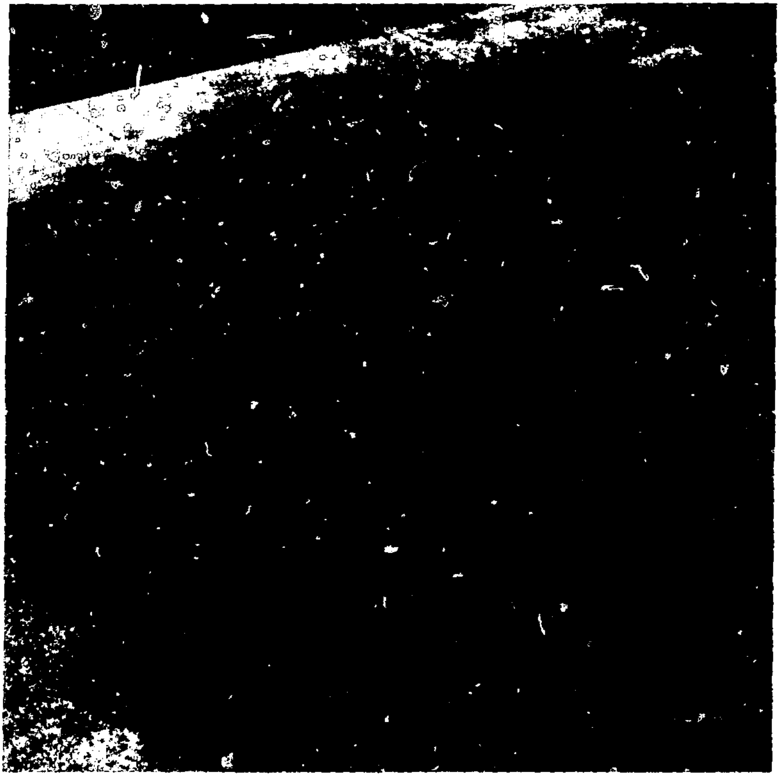


FIG. 7. One-quarter-scale model.

TABLE 2. One-quarter-scale experiments at location K south, narrow doorway.

Experiment number	Pressure at transducer position 1 (psi)	Time after detonation shock (ms)	Weight of HE, including detonator (g)	Remarks (SP = single peak; NP = narrow peak)
225	12.9	5.9	15.654	SP to 15.1 psi at 2.8 ms and NP to 16.3 psi at 4.9 ms
228	14.3	5.9	15.644	
229	14.7	6.0	15.644	SP to 15.7 at 5.6 ms
Average:	14.0	5.9	15.647	

TABLE 3. One-eighth-scale experiments at location K south, wide doorway.

Experiment number	Peak reflected pressure (psi)	Time after detonation (ms)	Explosive weight (g)
276	13.6	2.6	1.949
277	16.3	2.6	1.954
278	15.6	2.6	1.952
282	13.6	2.7	1.955
283	14.8	2.6	1.946
287	14.3	2.8	1.953
Average:	14.7	2.7	1.952

The standard deviation of the peak reflected pressures for experiments 225, 228, and 229 is ±0.8 psi. All pressure data fall within the range of 1.4 standard deviations from the average. The most probable error of the average peak pressure, as calculated by Bessel's formulas,[1] is ±0.4 psi. The standard deviation of the time of arrival of the peak pressure for these experiments is ±0.0 ms. The most probable error of the average time is ±0.0 ms.

Conclusions and Recommendations. The recorded data appeared to be sufficiently consistent for comparison with the results of experiments in the narrow doorway, 1/8-scale model, to prove scaling, and to confirm the peak reflected pressure that is credible at the hallway-maze doorway of a full-scale test cell with narrow doorways.

WIDE DOORWAY MODEL

One-Eighth-Scale Series

Procedure. The 1/8-scale model, with maze doorways widened from 3.5 to 4.0 in. was placed in the firing tank, the cell ceiling panel (with the HE charge located at position K) was bolted in place, and the detonator cable was connected. The tank door was then closed and secured and the explosive charge was detonated from the adjacent control room.

Results and Discussion. The peak reflected pressures sensed by the transducer positioned at the hallway-maze doorway, and the times after detonation at which the pressures occurred, are listed in Table 3. The average peak pressure for the six south-oriented detonations at K was 14.7 psi with an average arrival time of 2.7 ms after detonation. Pressure-versus-time graphs for these experiments (276-278, 282, 283, and 287) are included in Appendix A.

The standard deviation of the peak pressures for these experiments is ±1.0 psi. All pressure data fall within the range of 1.6 standard deviations from the average. The most probable error of the average peak pressure, as calculated by Bessel's formulas,[1] is ±0.3 psi. The standard deviation of the time after detonation for these experiments is ± 0.1 ms. All time data fall within the range of 1.0 standard deviations from the average. The most probable error of the average time is ±0.0 ms.

Conclusions and Recommendations. The recorded data appeared to be sufficiently consistent for comparison with the results of experiments conducted in the narrow doorway models to determine final cell explosive limits.

DETERMINATION OF CELL WORK-AREA LIMITATIONS

PROCEDURE

The only change in the test procedure was positioning of the explosive charge at locations other than K. Unless otherwise noted, all charges were oriented toward the south and the pressures were monitored at the hallway-maze doorway. See Fig. 2 for locations of HE charges and the position of transducer 1.

TABLE 4. Experiments at locations other than K.

Model scale	Experiment number (location)	Reflected pressure at position 1 (psi)	Time after initial shock (ms)	Weight of HE, including detonator (g)	Remarks (SP = single peak; NP = narrow peak) (HE oriented south unless otherwise noted)
Narrow doorway					
1/8	218(A)	11.1	3.4 and 4.5	1.953	SP to 13.3 psi late at 6.4 ms
1/8	220(G)	13.3	3.0	1.953	
1/8	221(J)	12.3	3.0	1.953	SP to 12.5 psi at 2.6 ms and peak to 16.0 psi late at 4.2 ms
1/4	226(G)	13.3	6.2	15.640	
1/4	227(G)	13.6	5.9	15.648	NP to 16.0 psi at 7.2 ms (late)
1/4	230(E)	11.2	6.7	15.648	Peak of 13.5 psi late at 9.8 ms
1/4	231(C)	11.9	7.3	15.652	
Wide doorway					
1/8	303(D)	11.8	3.7	1.951	
1/8	304(L)	14.5	4.5	1.952	
1/8	305(L)	13.1	2.8	1.956	HE oriented southeast

RESULTS AND DISCUSSION

Experiments involving detonations at locations other than K for both 1/8-scale and 1/4-scale are tabulated in Table 4. Experiment 218 resulted in a reflected pressure peak of 11.1 psi at 4.5 ms after detonation. An equal (11.1 psi) pressure peak was observed at 3.4 ms, and a single pressure peak to 13.4 psi occurred late at 6.4 ms.

The three experiments at location G resulted in an average of 13.4 psi for detonations at this location. A narrow peak to 16.0 psi occurred late at 7.2 ms on Experiment 227, apparently from a particle hitting the transducer diaphragm. This peak did not occur on either of the other two experiments (220 and 226) at G.

The pressure peak of the first reflected shock wave on Experiment 221 was to 12.3 psi at 3.0 ms following detonation. A single pressure peak to 12.5 psi occurred early at 2.6 ms, and a late peak to 16.0 psi was recorded at 4.2 ms after detonation.

The pressure from detonations at C and E were both below the average in these models (14.0 psi) for detonations at K.

After the doorways of the 1/8-scale model had been widened, three experiments were conducted to determine the acceptability of handling HE charges at locations D and L. Experiment 303 at D resulted in a peak pressure of 11.8 psi at 3.7 ms. Experiment 304 at L (oriented south) produced a 14.5 psi peak at 4.5 ms, and experiment 305 at L (oriented southeast) gave 13.1 psi at 2.8 ms after detonation. All three detonations in the wide-doorway model resulted in pressures less than the average of 14.7 psi for 1-kg equivalent detonations at K.

Pressure-versus-time graphs for the preceding experiments are in Appendix A.

CONCLUSIONS AND RECOMMENDATIONS

These results were considered satisfactory for determining cell work-area limitations. With the exception of location J (experiment 221), detonations at all locations produced peak pressures that were less than the average of those detonated at K. Experiments in the narrow-doorway models produced pressures less than 14.0 psi, and those in the wide-doorway model were less than 14.7 psi.

EFFECTS OF BLAST WALLS AND BAFFLES: NARROW DOOR MODEL

PROCEDURE

Two experiments (203 and 204) were first detonated near the cell-maze doorway (at locations c and f in Fig. 2) to determine the unbaffled peak reflected pressure at position 1. Then another experiment (205) was conducted at location c after installing a 0.25-in. steel baffle (BFL) that closed the midpoint of the maze from the ceiling down to the height of the maze door openings. Two different blast walls were then installed in the cell to determine their mitigating effect on the reflected shock pressure at the hallway-maze doorway. Both walls were of 0.25-in. steel plate, extending from the floor to the ceiling, and were secured to the floor and cell-maze wall with 2 by 2 by 0.25-in. steel angle and bolts. For experiments 206-211, a 13.5-in. long blast wall (LBW in Fig. 2) was installed. For experiments 212-217, it was replaced with a 7.75-in. short blast wall (SBW). Otherwise, the operating procedure was the same as with other experiments in this 1/8-scale narrow-doorway model.

RESULTS AND DISCUSSION

Comparing the two experiments at location c (see Fig. 2 and Table 5), the pressure pulse at position 1 was approximately the same for experiment 205 (baffle installed) as it was for experiment 204 (no baffle).

When experiment 206 (see Table 6) was fired in the temporary doorway formed by the LBW, an expectedly high pressure peak to 19.4 psi, 3.8 ms after detonation, was sensed by the transducer. When three charges were successively detonated in the center of the cell at location A (see Table 6), the average peak pressure was 12.6 psi at about 5.3 ms after detonation. On experiment 207, the pulse at 5.0 ms was only one signal wide above 12 psi (to 12.8 psi) and a single peak pulsed to 15.7 psi at 5.5 ms following detonation. The narrow (double-signal width) spike above 12.7 psi to 14.7 psi and the single spike on up to 16.0 psi on experiment 209 were considered inconsistent with the other two shots at A and were disregarded in determining the 12.6 psi average peak pressure for detonations at this location. The two experiments at location a, (210 and 211), 3 in. into the cell from the end of the LBW, were both 13.0 psi. On experiment 210, the pressure peak was a single spike above 11.9 psi and on experiment 211, a narrow peak extended on up to 16.4 psi.

With the SBW installed in place of the LBW, the four detonations at L averaged 5.7 psi. For three of these, experiments 212-214, side-on pressures were recorded by mounting the transducer in the previously described tapered disk facing perpendicular to the reflected shock front. These readings were converted to equivalent reflected pressures using curves based on the equation[2] $P_r/P_{so} = 2 +$

TABLE 5. One-eighth-scale experiments near cell-maze doorway (with and without maze-hallway baffle).

Experiment number	Location of HE charge	Reflected pressure at position 1 (psi)	Time after detonation (ms)	Weight of HE, including detonator (g)	Remarks (see Fig. 2 for locations of shots and baffle)
203	f	16.8	2.7	1.974	No baffle
204	c	22.0	2.7	1.974	No baffle SP to 23.5 psi at 3.0 ms
205	c	23.5	2.8	1.974	Baffle in maze ceiling

TABLE 6. One-eighth-scale experiments with blast walls installed.

Experiment number	Charge location (see Fig. 2)	Reflected pressure at position 1 (psi)	Blast wall (SBW = short) (LBW = long)	Time after detonation (ms)	Remarks All shots 1.974 g weight (SP = single peak, spike) (NP = narrow peak, double)
206	g	19.4	LBW	3.8	Expected high pressure
207	A	12.8	LBW	5.0	SP to 15.7 psi at 5.5 ms
208	A	12.3	LBW	5.2	
209	A	12.7	LBW	5.5	NP to 16.0 psi at 5.5 ms (SP above 14.7 psi)
210	a	13.0	LBW	5.5	
211	a	13.0	LBW	5.6	NP to 16.4 psi at 5.6 ms
212	h	8.2	SBW[a,c]	4.8	P_{so} = 3.8 psi recorded
213	h	4.4	SBW[a]	4.5	P_{so} = 2.1 psi at 4.5 ms P_{so} = 2.8 psi at 2.8 ms recorded (P_r =6.0)
214	h	4.7	SBW[b]	5.4	P_{so} = 2.2 psi at 5.4 ms, recorded P_r =4.2 psi (P_r =9.3 psi) at 8.3 ms
215	h	5.5	SBW[a]	5.3	P_r = 6.2 psi at 7.2 ms
216	d	15.8	SBW[a]	3.6	
217	e	10.2	SBW[a]	3.6	

[a]False ceiling.

[b]No false ceiling.

[c]Aluminum plate ceiling reduced cell height from 21.00 to 18.75 in.

$P_{so}/(7.2 + P_{so}/6)$. An aluminum plate ceiling panel that lowered the effective ceiling height of the cell from 21.00 to 18.75 in. was installed for experiments 212, 213, 215, 216, and 217. The ceiling height for experiment 214 was 21 in. At location d (3 in. from the wall in line with the SBW), the pressure peaked to 15.8 psi at 3.6 ms and again to 14.7 psi 1.6 ms later. On experiment 217 at location e (6.5 in. from the wall in line with the SBW), the pressure peaked to only 10.2 psi at 3.6 ms. Pressure-versus-time graphs for these experiments are in Appendix A.

SUMMARY AND CONCLUSIONS

Comparison of experiments 204 and 205 lead to the conclusion that baffles in the maze ceiling had negligible effect on the peak reflected shock pressure at the hallway-maze doorway.

We also concluded that blast walls between the detonation (accidental explosion) location and the maze doorway were quite effective in mitigating the reflected shock pressure at the hallway-maze doorway. If an accident occurred near the end of the blast walls, the pressure at the hallway-maze doorway would probably be higher than it would be if the blast wall was not there. We do not recommend revision of the cell design to incorporate either blast walls or baffles. For this series, lowering of the cell ceiling had no apparent effect on the reflected shock pressure of concern.

HALLWAY PRESSURE PROFILE

PROCEDURE

Transducer 3, mounted in the tapered disk described under Instrumentation, was centered 5 in. above the floor in the hallway of the wide-doorway model at predetermined distances from the doorway centerline. These distances (positions z, w, y, and x in Fig. 2) were 5, 6, 10 and 15 in., equivalent to 3.3,

TABLE 7. Hallway pressure profile, wide doorway.

Transducer 3 position (see Fig. 2)	Distance from centerline of doorway (in.)	Average peak reflected pressure (psi)	Average time after detonation (ms)	Remarks All detonations at K, random orientation
z	5	4.8	3.4	Experiments 301, 302, and 313
w	6	5.8	3.2	Experiments 316-321 and 327-329
y	10	4.7	5.8	Experiments 299, 300, 306, 311, 314, and 323
x	15	5.2	6.2	Experiments 308-310

4.0, 6.7 and 10.0 ft full-scale, respectively. The tapered disk was randomly oriented parallel and perpendicular to the hallway centerline.

RESULTS AND DISCUSSION

The average results of peak reflected pressures are listed in Table 7. The highest pressure recorded during this 20-experiment series was a narrow peak to 8.1 psi on experiment 320 at position w (6 in. from the doorway centerline). No meaningful profile was apparent from a preliminary plot of experimental data. Graphs of pressure-versus-time for individual experiments are in Appendix B.

CONCLUSIONS AND RECOMMENDATIONS

The peak reflected pressure dissipates rapidly once it exits the hallway-maze doorway. The peak reflected pressure resulting from a 1-kg detonation in the cell would not be expected to exceed the specified maximum of 10 psi beyond 6 in. (4 ft full-scale) from the doorway centerline.

DETERMINATION OF CELL EXPLOSIVE LIMIT

When model testing was initiated, the specified maximum allowable peak reflected pressure at the hallway-maze doorway was 15 psi. Before testing was completed, however, the pressure limit was reduced to 10 psi and it was necessary to widen the doorways. Account must also be taken of the fact that an accidental detonation would probably be randomly oriented, and preliminary explosive limits had been determined with all test charges facing toward the south.

PROCEDURE

To determine the cell explosive limit, certain conditions were met.

- We developed an *empirical equation* (pressure-versus-HE charge weight) to fit the peak reflected pressures from reduced and full 1-kg equivalent charges detonated at K, oriented south, in the narrow-doorway models.
- Based on similar reflected pressures at the hallway-maze doorway of the wide-doorway model, another empirical equation was developed to account for *widening the maze doorways* from 2 ft 4 in. to 2 ft 8 in.
- This equation was then shifted upward, in the ratio of the average peak pressure resulting from *randomly oriented* charges at K (17.5 psi) to the average from K south-oriented charges at K (14.7 psi), in the wide-doorway model.
- Where the plot of the resulting equation crossed the 10 psi pressure line determined the maximum permissible cell explosive limit.

