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Photo-Optical Studies of Nuclear Airblast
Operations BUFFALO (1956) and ANTLER (1957)

Volume 1 Part 1

The Measurement of Free Air Shock Overpressures - BUFFALO

Prepared by

R B Harvey

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Photo-Optical Studies of Nuclear Airblast Operations BUFFALO (1956) and ANTLER (1957)

Volume 1 Part 1

The Measurement of Free Air Shock Overpressures - BUFFALO

Prepared by

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PHOTO-OPTICAL STUDIES OF NUCLEAR AIRBLAST

OPERATIONS BUFFALO (1956) AND ANTLER (1957)

VOL I PART 1

THE MEASUREMENT OF FREE AIR SHOCK

OVERPRESSURES - BUFFALO

Prepared by

R.B. Harvey

ABSTRACT

Plots of radius versus time at ground level were compared for measurements of Time-of-Arrival taken along a gauge line and by direct photography of the shock front. Peak shock overpressures were computed from photographic data by the Rankine-Hugoniot relation.

Blast gauges recorded the blast wave contour in addition to the time-of-arrival. At shock overpressures greater than about 20 psi the sharp pressure front of the shock was not observed, and an irregular multi-peaked wave was recorded for two tower shots and an airburst. The pressure gauge records for a surface shot were clean, and close agreement was obtained between the two methods for Time-of-Arrival and for Peak Overpressure as a function of radius (distance from burst).

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Grateful acknowledgement is made to the U.K. for the opportunity to cooperate in making blast measurements on Operation BUFFALO, and for the data from frequency modulated tape records.

Without the support of the Photographic Section, DRES, it would not have been possible to carry out this project, involving as it did, the most tedious work in the printing of the many film frames requiring the most exacting control of exposure and processing.

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PHOTO-OPTICAL STUDIES OF NUCLEAR AIRBLAST

OPERATIONS BUFFALO (1956) AND ANTLER (1957)

Operations Buffalo and Antler were the code names of two series of nuclear trials carried out in 1956 and 1957 by the UK Atomic Weapons Research Establishment (AWRE) at Maralinga, Australia. Canada was invited to participate in the measurement of peak shock overpressures of the blast wave using a photo-optical technique, and the results were reported to the UK in the period 1956-9. A review of the photographic data has been prompted by substantial progress in the understanding of blast wave propagation, and by a more general review and compilation of UK and USA data into a set of "best values" for the parameters. The photographic data have been reviewed and compared with UK gauge measurements. The results are reported in a series of papers under the general heading "Photo-Optical Studies of Nuclear Airblast - Operations Buffalo (1956) and Antler (1957)".

The publications are grouped into four volumes. Volume I describes the calculations of the free air shock and of the shock near the surface of the ground for Operation Buffalo and for Operation Antler. The results are compared and combined in a scaled form, and some observations are made on the precursor.

Volume II provides data from a more detailed observation of the precursor and of a related phenomenon, the massive dust clouds raised by the shock as it moves outward from the explosion along the ground.

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Volume III provides tables of values of the time-of-arrival and of the peak overpressures as a function of radius out from the point-of-burst. These are presented in unscaled form, and scaled to 1 kt and to a standard atmosphere (14.7 psi) and temperature (15^{o}C). Data are similarly presented (scaled and unscaled), for the locus of the triple point and for the time-of-arrival of the precursor.

Volume IV provides data on the gamma values (density versus exposure) of the original films as well as some information on copying of the originals to provide duplicate negatives and prints. A second report provides the results of measurements of the frame-to-frame intervals of the films.

Volume V provides a listing of the motion picture films including available technical data. A classification was devised to list the films, and a variety of tracings, tabulations and graphs made during the original analyses (1956-9). This is included in the report.

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PHOTO-OPTICAL STUDIES OF NUCLEAR AIRBLAST

OPERATIONS BUFFALO (1956) AND ANTLER (1957)

Vol I Part 1 - "The Measurement of Free Air Shock Overpressures - Buffalo" by R.B. Harvey. August 1984.

Part 2 - "The Measurement of Free Air Shock Overpressures - Antler" by R.B. Harvey. September 1984.

Part 3 - "A Comparison of Free Air Pressure Measurements for Buffalo and Antler" by R.B. Harvey. November 1984.

Part 4 - "Some Comparisons of Blast Data from Gauges and Photo-Optical Records". A paper prepared for TTCP TLG-3. June 1984.

Vol II Part 1 - "Some Notes on the Precursor" by R.B. Harvey and H.B. Lutz. February 1985.

Part 2 - "The Development of the Dust Cloud from Nuclear Explosions" by H.B. Lutz and R.B. Harvey. June 1985.

Part 3 - "The Formation of Dust Clouds from Nuclear Explosions" by R.B. Harvey and H.B. Lutz. December 1985.

Part 4 - "Some Measurements of the Time-History of Dust Clouds" by R.B. Harvey and H.B. Lutz, (in preparation).

Vol III Part 1 - "A Compilation of Photo-Optical Airblast Data - Scaled and Unscaled" by R.B. Harvey and H.B. Lutz. May 1985.

Vol IV Part 1 - "Copying of Photo-Optical Films and Measurements of Film Density" by R.B. Harvey and M.L. Fach. May 1984.

Part 2 - "Measurements of Elapsed Time" by R.B. Harvey and H.B. Lutz. November 1984.

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Vol V Part 1 - "A listing of Films, Tracings, Graphs and Tabulations" by R.B. Harvey. December 1984.

Part 2 - "A Listing of Films, Tracings, Graphs and Tabulations, Section 5 - Tabulations" by R.B. Harvey. December 1984.

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DEFINITIONS

Free Air Shock - the incident shock wave expanding out from the point-of-burst in that region where it is not affected by reflection or formation of the Mach stem. This direction is usually along a radial line upward from burst.

Ground level shock - the shock moving out close to the surface of the ground from Ground Zero as centre. Close to GZ it may be the incident shock, which becomes the Mach stem after fusion of the incident and reflected shocks.

Ground Zero (GZ) - the point on the surface of the ground directly below the point-of-burst. All ground level shock distances (radii) are measured from Ground Zero unless otherwise stated.

Slant range - the distance from the point-of-burst of the explosion (above the ground) to any point on the ground surface. Whenever this measurement is used it is designated as "slant range".

Overpressures of the shock are calculated on a basis of a standard atmosphere (14.7 psi) at the trial site. A correction (usually 1-2%) is required to convert overpressures to psi on a basis of the ambient pressure at the time of the trial.

