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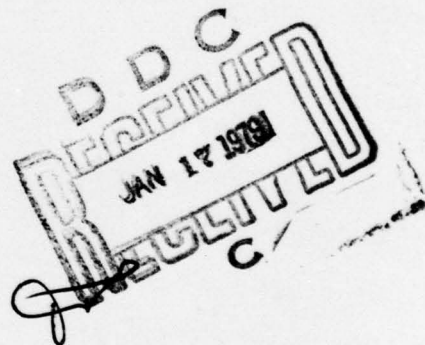
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## Results of Air-Gun Tests at St. Croix, April 1978

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



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Defense Advanced Research Project Agency

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⑥ RESULTS OF AIR-GUN TESTS AT ST. CROIX, APRIL 1978

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⑨ Technical memo.

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## 1. INTRODUCTION

This technical memorandum presents the results of source level measurements made on two Bolt Associates air guns - with and without various modifications. The objective of the tests was to determine the air-gun configuration that would best meet the requirements developed in Ref. [1] for an array element. The energy source level required from each array element is 223 dB  $\text{re } \mu\text{Pa}^2 \text{ sec}$  in the fundamental frequency band.

223 dB re (micro Pa<sup>2</sup> a-second)

Earlier test results [2] showed that this source level can be achieved - but only at low fundamental frequencies (shallow depths). The energy source levels were seen to decrease with increasing fundamental frequency obtained at increased source depths. An additional test objective, therefore, was to study the causes of this decrease in source level. Diagnostic measurements were made, using a pressure transducer mounted inside the air gun, and various modifications were introduced to the two basic air guns in an attempt to improve their acoustic performance at large depths.

## 2. PROCEDURE

The measurement program was conducted during the period from 3 to 21 April 1978 in the deep ocean channel 6 miles north of Christiansted, St. Croix, USVI. The measurements were staged from the laboratory barge YFN1126, 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 air guns were deployed, one at a time, from a 2000-ft 1/2-in. wire rope fitted to an oceanographic winch on the 01 deck amidships via an A-frame and sheave on the starboard side. The 3/8-in. air hose, rated at 4500 psi working pressure, was taped to the firing line and the pressure transducer signal cable. This 1700-ft-long taped bundle was flaked out on the 01 deck next to the winch. A small platform on the main deck provided working space for lashing the taped bundle to the wire rope as the air gun was lowered to the test depth.

Returning the air gun to the deck involved use of a Pettibone hydraulic crane. The oceanographic winch raised the air gun/accumulator to just below the water surface (to prevent swinging due to ship motion). At this point, the Pettibone cable was attached to a bridle on the accumulator, and the air gun assembly was hauled aft onto the main deck.

The air compressor was a multistage Ingersoll Rand Model D4R15MX25, having 40 SCFM capacity at 5000 psi. The final stage output via a small accumulator was piped to a control manifold where precision gauges measured air-compressor pressure on one side and air-gun pressure on the other. Manual control valves allowed air connections to be made among the air compressor, the air gun, and the atmosphere, thus providing the ability to make fine

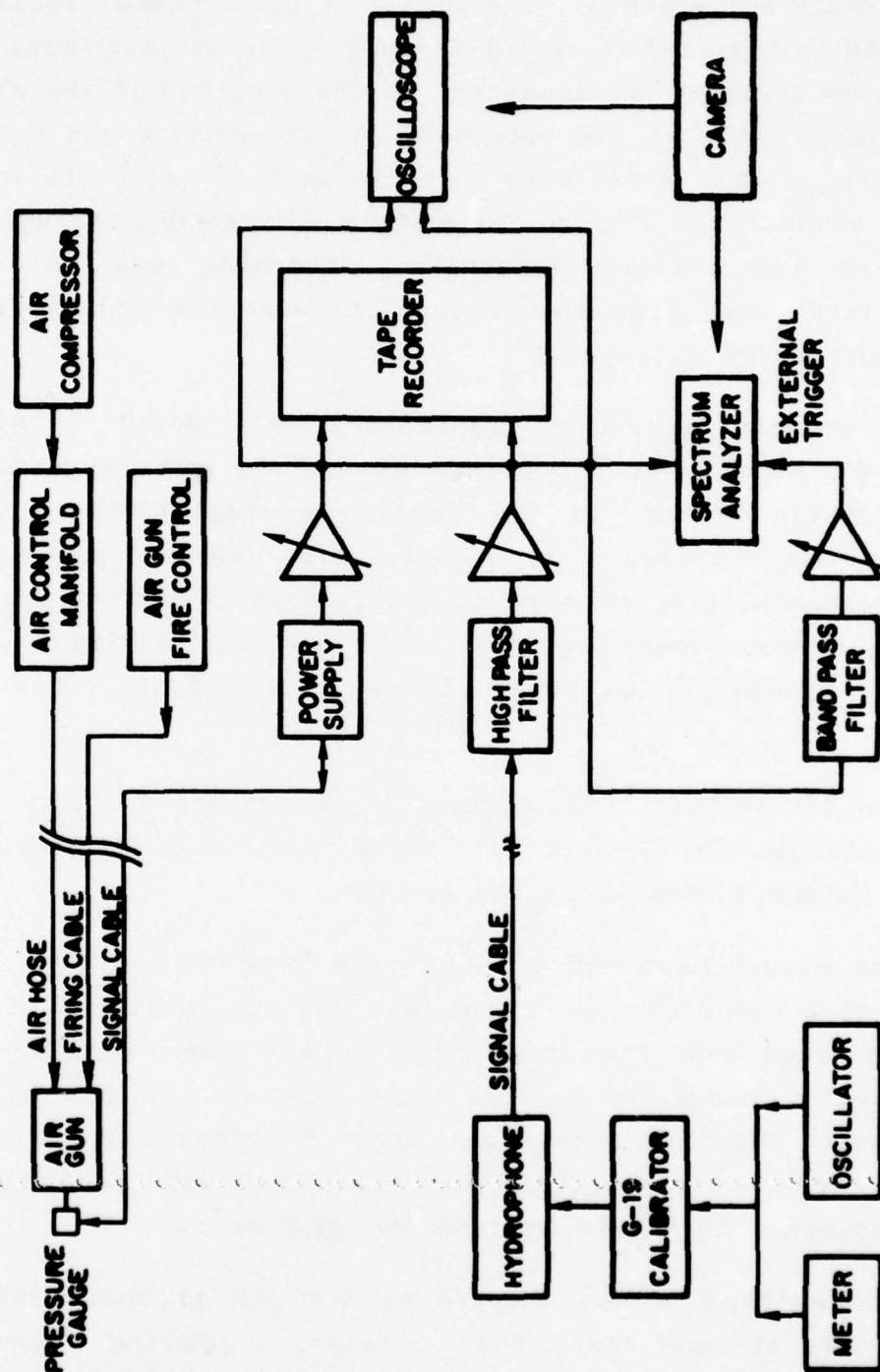


FIG. 1. BLOCK DIAGRAM OF EXPERIMENTAL APPARATUS.

air-pressure adjustments. The output of this control manifold was connected to the 1700 ft of 3/8-in. high-pressure air hose. A large 10-gal. accumulator was connected to the deep end of the air hose, providing storage of high-pressure air to enhance gun sealing at the deeper depths. A manually operated shutoff valve was installed at this accumulator output. The air gun was charged through a 22-ft air hose just before immersion. Charging was able to be accomplished away from the riggers, because the manual valve was opened by use of a lanyard.

A dynamic pressure transducer, PCB Model 111A22, was installed, usually at the bottom of the air gun, to measure the air-discharge history in the lower air 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 5000 psi.

The air gun was fired from an AG Series air-gun fire control, which provided a 90-V electrical pulse down the firing cable to the firing solenoid mounted on the air gun.

The measurement hydrophone, Type F-50 Series No. 21, 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 and after testing, was -222.0 dB re v/ $\mu$ 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 deploying rope. 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. 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 pressure waveform
- . Fourier transform of each waveform
- . Average of two transforms per condition
- . Summation of the energy in all analysis bands that comprise the fundamental-frequency band
- . Measurement of source-to-receiver acoustic transient 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 recorded and photographed on-line for both chamber pressure waveforms and the acoustic transit timing.

