

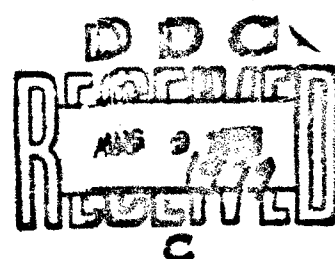
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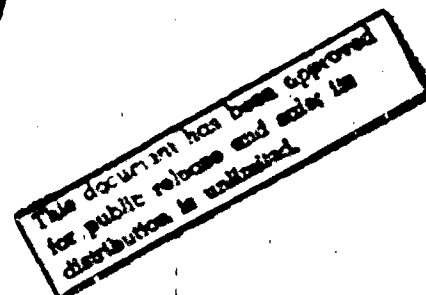
Results of Air Gun Tests (St. Croix):
November 1978

W.R. Hamblen, C.M. Gogos, and J.E. Barger

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1. INTRODUCTION

This technical memorandum presents the results of source level measurements made on a Western Geophysical (WG), Walker-type airgun. The objective of these tests was to determine if this type of airgun could meet the requirements developed in Ref. 1 for a single element of an active array. The energy source level (ESL) required is 223 dB re $\mu\text{Pa}^2\text{-sec}$ in the fundamental frequency band.

Earlier tests (Refs. 2 and 3), with air guns designed and built by Bolt Associates showed that this source level was achieved only at low fundamental frequencies (shallow depths). As the depth was increased, the ESL's rolled off sharply. It was felt that this was due primarily to extended open port durations which allowed cushioning of the collapsing bubble. The WG air gun has several features which indicated that the open port duration would be much shorter than previous guns and that this time would be relatively independent of depth. Thus it was hoped that high ESLs could be achieved at the required fundamental frequencies.

2. PROCEDURE

2.1 Equipment

The measurement program was conducted during the period from 6 to 17 November 1978 in the deep ocean channel 6 miles north of Christiansted, St. Croix, USVI. The measurements were staged from the laboratory barge YFN 1126, which is operated by the Key West Detachment of the Naval Air Development Center. The barge was outfitted with the experimental apparatus shown schematically in Fig. 1.

The WG air gun is configured quite differently from previous air guns and this necessitated slightly different handling. The WG design consists of two concentric cylinders with sets of matching holes or ports. As the gun fires the inner cylinder is slid longitudinally, opening the ports as the holes align and then, as the inner cylinder continues to move, closing them. To fire the gun again, the inner cylinder is slid in the opposite direction, repeating the process. The volume of the gun is about 1,100 cubic inches.

This design requires two air supplies and two firing circuits; one air supply and one firing circuit for each end of the gun. In addition, the present design must be fired with the axis of the cylinder horizontal. To achieve these requirements, WG supplied a bridle which supported the gun in a horizontal position and split the air supply in order to supply both ends of the gun. The bridle-air gun assembly was connected to the cable bundle with quick-disconnect type of connectors for ease of assembly.