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PHOTO-OPTICAL STUDIES OF NUCLEAR AIRBLAST

OPERATIONS BUFFALO (1956) AND ANTLER (1957)

VOL I PART 1

THE MEASUREMENTS OF FREE-AIR SHOCK OVERPRESSURES-BUFFALO

PREPARED by

by

R.B. HARVEY

INTRODUCTION

Peak shock overpressures of an expanding blast wave have been measured by two independent methods. Mechanical recording gauges provide a value of the peak shock front overpressure as well as the pressure contour through the blast wave. Direct photography of the motion of the shock wave outward from an explosion permits calculations of the peak shock overpressure as the blast advances, but provides no information on the blast wave structure. It does, however, permit observation of the shock at inaccessible locations, and at very high overpressure.

The photographic (or photo-optical) measurements described here were made on the invitation of the U.K. at a series of nuclear tests in 1956 (Operation BUFFALO). All photo-optical data were reported in Reference 1, from which all the data used in this report were taken.

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Time-of-Arrival (T of A) and blast wave contour data were obtained from FMT gauge measurements carried out on the same trials by a U.K. team. The data (observations) were obtained from a report prepared by the U.K. (Reference 2).

METHOD

Data from Table 2 (Ref 1) "Shock Radius-Time at Ground Level" were used to fit an arbitrary function of the form

$$R = a_0 + a_1 t + a_2 \ln t + a_3 / t + a_4 / t^2$$

where R is the shock radius in feet,

t is the time of shock arrival in seconds,

a_1 is assigned the value of the velocity of sound (feet per second) in the air ahead of the shock,

a_0 to a_4 are fitted constants.

Standard curve fitting techniques with a least squares error criterion (Reference 4) were used throughout. Appendix A provides some detail of the curve fitting procedure, using the ground level data of radius versus time for Round 2. The peak overpressure is calculated from the velocity of the shock by the Rankine-Hugoniot relationships. The tabulations of Hirschfelder and Curtiss (Reference 3) were used to convert shock velocity to peak overpressure.

A comparison of the results from each of the two experimental methods was made for plots of radius versus time and for radius versus peak shock overpressure for four events of Operation BUFFALO.

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RESULTS

1. Time-of-Arrival and Peak Shock Overpressures

Primary data taken from Ref 1 and 2 and the results of calculations are presented in tabular form in Table I to IV for Rounds 1 to 4 respectively. Observations of shock radius versus time at Ground Level were taken from Ref 1 (Table 2). FMT observations of radius versus time were read from plotted curves (Ref 2).

Column 1 - Identification of the FMT gauge position

2 - the distance (radius) of each gauge position from Ground Zero (GZ), in feet

3 - The Time-of-Arrival of the shock front at the gauge position, in milliseconds

4 - the peak shock overpressure read from the FMT gauge record, in psi

5 - the peak overpressure at gauge sites where the wave form was irregular, estimated by a reconstruction of the wave form shape for the particular pressure level

6 - Time-of-Arrival of the shock front estimated from photo-optical (PO) measurements, in milliseconds

7 - peak shock overpressures calculated from PO data, in psi

8 - difference in Time-of-Arrival (FMT-PO), in milliseconds

9 - difference in Peak Shock Overpressure (FMT-PO), in psi.

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TABLE I

BUFFALO - ROUND 1
22°C 1130 fps 18%RH

AG SITE (1)	FMT DATA R (feet) (2)	FMT DATA t (msecs) (3)	FMT DATA PEAK PRESSURE FMT (psi) (4)	FMT DATA PEAK PRESSURE EXTRAP (psi) (5)	PO DATA Ground Level t (msecs) (6)	PO DATA Ground Level P (psi) (7)	DIFFERENCE (FMT - PO) t (msecs) (8)	DIFFERENCE (FMT - PO) P (psi) (9)
104	1170	245	36.0P*	57.0	257.7	52.5	-13	-16.5
106	1346	330	27.1P	-	340.0	38.4	-10	-11.3
108	1520	425	22.7P	35.3	430.0	29.3	- 5	- 6.6
109	1730	560	20.4P	23.2	549.0	22.1	11	- 1.7
111	1960	700	15.0P	16.5	689.0	17.1	11	- 2.0
112	2140	820	13.5		804.0	14.3	16	- 0.8
114	2540	1095	9.76		1076.0	10.4	19	- 0.6
115	2920	1390	7.32		1348.0	8.1	42	- 0.8
117	3330	1700	5.64					
118	3780	2050	4.65					
121	4300	2475	3.38					
123	4860	2940	3.07					
124	5550	3470	2.61					

*P indicates that the FMT record consisted of an irregular, multi-peaked wave form.

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TABLE II

BUFFALO - ROUND 2
22.6°C 1131 fps 35%RH

AG SITE (1)	FMT DATA R (feet) (2)	FMT DATA t (msecs) (3)	FMT DATA PEAK PRESSURE FMT (psi) (4)	FMT DATA PEAK PRESSURE EXTRAP (psi) (5)	PO DATA Ground Level t (msecs) (6)	PO DATA Ground Level P (psi) (7)	DIFFERENCE (FMT - PO) t (msecs) (8)	DIFFERENCE (FMT - PO) P (psi) (9)
209	530	140	37.0		140	37.5	0	-0.5
211	610	190	26.0		183	26.2	7	-0.2
212	690	240	19.3		230	19.5	10	-0.2
214	780	290	15.1		286	14.8	4	0.3
215	870	350	12.3		346	11.7	4	0.6
217	1020	460	9.30		452	8.6	8	0.7
					- - - - - - - - - - - - - - - - - -			*
219	1160	560	7.03		556	6.8	4	0.2
220	1330	690	5.88		685	5.4	5	0.5
222	1510	840	4.80		826	4.4	14	0.4
223	1720	1000	3.96		993	3.7	7	0.26
225	1960	1200	3.26		1188	3.0	12	0.26
226	2210	1400	2.67		1393	2.6	7	0.07
228	2520	1650	2.35		1651	2.2	-1	0.15

* Data below the dashed line were obtained by extrapolation of the fitted curve.