The test program was conducted in accordance with the test plan [3]. Two basic Bolt Associates air guns - a PAR 800C and a PAR 1500C - and various configurational modifications of these basic guns were tested in an effort to maximize the acoustic output. The PAR 800C was fitted with three air-chamber combinations - 400, 1000, and 2000 cu in.; the PAR 1500C was fitted with two-300 and 1000 cu in. These air chambers were used to study the effects of charge volume on radiated source level for various charge and ambient pressures. Other modifications to the air guns were made for the following reasons.

The maximum ambient pressure differential for the 800C gun was limited to 3500 psi, to avoid structural damage to the gun. Bolt had indicated there might be problems with gun sealing at our highest test pressure of 4000 psi. In an attempt to correct this problem, a special shuttle was provided with a large diameter shaft and thicker sealing flanges to reduce distortion under pressure.

Previous testing on the 1500C gun [2] indicated that the charged air might not be fully discharged either because of exhaust-port constriction or because of turbulence generated by sharp edges at the throat of the air chamber. Two hardware modifications were implemented to investigate this air-discharge problem: extended exhaust ports and a streamlined throat nozzle. Reference 2 also indicated that the shuttle was not staying open long enough, thus prematurely cutting off the air discharge. An additional hardware modification was therefore introduced to delay shuttle closure: An upper chamber sleeve was cut down to allow the shuttle to travel higher into the upper chamber (increasing shuttle throw) before trapping the air necessary to reverse shuttle direction.

Each of these modifications were tested independently. In all, the testing involved 6 configurations for the 800C and 16 for the 1500C.

Two problems encountered in these preliminary measurements extended the testing time and, to some extent, limited the data acquisition. First, the air compressor developed a loud knock in its left side during the third day (13 April) of testing. The air compressor was judged unsafe, and testing was temporarily suspended. Action was taken to repair the air compressor and to acquire a backup machine. Hoffart Marine Inc. rebuilt the left section in time to start testing by 17 April. A Worthington Model

SABC 20 SCFM air compressor rated at 5000 psi was rented from Innerspace Research for the backup. This machine arrived at St. Croix on 17 April. On 19 April, the 40 SCFM air compressor froze, necessitating the use of the smaller capacity Worthington. Little testing time was lost in implementing this air compressor but because of its 20 SCFM capacity, the time to recharge the air gun system was significantly increased, thus slowing the data-acquisition process.

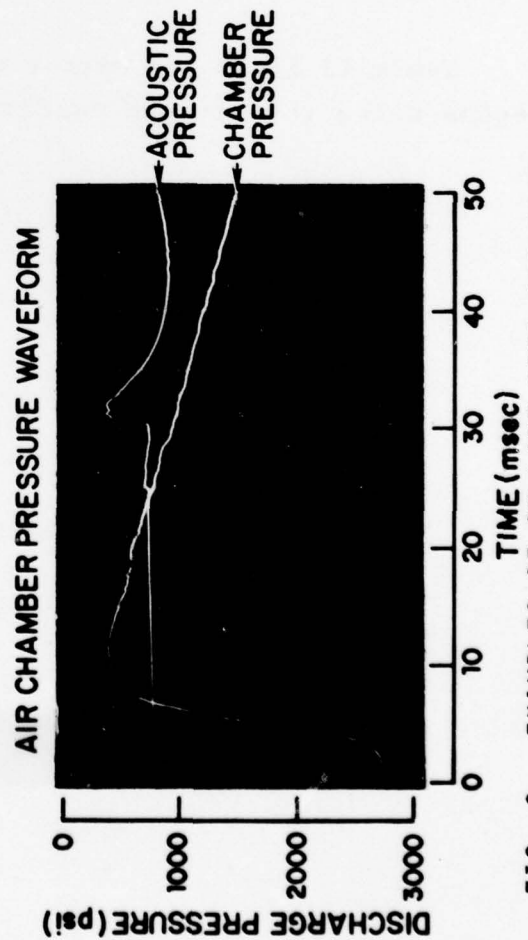
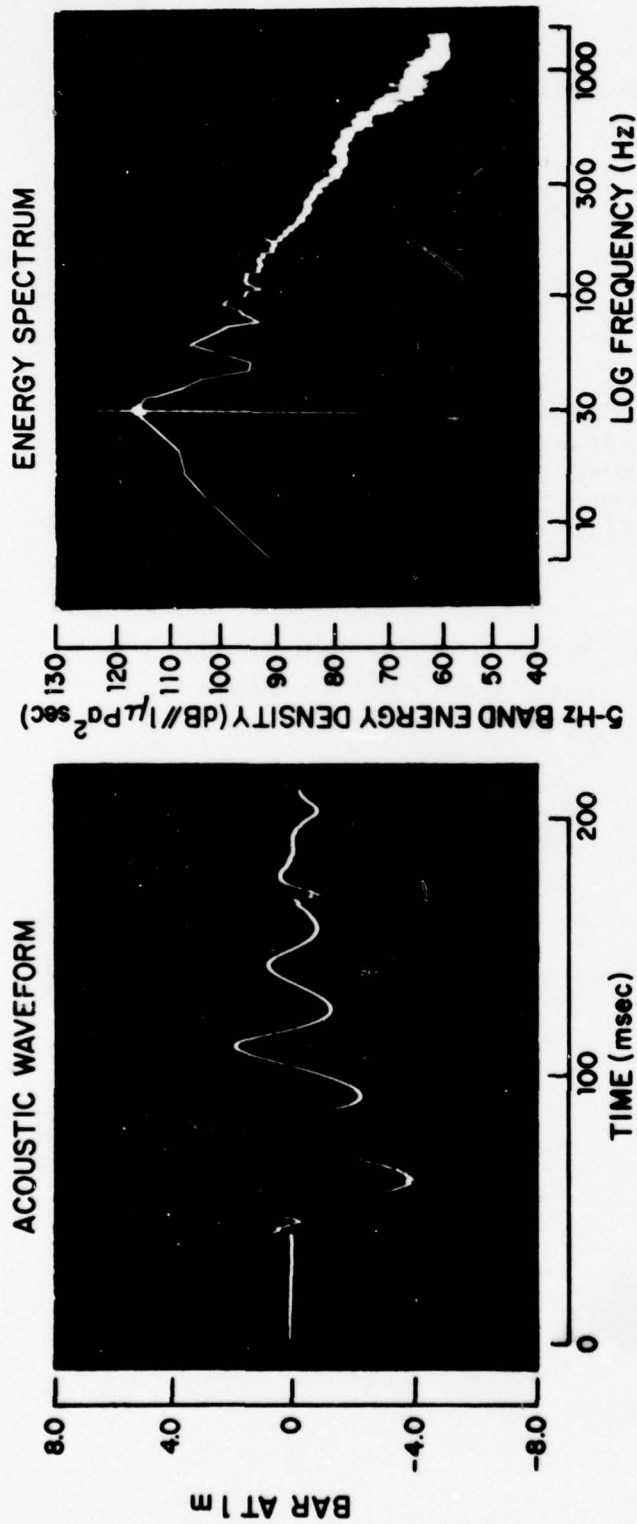
The second problem encountered was the physical deformation of the PAR 800C air gun. The gun body was deformed out-of-round, causing the air seals to leak at charge pressures greater than about 2200 psi. This problem prevented the acquisition of the 1600-ft, 4000-psi data point.

### 3. RESULTS

Each shot was analyzed on-line as described in Sec. 2. An example of the results obtained with this on-line processing is given in Fig. 2 for 800C air gun configured with the large shuttle and the 1000-cu in. air chamber. The gun was charged to 3000 psi and detonated at a depth of 400 ft. The pertinent features of this on-line analysis are:

- . The waveform resembles a damped sinusoid with a bubble pulse period of about 32 msec as seen in Fig. 2a.
- . The fundamental energy component is centered at 30 Hz with about a 5-Hz bandwidth (Fig. 2b).
- . The lower chamber discharged 2700 psi of the 3000 psi static pressurization in about 5 msec (Fig. 2c).
- . The acoustic transit time is about 27 msec, reckoned from the time of the sharp rate of the pressure discharge to time of reception of the acoustic shock wave.