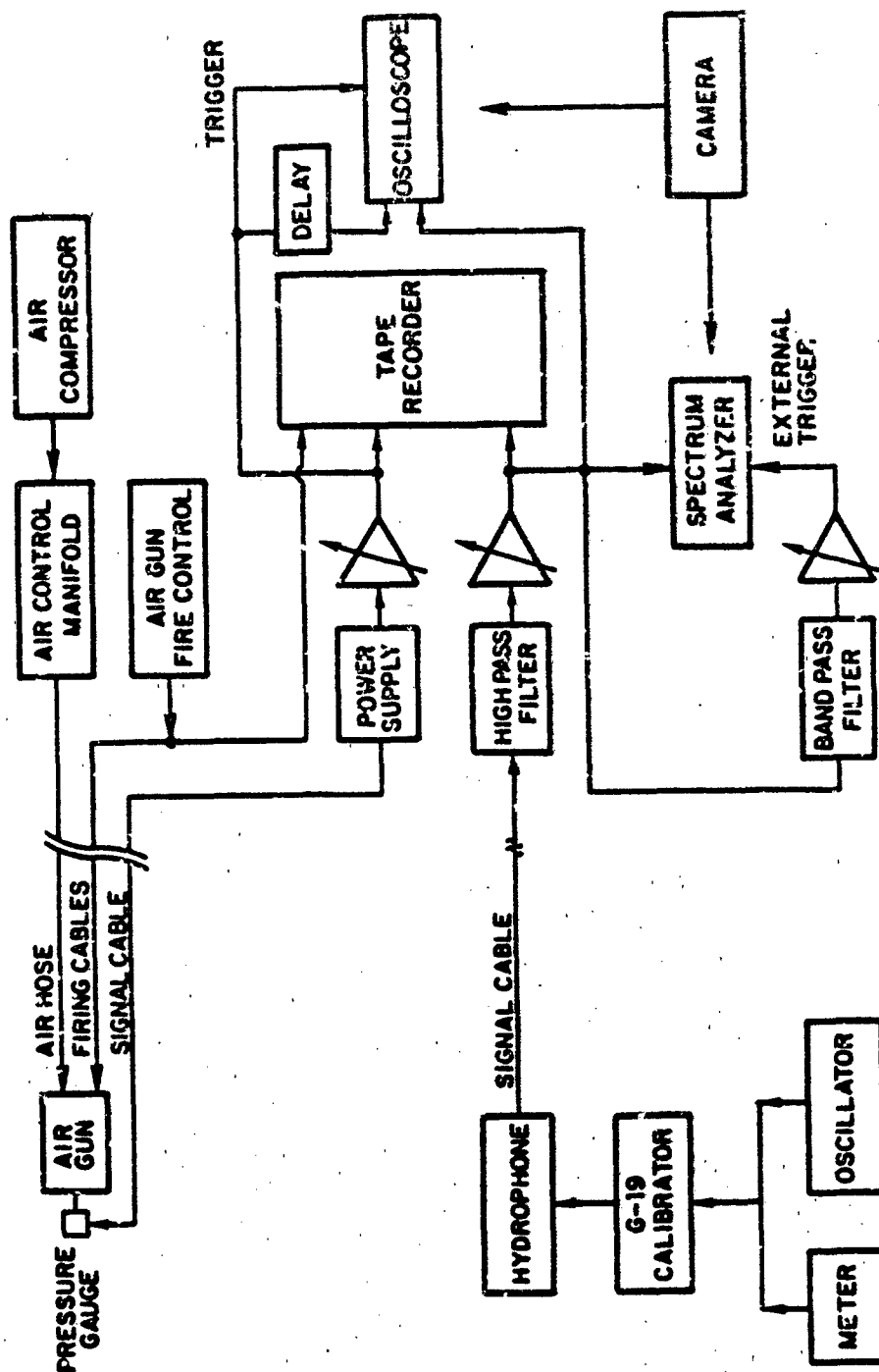


FIG. 1. BLOCK DIAGRAM OF EXPERIMENTAL APPARATUS.

The cable bundle consisted of three electrical cables; two firing cables and one pressure transducer cable, plus the air hose. This bundle was taped to the strength member as the gun was deployed. The gun was deployed from an oceanographic winch on the 01 deck of the barge with the aid of a Pettibone hydraulic crane for handling the gun at the surface. In this respect, the handling was identical to previous tests, (Ref. 3).

The anticipated testing at 5 and 6 thousand psi predicated a new air supply system. The air compressor was an Ingersoll Rand, having 100 scfm capacity at 6,000 psi. The air compressor fed a new air supply manifold built and supplied by WG. The manifold provided precise control over compressor pressure and air gun pressure. The air gun pressure gauge on the manifold was calibrated with a dead weight calibration just prior to installation on the barge and all pressures were referenced to this gauge. Finally, 2,000 feet of 3/8 Synflex air hose, rated to 7,500 psi was supplied by WG.

A dynamic pressure transducer, PCB Model 111A22, was installed in the air gun to measure the air-discharge history of the chamber. The electrical cable of the pressure transducer provided dc power to the transducer amplifier via a power supply topside, and the signal line up to the measurement equipment. The nominal sensitivity of the pressure transducer is 1 mV/psi with a full-scale range of 6,000 psi. The transducer was located at the end of an 18-inch air hose that was connected to the gun's air chamber. This mounting system provided shock isolation for the transducer. Earlier direct mountings had shown a high incidence of shock-related transducer failures. Tests conducted by WG indicated that no artifacts were introduced in the pressure trace with this mounting system.

The air gun was fired from a dc power supply and a switch box. The switch box simply provided a means to select which side of the gun to fire.

The measurement hydrophone, Type F-50, Serial No. 88, was lashed to a weighted nylon line that was run through a block on a davit located near the stern on the port side. The hydrophone sensitivity, based on calibrations made in the BBN hydrophone calibration facility before testing, was -218.5 dB v/re μ Pa. Frequent checks on this calibration were made during the test program with a G-19 hydrophone calibrator.

The hydrophone was lowered to a depth of about 300 ft and about 80 ft aft of the air gun line. The gun-to-hydrophone distance was obtained by measuring the elapsed time between the pressure-transducer air-discharge pulse and the direct acoustic arrival. Both the hydrophone and the pressure signals were displayed on a 2-channel oscilloscope and tape recorded. In addition, the firing current was also recorded. The hydrophone signals were spectrum-analyzed upon arrival.