RESULTS AND DISCUSSION

Development of the Basic Empirical Equation

High Explosive charges equivalent to approximately 1.0-, 0.8-, 0.7-, 0.5-, and 0.3-kg full-scale were detonated at K (oriented south) in the 1/4-scale and in the 1/8-scale models (both narrow and wide doorways). The normal operating procedure was followed and peak pressures at position 1 were recorded in Tables 8 and 9, and plotted in Figs. 8 and 9.

Net pellet weights were determined by cube-root scaling, including consideration of the 0.021-g weight of the M 1957A detonator used. For the 500-g equivalent for experiment 232 in the 1/4-scale

TABLE 8. Reduced explosive series, narrow-doorway models.

Experiment number	Model scale	Explosive weight (g) Actual	Scale factor	Equivalent full-scale	Peak reflected pressure (psi)	Time after detonation (ms)	Remarks (SP = single peak) (NP = narrow peak)
235	1/4	4.646	64	297.34	3.8	7.3	SP to 4.2 psi at 4.2 ms NP to 4.7 psi at 12.7 ms
232	1/4	7.832	64	501.25	6.3	6.6	SP to 6.6 psi at 5.5 ms
233	1/4	10.339	64	661.70	8.7	6.4	SPs to 8.9 psi at 8.2 ms and at 11.0 ms
236	1/4	12.406	64	793.98	10.0	6.2	SP to 10.3 psi at 6.6 ms
Average[a]	1/4	(15.645)	64	(1001.28)	(14.0)	(5.9)	
265	1/8	0.584	512	299.01	2.8	3.2	NP to 3.7 psi at 1.8 ms
264	1/8	0.977	512	500.22	5.9	3.0	SP to 7.1 psi at 1.8 ms
263	1/8	1.292	512	661.50	7.6	2.9	NP to 8.9 psi at 4.6 ms
264	1/8	1.545	512	791.04	10.8	2.8	SP to 1.8 psi at 2.6 ms
Average[b]	1/8	(1.950)	512	(998.40)	(14.0)	(2.9)	

[a]Average explosive weight, pressure, and time from Table 3.

[b]Average explosive weight, pressure and time from Table 1.

Notes: All charges detonated at Location K, oriented south.

Data plotted in Fig. 8.

Numbers in parentheses are included for plotting reference and comparison only.

TABLE 9. Reduced explosive series, 1/8-scale wide-doorway model.

Experiment number	Explosive charge weight (g) Actual	Scale factor	Equivalent full-scale	Peak reflected pressure (psi)	Time after detonation (ms)
288	0.585	512	299.52	2.7	3.2
289	0.978	512	500.74	6.0	3.1
290	1.291	512	660.99	8.5	2.9
291	1.547	512	792.06	11.7	2.9
Average[a]	(1.952)	512	(999.42)	(14.7)	(2.7)

[a]Average explosive weight, pressure, and time from Table 3 (entered in parentheses) for plotting reference and comparison only.

Note: Above data plotted in Fig. 9.

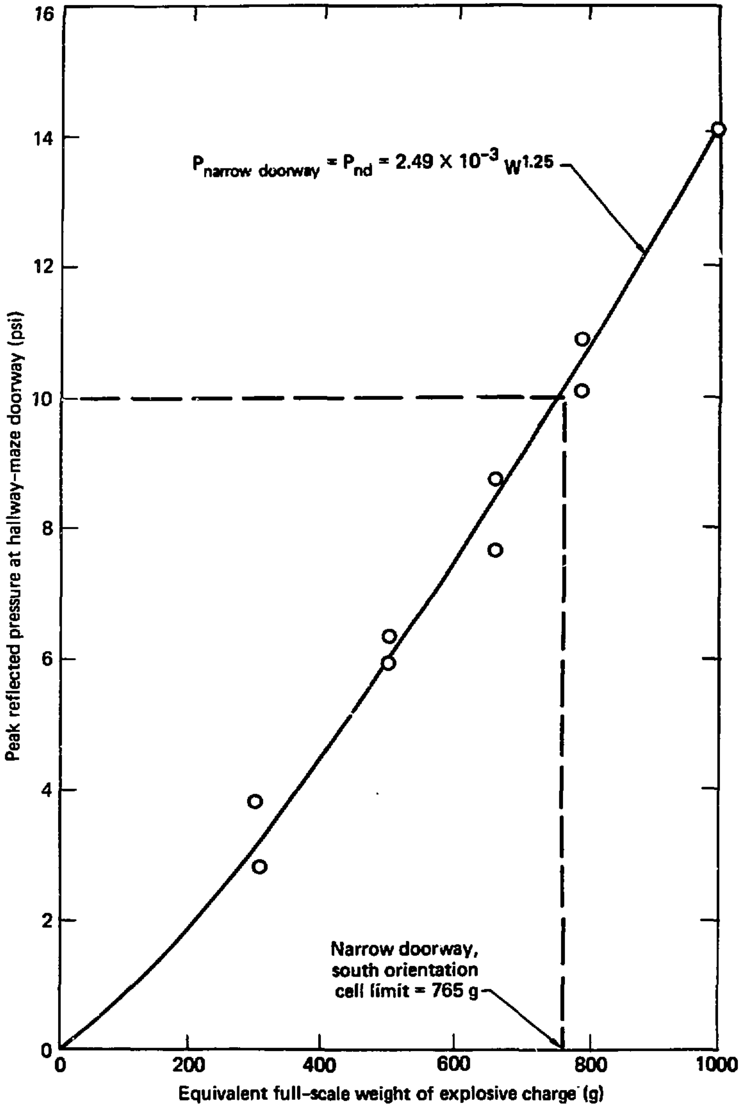


FIG. 8. Cell explosive limit, narrow doorway, south orientation.

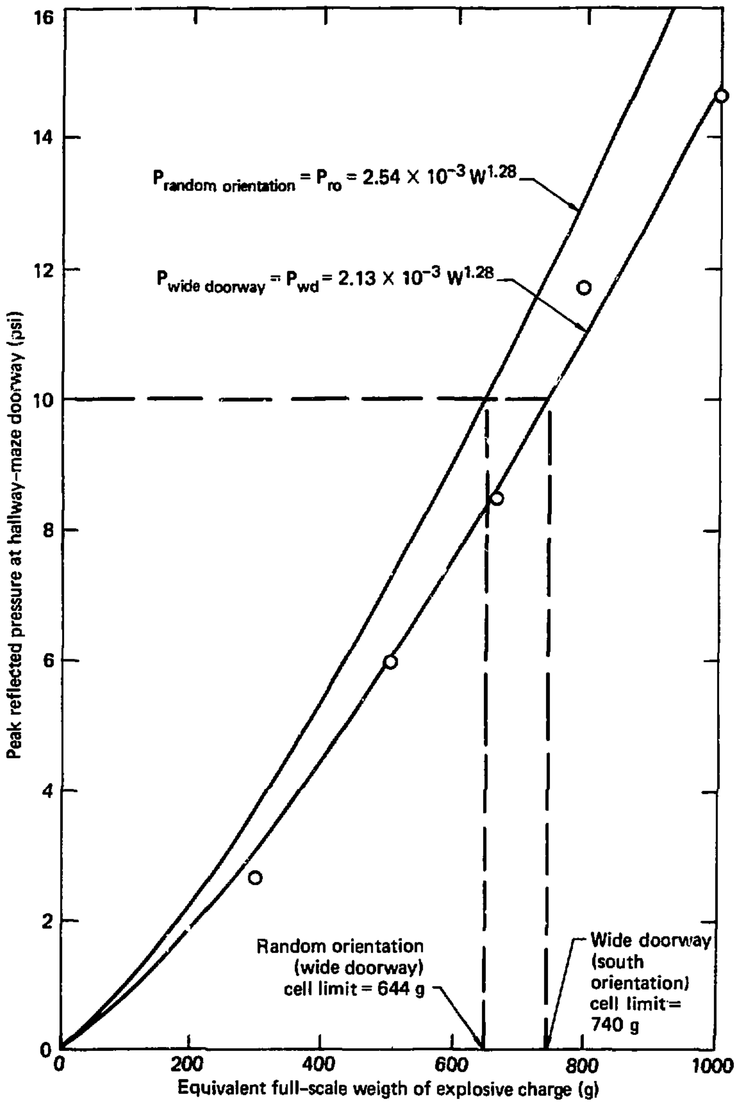


FIG. 9. Cell explosive limit, wide doorway, random orientation.

model, for example, the pellet weighed approximately $[(500/4^3) - 0.021]$ or 7.792 g (actually 7.832 g). For the 800-g equivalent for experiment 262 in the 1/8-scale model, the pellet weighed approximately $[(800/8^3) - 0.021]$ or 1.542 g (actually 1.545 g). All HE charges were of PBX 9407 assembled to MC 1957A detonators, as previously described.

The single and narrow pressure peaks that complicated rational analysis of the experimental data are listed under Remarks in Table 8. Due to their typical occurrence early, during a period of increasing impulse, or very late, they were disregarded in comparing the pertinent peak reflected pressures.

Figure 8 plotted from the experimental data in Table 8 shows the close correlation between reflected pressure measured on narrow-doorway 1/8-scale and 1/4-scale model experiments with reduced explosive charges. The standard deviation of plotted data is ±0.44 psi from the empirical equation generated from this data: $P_{nd} = 2.49 \times 10^{-3}\ W^{1.25}$, where P_{nd} is the peak reflected pressure at the hallway-maze doorway in psi and W is the total weight of the full-scale HE charge in grams. Figure 8 indicates that the explosive limit for a narrow-doorway cell would be about 765 g. The wide-doorway curve in Fig. 9 plotted from the data in Table 9 shows the similarly close correlation between the pressures sensed on the wide-doorway 1/8-scale model experiments (with reduced explosive charges) and the equation developed to account for doorway widening. This equation is: $P_{wd} = 2.13 \times 10^{-3}\ W^{1.28}$, which indicates an explosive limit of 740 g for south-oriented detonations in a wide-doorway cell. The standard deviation of the experimental data from this recalculated curve is ±0.41 psi.

Expected decrease in transit times for increased weight of explosive charges, as consistently evidenced in both Tables 8 and 9, attests to the reliability of the recorded data.

Effect of Widening Maze Doorways

The average peak reflected pressure sensed in both the 1/8-scale and 1/4-scale models with maze doorways modeled to 2 ft 4 in. (narrow) was compared to the average recorded for the 1/8-scale model after the doorways were widened to 4.0 in. to represent 2-ft-8-in. (wide) doorways. An empirical equation was developed to describe the relationship between the peak reflected pressures from reduced and full-scale equivalent charges detonated in the wide-doorway 1/8-scale model.

The average peak reflected pressure for both the 1/8-scale and 1/4-scale narrow-doorway models for south-oriented detonations at location K was 14.0 psi, as listed in Tables 1 and 2. The average for similar detonations at K in the 1/8-scale wide-doorway model was 14.7 psi (Table 3).

The empirical equation, $P_{wd} = 2.13 \times 10^{-3}\ W^{1.28}$ can be used to predict the peak reflected pressure (in psi) at the hallway-maze doorway for any south-oriented charge W (in grams). The peak reflected pressure from any accidental, south-oriented detonation within the cell working area (shown in Fig. 2) should not exceed this calculated pressure.

Effect of Randomly Orienting HE Charges

Equivalent 1-kg charges were oriented at K so that explosive propagation was toward the north, east, or west rather than toward the south, to determine the effect of charge orientation on the peak reflected pressure at the hallway-maze doorway. See Fig. 2 for charge locations and orientations.

The average of the maximum peak pressures for charges randomly oriented (north, east, and west) was 17.5 psi at an average time after detonation of 2.7 ms, shown in Table 10.

The result of moving the wide-doorway equation upward in the ratio of 17.5:14.7 from $P_{wd} = 2.13 \times 10^{-3}\ W^{1.28}$ to $P_{ro} = 2.54 \times 10^{-3}\ W^{1.28}$ (to conservatively account for the probability of an accidental detonation being randomly oriented) is shown in Fig. 9. The weight limit of PBX 9407 to be handled in the 1-kg cells is therefore 644 g (1.42 lb) to prevent the peak reflected pressure at the hallway-maze doorway from exceeding 10 psi.

CONCLUSIONS

PROOF OF SCALING

To show that results of testing in a 1/8-scale model can be reliably extrapolated to the full-scale HEAF cell, we constructed the 1/4-scale model and conducted experiments based on the cube-root scaling relationship $W_m = (V_m/V_f)\ W_f$, where W_m is the

TABLE 10. One-kg, wide-doorway-charge orientation experiments at location K.

Experiment number	High explosive charge (wt = 1.954 × 0.002 g) location	orientation[a]	Reflected pressure at position 1 (psi)	Time after detonation (ms)	Remarks (SP = single peak and NP = narrow, double width, pressure peak)
299	K	east	18.4	2.7	SP above 17.0 psi and NP above 15.7 psi (at 2.7 ms)
301	K	north	17.2	2.6	SP above 10.5 psi to 17.4 psi at 1.0 ms and NP above 14.7 psi (at 2.6 ms)
302	K	west	16.9	2.9	NP to 17.5 psi at 1.4 ms and SP above 15.4 psi (at 2.9 ms)
Average maximum for location K, random:			17.5	2.7	Use for setting conservative cell limitations

[a]See Fig. 2 for direction of explosive propagation.

weight of explosive detonated in the model, W_f is the equivalent full-scale explosive charge weight, V_m is the volume of the model, and V_f is the volume of the proposed cell.

Comparison of south-oriented detonations at K in the 1/4-scale and 1/8-scale narrow-doorway models proved that cube-root scaling of the full-scale cell-maze was reliable. The average peak reflected pressure at the hallway-maze doorway in both models was 14.0 psi. This pressure was recorded at an average time interval of 2.9 ms after detonation of the explosive charge for experiments in the 1/8-scale model (Table 1) and at about twice the time interval, 5.9 ms, in the 1/4-scale model (Table 2).

CELL WORK-AREA LIMITATIONS

By detonating charges in selected locations inside the narrow-doorway model cells, we determined that cell-limit quantities could be handled within the area shown shaded in Fig. 2. This includes all floor space to within 2 ft of the wall except for the area within a 4 ft radius of F, near the cell-maze doorway.

CELL EXPLOSIVE LIMIT

Peak pressure-versus-charge weight for experiments in the narrow-doorway models were plotted and the empirical equation $P_{nd} = 2.49 \times 10^{-3} W^{1.25}$ was developed to calculate the peak pressure at the hallway-maze doorway for the detonation of various HE charges.

Midway through testing, when we were told that the cell doorway must be wider, this equation was revised to $P_{wd} = 2.13 \times 10^{-3} W^{1.28}$ to account for widening of the doorways.

The resulting equation for reflected pressure was finally adjusted to $P_{ro} = P_r = 2.54 \times 10^{-3} W^{1.28}$ to recognize the probability that an accidentally detonated charge could be randomly oriented.

The cell explosive limit, the weight of HE that could credibly cause a peak reflected pressure of 10 psi at the hallway-maze doorway of the proposed cell, is 644 g or 1.42 lbs.

Peak pressures from hallway transducers at full-scale equivalent distances of 4 ft and over from the doorway centerline were all less than 10 psi when randomly oriented 1-kg equivalent charges were detonated in the wide-doorway cell model. If charges in excess of the cell limit are to be handled in the cell, the hallway within 4 ft of the doorway must be administratively restricted or barricaded to control personnel access.

REFERENCES

1. Theodore Baumeister, *Marks Mechanical Engineers Handbook* (McGraw-Hill Book Company, New York, NY. 1958), 6th ed., pp. 2-32–2-33.