The following table lists the air-gun configurations tested. A number of possible configurations were not tested for a variety of reasons, the most common being that the source levels extrapolated from the test data would not be high enough to be of interest and/or other configurations showed greater promise. There were cases, however, that provided significant information about how air guns work for these specific environmental conditions and how to improve their performance in spite of rather low source levels. For these cases, sufficient data were acquired to establish performance trends that suggested specific configurations or gun modifications to be tested.



PAR 800C AIR GUN  
1000 cu.in. CHAMBER  
3000 psi PRESSURIZATION  
400-ft DEPTH

FIG. 2. EXAMPLES OF ON-LINE DATA ANALYSIS.

**TABLE I. SUMMARY OF AIR-GUN CONFIGURATIONS TESTED****Model: PAR 800C**

|                     |                        |
|---------------------|------------------------|
| 400-cu in. chamber  | standard configuration |
| 1000-cu in. chamber | large shuttle          |
| 2000-cu in. chamber | standard configuration |
| 2000-cu in. chamber | large shuttle          |

**Model: PAR 1500C**

|                     |                                                           |
|---------------------|-----------------------------------------------------------|
| 1000-cu in. chamber | standard configuration                                    |
| 1000-cu in. chamber | extended ports                                            |
| 1000-cu in. chamber | extended ports and ring nozzle                            |
| 300-cu in. chamber  | extended ports and ring nozzle                            |
| 300-cu in. chamber  | extended ports, ring nozzle, and<br>modified upper sleeve |

Table II lists the energy source levels obtained at different depths using the air-gun configurations described in Table I.

TABLE II. ENERGY SOURCE LEVELS AT FUNDAMENTAL FREQUENCIES FOR AIR-GUN WAVEFORMS (AVERAGE OF TWO WAVEFORMS).

| Air-Gun Configuration                         | Energy Source Level in dB re $\mu\text{Pa}^2 \text{ sec}$<br>at 1m at Depths of: |                  |                  |                               |
|-----------------------------------------------|----------------------------------------------------------------------------------|------------------|------------------|-------------------------------|
|                                               | 200 ft                                                                           | 400 ft           | 800 ft           | 1600 ft                       |
| 800C/400-cu in.<br>standard shuttle           |                                                                                  |                  |                  |                               |
| 2000 psi                                      | 111.5 at 32 Hz                                                                   | 110.4 at 50 Hz   | 106.6 at 87.5 Hz | ----                          |
| 3000 psi                                      | 113.3 at 27.5 Hz                                                                 | 111.8 at 45 Hz   | 109.8 at 80 Hz   | ----                          |
| 4000 psi                                      | ----                                                                             | ----             | ----             | ----                          |
| 800C/2000-cu in.<br>standard shuttle          |                                                                                  |                  |                  |                               |
| 2000 psi                                      | 120.2 at 17.5 Hz                                                                 | 118.9 at 30 Hz   | 111.1 at 62.5 Hz | 104.1 at 100 Hz               |
| 3000 psi                                      | 122.6 at 15 Hz                                                                   | 112.8 at 25 Hz   | 113.9 at 50 Hz   | 108.5 at 90 Hz                |
| 4000 psi                                      | ----                                                                             | ----             | ----             | ----                          |
| 800C/2000-cu in.<br>large shuttle             |                                                                                  |                  |                  |                               |
| 2000 psi                                      | ----                                                                             | 121.1 at 30 Hz   | 115.2 at 27 Hz   | 110.7 at 62.5 Hz <sup>†</sup> |
| 2500 psi                                      | ----                                                                             | 122.1 at 30 Hz   | 115.0 at 69 Hz*  | 114.4 at 75 Hz <sup>†</sup>   |
| 3000 psi                                      | ----                                                                             | 122.7 at 27 Hz   | 118.6 at 44.6 Hz | ----                          |
| 4000 psi                                      | ----                                                                             | ----             | 120.1 at 50 Hz   | ----                          |
| 800C/1000-cu in.<br>large shuttle             |                                                                                  |                  |                  |                               |
| 2000 psi                                      | 118.0 at 20 Hz                                                                   | 116.3 at 38 Hz   | 112.4 at 73 Hz   | 104.5 at 125 Hz               |
| 3000 psi                                      | 120.3 at 18.1 Hz                                                                 | 118.3 at 37 Hz   | 115.5 at 62.5 Hz | 108.9 at 104 Hz               |
| 4000 psi                                      | ----                                                                             | ----             | ----             | 110.8 at 100 Hz               |
| 1500C/1000-cu in.<br>standard configuration   |                                                                                  |                  |                  |                               |
| 2000 psi                                      | ----                                                                             | 109.4 at 45 Hz   | 105.8 at 75 Hz   | ----                          |
| 3000 psi                                      | ----                                                                             | 112.6 at 40 Hz   | 109.0 at 70 Hz   | 101.4 at 125 Hz               |
| 4000 psi                                      | ----                                                                             | ----             | 111.7 at 62.5 Hz | 105.0 at 112 Hz               |
| 1500C/1000-cu in.<br>extended ports           |                                                                                  |                  |                  |                               |
| 2000 psi                                      | 112.0 at 22.5 Hz                                                                 | 109.5 at 45 Hz   | 103.6 at 75 Hz   | ----                          |
| 3000 psi                                      | 116.2 at 20 Hz                                                                   | 112.4 at 40 Hz   | 108.3 at 70 Hz   | ----                          |
| 4000 psi                                      | ----                                                                             | ----             | 111.3 at 62.5 Hz | ----                          |
| 1500C/1000-cu in.<br>ports and ring nozzle    |                                                                                  |                  |                  |                               |
| 2000 psi                                      | 112.1 at 22.5 Hz                                                                 | 109.1 at 45 Hz   | 103.5 at 75 Hz   | ----                          |
| 3000 psi                                      | 116.7 at 20 Hz                                                                   | 112.2 at 40 Hz   | 107.8 at 68 Hz   | ----                          |
| 3800 psi                                      | ----                                                                             | ----             | 111.3 at 62.5 Hz | ----                          |
| 1500C/300-cu in.<br>ports and ring nozzle     |                                                                                  |                  |                  |                               |
| 2000 psi                                      | 110.4 at 35 Hz                                                                   | 109.2 at 62.5 Hz | 105.6 at 100 Hz  | ----                          |
| 3000 psi                                      | 113.3 at 32.5 Hz                                                                 | 112.2 at 54 Hz   | 108.3 at 91 Hz   | ----                          |
| 3800 psi                                      | ----                                                                             | ----             | 110.0 at 82 Hz   | ----                          |
| 1500C/300-cu in.<br>ports, nozzle, and sleeve |                                                                                  |                  |                  |                               |
| 2000 psi                                      | 110.7 at 35 Hz                                                                   | 109.4 at 62.5 Hz | 104.9 at 105 Hz  | ----                          |
| 3000 psi                                      | 112.9 at 30 Hz                                                                   | 111.6 at 50 Hz   | 108.1 at 90 Hz   | ----                          |
| 3700 psi                                      | ----                                                                             | ----             | 109.0 at 82 Hz   | ----                          |

\*Measured at 1000-ft depth.

†Measured at 1200-ft depth.

#### 4. ANALYSIS OF RESULTS

An objective of these tests was to acquire a better understanding of the dynamics of these air guns in an effort to optimize their energy source level through selective configuration changes. As mentioned in Sec. 2, results from the Key West tests suggested that significant amounts of air were unavailable for acoustic source level generation: Either the shuttle action was too fast (thus cutting off prematurely the air discharge from the lower chamber and resulting in reduced source levels), or the air flow was unduly constricted. Consequently, these St. Croix tests were designed (1) to extend the shuttle motion to give the charged air more time to exit and (2) to expedite the air flow from the lower chamber by increasing the exhaust areas and decreasing air flow turbulence.

The extended-port modification provided more area for the discharging air, while the streamlined throat nozzle effectively increased the cross-sectional area at the exit of the lower chamber by decreasing turbulence. The modified upper sleeve provided an opportunity for the shuttle to extend its upward travel before reversing its direction, thus staying open longer.

In testing the effects of the extended ports, we looked at both the radiated source levels and the radiation efficiency, which is the ratio of acoustic energy to the work expended on the ocean in expanding the bubble to its maximum size. The detailed development of radiation efficiency is given in Appendix A.