Each shot was analyzed on-line, in addition to being tape recorded. Each source-level data point required the following processing:

- Capture of the acoustic pressure waveform
- Fourier transform of each waveform
- Summation of the energy in all analysis bands that comprise the fundamental-frequency band
- Measurement of source-to-receiver acoustic transit time and computation of distance

- Calculation of transmission loss on the basis of spherical spreading
- Calculation of the energy source level in the fundamental-frequency band.

In addition, the chamber pressure-amplitude time history was also photographed on-line along with the acoustic pressure waveform for the purpose of both gun performance analysis and as a measure of the acoustic transit time.

2.2 Testing

The test was conducted in accordance with the objectives outlined in the test plan, Ref. 4. These objectives were to establish as quickly as possible the required parameters (depth and timing insert) for obtaining the highest ESL at the desired fundamental frequency and to then obtain that data point.

The depth parameter arises because the WG air gun is cylindrical in shape and previous theoretical and experimental work indicated that the resonant frequency of a cylindrical bubble is higher than the resonant frequency of a spherical bubble of the same total volume at the same depth. Thus, a new frequency-depth relation had to be obtained for the gun. It was hoped that the 100 Hz fundamental frequency could be obtained at a significantly shallower depth than previously. This would provide important system (and source level) benefits.

It was hoped to vary the timing in order to prevent bubble cushioning as had been seen in other air guns. To obtain the optimum time of 5 to 7 msec a series of timing washers were to be inserted in the gun. These washers varied in thickness and

essentially spanned the range from 0 to $5/16$ in. in $1/16$ -in. steps. Actually, it was discovered that these washers were much less critical to the timing than anticipated.

The major impediment to data acquisition was the reliability of the gun when operating at depth. Frequently, at depths over 400 feet, the gun would fire once then hang "open," necessitating retrieval and reworking of the gun. These failures typically appeared to be one of two types. Either water would infiltrate behind the open end of the piston (inner cylinder) preventing complete piston travel thus causing the gun to remain open, or compression of the (ambient) air behind the open end of the piston would cause the piston to rebound, leaving the ports open. Once the ports were open, there was no way to reseal the gun or to move the piston, short of retrieving the gun to the deck. Thus, toward the latter stages of the test when the gun was being fired at depth, frequently only one data point per lowering was obtained. The only other difficulty experienced were breaks in the electrical splices.

3. RESULTS

3.1 ESL

The major result of this test is that the W1 air gun appears to provide an ESL of 218 to 219 dB re $\mu\text{Pa}^2 \text{ sec}$ independent of frequency (depth) over the range from 25 to 110 Hz. This is demonstrated most clearly by Fig. 2, which plots the measured ESL as a function of frequency. Table 1 lists the average ESLs obtained during the course of the test. The fact that the ESLs are independent of depth confirms the contention that the parameters of this gun (when it operates) are independent of depth. If this indeed is the case, then the ESL would not begin to roll off until the fundamental frequency is on the order of the reciprocal of the open port duration. For this gun that would be approximately 150 to 170 Hz.

3.2 Timing

There are two concerns with regard to the timing of this air gun. The first concern is that the open port duration lie in the 5 to 7 msec range. It was found that the duration (fortuitously) fell within this range irrespective of what timing insert was used. The inserts were varied between 0 (no insert) and 5/16 in. (the maximum) and while some changes in gun performance were noted (mainly source level changes at the low frequencies), basically the open port duration remained constant at about 6 msec. Consequently, timing insert "B" (1/4 in.) was used for the remainder of the shots.

The second concern, while not immediate to this test, is the amount of jitter in the gun firing. In post analysis, the time between the initiation of the firing current and the initiation of the pressure drop in the gun was measured and compared for shots taken under identical conditions. While the data base is too small to be conclusive, it does indicate that this time may vary by several milliseconds. This will impact the ability to array this airgun.

3.3 Frequency-Depth Dependence

As had been hoped, the WG achieved a fundamental frequency of 100 Hz at a shallower depth than previous 1,000 cubic in. air guns, approximately 1,400 ft rather than 1,600 ft. A linear regression on the data indicates that the frequency is proportional to the depth to the 0.929 power. This is virtually identical to the dependence of the other air guns, however, the constant of proportionality is less. For this gun, the fundamental frequency is given by $f = 0.13 (d+33)^{0.929}$, where d is the depth in feet.