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TABLE III

BUFFALO - ROUND 3
24.1°C 1134 fps 35%RH

AG SITE (1)	FMT DATA R (feet) (2)	FMT DATA t (msecs) (3)	FMT DATA PEAK PRESSURE FMT (psi) (4)	FMT DATA PEAK PRESSURE EXTRAP (psi) (5)	PO DATA Ground Level t (msecs) (6)	PO DATA Ground Level P (psi) (7)	DIFFERENCE (FMT - PO) t (msecs) (8)	DIFFERENCE (FMT - PO) P (psi) (9)
403/2	420P	158	-	-	170	134	-12	-
405	580P	172	15.9P	-	223	82	-51	-66
405/1	740P	212	24.7P		288	54	-76	-29
407	990P	295	16.4P		409	31	-114	-15
408	1320P	507	9.87P		599	18	-92	-8
411	1750	850	8.90	9.0	881	11	-31	-2
414	2290	1250	5.84	6.0	1268	7.2	-18	-1.4
416	2850	1680	4.23	4.2	(1694)	(5.2)	(-14)	(-1)
419	3440	2170	3.08	3.1				
422	3990	2620	2.44	2.4				

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TABLE IV

BUFFALO - ROUND 4
13.1°C 1112 fps 84%RH

AG SITE (1)	FMT DATA R (feet) (2)	t (msecs) (3)	PEAK PRESSURE FMT (psi) (4)	EXTRAP (psi) (5)	PO DATA Ground Level t (msecs) (6)	P (psi) (7)	DIFFERENCE (FMT - PO) t (msecs) (8)	P (psi) (9)
304								
306	1140	225	31.9P	50.0	253	53.1	-28	-21.1
308	1290	320	28.1P	37.5	327	39.1	-7	-11
310	1480	422	24.4P	32.0	430	27.9	-8	-3.5
311	1680	550	17.8P	18.0	546	20.4	4	-2.6
312	1920	707	14.2		689	15.4	18	-1.2
313	2180	890	11.6		869	11.8	21	-0.2
314	2500	1110	8.9		1102	9.1	8	-0.2
315	2840	1360	7.3		1348	7.2	12	0.1
316	3230	1660	5.6		(1649)	(5.8)	(11)	(-0.2)
318	3680	2020	4.47					
319	4160	2400	4.00					
	4740	2870	1.77					

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(a) ROUND 2 - SURFACE BURST - TABLE II

Data of Time-of-Arrival recorded by FMT gauges (which is defined as that time at which a pressure rise occurs above baseline) agree well with the values measured by photography of the shock. Good agreement is obtained between the two methods for the peak shock overpressures at the FMT gauge sites. Note that photographic observations of the shock were made only to a distance of 1,000 feet from burst. Tabulated values for PO radii greater than 1,000 feet were extrapolated from the fitted curve, and the agreement of the extrapolated part of the (photo-optical) curve with the FMT measurements is excellent. Only one gauge record (Fig 1, for AG site 209) showed some disturbance in the early part of the pressure record. An attempt to "reconstruct" the record yielded a peak pressure value of 40 psi, slightly higher than the FMT or PO values.

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(b) ROUND 1 - TOWER BURST - TABLE I

The time-of-arrival and the blast wave contour were recorded by the FMT gauges to a distance of 5550 feet. Photo-optical (PO) observations were available from the Ground Zero (GZ) to 3,000 feet (Ref 1, Table 2). The position of the shock is obscured close to ground level in the photographic data due to dust, heat shimmer and vegetation so that the "ground level shock" is an extrapolation to ground level of the air shock (usually the Mach stem).

The gauges record the arrival of a pressure wave well in advance of the PO measurement for locations close to GZ, but at lower pressure levels (less than 20 psi) the PO wave appears to have caught up with, or outrun the gauge wave.

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(c) ROUND 4 - TOWER BURST - TABLE IV

Data for this round are presented in Table IV and FMT gauge tracings for three close-in positions are copied in Fig 2.

The comparison of FMT and PO records is similar to that of Round 1.

(i) The times-of-arrival are smaller for FMT gauges at the close-in gauges, but the situation is reversed at distances greater than 1700-1800 feet.

(ii) Peak pressure values are substantially smaller than those for the PO method at radii less than some 1700 feet, but agreement is reasonably good at larger distances.

(iii) Irregular FMT wave forms are noted for the three closest sites (Fig 2) marked by "P" but extrapolation of the FMT pressure records to Time Zero (TZ) yields values in line with PO estimates.

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(d) ROUND 3 - AIRBURST - TABLE III

Data for this Round are presented in Table III and three FMT gauge tracings from close-in positions are copied in Fig. 3. Columns 8 and 9 of Table III give the discrepancies between FMT observations and estimates from PO observations:

(i) Initial pressure increases recorded by the FMT gauges show an earlier Time-of-Arrival than photo optical measurements. At 420 feet the difference in Time-of-Arrival is 12 msecs, increasing to 114 msecs at 990 feet and decreasing to 14 msecs at 2860 feet.

(ii) Peak pressures read on FMT records are smaller than those calculated from PO observations at the FMT sites closer to GZ (AG 405 to 408), and the wave forms are distorted. Agreement is much better at distances greater than 1500-1600 feet, a region where the FMT recorded waveform is similar to the Friedlander shape.

(iii) Attempts to extrapolate the later part of the pressure tracing to time zero (TZ) produced no worthwhile results.

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2. PEAK SHOCK OVERPRESSURES - FMT RECORDS

Figures 1A, 1, 3 and 2 show the FMT pressure gauge records (UK) for Rounds 1, 2, 3 and 4 (corresponding to Tables I, II, III and IV respectively). The wave shape of the FMT records at higher pressure levels exhibits "irregular multi-peaked wave shapes considered to be in a precursor region" (Ref 2) and the UK has marked records of this kind with a letter "P".

An attempt was made to estimate a peak overpressure, assuming that the pressure wave was a Friedlander shape originally and it had not been degraded to the irregular shape actually observed. One method was the projection of the latter part (tail) of the pressure wave to the point (time) of the initial pressure increase. Another method used the Brode wave shape calculations (Ref 6) to reconstruct the wave contour. The latter method uses the pressure at the mid-point (t 1/2) of the positive duration (t_+) to estimate the pressure intercept with the pressure axis at time zero. The results are given in Table V.