Figure 3 shows the effect on source level and radiation efficiency of extending the exhaust ports on the 1500C air gun. The effect is seen to be insignificant, indicating either that the original ports were already large enough or that the flow is being restricted elsewhere - such as at the lower chamber/throat. The

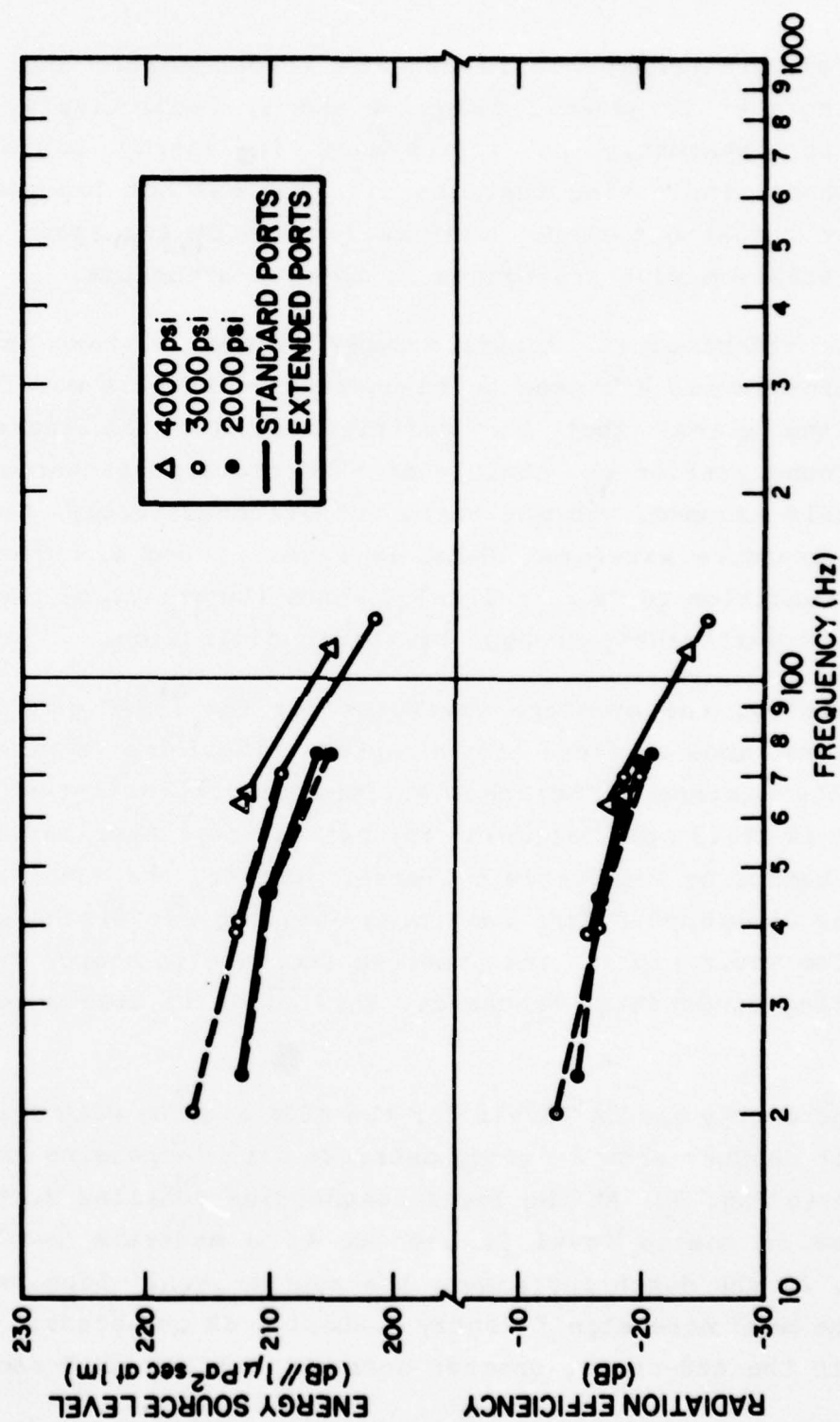


FIG. 3. EFFECT OF EXTENDED PORTS ON ENERGY SOURCE LEVELS OF 1500C AIR GUN WITH 1000-cu in. CHAMBER.

effect of the throat nozzle and the throat nozzle and extended ports together is given in Figs. 4 and 5, respectively. Again, there is apparently no improvement in energy source level performance, indicating that the air flow was not impeded by the ports or throat but rather must be limited by the speed at which the rarefaction wave propagates in the gun structure.

The effect of the modified upper sleeve is shown in Fig. 6. The source levels are seen to be unaffected by this modification, indicating either that the modification did not increase the turn-around time of the shuttle or that the air discharge, as was previously assumed, was not being cut off prematurely. Comparison of the pressure waveforms shown in Figs. 5 and 6 indicates the former condition to be more likely, since the motion of the shuttle was not significantly changed by this modification.

Finally, the pressure waveforms for the 1500C gun, for deep conditions, show evidence of gun repressurization at a time shortly after the maximum air discharge. This result indicates that the shuttle is still open, allowing for partial repressurization of the lower chamber by the bubble collapse. Further, the bubble collapse could be cushioned by the remaining outgoing air discharge. This mechanism would explain the observed decrease in source level with increasing fundamental frequency. This point is discussed further below.

The energy source levels for the 800C air gun with the 2000-cu in. air chamber show a strong decrease with increasing frequency, as seen in Fig. 7. At the lower frequencies (shallow depths), the decrease in source level is seen to be a moderate 1-1/2 dB per octave. As the depth increases, the source-level slope is seen to decrease much more significantly - about 8 dB per octave. The 800C gun with the 400-cu in. chamber does not exhibit this same trend.