2. N. M. Newmark, Separate No. 306, in *Proc. Amer. Soc. Civil Engr.*, Vol. 79, Oct. 1953.

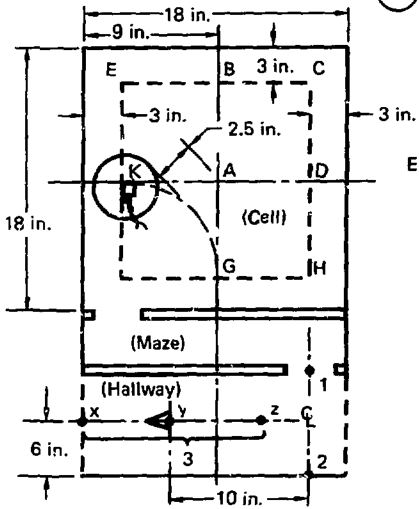
APPENDIX A.
SAMPLE PRESHOT RECORD:
1/8-SCALE MODEL

Crew:

Test date: 9-4-80 Electronics: Ken Griffin

Test number: 260 Explosives: Terry Harris

Shot position: A B C D E F G H J (K) Other (show on sketch)



Explosive weight (grams)

Pellet : 1.932

Detonator: 0.021

Total shot: 1.953

Transducer information:

Transducer position	Cable number	E_{in}	Remarks
1	1	13.000(Z225)	0.1 v/psi
3	3	13.340(A298)	0.1 v/psi

Comments:

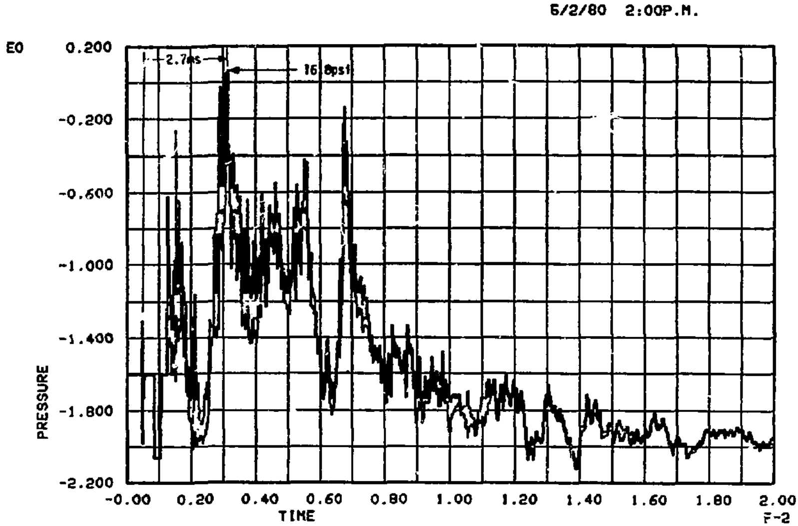
Same as 257-259 except Tdcr 3 moved to 10" from doorway ℄. Tdcr 3 in tapered disk.

Ramrod (initials): CMB/WAB

APPENDIX B.
GRAPHS OF PRESSURE VERSUS TIME

On the following graphs of original field data, time is indicated in hundredths of seconds (seconds × 10^{-2}) and pressure is shown in volts.

To convert time to milliseconds, the printed number was multiplied times 10. To read the pressure in psi, the printed number was also multiplied times 10.



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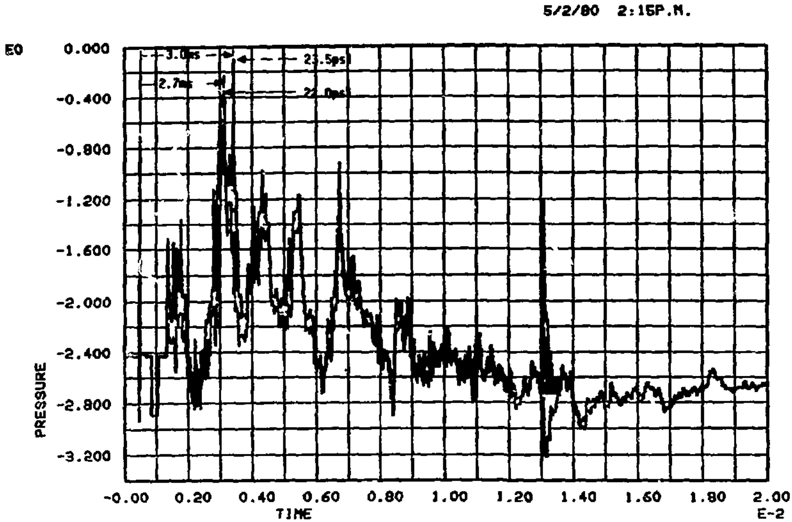

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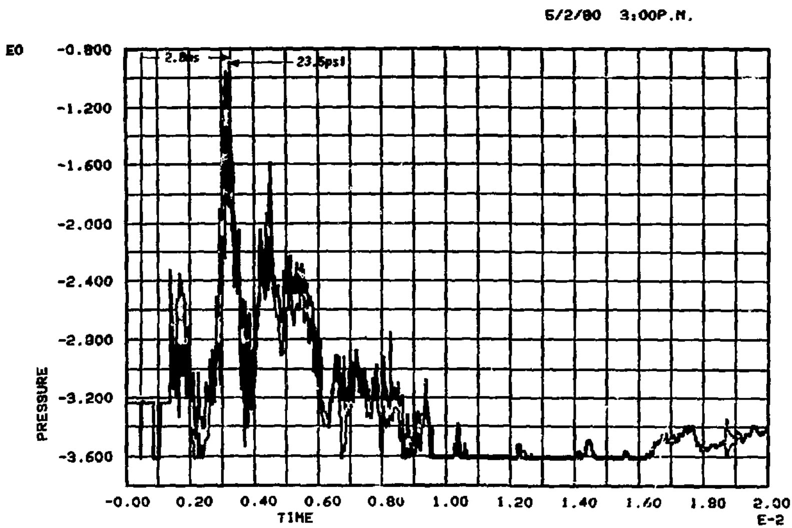

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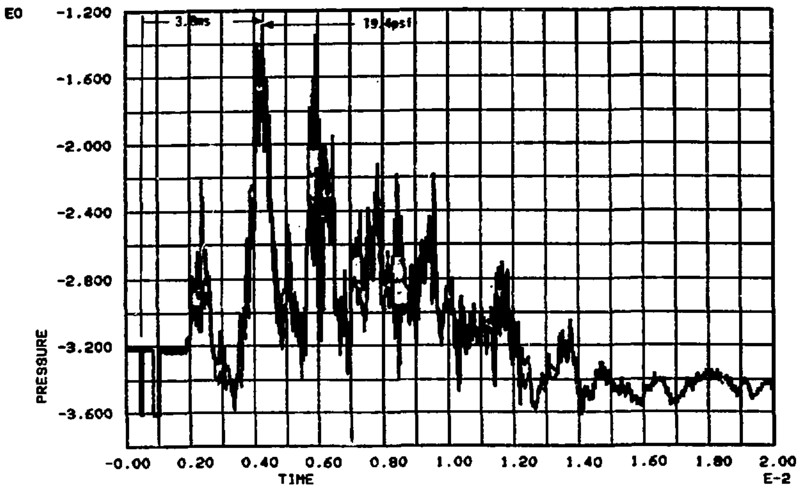

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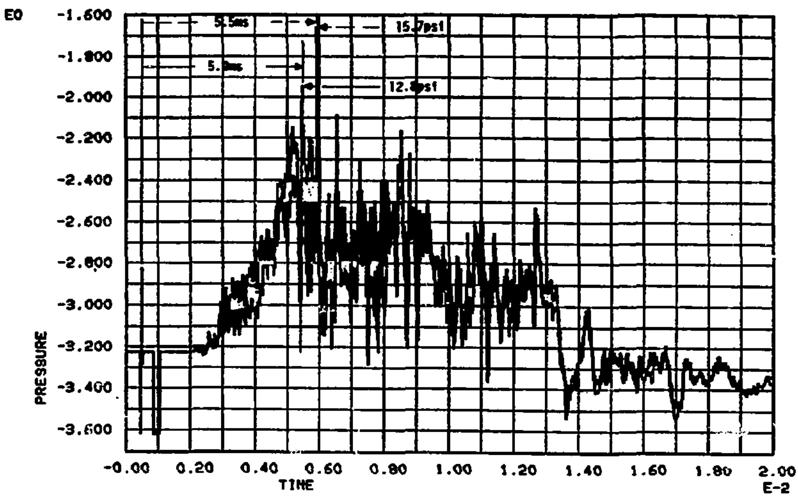

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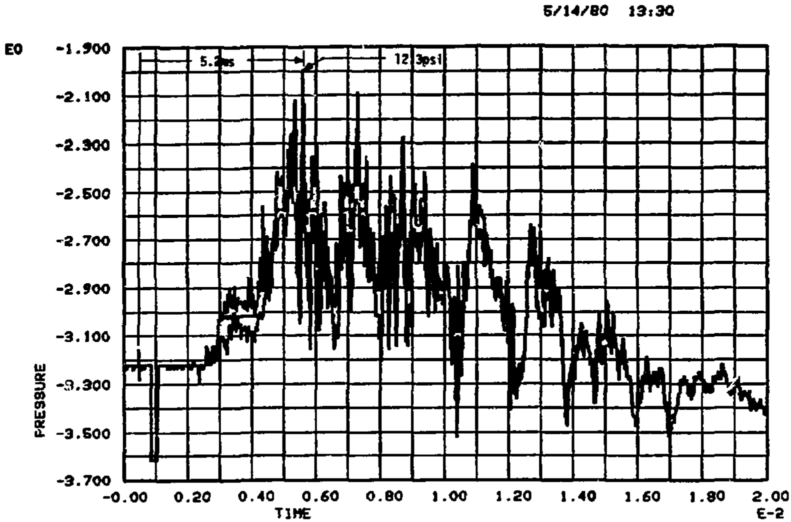

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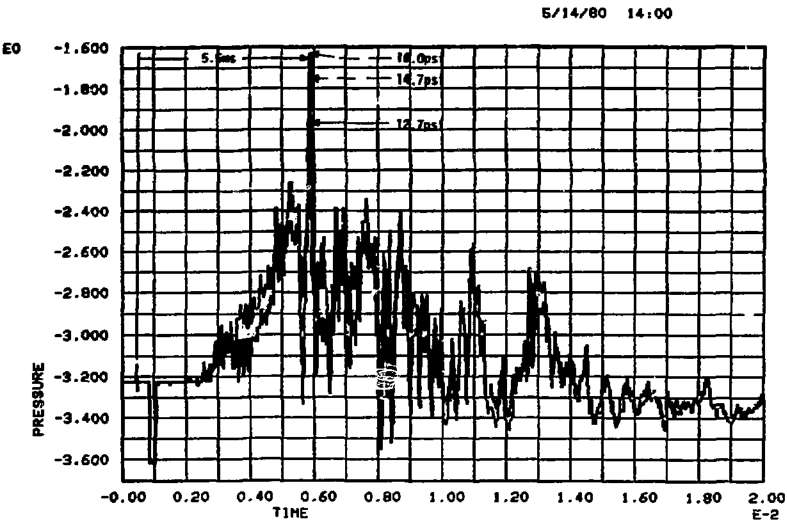

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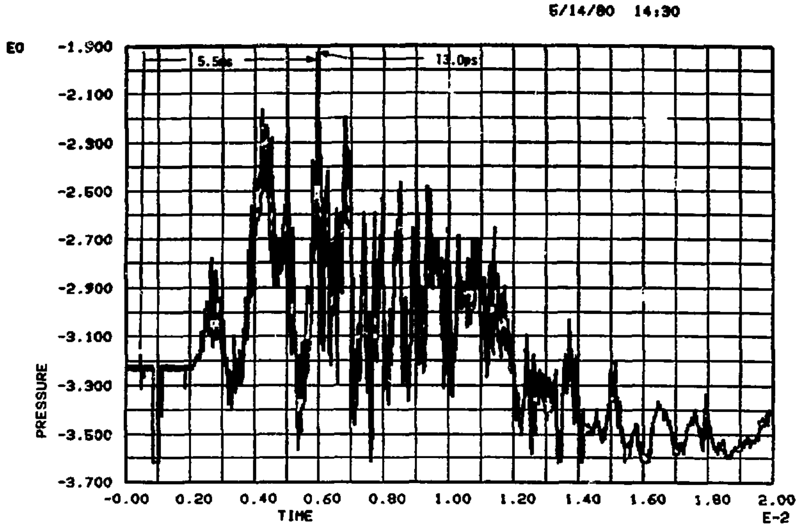

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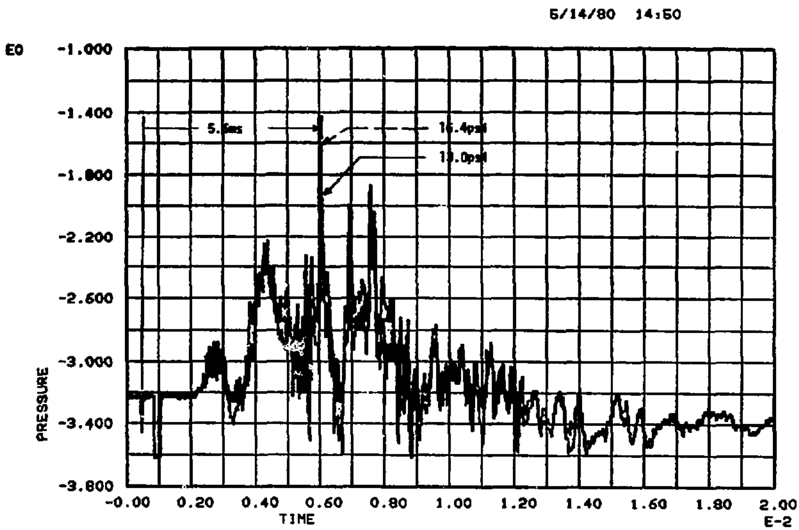

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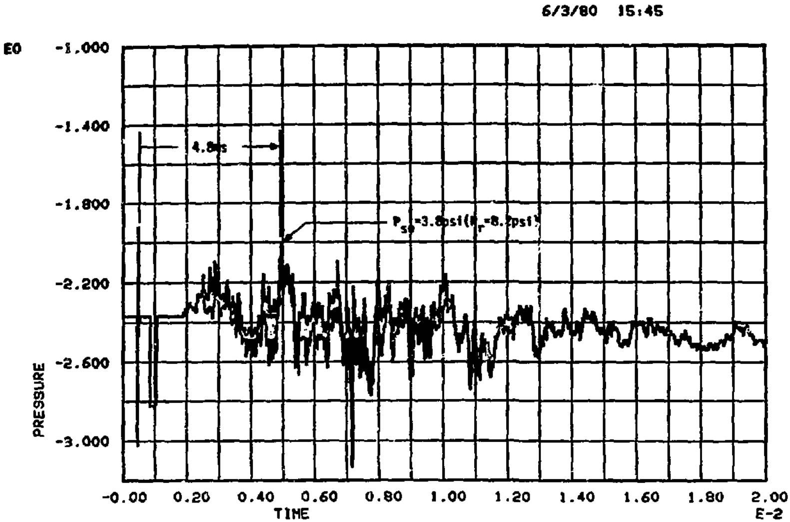

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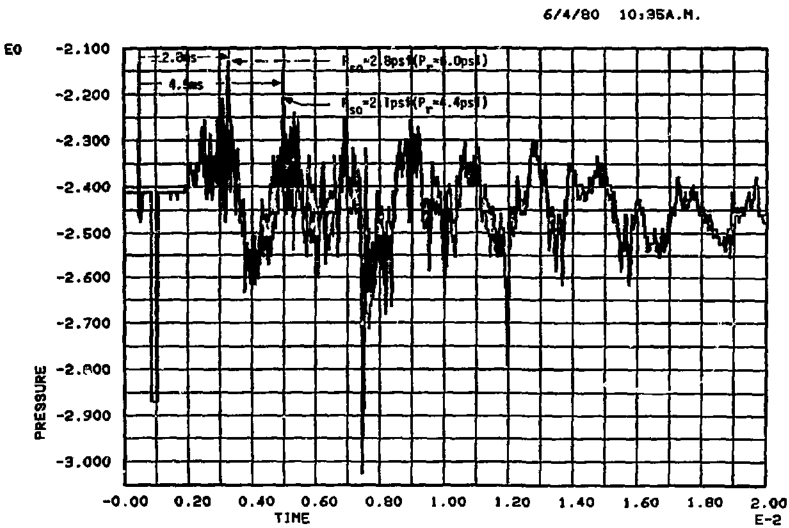

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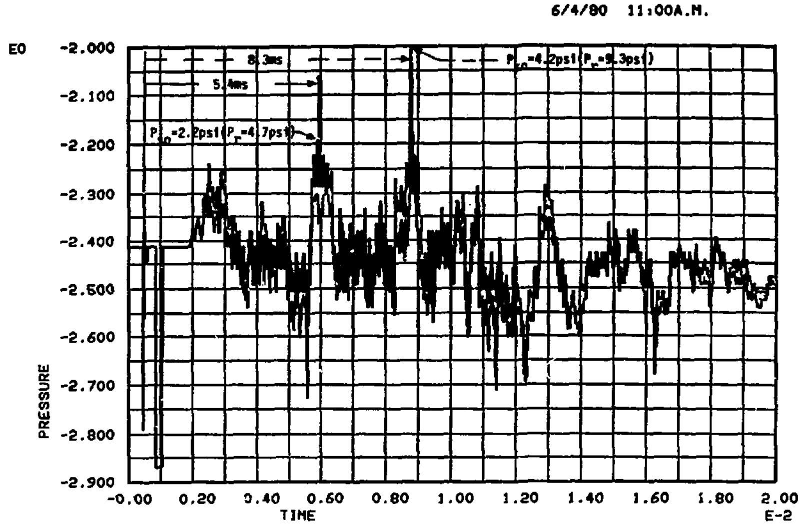