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TABLE V
COMPARISON OF ESTIMATES OF PEAK SHOCK PRESSURES

SITE	R (feet)	PEAK SHOCK OVERPRESSURE (psi)			
		FMT Gauge	EXTRA-POLATED	Matching Shape (Brode)	Photo-Optical
ROUND 1					
AG 104	1170	36.0	57.0	51.0	52.5
AG 106	1346	27.1	-	-	38.4
AG 108	1520	22.7	29.0	29.4	29.3
AG 109	1730	20.4	23.2	20.5	22.1
AG 111	1960	15.2	16.5	15.0	17.1
ROUND 3					
AG 405/1	740	24.7	-	96	54
AG 407	990	16.4	-	60	31
AG 408	1320	9.87	-	27	18
ROUND 4					
AG 304	1140	31.9	51	57	53.1
AG 306	1290	28.1	38.5	31	39.1
AG 308	1480	24.4	33	33	27.9

A tabular listing of the differences in peak shock overpressures between FMT gauge readings and photo-optical measurements for Rounds 1, 3 and 4 can be made as a function of peak overpressure from photo-optical measurements. The listing of values for 23 sites is shown in Table VI and plotted in Fig 4. The tower bursts (Rounds 1 and 4) plot fairly well together and, while the airburst values of p (difference between PO and FMT peak overpressure) follow the same trend, the line lies well above that for the tower bursts.

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TABLE VI
DIFFERENCE IN PEAK OVERPRESSURE [P(PO) - P(FMT)] VERSUS PEAK OVERPRESSURE (PO)

ROUND	PEAK OVERPRESSURE P (psi)		P (psi)
	P O	F M T	
3	54	24.7 P*	29.3
4	53.1	31.9 P	21.2
1	52.5	36.0 P	16.5
4	39.1	28.1 P	11.0
1	38.5	27.1 P	11.3
3	31.0	16.4 P	14.6
1	29.3	22.7 P	6.6
4	27.9	24.4 P	3.5
1	22.1	20.4 P	1.7
4	20.4	17.8 P	2.6
3	18.0	10.0 P	8.0
1	17.1	15.0 P	2.1
4	15.4	14.2	1.2
1	14.3	13.5	0.8
4	11.8	11.6	0.2
3	11.1	8.9	2.2
1	10.4	9.8	0.6
4	9.1	8.9	0.2
1	8.1	7.32	0.8
4	7.2	7.3	-0.1
3	7.2	5.84	1.4
1	6.5	5.64	0.9
3	5.2	4.23	1.0

*P "Irregular multi-peaked wave shapes considered to be in a precursor region."

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DISCUSSION

Round 2 provides data to test the consistency of the two methods of measurement (FMT gauges and PO photography) for the Time-of-Arrival of the shock at the FMT gauges and for the peak shock overpressure. The greatest difference in Time-of-Arrival (10 msecs) occurred at AG 212. The differences in peak overpressure are less than one psi, including values computed well beyond the range of the photo-optical measurements (270 to 1000 feet). Little or no evidence of a precursor wave shape was observed on the FMT gauge records. Several camera frames taken 60 to 100 msecs after Time Zero show the shock meeting the surface at right angles, with no suggestion of precursor formation.

In all comparisons, actual FMT gauge observations were used. Values for the PO data were taken from a least squares fit of the observations reported in Ref. 1, Table 2 "Shock Radius - Time at Ground Level".

TIME-OF-ARRIVAL

Photo-optical and FMT gauge estimates of the Time-of-Arrival at the FMT gauge positions agreed well for a surface burst, but this is not the case for the tower shots or the airburst. An irregular multi-peaked wave (attributed to a precursor) was recorded at the FMT sites

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before the arrival of the main shock as calculated from the PO records. When the overpressure had dropped to some 20 psi (tower) or 15 psi (airburst) the irregular wave appeared to dissipate, the gauge records again exhibited the vertical pressure front, and the PO and FMT arrival times came more into agreement. Photo-optical estimates of arrival time at gauge sites beyond the precursor region are smaller than the FMT extimates, i.e. the "photo-optical shock" arrives before the "FMT shock". No explanation is offered for this, but possibilities might include a curving-in of the shock close to the ground or an effect of down hill travel.

The lead of the precursor in Round 3 is 12 msecs at the first gauge site (AG 403/2) at 420 feet from GZ. This increases to a lead of 114 msecs at 990 feet and then drops off to 18 msecs at 2290 feet. Differences from time-of-arrival (Δt), and for peak overpressure (Δp), are given in Table VII.

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TABLE VII
t (TIME-OF-ARRIVAL) AND P (PEAK PRESSURE) AS A FUNCTION OF PHOTO-OPTICAL PEAK PRESSURE

ROUND 1			ROUND 4			ROUND 3		
Peak Press PO (psi)	Δt (PO-FMT) (msecs)	ΔP (PO-FMT) (psi)	Peak Press PO (psi)	Δt (PO-FMT) (msecs)	ΔP (PO-FMT) (psi)	Peak Press PO (psi)	Δt (PO-FMT) (msecs)	ΔP (PO-FMT) (psi)
52.5 38.4	13 10	16.5 P 11.3 P	53.1 39.1	28 7	21.2 P 11.0 P	54.0	76	29.0 P
29.3 22.1	5 -11	6.6 P 1.7 P	27.9 20.4	8 -4	3.5 P 1.6 P	31.0	114	14.6 P
17.1 14.3	-11 -16	2.0 P 0.8	15.4 11.8	-18 -21	1.2 0.2	18.0	92	8.0 P
10.4 8.1	-19 -42	0.6 0.8	9.1 7.2	-8 -12	0.2 0.1	11.1 7.2	31 18	2.0 1.4
(6.6)	-47	(1.0)	(5.8)	(-11)	(0.2)	(5.2)	(14)	(1.0)

Column 1 - The peak shock overpressure at FMT gauge sites as calculated from PO observations.

Column 2 - The difference in time-of-arrival at the FMT gauge sites between the PO shock front and the pressure wave recorded on the gauge.

Column 3 - The difference in estimates of peak overpressure at the FMT gauge sites. The letter "P" in Column 3 indicates irregular wave forms.

Figures in brackets (bottom line) are extrapolated beyond direct PO observations.

PEAK SHOCK OVERPRESSURE

Estimations of peak shock overpressures by FMT gauges and PO observations agree well for all gauge locations of Round 2. Rounds 1, 4 and 3 show considerable divergence at the highest pressure levels (gauge locations closest to GZ), but the differences in pressure decrease with distance, and they become small at gauge positions where clean wave forms are recorded. Brode (Ref 6) has calculated the pressure vs time contour for a number of peak overpressures of the blast wave of a point source explosion. Assuming the PO value for the peak overpressure and the FMT gauge value for the positive duration, the appropriate theoretical wave shape can be matched to the FMT record. The results are shown for the fitted Brode curves in Figure 3 for Round 3. The gauge records for Rounds 1 and 4 are not greatly different from the Brode shape after a time equal to one half the positive duration, and an estimation of the peak overpressure can be made by using the latter part of the pressure to extrapolate to an initial peak pressure. This is shown in Figures 1A and 2. A discussion of extrapolation to Time Zero is given by Ethridge (Ref 7). Round 3 shows substantial departures from the Brode shape, and attempts to extrapolate the gauge records to Time Zero produced no useful results.