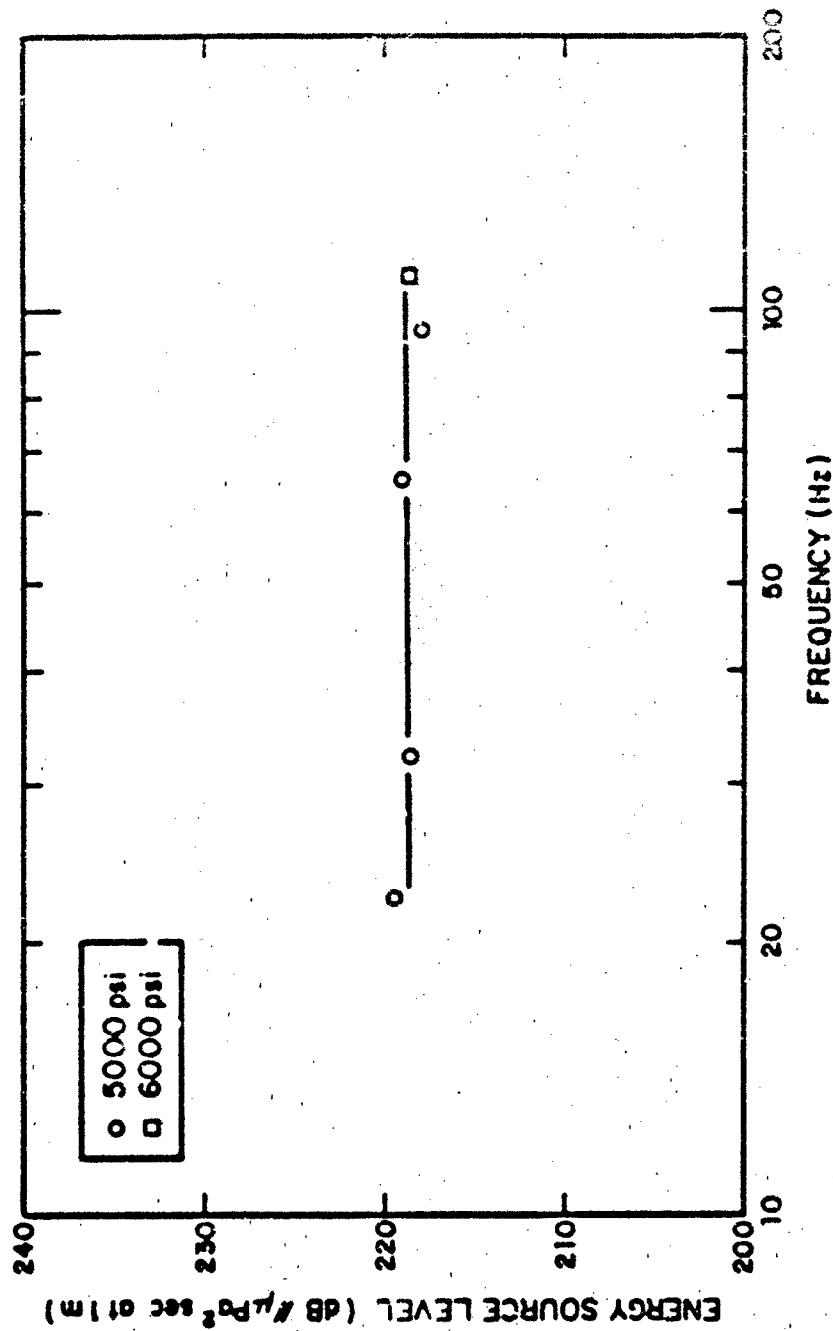


FIGURE 2. ENERGY SOURCE LEVEL FOR THE WESTERN GEOPHYSICAL AIR GUN AS A FUNCTION OF FREQUENCY.

TABLE 1

Depth (ft)	ESL, dB re $\mu\text{Pa}^2 \text{ sec}^*$
200	219.5 at 20 Hz average of 4 shots
400	218.3 at 35 Hz average of 7 shots
800	219.1 at 65 Hz average of 6 shots
1,200	218.2 at 92 Hz average of 2 shots
1,400	218.8 at 110 Hz average of 1 shot [†]

* tested at 5,000 psi, timing insert B

[†] tested at 6,000 psi, timing insert D.

4. ANALYSIS

Setting aside the question of gun reliability, the analysis of the data is straightforward. The most important point is that the open port duration at 5 to 6 msec, is compatible with fundamental frequencies of at least 100 Hz. Thus, no roll-off in ESL was seen. It would be desirable in a successor test to prove the existence of such a roll-off and to quantify its location in frequency.

The theory of the gun timing is more complex. Presently, the best hypothesis is that the value of the static friction between the inner and outer cylinders is the controlling factor in the open port duration. The following facts and observations support this. First, the volume of high pressure air that initiates the piston movement is so small that once the piston begins to move the force decrease so rapidly (due to the expanding volume, dropping the pressure) that the piston only sees an impulse. Thus, there is no effective way to vary the driving force. This is supported by the data. The timing inserts which control the rate at which high pressure air flows into the volume behind the piston had little effect on the open port duration (piston velocity) but effected the time between the firing current pulse and the pressure dump markedly. Thus, while it may have taken longer for the air to flow behind the piston with a timing insert in place, the force sufficient to break the piston loose was the same as the force in the absence of a timing insert. Second, experiments by WG indicated that the piston velocities are approximately constant during the open port duration. This indicates that the inner cylinder is effectively free from external forces during this time. Our

test indicates that this is true only on the surface where the compression effects of the ambient air in the "dead" end of the gun are minimal. As the gun went down in depth, the higher ambient pressures caused a premature stopping of the piston, causing the gun to hang open.