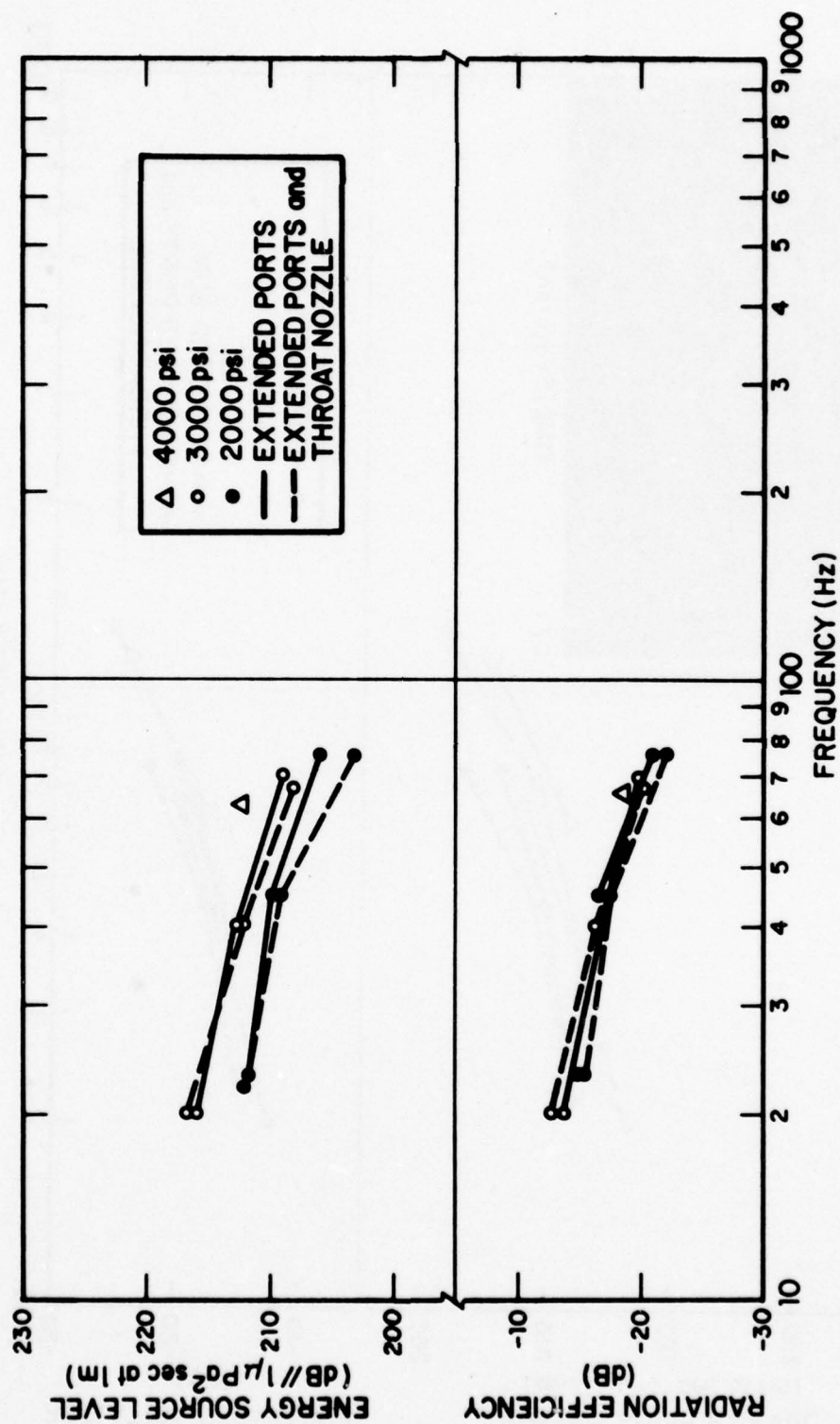


FIG. 4. EFFECT OF THROAT NOZZLE ON ENERGY SOURCE LEVELS OF 1500C AIR GUN WITH 1000-cu in. CHAMBER.

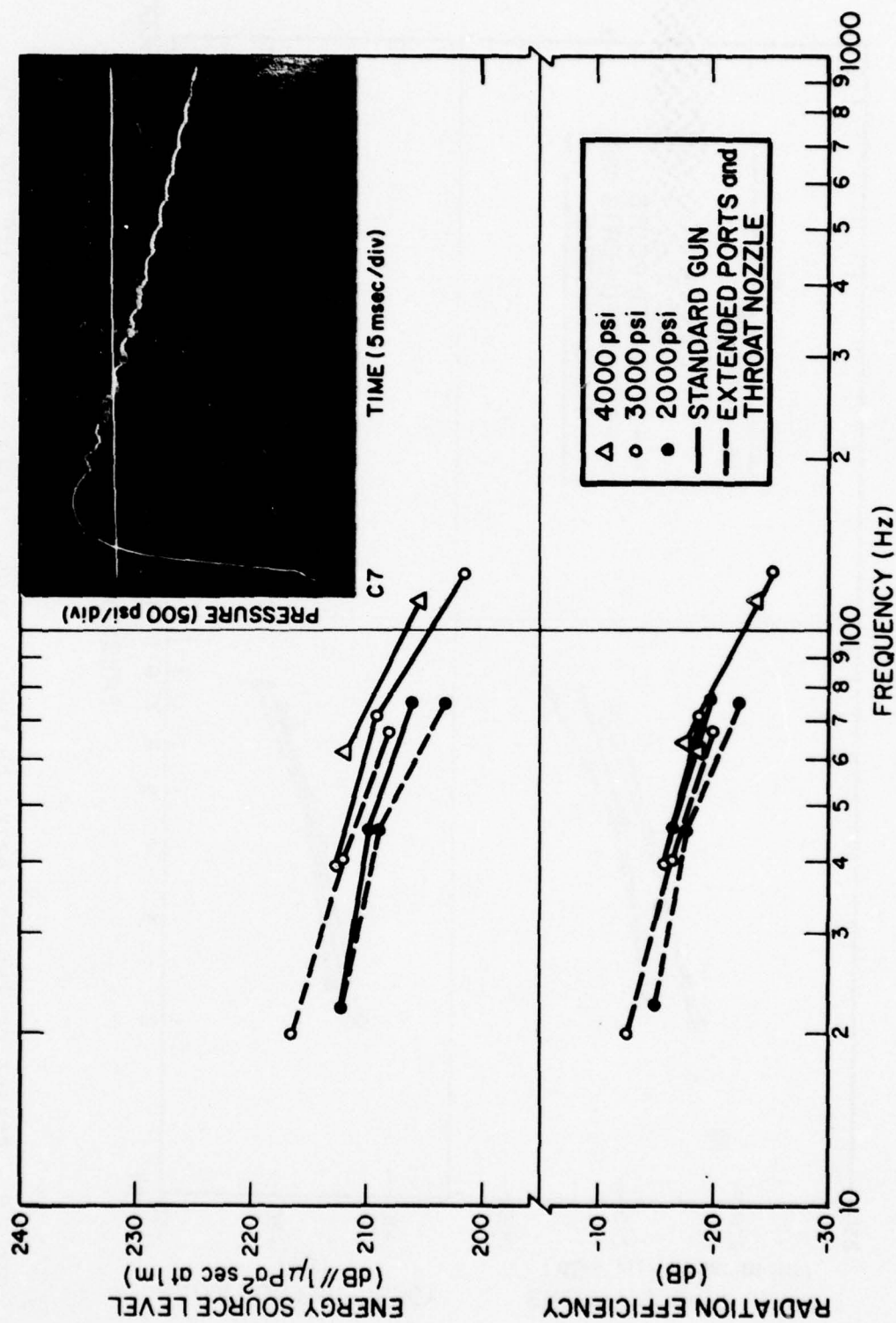


FIG. 5. EFFECT OF EXTENDED PORTS AND THROAT NOZZLE IN ENERGY SOURCE LEVELS OF 1500C AIR GUN WITH 1000-cu in. CHAMBER.

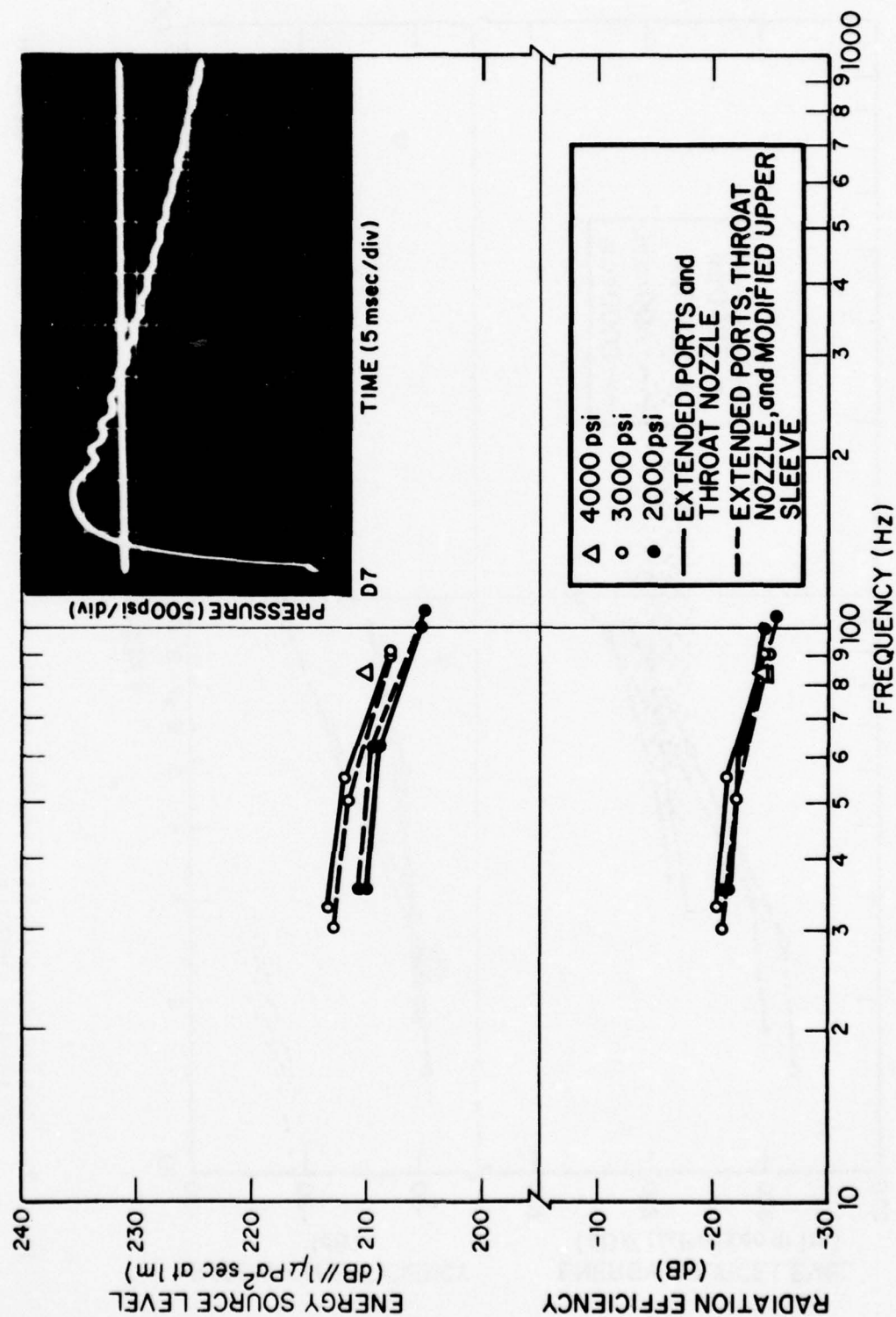


FIG. 6. EFFECT OF MODIFIED UPPER SLEEVE ON ENERGY SOURCE LEVELS OF 1500C AIR GUN WITH 300-cu in. CHAMBER.