PRECURSOR

Precursor is the name given to a pressure wave travelling ahead of the main shock. It is characterized by an irregular multi-peaked wave shape, and it results in extreme sand blasting of any objects in its path. FMT gauge records in the precursor region have been labelled "P". The precursor of Round 3 is very strongly developed and some additional data are provided in Table VIII.

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The data suggest that:-

- the precursor forms only for bursts above ground level. There is no visible precursor effect in Round 2 and the gauge records are clean. Round 3 exhibits strong precursor effects, visible by direct shock photography from 350 to about 900 feet (Ref 1, Fig. 6). The precursors of Rounds 1 and 4 (tower) are not visible in photographs, although a "skirt" in early frames appears to move ahead of the expanding fireball.

- Extreme shock overpressures do not appear to be essential to precursor formation. The overpressure of the airburst is about 65-70 psi when it intersects the ground and a strong precursor develops.

- The precursors of Rounds 1 and 4 appear to be already fully developed, and may be declining by the time they reach the first gauge location (roughly 50 psi by PO observation) at which a record was obtained. The precursor of the airburst is initiated within 400 feet of GZ, reaches a maximum lead over the main shock at about 1000 feet, and then weakens.

- The precursors do not exhibit the vertical wave front of a classical shock, and the pressure contour does not decay smoothly with time (Figs 1A, 2 and 3).

- The precursor effects appear to dissipate at some 15 to 20 psi shock pressure, at which point the FMT records assume the classical Friedlander shape. FMT gauge records then come into better agreement with PO observations for time-of-arrival and pressure.

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Questions of the development of the precursor and its dissipation cannot be answered by the data available. A look at the wave contours with a planimeter indicates that the areas for the irregular wave shape and for the constructed Brode shape are roughly equal. Some combination of shock and thermal radiation appears to be necessary since the surface shot exhibits no precursor. The airburst produces the strongest precursor, developed from an incident blast wave of 67 psi when it touches the ground. It is recorded to 1320 feet (AG 408).

CONCLUSIONS

The data permit only some generalizations:

(a) Two independent methods for determining time-of-arrival and peak overpressure for an expanding shock agree well for a surface burst (Round 2).

(b) Two tower shots (Rounds 1 and 4) and an airburst (Round 3) exhibit irregular wave forms attributed to a precursor. The effects appear to dissipate when the overpressure has dropped to 15 to 20 psi and the FMT gauge records then follow a Friedlander shape.

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Wave forms of the surface burst (Round 2) appear to be conventional. Tower bursts (Rounds 1 and 4) depart from a computed Brode shape in the early part of the positive duration. Wave shapes for an airburst depart substantially from the shape computed by Brode. The precursor of the airburst was visible photographically.

SOME POSSIBLE EXTENSIONS TO THE WORK ARE:-

(a) Examination and comparison of FMT and photo-optical records of Operation ANTLER, similar to this work on BUFFALO.

(b) Comparison and correlation of rounds for BUFFALO and ANTLER.

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1. "A Photo-Optical Method for the Measurement of Free Air Overpressures" (U), by Harvey, R.B., J.M. Mayhood, and E.A. Jackman. AWRE Report T67/57 Nov 1957 UNCLASSIFIED.

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"The security classification of AWRE Report T67/57 is regraded to UNCLASSIFIED by authority of Reference SCO 505 dated 15 Jan 1985 AWRE Foulness."

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APPENDIX "A"

CURVE FITTING TO TIME-OF-ARRIVAL DATA

Observations of radius versus time were used to fit a function of the form:-

$$R(t) = a_0 + a_1 t + a_2 \ln t + \frac{a_3}{t} + \frac{a_4}{t^2}$$

where R(t) is the radius in feet at time t in seconds

a_0, a_2, a_3, a_4 are fitted constants

a_1 is the velocity of sound in the ambient air.

The best estimates of a_0 through a_4 were obtained by standard curve fitting procedures (Ref 4). Details of the procedures for the UK FMT (Frequency Modulated Tape) data are given in Table A-I, and details are given in Table A-II for the Canadian PO (photo-optical) data.

Columns 1 and 2 of Table A-I give the primary data of radius and time (Time-of-Arrival or T of A) for the FMT stations for the case of a ground level burst. Column 3 gives the calculated values of radius for the fitted equation and column 4 gives the deviations of the observed values of R (ft) from those calculated. Column 5 gives the

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values of the squared deviations. Column 6 gives the values of standard deviation (feet) for each value of radius R (feet) calculated for a Time t (secs).

The computed best estimates for the coefficients (a_0 to a_4) are given in the subsidiary table, together with the standard deviation of each.

Similar computations were carried out for Photo-Optical (PO) data, obtained from Table 2 (Shock Radius-Time at Ground Level) of Ref 1 for the same case as for Table A-I. These are tabulated in Table A-II. A value of 1131 ft/sec was assigned to a_1 (velocity of sound at 22.6^{0}C).

An added part of the table is the extrapolation to the distances (R) of FMT gauge positions beyond the region where photo-optical data were available (i.e. 1020 feet to 2520 feet).

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APPENDIX "A"

TABLE A-I

"BUFFALO" - ROUND 2 - CURVE FITTED TO FMT TIME-OF-ARRIVAL DATA

22.6°C, 1131 fps

FMT DATA R (feet)	t (secs)	R calc (feet)	ΔR (feet)	ΔR^2 (feet)	$\sigma R(t)$ (feet)
530	0.140	527.69	-2.31	5.34	6.14
610	0.190	614.32	4.32	18.66	3.88
690	0.240	696.47	6.47	41.86	3.60
780	0.290	774.54	-5.46	29.81	3.08
870	0.350	864.10	-5.90	34.81	2.74
1020	0.460	1020.23	0.23	0.05	2.82
1160	0.560	1156.12	-3.88	15.05	2.95
1330	0.690	1327.22	-2.78	7.73	2.90
1510	0.840	1519.41	9.41	88.55	2.67
1720	1.000	1720.24	0.24	0.06	2.48
1960	1.200	1967.10	7.10	50.46	2.67
2210	1.400	2210.68	0.68	0.46	3.33
2520	1.650	2511.88	-8.12	65.93	4.49
			$\Sigma = 0$	$\Sigma = 358.7292$	

Coefficient	Best Estimate	Standard Deviation
a_0	594.58	15.1
a_1	1131.0	-
a_2	108.9	18.2
a_3	-5.96	15.1
a_4	0.617	1.21

$\sigma R(t)$ is the standard deviation of a value of the radius (R) feet calculated for any time (t) secs.