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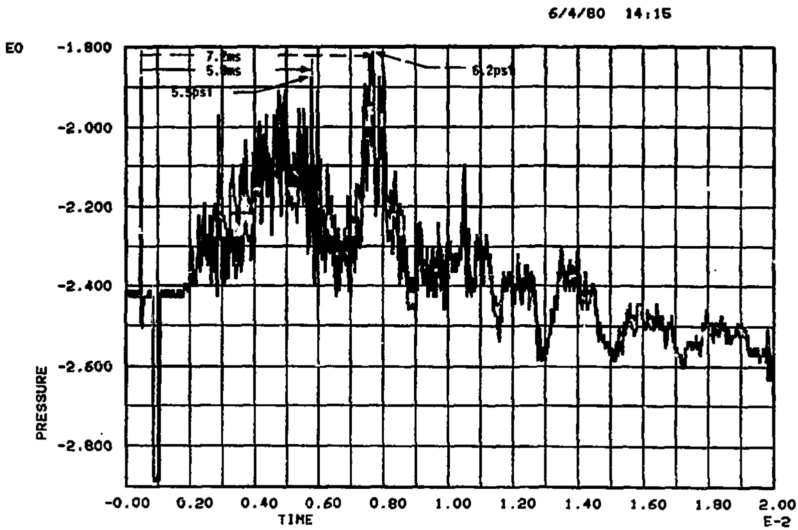

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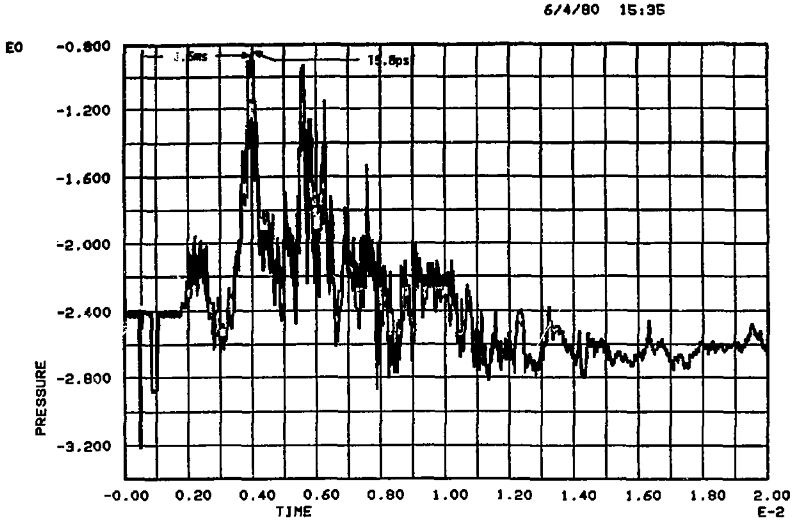

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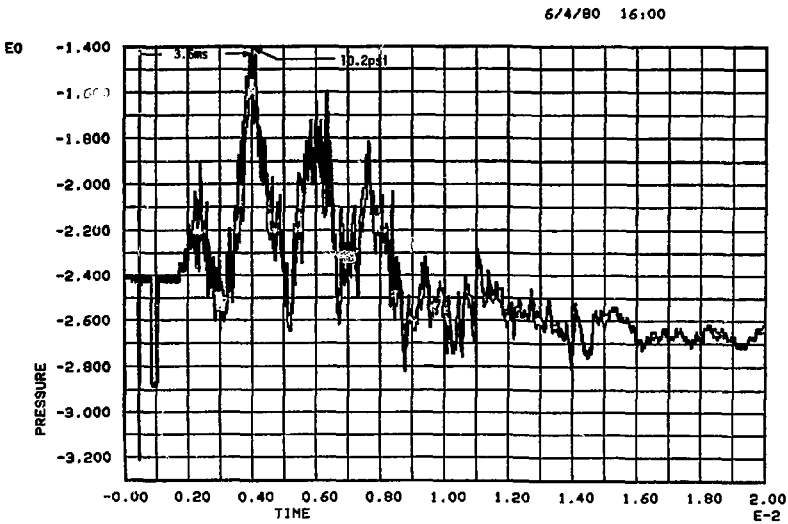

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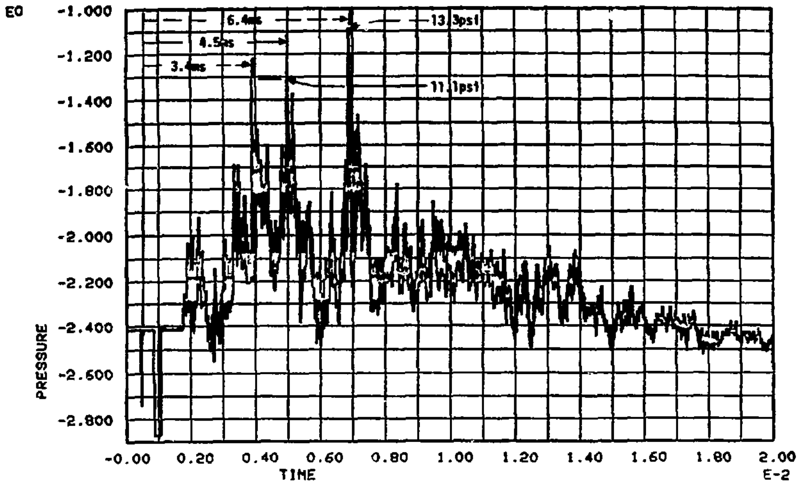

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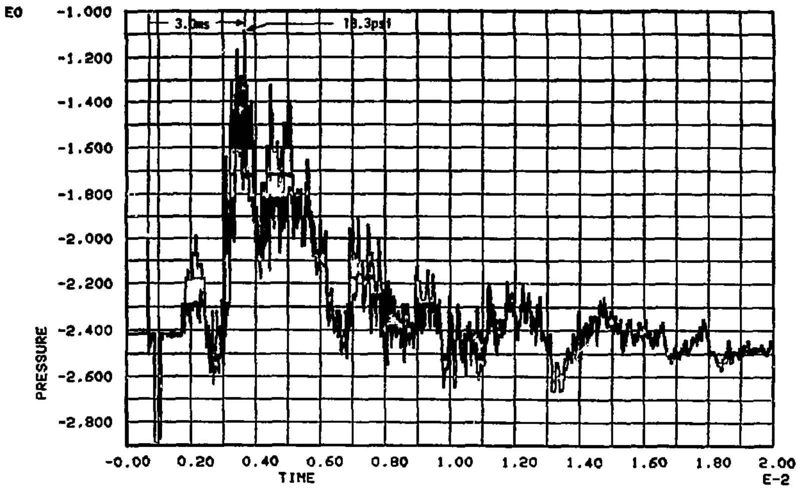

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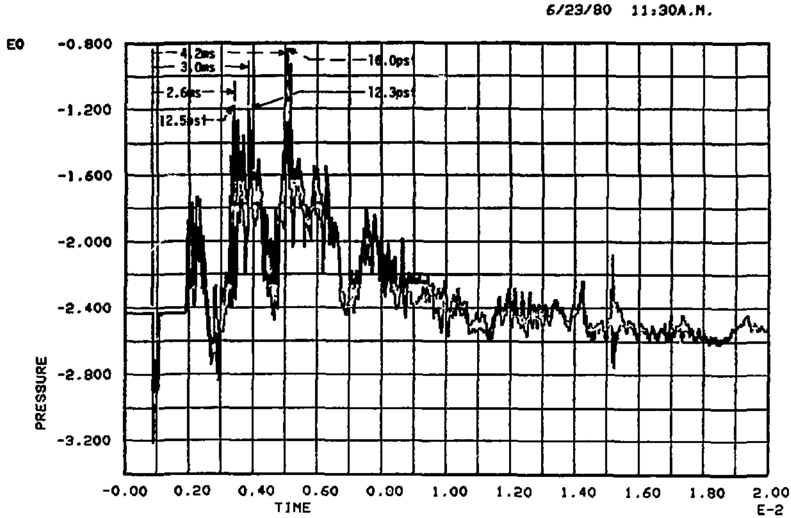

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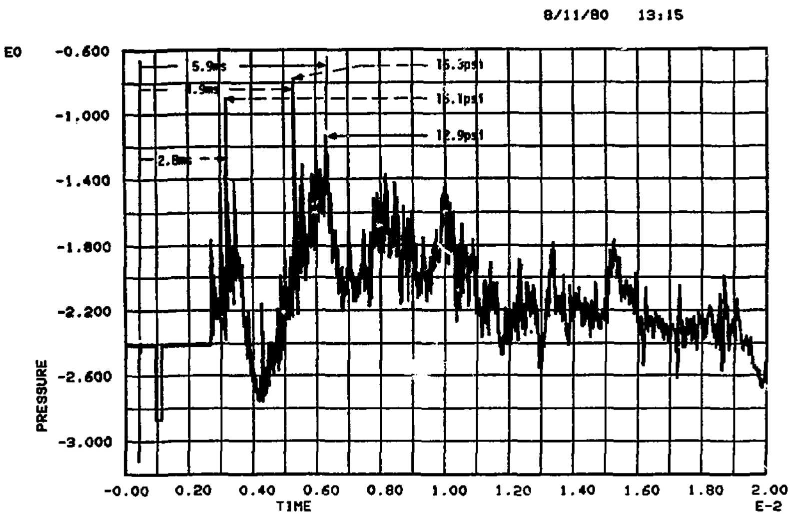

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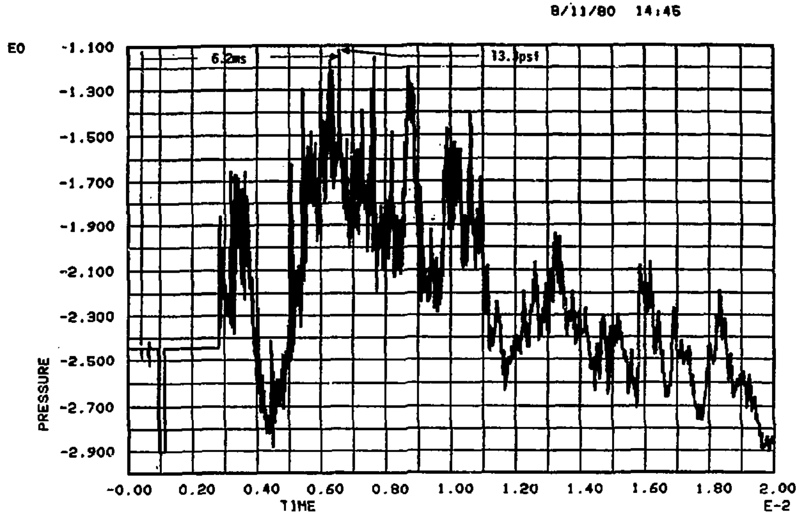

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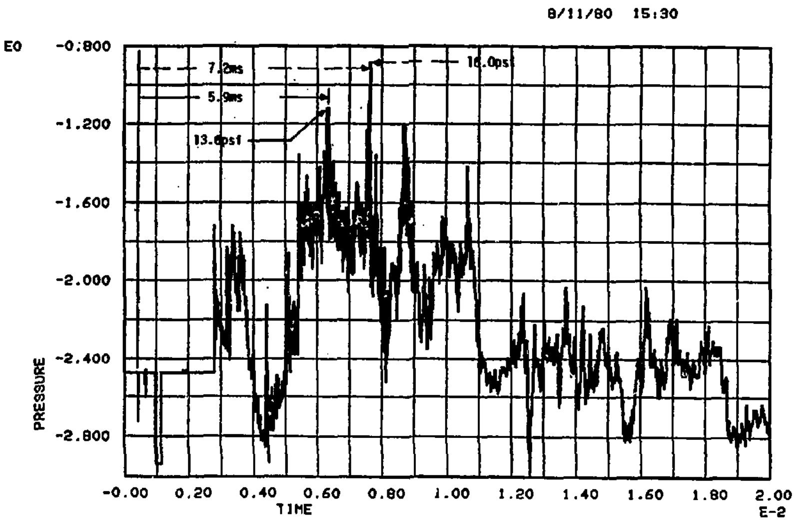

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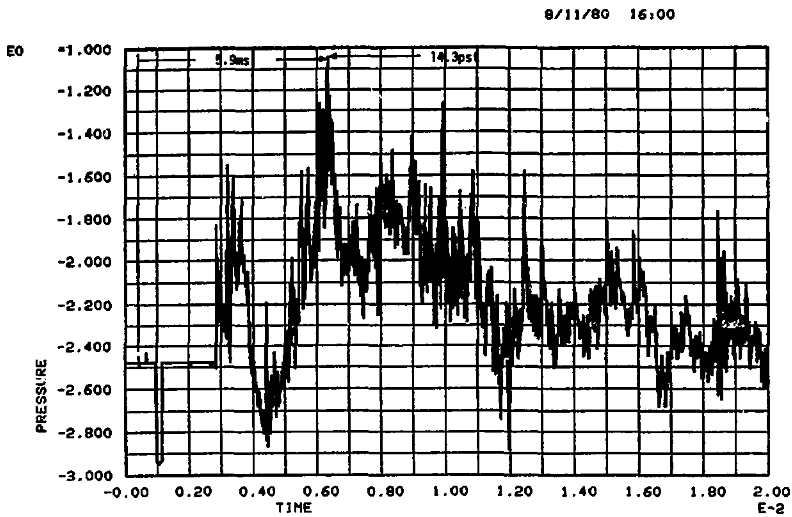

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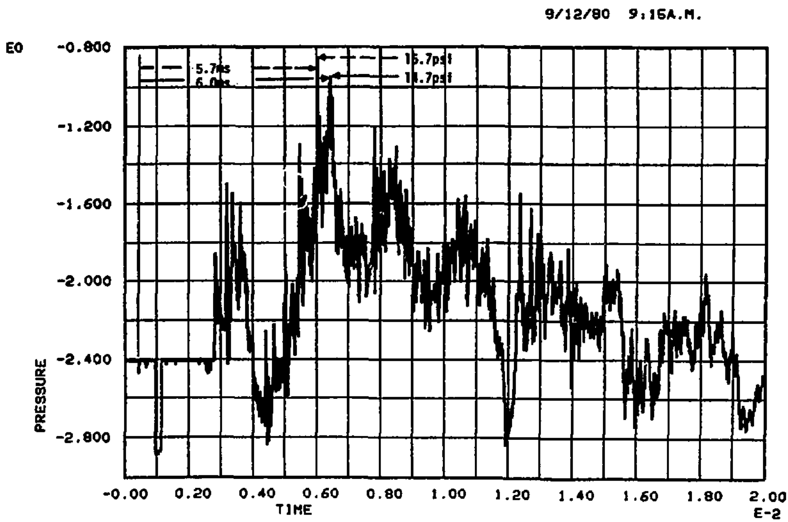

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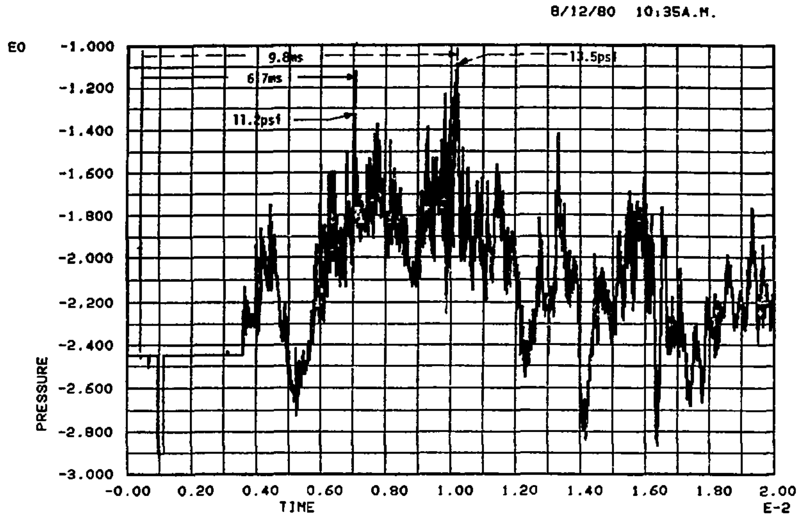