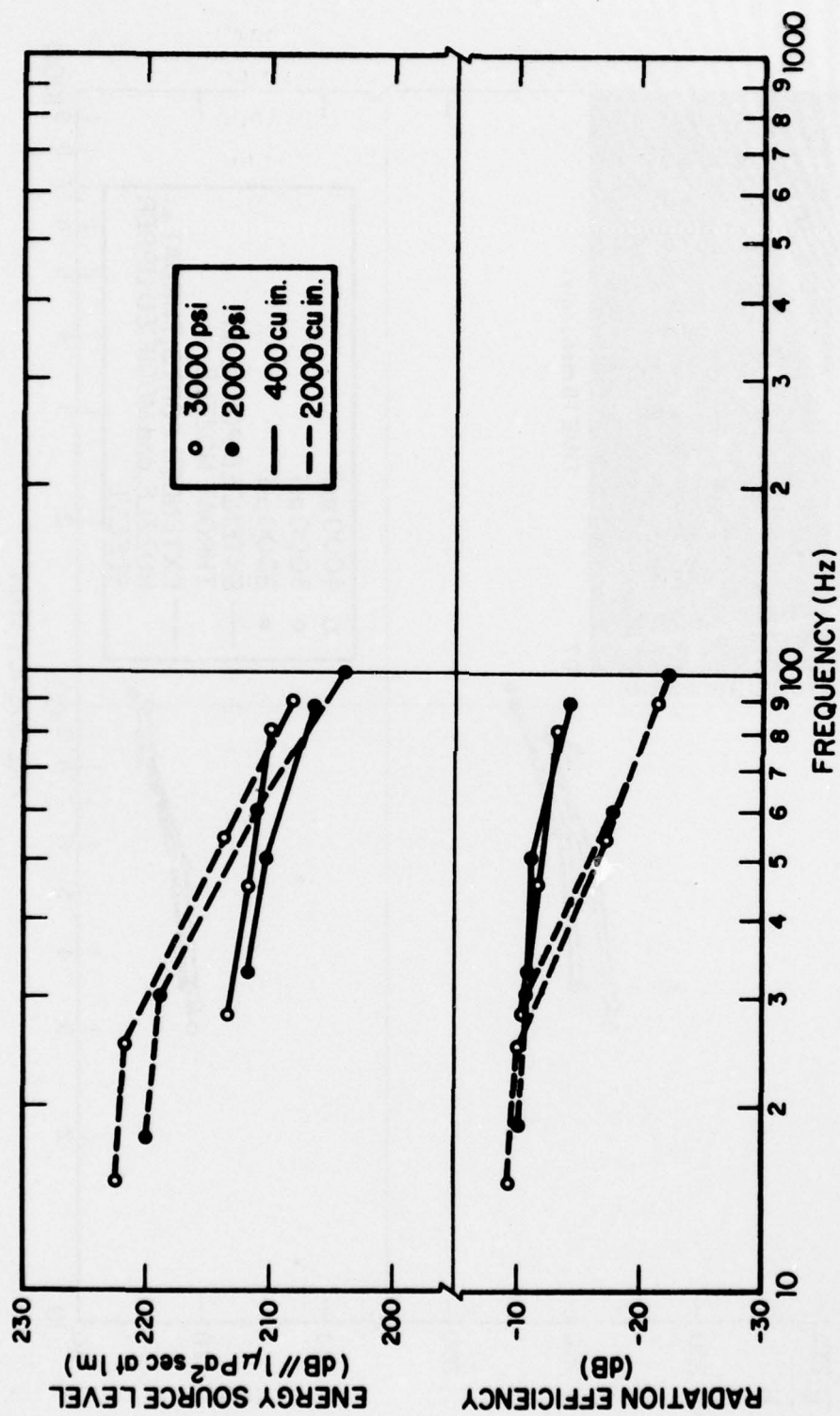


FIG. 7. EFFECT OF CHAMBER VOLUME ON ENERGY SOURCES LEVELS OF 800C AIR GUN WITH STANDARD SHUTTLE.

The difference in source levels due to the difference in air-gun volume (400-cu in. vs 2000-cu in.) is about 7 dB, approximately that seen at the lower frequencies.

The analysis of the lower chamber pressure waveforms suggests that the shuttle is staying open 20 to 25 msec. At the lower frequencies (shallow depths), the time to bubble collapse is sufficiently long to allow the shuttle to close before the bubble collapse forces air back into the gun chamber. At the higher frequencies (deep depths), the time to bubble collapse is much less than 20 to 25 msec; thus, the bubble collapse is cushioned by outflowing air and eventually repressurizes the gun's chamber. The lower-chamber pressure waveforms shown in Fig. 8 for the standard configuration with a 2000-cu in. chamber demonstrate this effect. The slope of 30 psi/msec is associated with the electrical-discharge time constant of the voltage amplifier used with the pressure transducer. Pressure increases having slopes greater than 30 psi/msec are interpreted as bubble-collapse repressurization of the air chamber. No repressurization is observed for the 200-ft (15-Hz) and 400-ft (25-Hz) conditions, since the bubble period is longer than the shuttle closure time of about 25 msec. At 800 ft (63 Hz), some repressurization is evident, with the resultant drop in source level. In this case, the bubble period is slightly shorter than the closure time. At 1600 ft (90 Hz), the repressurization is very evident, as indicated by the slope of 130 psi/msec after the maximum pressure discharge.

This effect is greatest in the large-volume configuration, where a significant amount of air is still discharging at the time of bubble collapse. For the small-volume configuration, the air discharge is essentially complete at the bubble-period timing and there is no outgoing air to cushion the bubble and reduce source levels.