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APPENDIX "A"

TABLE A-II

"BUFFALO" - ROUND 2 - CURVE FITTED TO PHOTO OPTICAL TIME-OF-ARRIVAL DATA

22.6°C 1131 fps

PO DATA

R (feet)	t (secs)	R calc (feet)	ΔR (feet)	ΔR^2 (feet)	σR(t) (feet)
(270)	0.044	269.59	-0.41	+0.17	1.56
300	0.052	301.00	1.00	1.00	1.18
400	0.083	398.11	-1.89	3.57	1.29
500	0.127	502.17	2.17	4.71	0.967
600	0.177	599.52	-0.48	0.23	0.988
700	0.236	700.64	0.64	0.41	0.894
800	0.298	798.09	-1.91	3.64	0.789
900	0.367	900.18	0.18	0.03	0.925
1000	0.438	1001.69	0.69	0.48	1.31

Σ 14.2457

EXTRAPOLATION TO FMT POSITIONS

1020	0.46	1031	-11	1.46
1160	0.56	1166	- 6	2.14
1330	0.69	1337	- 7	3.03
1510	0.84	1528	-18	3.97
1720	1.00	1729	- 9	4.88
1960	1.20	1975	-15	5.9
2210	1.40	2218	- 8	6.8
2520	1.65	2519	+ 1	7.8

Coefficient	Best Estimate	Standard Deviation
a_0	600.424	3.38
a_1	1131.0	-
a_2	107.95	7.185
a_3	-2.7044	1.838
a_4	0.03496	0.045

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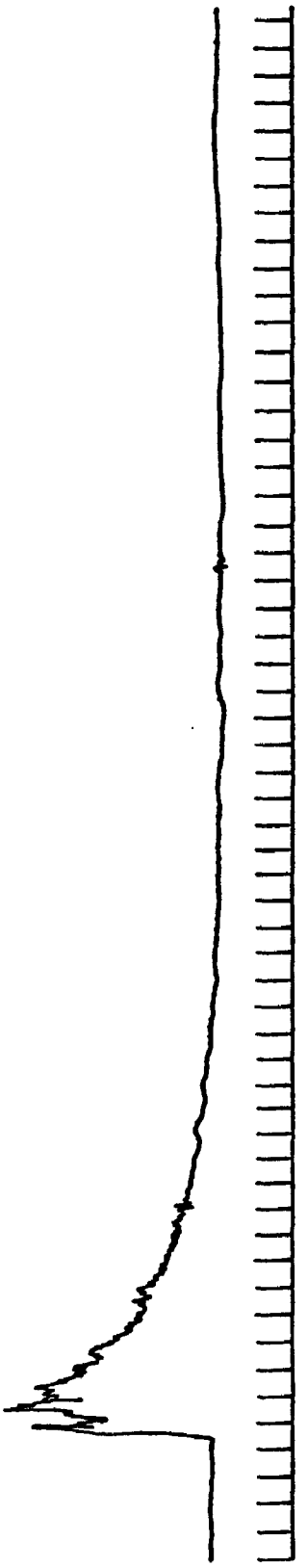

Figure 1 FMT RECORD OF BLAST WAVE PRESSURE - BUFFALO 2

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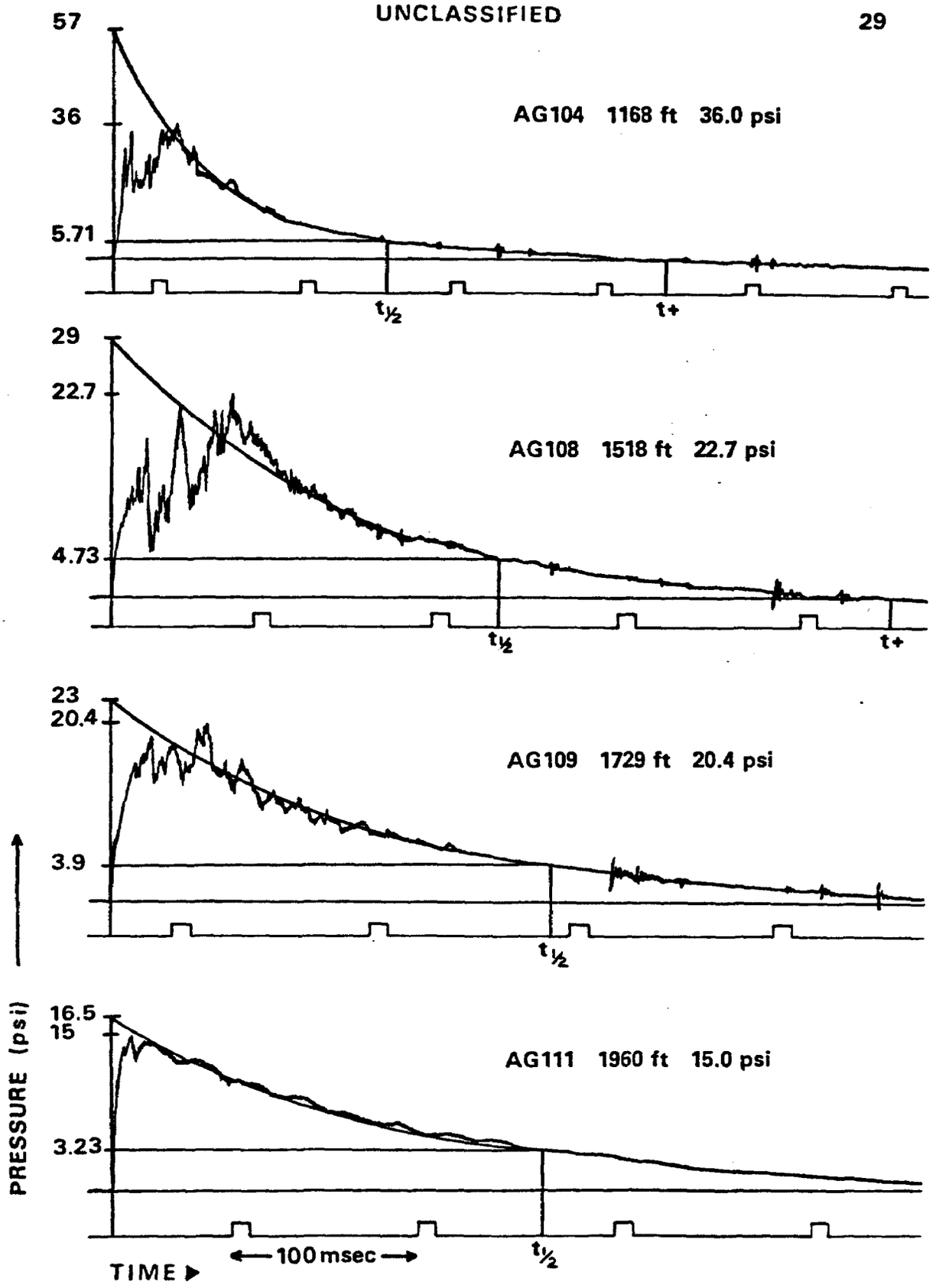