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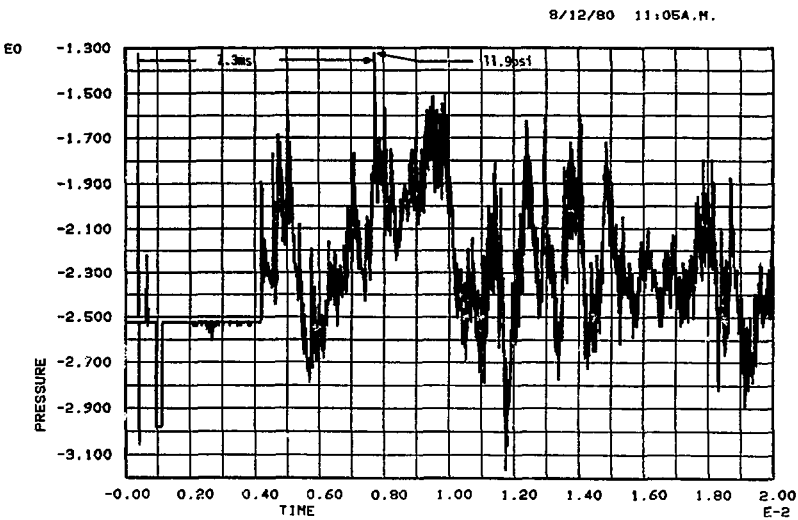

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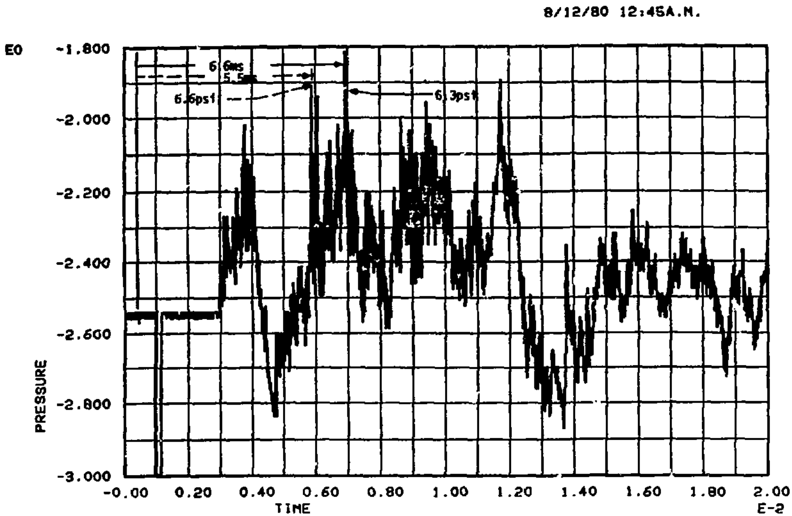

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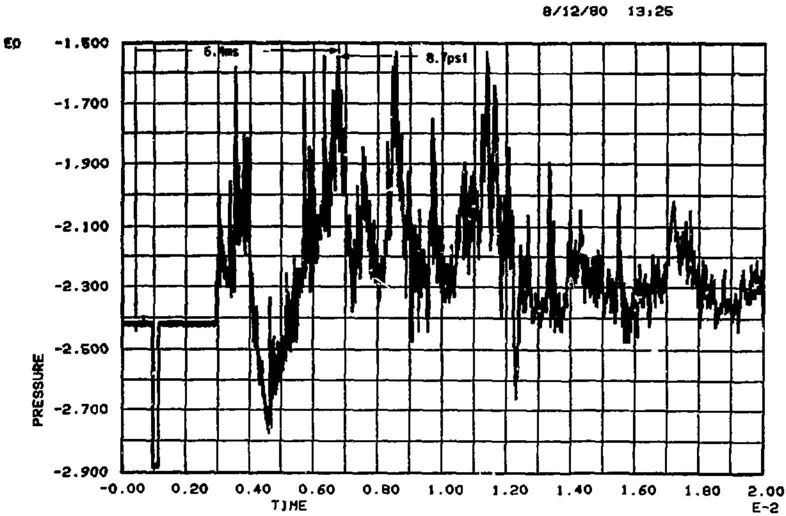

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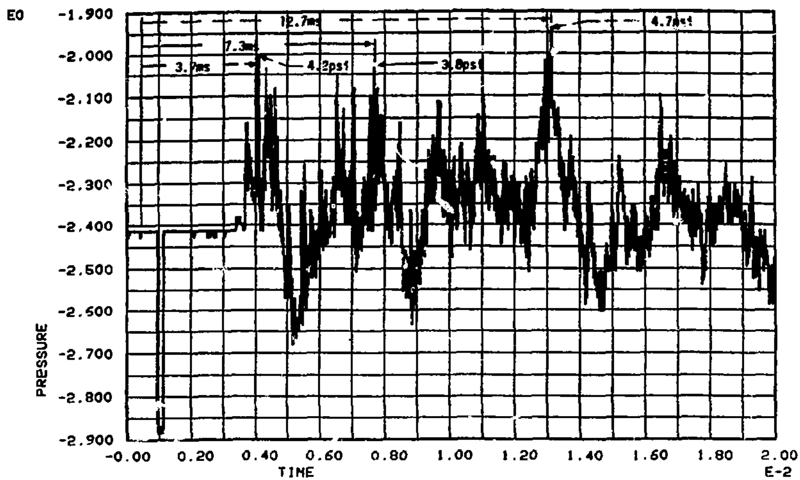

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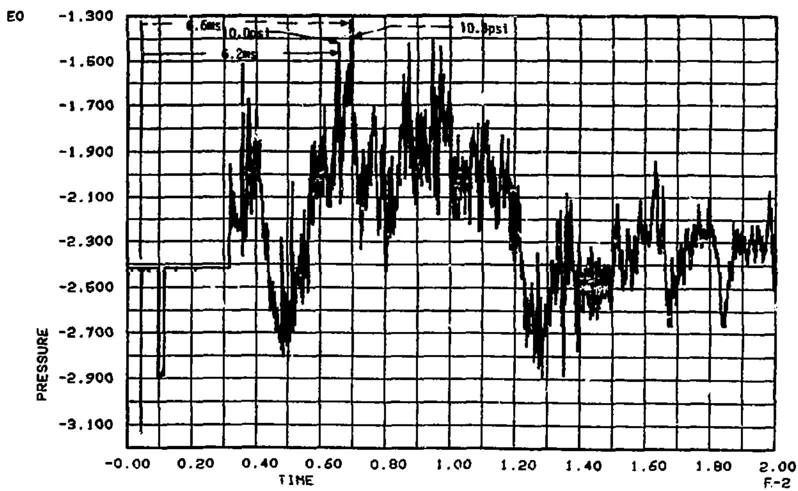

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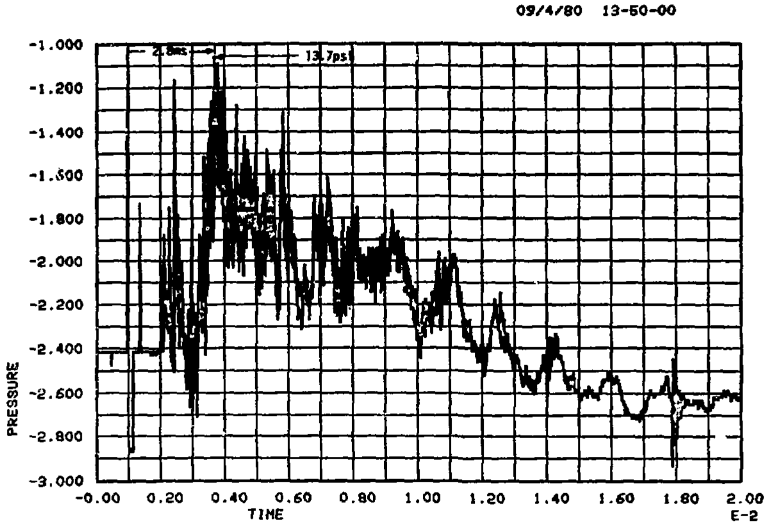

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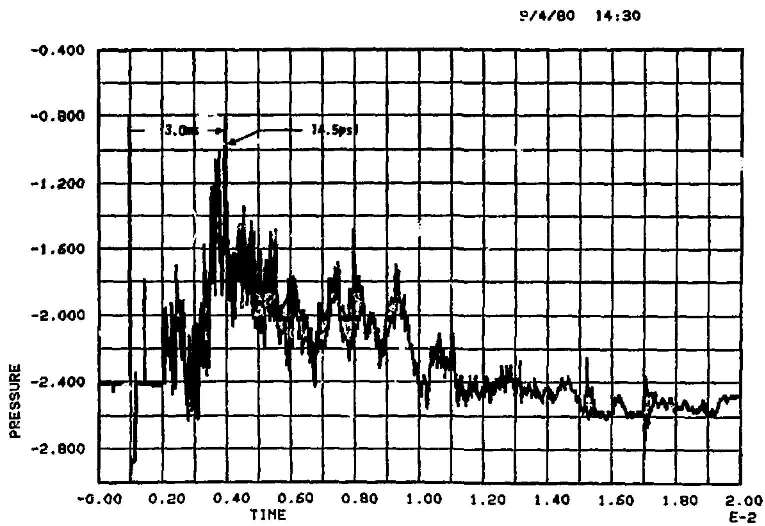

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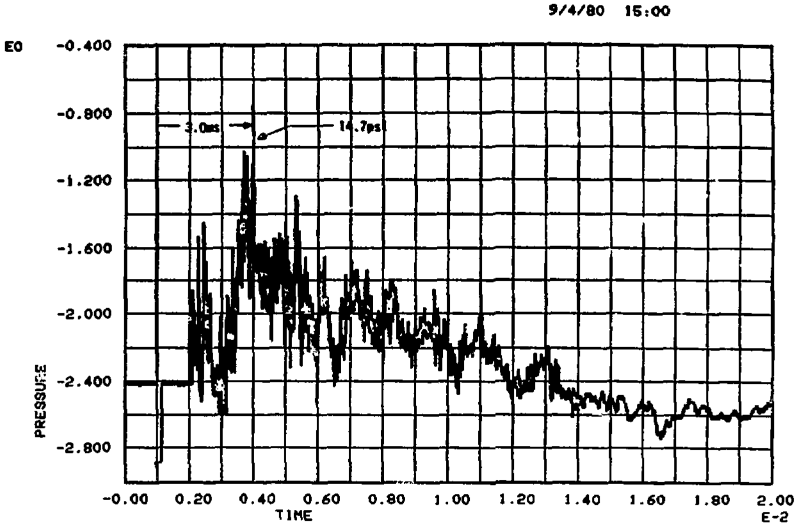

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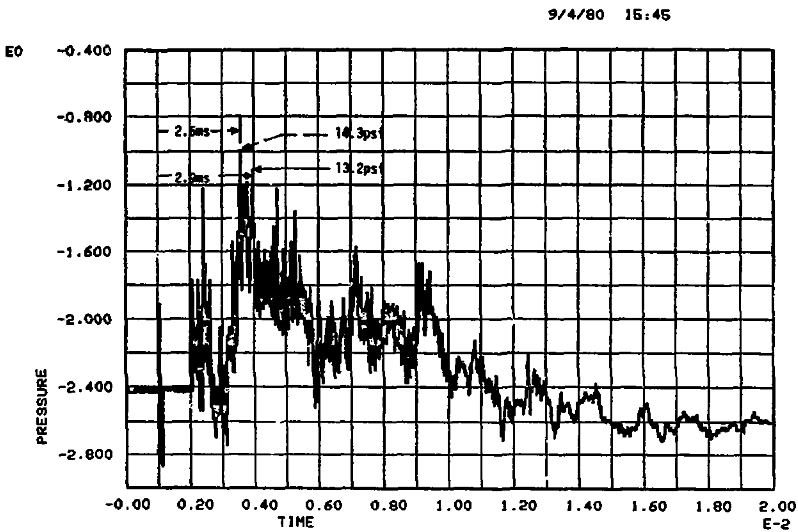

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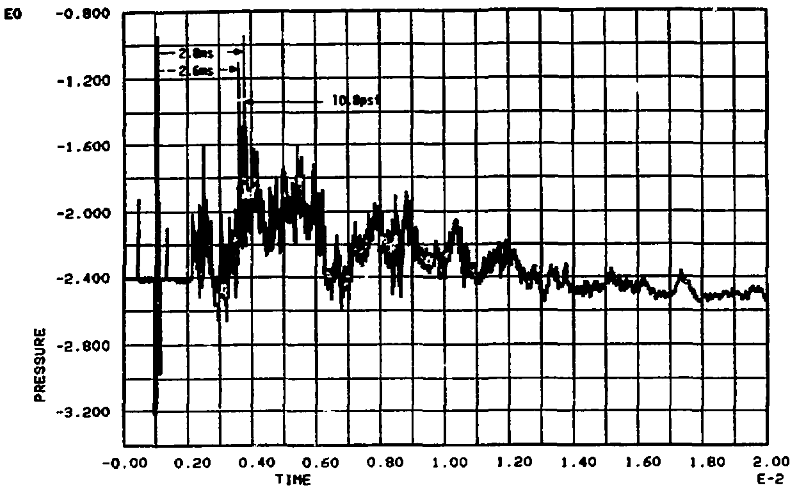

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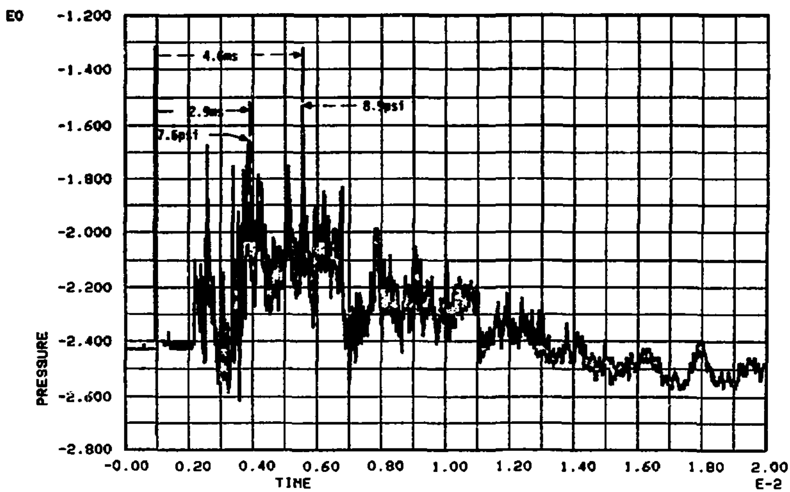

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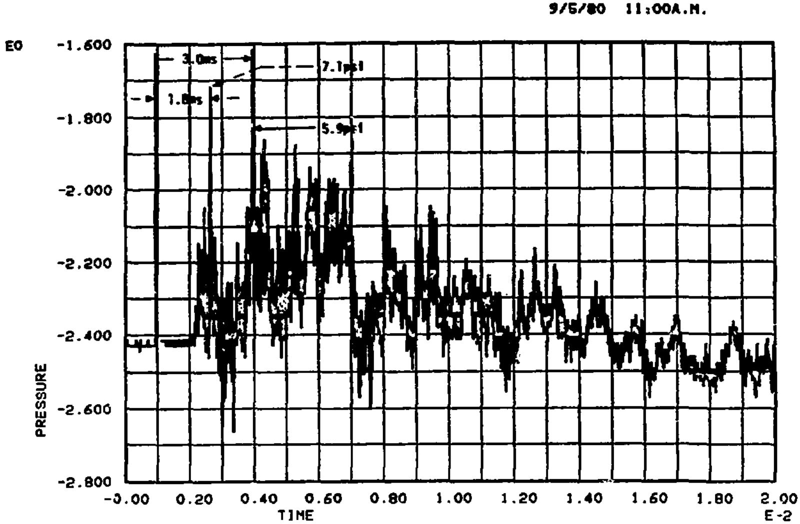

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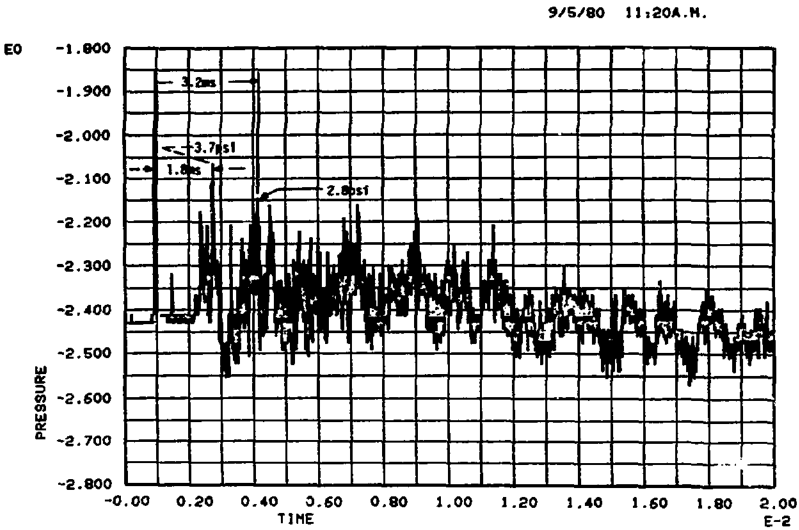