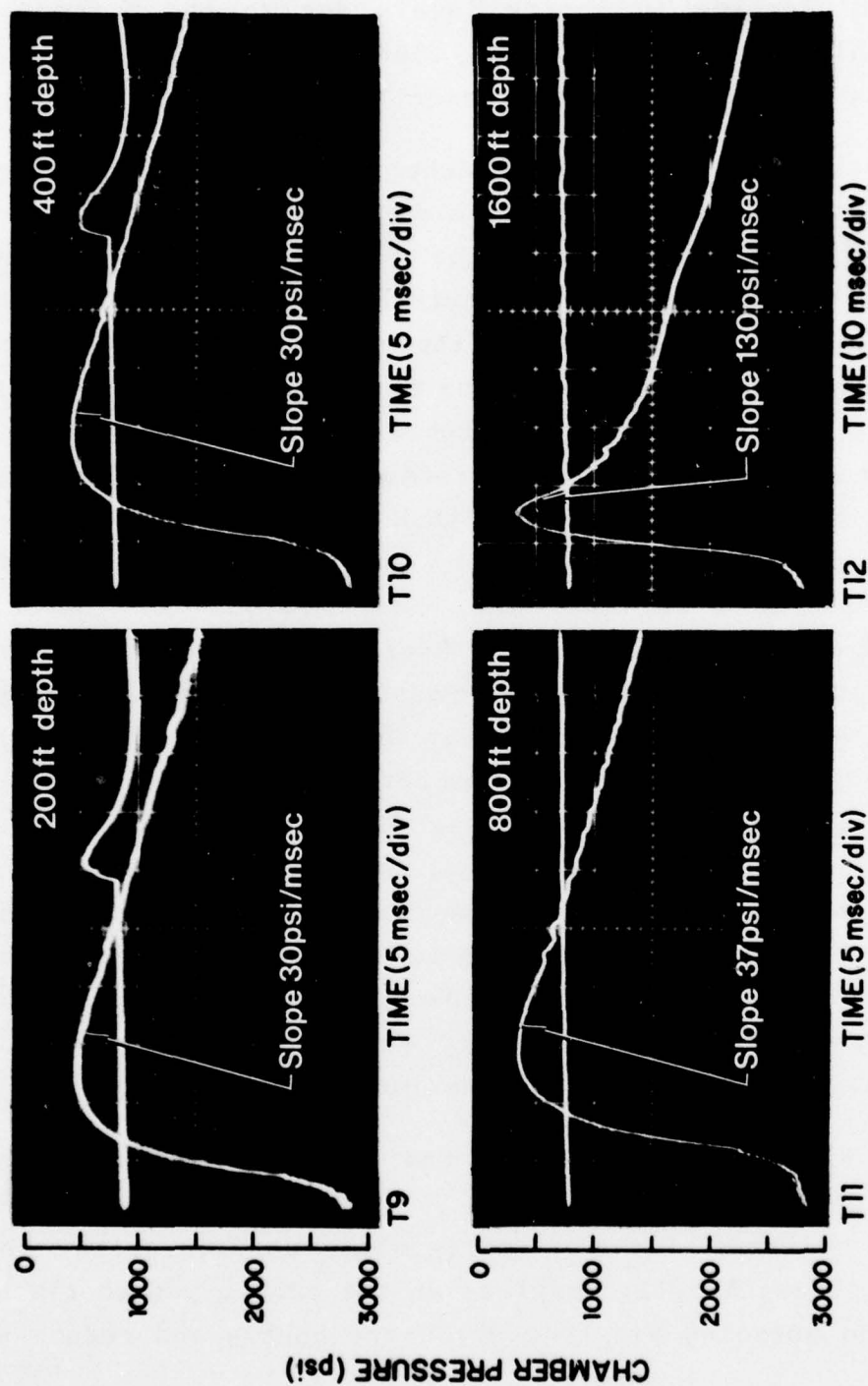


FIG. 8. EXAMPLE OF GUN REPRESSURIZATION DUE TO BUBBLE COLLAPSE: 800C AIR GUN WITH 2000-cu in. CHAMBER AND STANDARD SHUTTLE AT 3000 psi.

A special shuttle having a larger diameter shaft than that of the standard shuttle was tested with the 800C air gun. Theoretical analysis of the air-gun parameters (see Appendix B) showed that the larger shaft provided a larger restoring force on the down motion, thereby decreasing the closure time (as indicated in Fig. B.3). The effect of this larger shuttle on energy source level is seen in Fig. 9. At low frequencies, the effect is minimized, since bubble-pulse cushioning is not an issue. As the depth is increased, the effect of a faster shuttle is seen in larger source levels. The pressure waveform seen in Fig. 9 for the 1000-ft condition using the faster shuttle shows no evidence of repressurization. For this condition, the source level is greater by about 7 dB than for the slow-shuttle case.

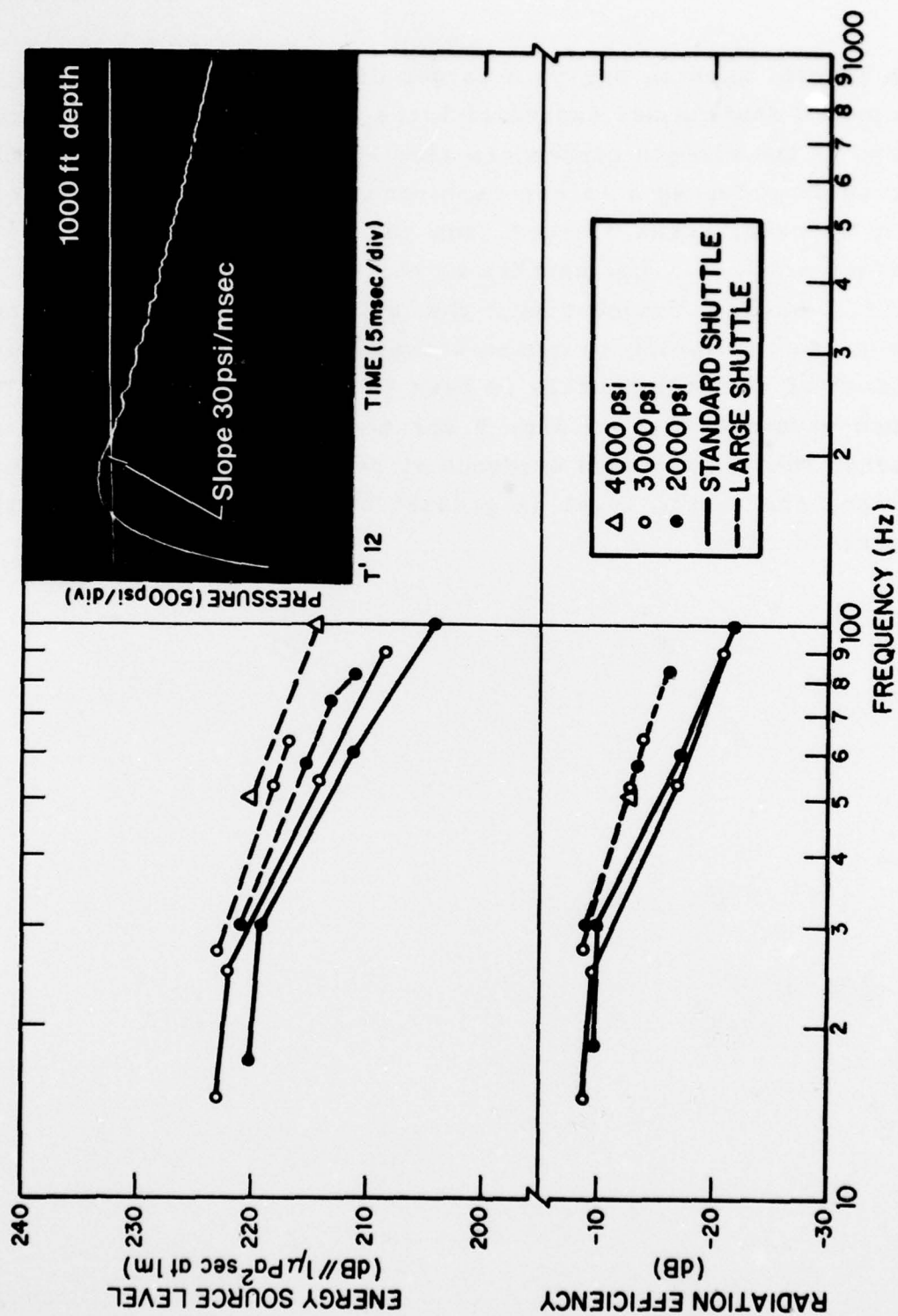


FIG. 9. EFFECT OF LARGE SHUTTLE ON ENERGY SOURCE LEVELS OF 800C AIR GUN WITH 2000-cu in. CHAMBER.

## 5. SUMMARY AND CONCLUSIONS

1. The maximum energy source level for the 800C at 80 Hz is about 216 dB re  $\text{Pa}^2 \text{ sec}$ , for the fast-shuttle 2000-cu in.-chamber configuration at 4000 psi. Similarly, the maximum source level at 80 Hz for the smaller 1500C air gun is about 210 dB re  $\text{Pa}^2 \text{ sec}$  at 4000 psi.

2. The lower-chamber pressure waveforms indicate that the shuttle is not closing fast enough relative to the bubble period, resulting in reduced source levels. Evidence indicates that it is more important to close the shuttle rapidly than to attempt to utilize the remaining air (typically 10 to 20%).

3. The characteristics of air discharge for the various configurations tested did not show port or throat size to be restrictive. About 80 to 90% of the initial charge pressure was discharged in less than 10 msec independent of configuration.

4. These air guns have the potential of higher radiation efficiency, which could be achieved by:

- . Increasing the shuttle speed to prevent the interference of the bubble collapse with the outgoing air discharge, and
- . Eliminating water transport by the upgoing shuttle.