Figure 1A FMT PRESSURE RECORDS - BUFFALO 1
(WITH EXTRAPOLATION TO ZERO TIME)

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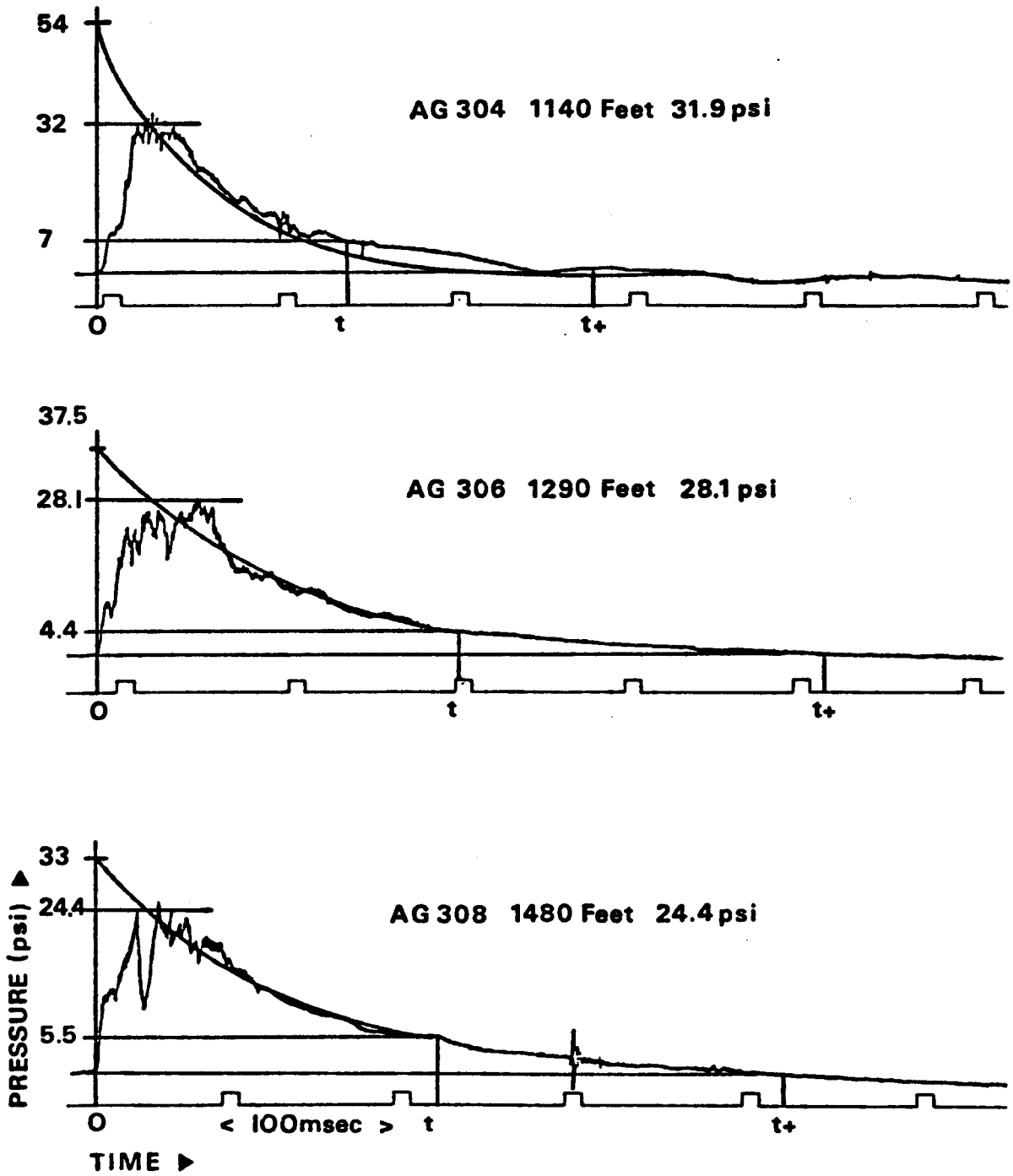

Figure 2 FMT PRESSURE RECORDS - BUFFALO 4
(WITH EXTRAPOLATION TO ZERO TIME)