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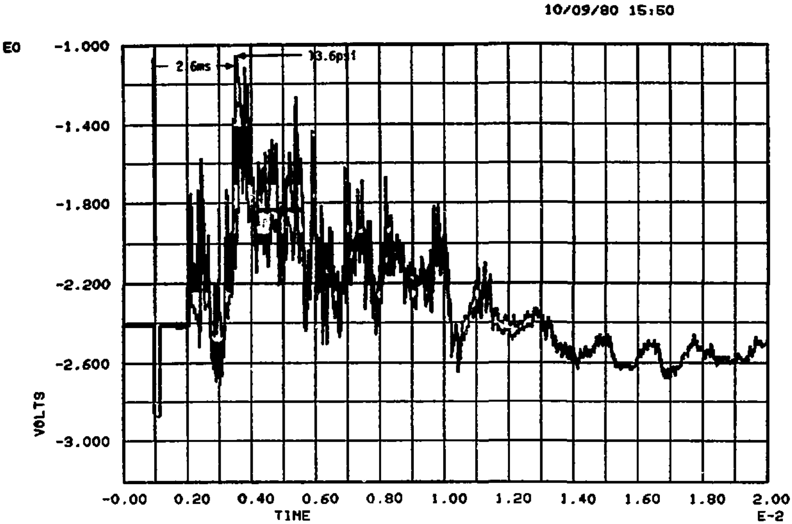
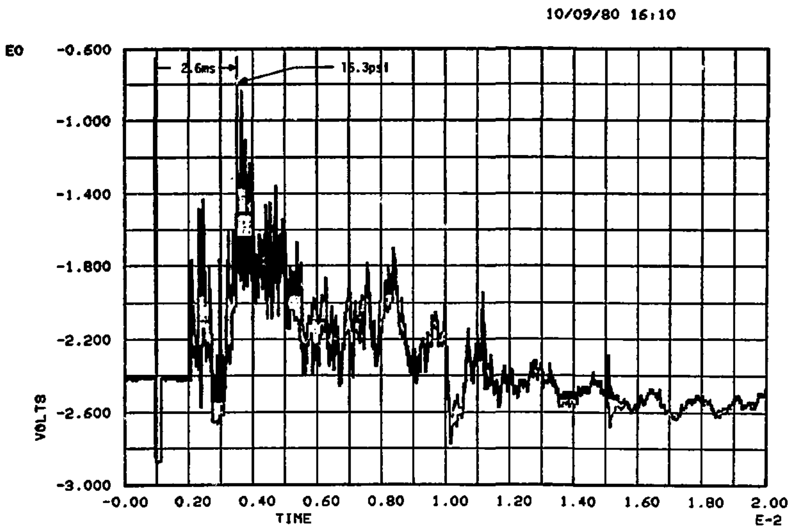


HEAF 276 .1V=1PSI LOCATION K



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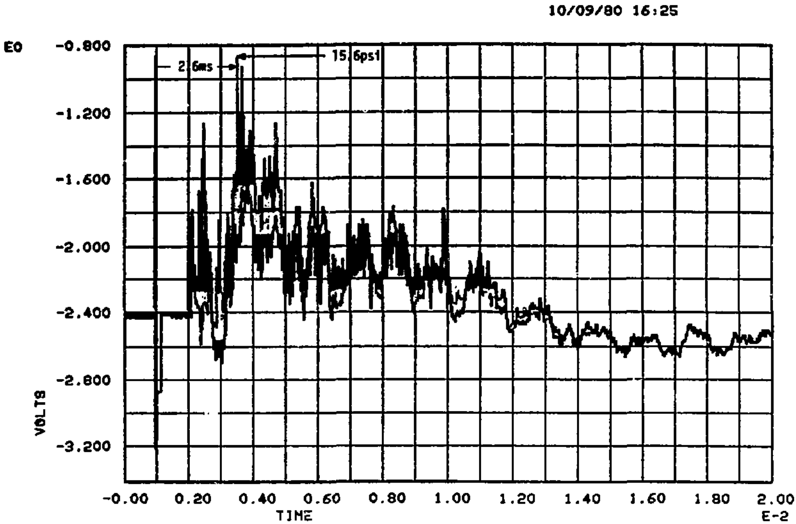

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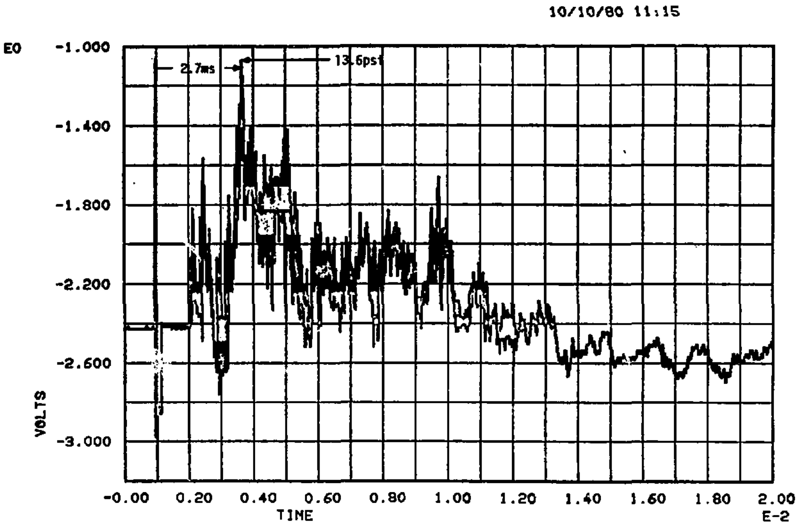

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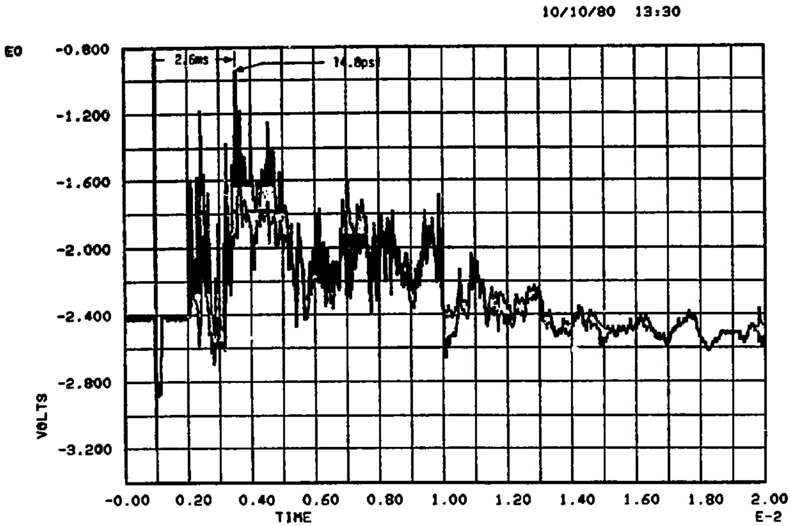

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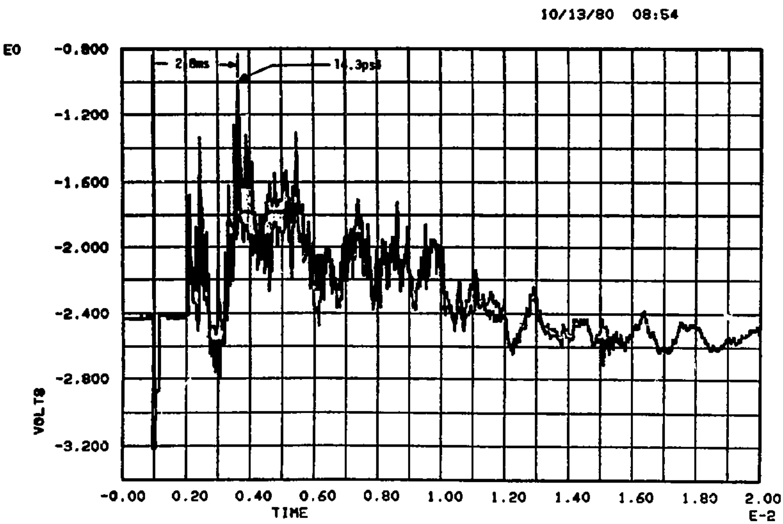
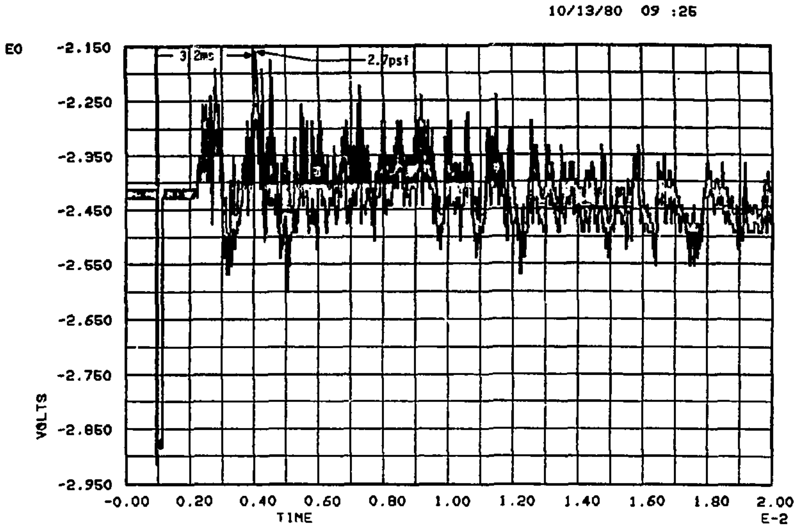
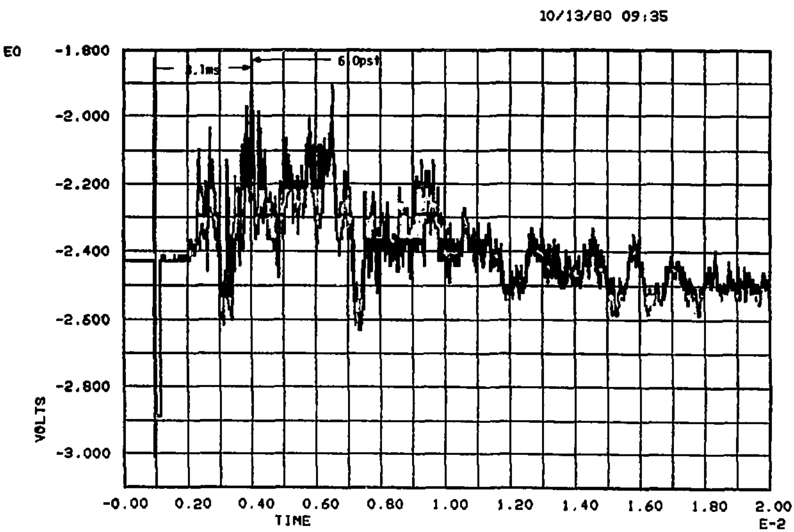


HEAF 287 .1V/1PSI LOCATION K



HEAF 288 .1V/1PSI LOCATION K .6GRAMS



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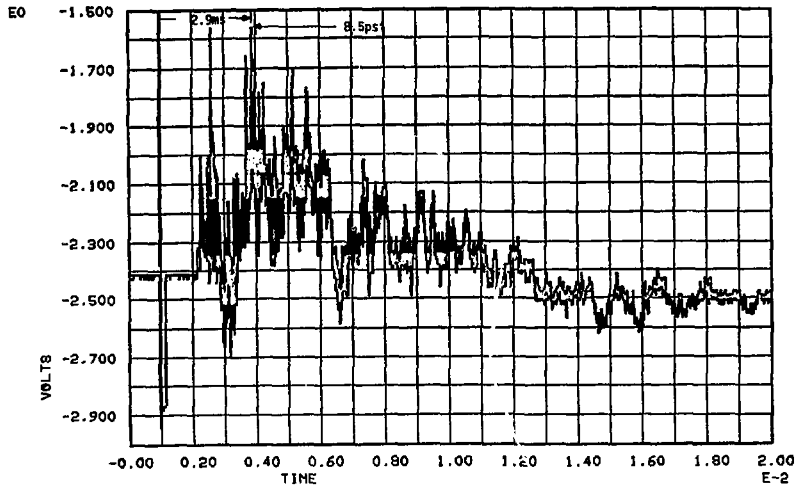
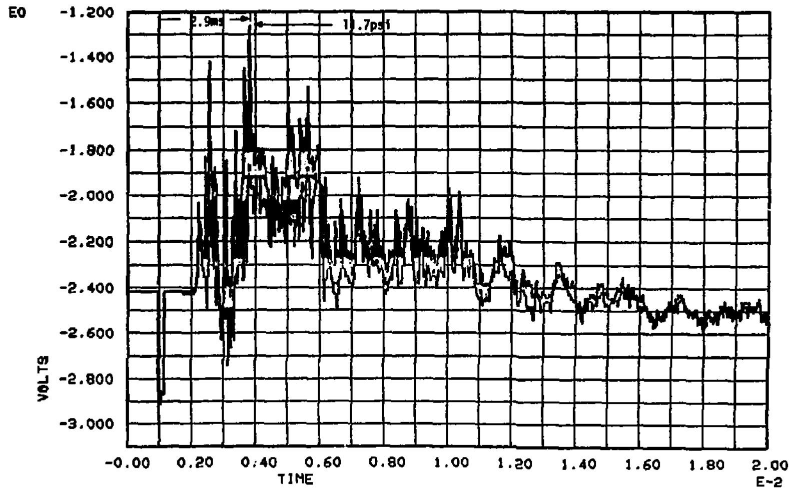
10/13/80 09:55

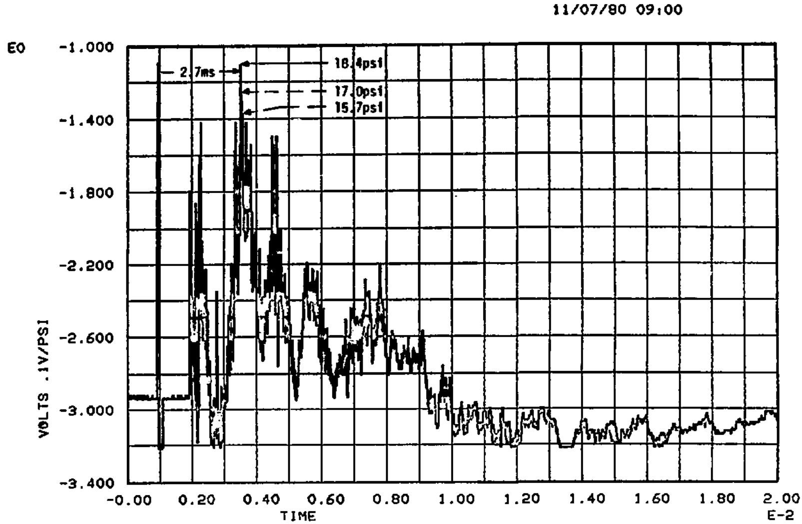


HEAF 290 .1V/1PSI LOCATION K 1.3 GRAMS

10/13/80 10:46



HEAF 291 .1V/1PSI LOCATION 1.5 GRAMS



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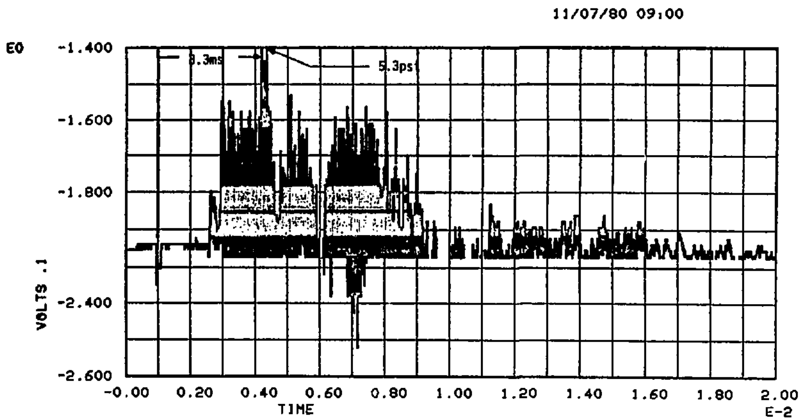