Generally little can be presently envisioned to increase the gun's performance. It was noted, however, that the $1/e$ time of a total air dump (which occurred when the gun hung open), was somewhat longer than desired. This may be seen in Fig. 3, which displays the photographs obtained from a 5000 psi, 1200 foot deep shot. The gun hung open as may be seen from the pressure trace. This would indicate that by increasing the port area a greater percentage of air could be released in the 6 or so msec available. An effective increase in the port area could be obtained by drilling out the ports, smoothing the edges to increase flow, or both. Note in Fig. 4, a "good" shot that only 68 percent of the pressure was dumped; opening the ports should raise this figure. Figures 3 and 4 provide a good comparison between a cushioned shot and a normal shot.

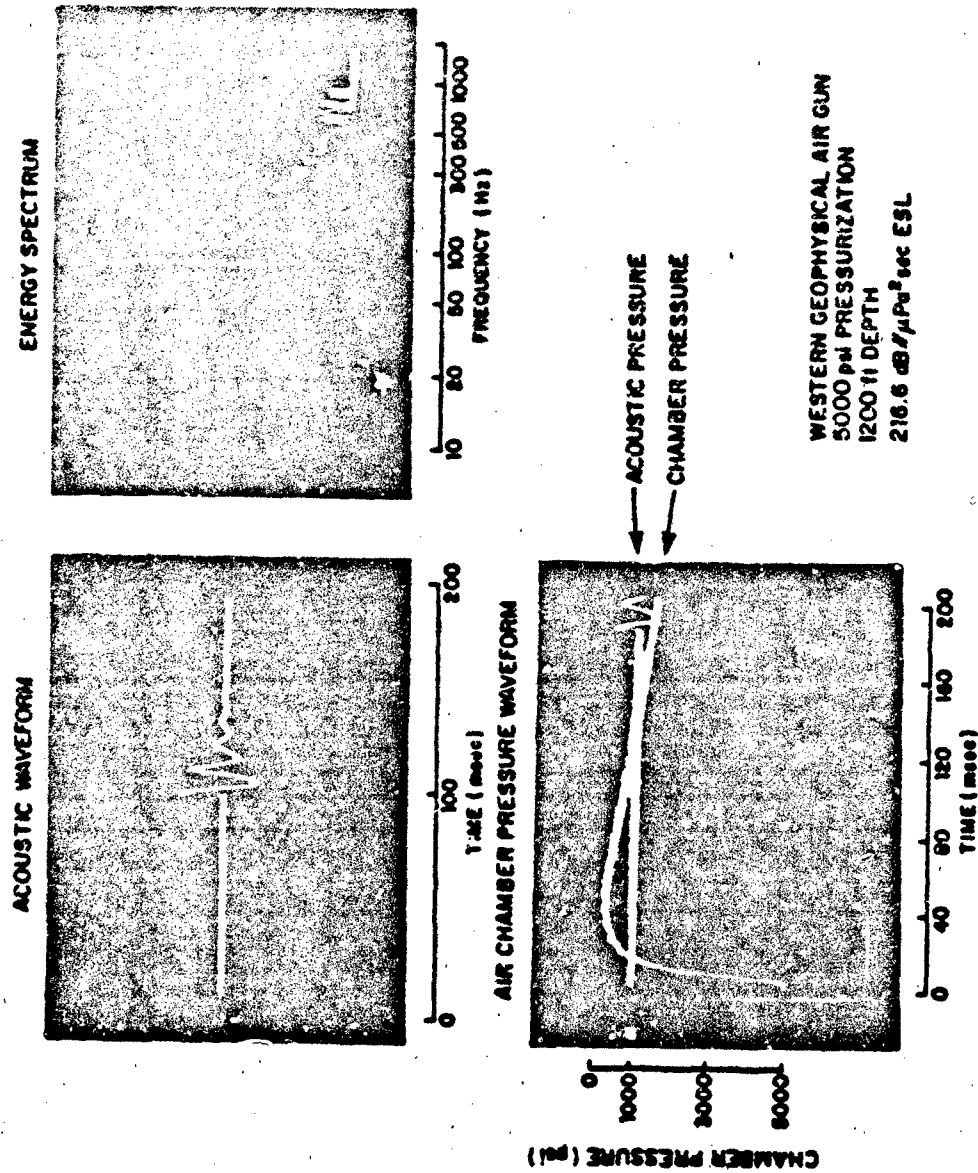


FIGURE 3: EXAMPLE OF ON-LINE DATA ANALYSIS: GUN FAILED TO CLOSE.