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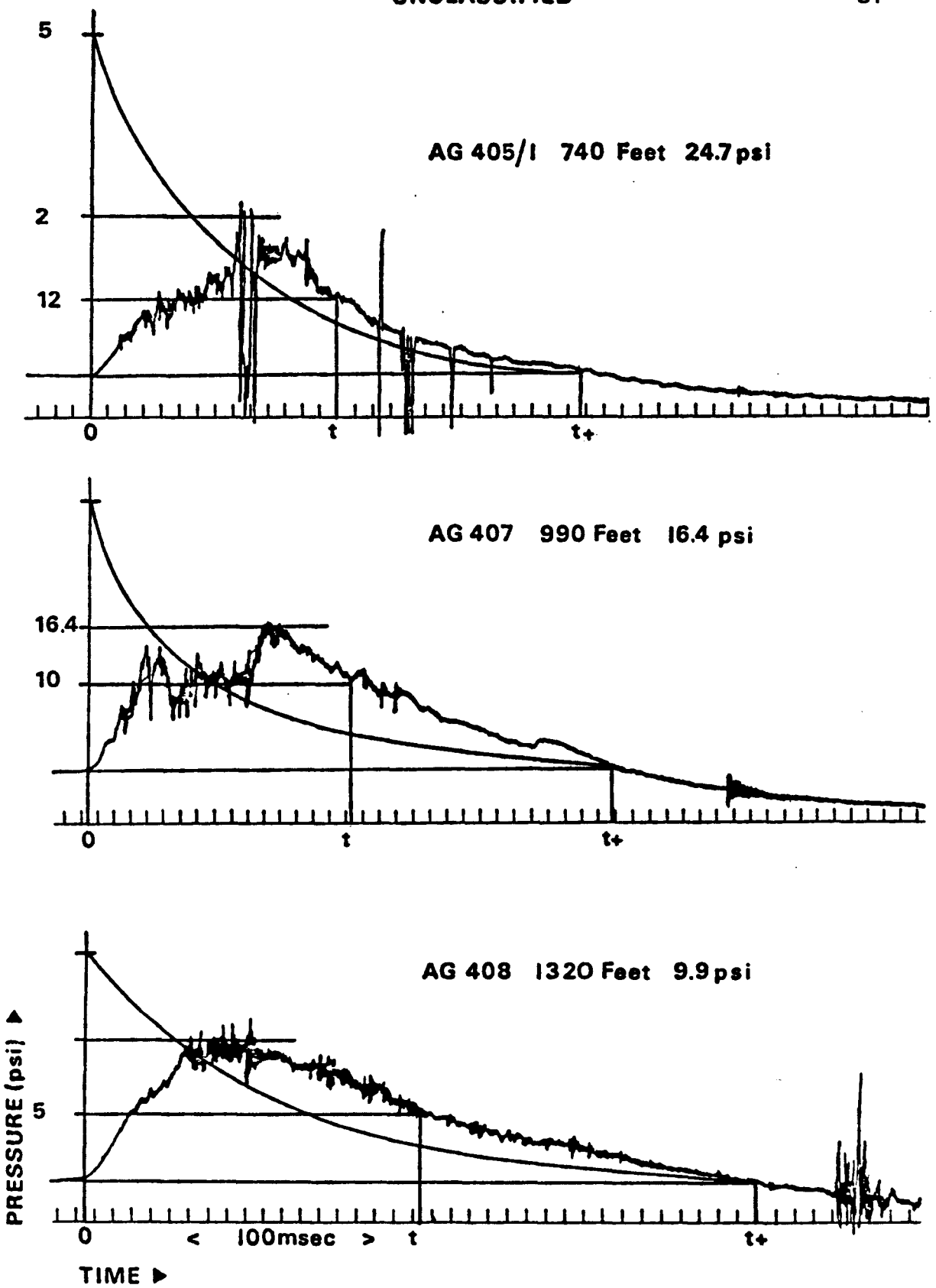

Figure 3 FMT PRESSURE RECORDS - BUFFALO 3
(WITH EXTRAPOLATION TO ZERO TIME)

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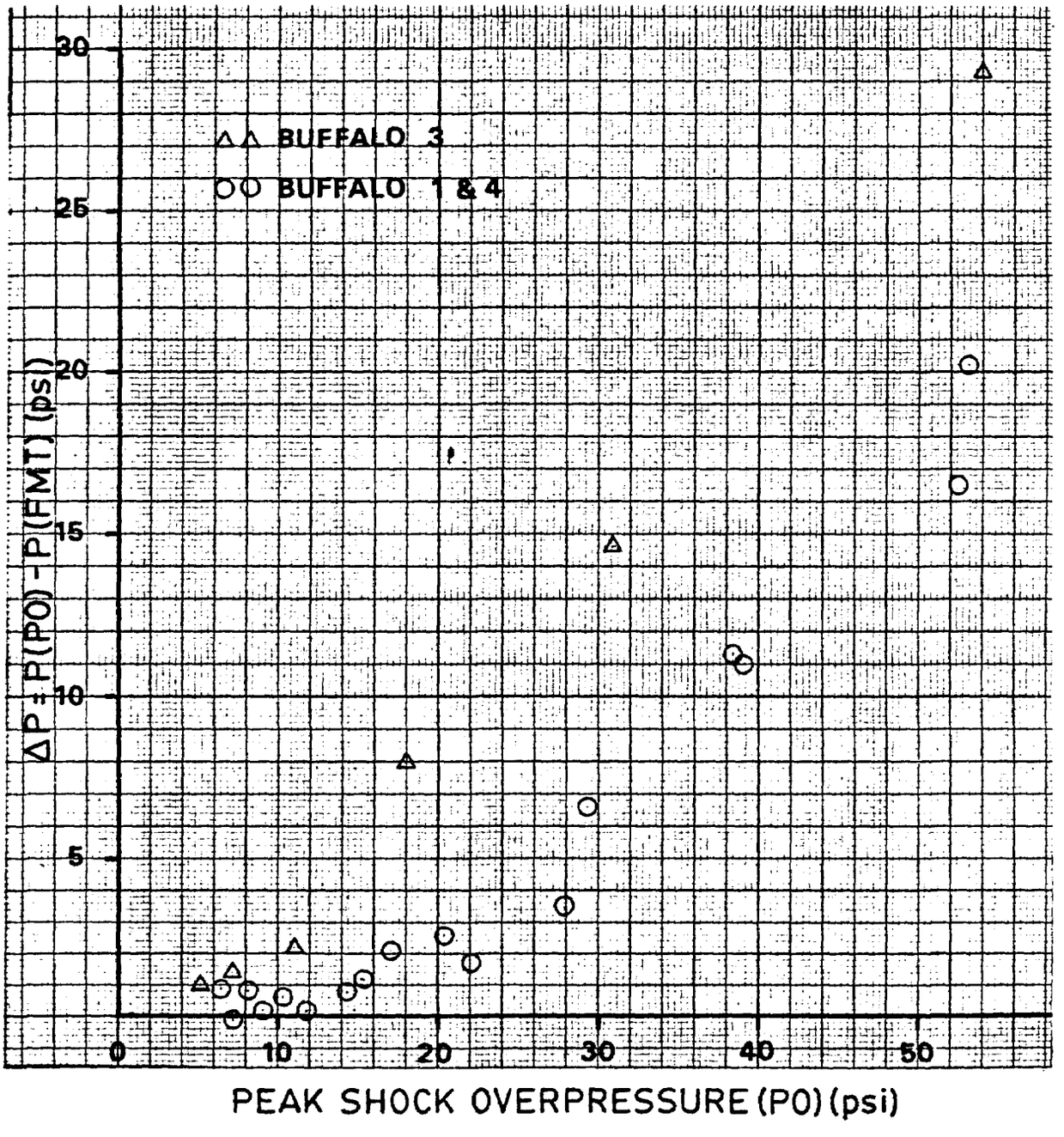

FIGURE 4 PEAK (PHOTO-OPTICAL) SHOCK OVERPRESSURE VERSUS [P(PO)-P(FMT)

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