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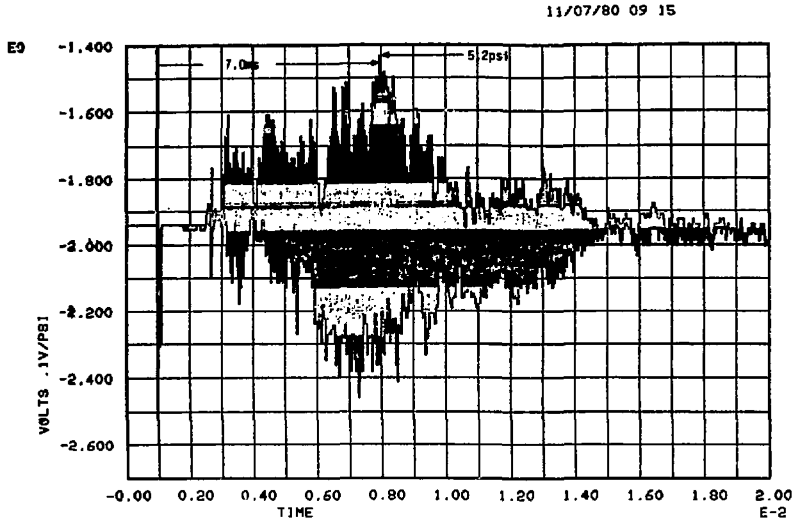

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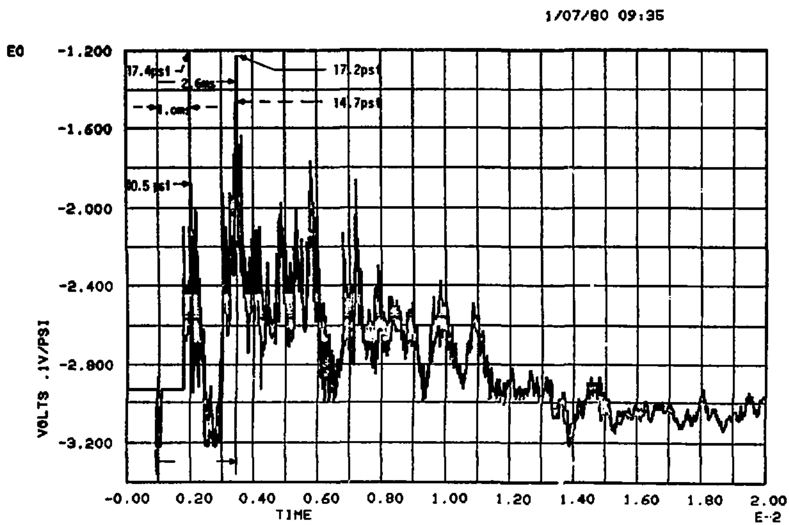

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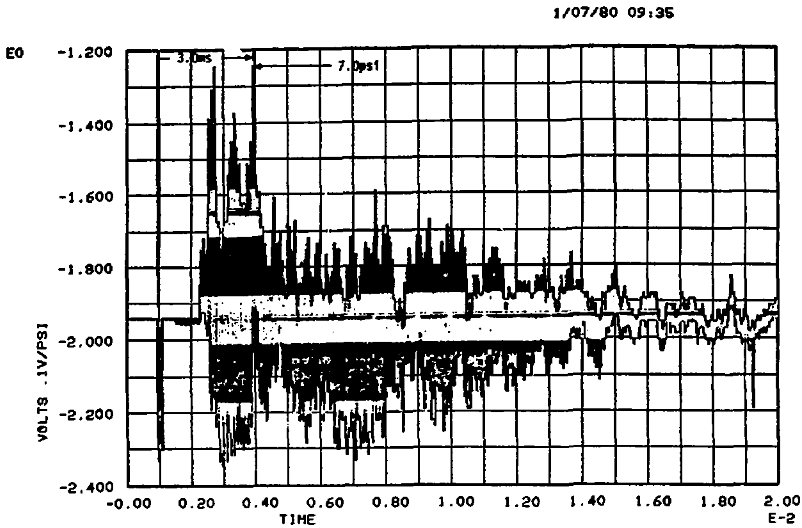

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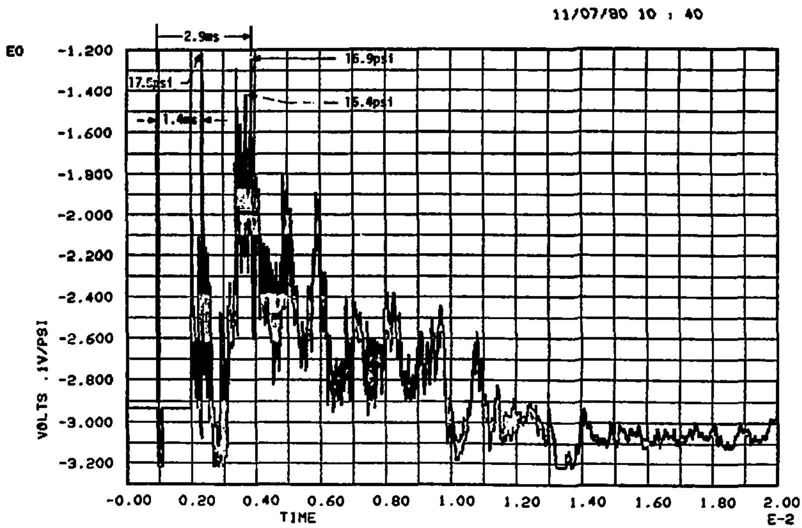
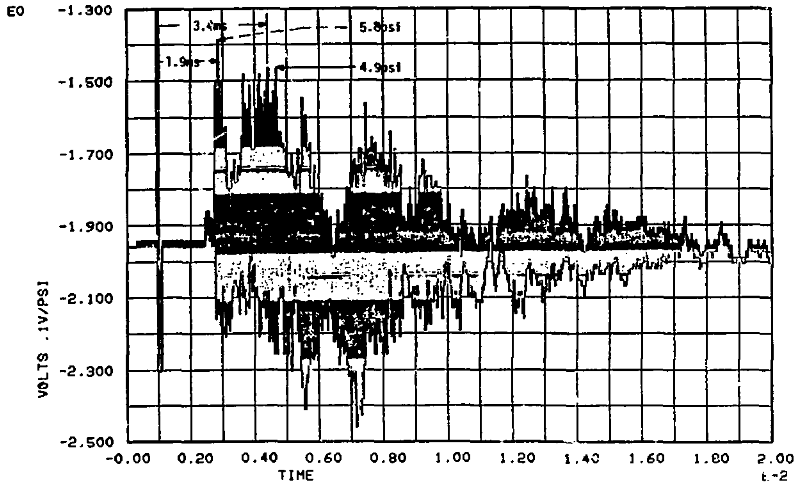
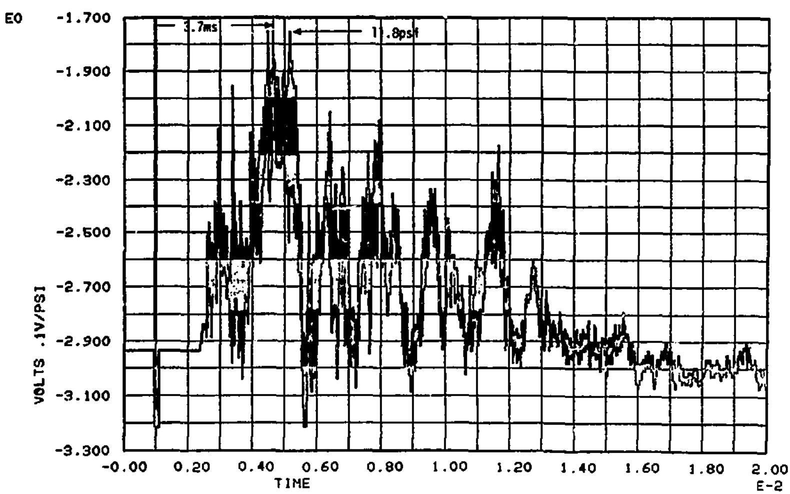


HEAF 302 11/07/80

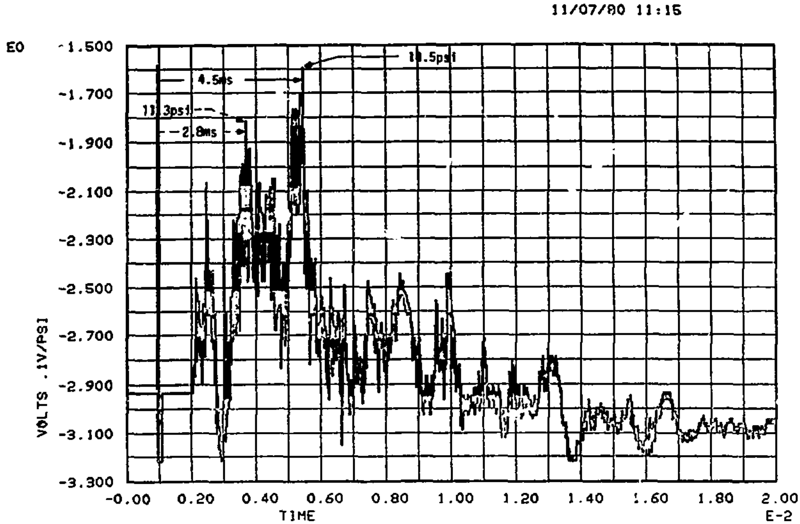
11/07/80 10 : 40



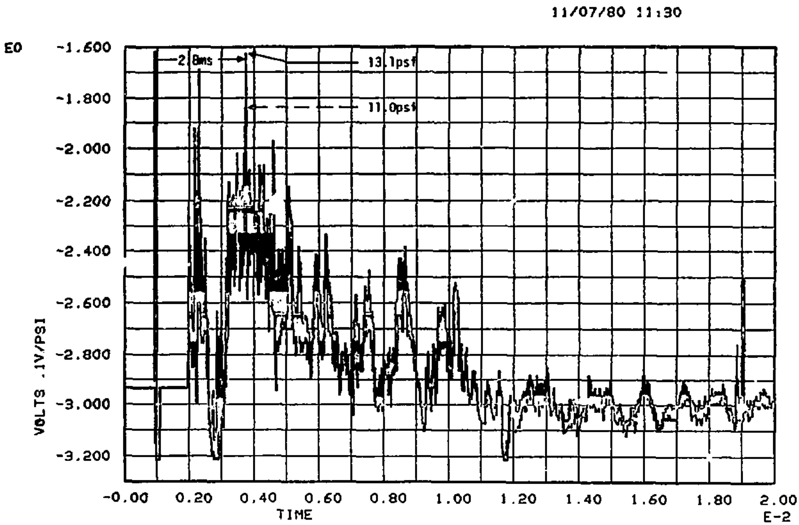
HEAF 302 11/07/80



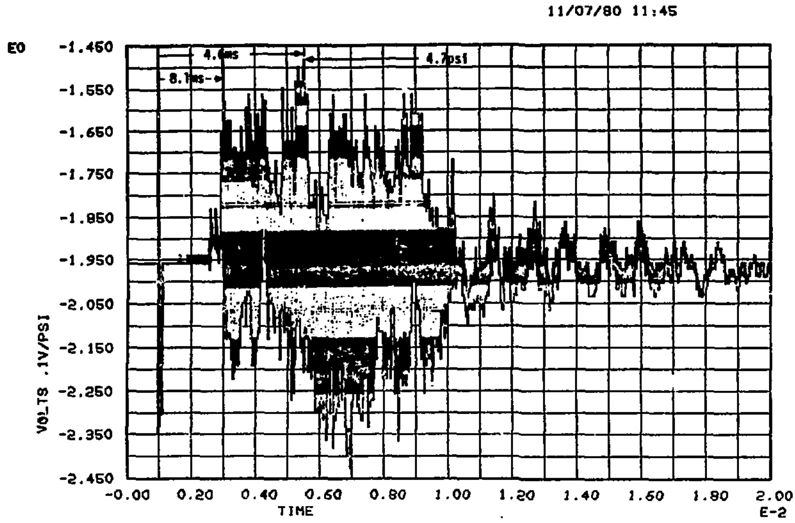
HEAF 303 LOCATION D



HEAF 304 11/07/80



HEAF 305



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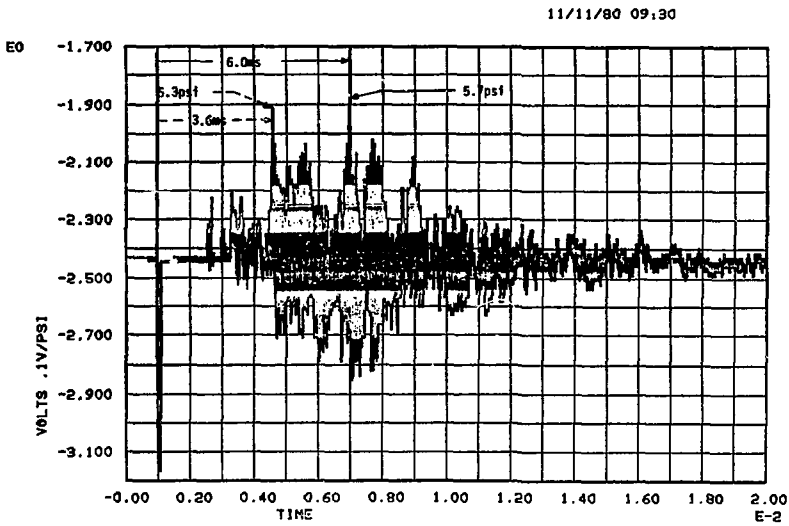

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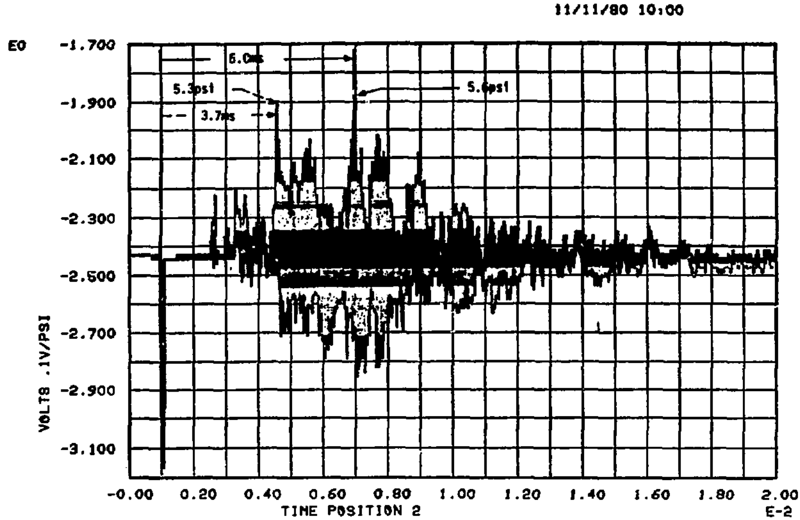

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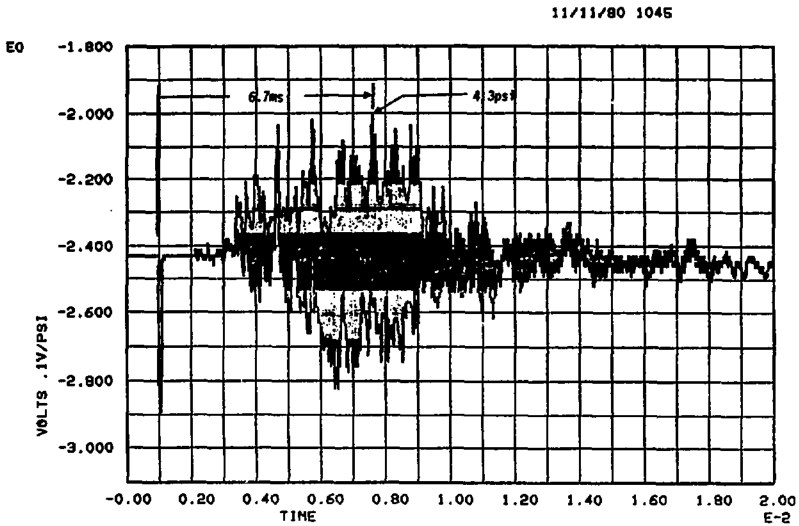

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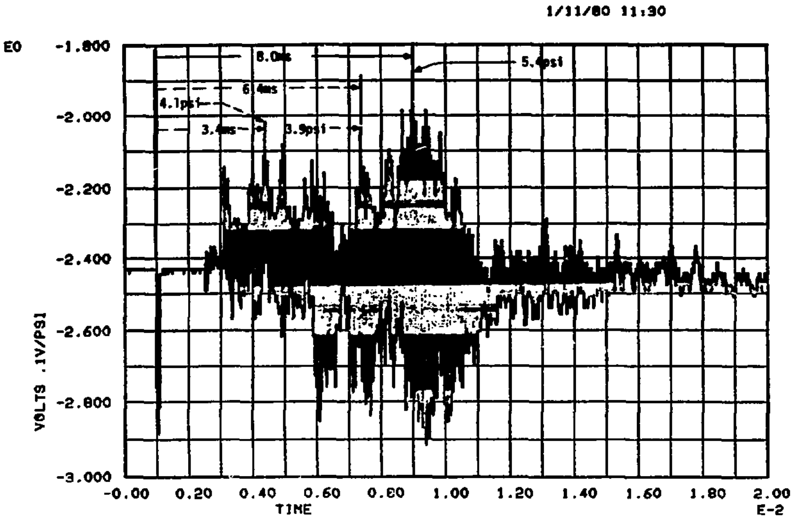