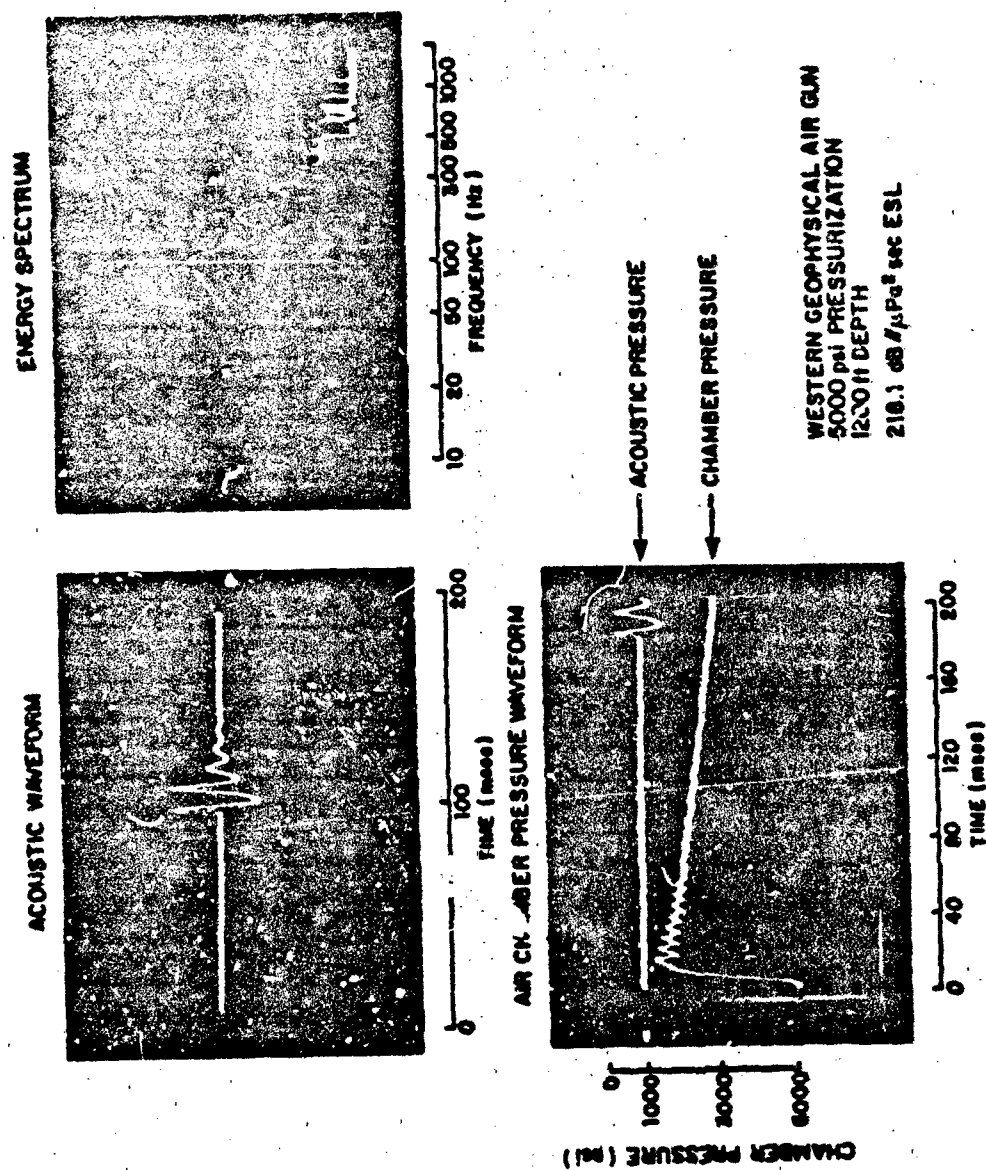


FIGURE 4. EXAMPLE OF ON-LINE DATA ANALYSIS: PROPER GUN OPERATION.

5. SUMMARY AND CONCLUSIONS

1. The maximum ESL for the WG gun is 218.8 db re $\mu\text{Pa}^2 \text{ sec}$ at 110 Hz generated at a depth of 1,400 ft and a pressure of 6,000 psi.
2. The timing of the gun appears to be very good and is relatively insensitive to changes in the gun configuration.
3. Performance of the gun could be slightly improved by increasing the effective port size.
4. The reliability of the gun operation is poor and must be addressed in future tests.

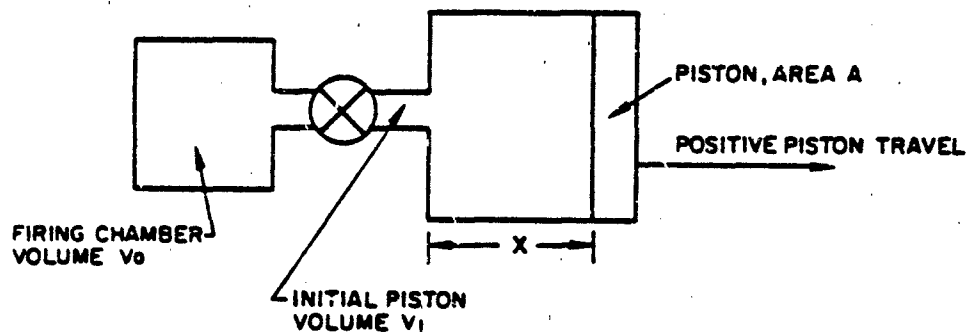
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3. J.E. Barger, C.M. Gogos, and W.R. Hamblen, "Results of Air Gun Tests at St. Croix, April 1978," BBN Tech Memo No. 457, August 1978.
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APPENDIX A

The following is a simple analysis of the initial shuttle dynamics, immediately after firing, of the Walker-type air gun. This analysis describes only the expansion of firing-chamber air, and not the compression of recoil-chamber air. The analysis, therefore, applies only during the period from firing to port-opening.

The system is modeled as shown in the sketch. The instantaneous piston volume is a linear function of the piston



travel distance x . The total volume of the system before firing is V_0 . After the valve opens, the total system volume is V .

$$V = V_0 + V_1 + Ax \quad (1)$$

We will simplify by taking the air expansion to be adiabatic and assume no throttling losses at the valve. Then the pressure P acting on the piston is given by

$$P/P_0 = (V_0/V)^v, \quad (2)$$

where v is the ratio of specific heats.

The force F acting on the piston is partitioned into a friction drag force F_d and an acceleration force to move the shuttle, having mass M .

$$F = AP = M\ddot{x} + F_d \quad (3)$$

The equation of piston motion is obtained by combining Eqs. 1, 2, and 3.

$$\ddot{u} = a(bu^{-v}-1) \quad (4)$$

where

$$u = u_0 + Ax/V_0, \quad u_0 = 1 + V_1/V_0$$

$$a = AF_d/V_0 M$$

$$b = AP_0/F_d$$

The equation for piston velocity $v = \dot{u}$ is obtained by integrating Eq. 4 with respect to the normalized piston displacement u .

$$\int_{u_0}^u a(bu^{-v}-1) du = \int_0^v v dv = \frac{1}{2} v^2$$

$$v^2 = 2a \left[\frac{b}{1-v} \left(u^{1-v} - u_0^{1-v} \right) + u_0 - u \right] \quad (5)$$

The position of the piston u is obtained as a function of time by integrating Eq. 5 with respect to u .

$$t = (2a)^{-\frac{1}{2}} \int_{u_0}^u \left[\frac{b}{0.4} \left(u_0^{-0.4} - u^{-0.4} \right) + u_0 - u \right]^{-\frac{1}{2}} du \quad (6)$$

We have simplified the expression by taking $\gamma = 1.4$ for air. Equation 6 was solved for a series of parameters by using Simpson's approximation. The parameters used were:

$$V_0 = 1.46 \cdot 10^{-5} \text{ m}^3$$

$$V_1 = 1.37 \cdot 10^{-5} \text{ m}^3$$

$$A = 9.0 \cdot 10^{-3} \text{ m}^2$$

$$P_0 = 3.45 \cdot 10^7 \text{ N/m}^2 \text{ (5000 psi)}$$

$$M = 3.17 \text{ kg (70 lb)}$$

$$F_d = C_f \cdot 9.56 \cdot 10^5 \text{ N (hole area totals 43 in.}^2\text{)}$$

$$C_f(\text{drag coefficient}) = 1/4, 1/6, 1/8, 1/16.$$

The calculated values of piston displacement x are plotted on the vertical scale, in mm. The time after firing is plotted on the horizontal scale in ms. The holes begin to uncover at a displacement of about 10 mm, and then close again at a displacement of about 21 mm. These two displacements are marked on the graph.

When the drag coefficient is as large as $1/4$, the initial air charge is insufficient to fire the gun, as the piston comes to rest after 3.4 ms at a position of 6.5 mm short of hole overlap. The length of the air passages from the firing chamber

back to the main chamber is about 6 in. Therefore, a new charge of firing air will begin to replenish air in the firing chamber behind the piston after about 1 ms. Thus, the gun would eventually fire, but it would not reseal.