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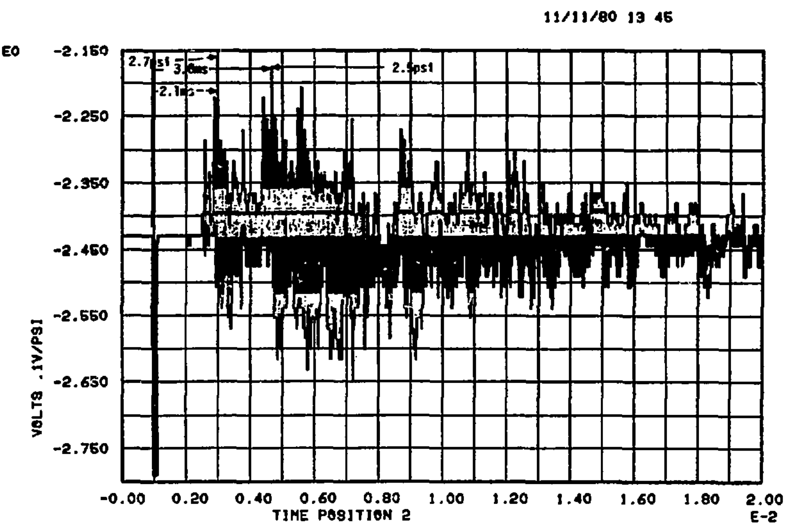

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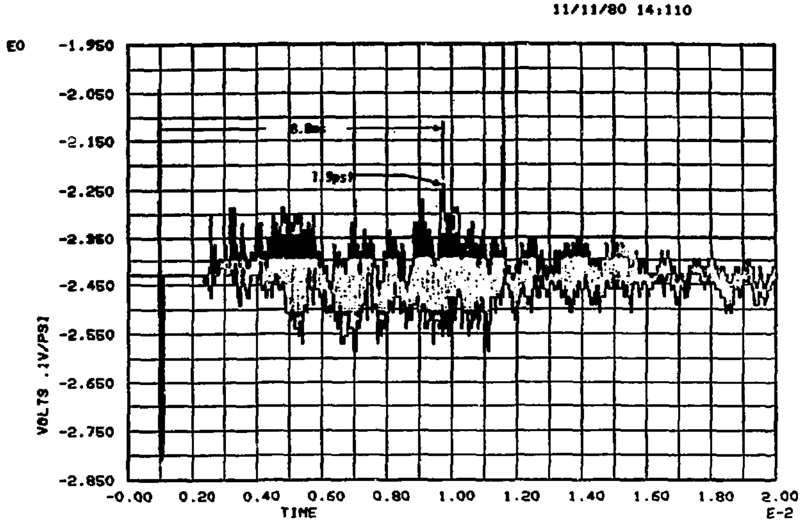

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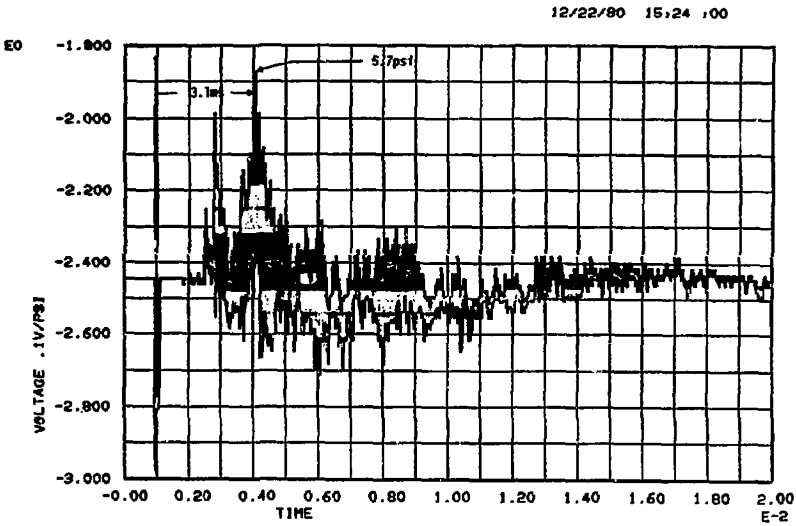
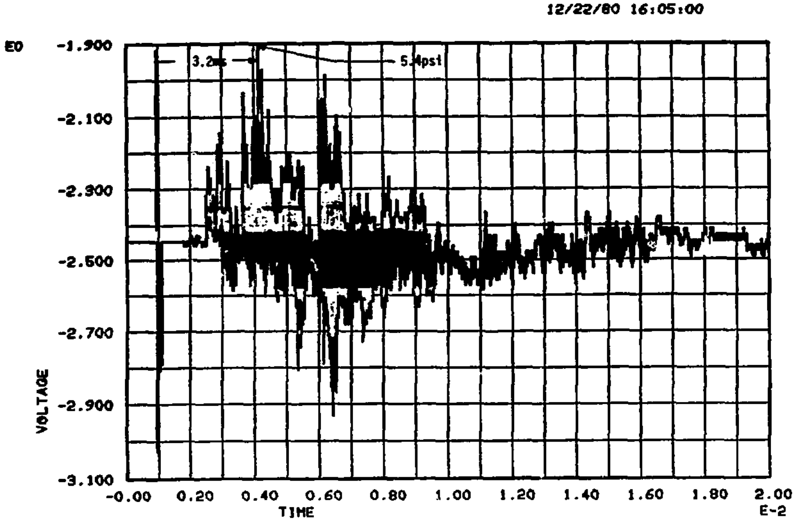
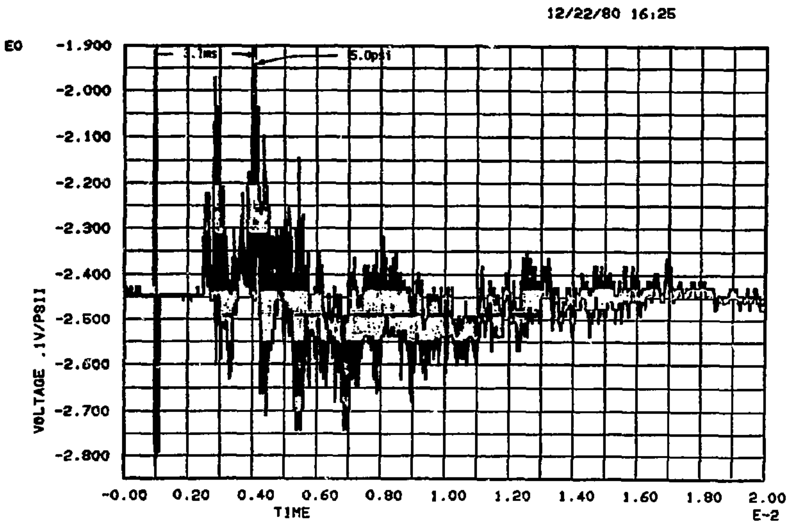


HEAF 316

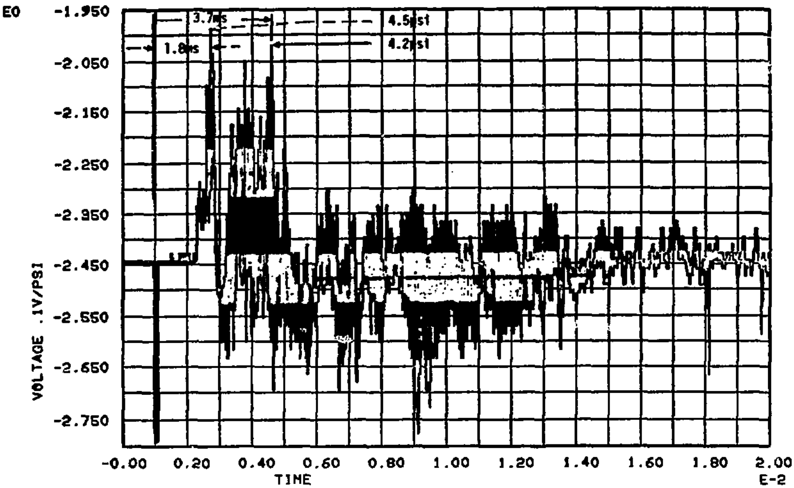


HEAF 317 POSITION



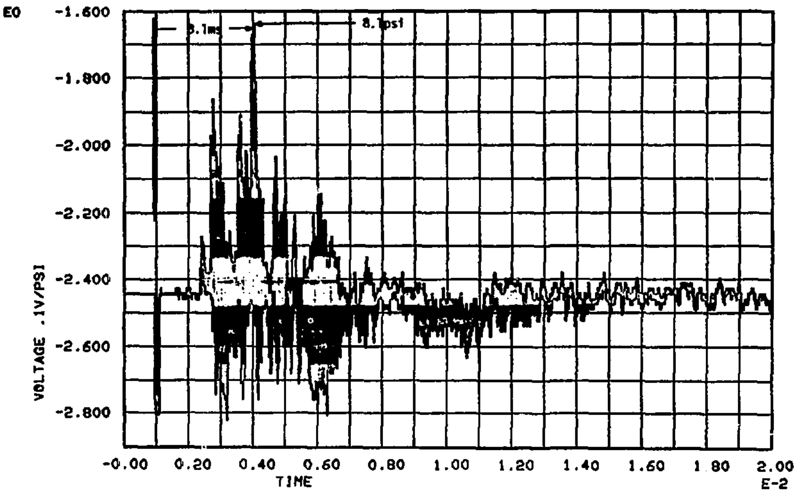
HEAF 318 POSITION

12/23/80 08:42:00



HEAF 319 POSITION 3

12/23/80 08:55:00



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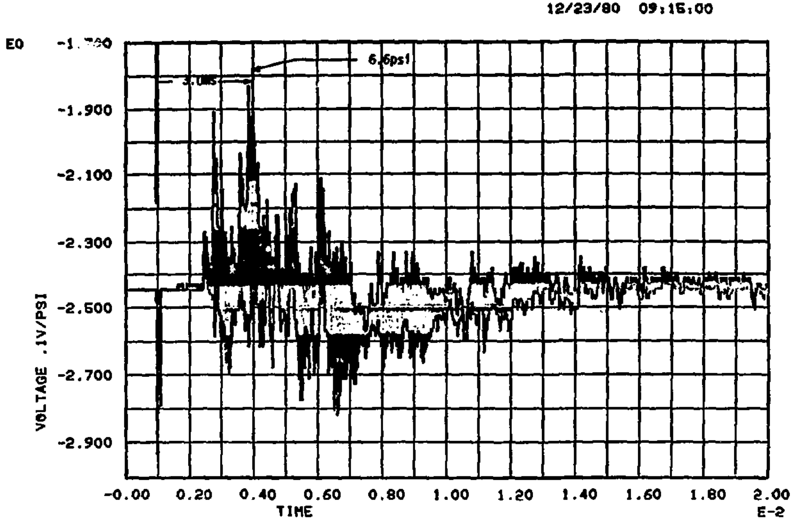

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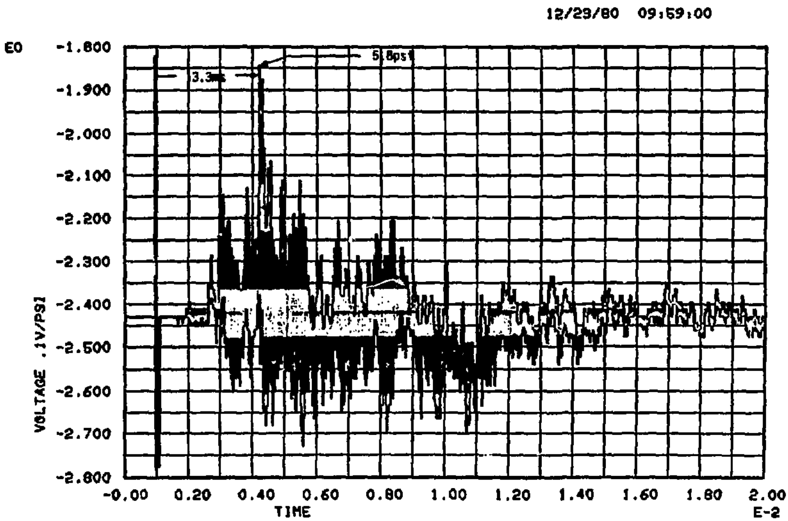

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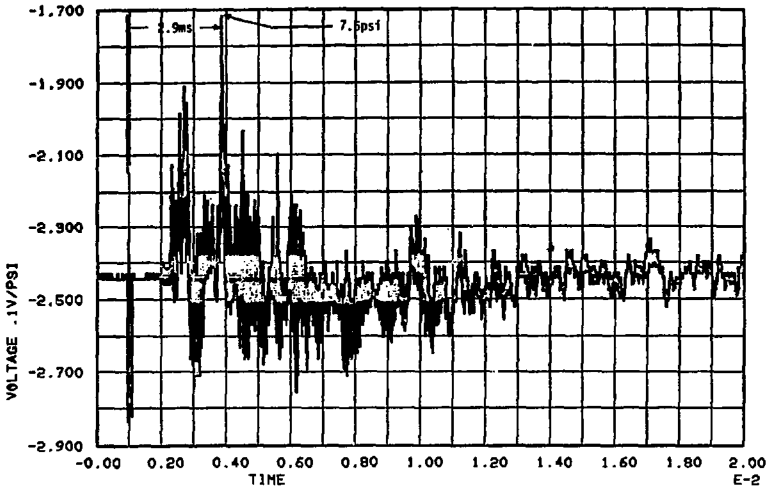

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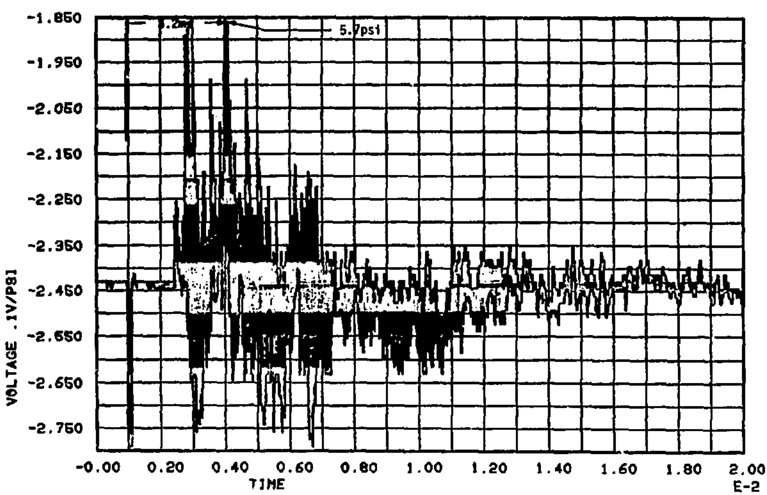

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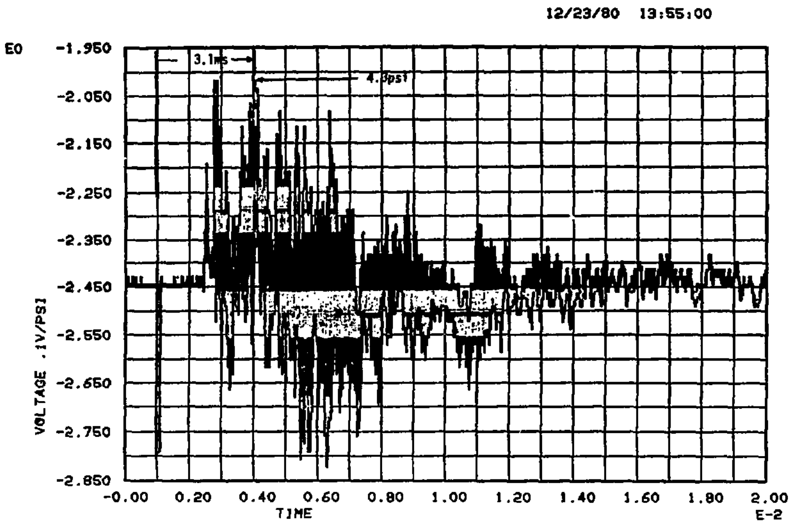

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