When the drag coefficient is smaller, and equal to $1/6$, the gun will fire after 2.3 ms, but will not reseal.

When the drag coefficient is even smaller, and equal to $1/8$, the gun will fire after 1.9 ms and reseal at 3.1 ms.

When the drag coefficient is only $1/16$, the gun will fire after 1.5 ms and reseal at 2.3 ms.

Since the firing times are all larger than the replenishment time, more air will be available for firing than was assumed to be available in the simple model. Therefore, the gun should be expected to start firing sometime in the range of 1 ms to 2 ms. It appears that the shuttle inertia is such that the open durations would be in the range of 1 ms to 2 ms. Since these durations are shorter than the observed durations, the retarding force of the recoil chamber must be very important when the shuttle reaches about mid position. Nevertheless, the range of initial firing times is apparently about 1 ms for coefficients of friction in the range of $1/6$ to $1/16$.

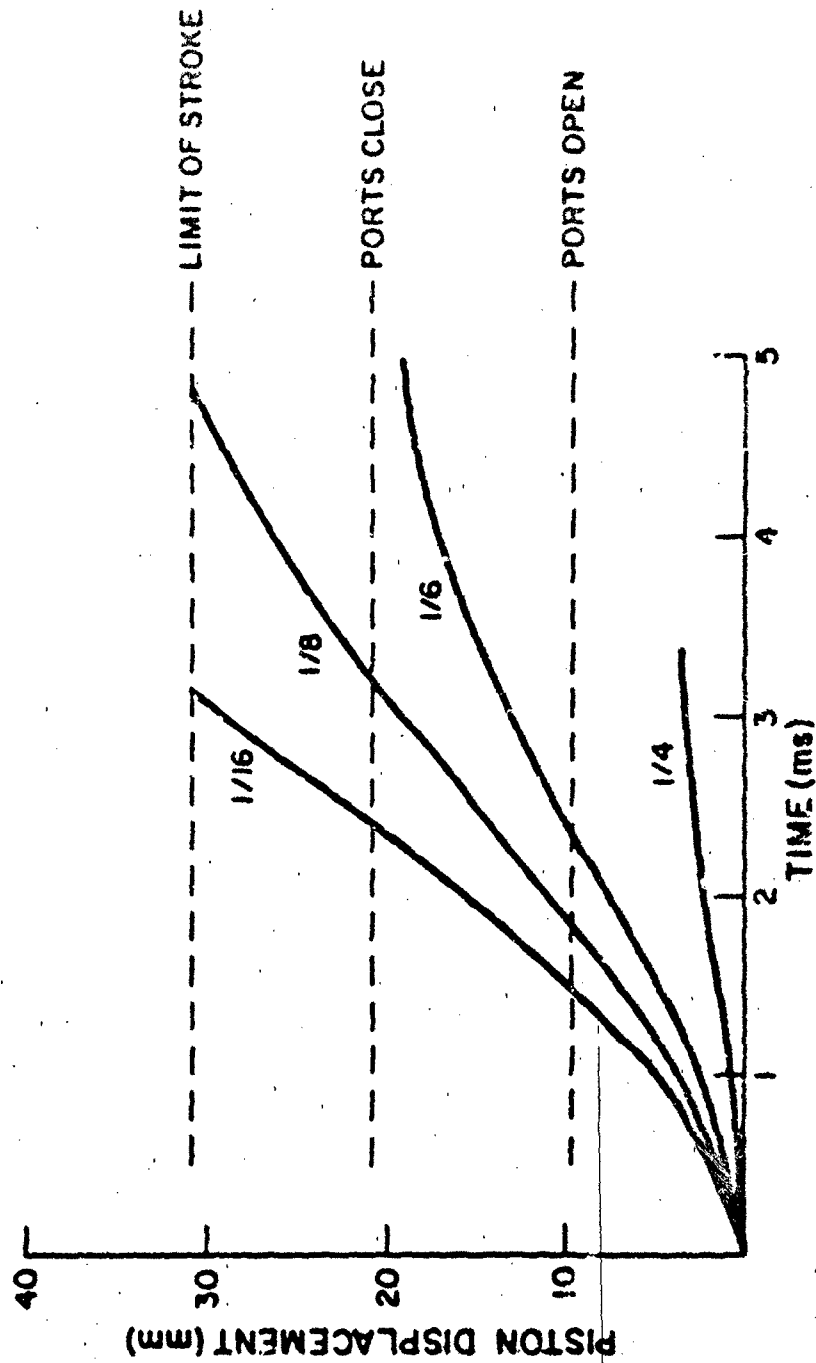


FIG. A-1. SHUTTLE TRAJECTORY FOR FOUR VALUES OF THE COEFFICIENT OF FRICTION.