**References**

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## APPENDIX A. CALCULATION OF RADIATION EFFICIENCY

The radiation (acoustical) efficiency of an air gun is defined to be the fraction of available energy that is radiated in the fundamental frequency band. We take the available energy to be the work done on the ocean by the adiabatic expansion of the gas to the maximum bubble radius.

The analysis assumes the initial gas to be in a spherical container having volume  $V_1$ , radius  $r_1$ , and pressure  $P_1$ . The maximum bubble volume is  $V_2$ , where the radius is  $r_2$ , and the pressure is  $P_2$ .

The work  $W$  done on the ocean is  $P_0 V_2$ , where the ambient pressure is  $P_0$ . The adiabatic work of expansion of an ideal gas is equal to  $(P_1 V_1 - P_2 V_2) (\gamma - 1)^{-1}$ , where  $\gamma$  is the ratio of specific heats. Since all of the work done on the ocean is done by the gas, these two quantities of work are equal. Together with the relationship for adiabatic expansion of an ideal gas,  $P_2/P_1 = (V_2/V_1)^{-\gamma}$ , the equality of the two work quantities give

$$1 = (\gamma - 1) (P_0/P_1) x + x^{(1-\gamma)}, \quad (A.1)$$

where the volume ratio  $V_2/V_1$  is equal to  $x$ .

Equation A.1 has been solved for spherical air bubbles initially pressurized to 4000 psi and having initial volumes of both 300 cu in. and 2000 cu in. The maximum bubble radius  $r_2$  in cm and available work  $W$  in MJ are plotted on Fig. A.1 for bubbles at initial depths of from 100 to 1600 ft.

The quantities are plotted as functions of the bubble fundamental frequency in Hz. The bubble period  $T$  is estimated as twice the collapse time of a hollow spherical void, as originally calculated by Rayleigh.

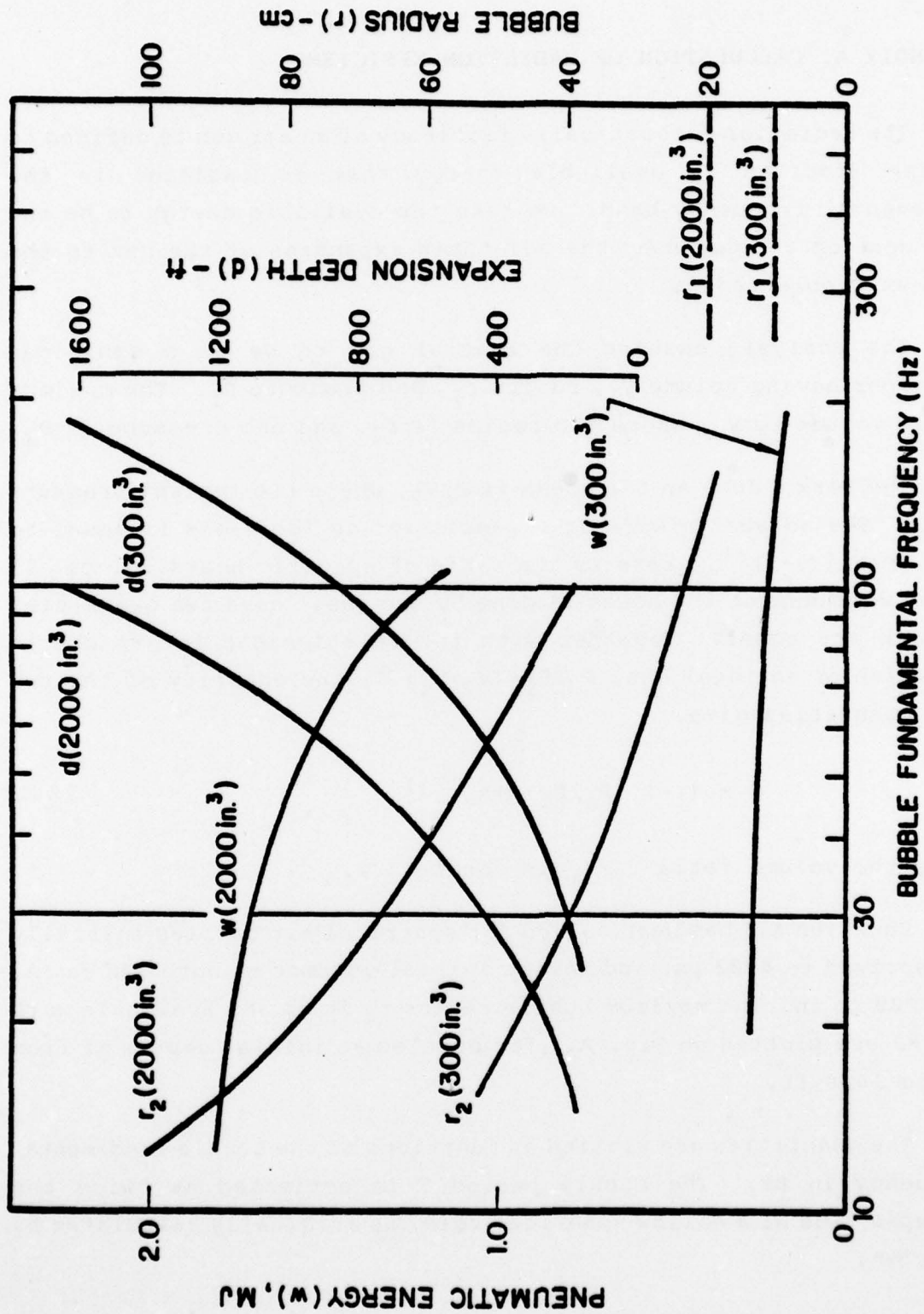


FIG. A.1. ADIABATIC EXPANSION OF TWO SPHERICAL AIR BUBBLES CHARGED AT 4000 psi.

$$T = 1.83 r_2 (\rho/P_0)^{1/2}.$$

The acoustical energy radiated in the fundamental frequency band is calculated from the pressure waveform  $p(t)$ , measured at a radius  $r_0$  and through a bandpass filter centered on the fundamental frequency.

$$E = (4 r_0^2 / \rho c) \int p^2(t) dt.$$

The acoustical efficiency,  $\eta$ , of the air gun is the fraction of available energy that is radiated:

$$\eta = E/W,$$

where the adiabatic work of expansion for an ideal gas is

$$W = \frac{P_1 V_1 - P_2 V_2}{\gamma - 1}$$

## APPENDIX B. DEPENDENCE OF AIR DISCHARGE ON AIR GUN PARAMETERS

The equation for the fractional pressure remaining in an air gun  $t$  seconds after firing may be written:

$$\frac{p(t)}{P_1} = \frac{(At^3+1)^{-7.14}}{[3\sqrt{B}At^2 - At^3 + 3(1-R)BA t - 2AB^{3/2}(1-R/2)+1]^{-7.14}} \quad \begin{matrix} 0 < t < \sqrt{B} \\ B < t < t_C \end{matrix}$$

where

$$A = \frac{P_1 S_L P_W}{M_S V_1} K$$

$$B = \frac{2P_L M_S}{P_1 S_L}$$

$$R = \frac{S_U}{S_L}$$

and

$P_1$  = initial pressure  
 $V_1$  = initial volume  
 $P_W$  = effective port width  
 $P_L$  = effective port length  
 $M_S$  = mass of shuttle  
 $S_L$  = effective area of lower shuttle face  
 $S_U$  = effective area of upper shuttle face  
 $K$  = constant  
 $t_C$  = port closure time =  $B(1+1/\sqrt{R})$

The dependence of these equations on  $A$ ,  $B$ , and  $R$  and, hence, upon the 7 air-gun parameters, has been plotted in Figs. B.1, B.2, and B.3. Figure B.1 shows the dependence on  $A$  alone. Figure B.2 shows the dependence on  $B$ , and Fig. B.3 shows the dependence on  $R$ . In addition to the fractional pressures, the fraction of available mass that is actually emitted is also shown on the same plots.

Figure B.1 shows that variations in  $A$  serve to vary the rate of air discharge. High values of  $A$  discharge more rapidly than lower values and, consequently, the fractional pressure falls more rapidly and reaches a lower level than with a lower value of  $A$ . Thus,  $A$  may be identified as the discharge-rate parameter. Note that the port closure times are unaffected by variations in  $A$ .

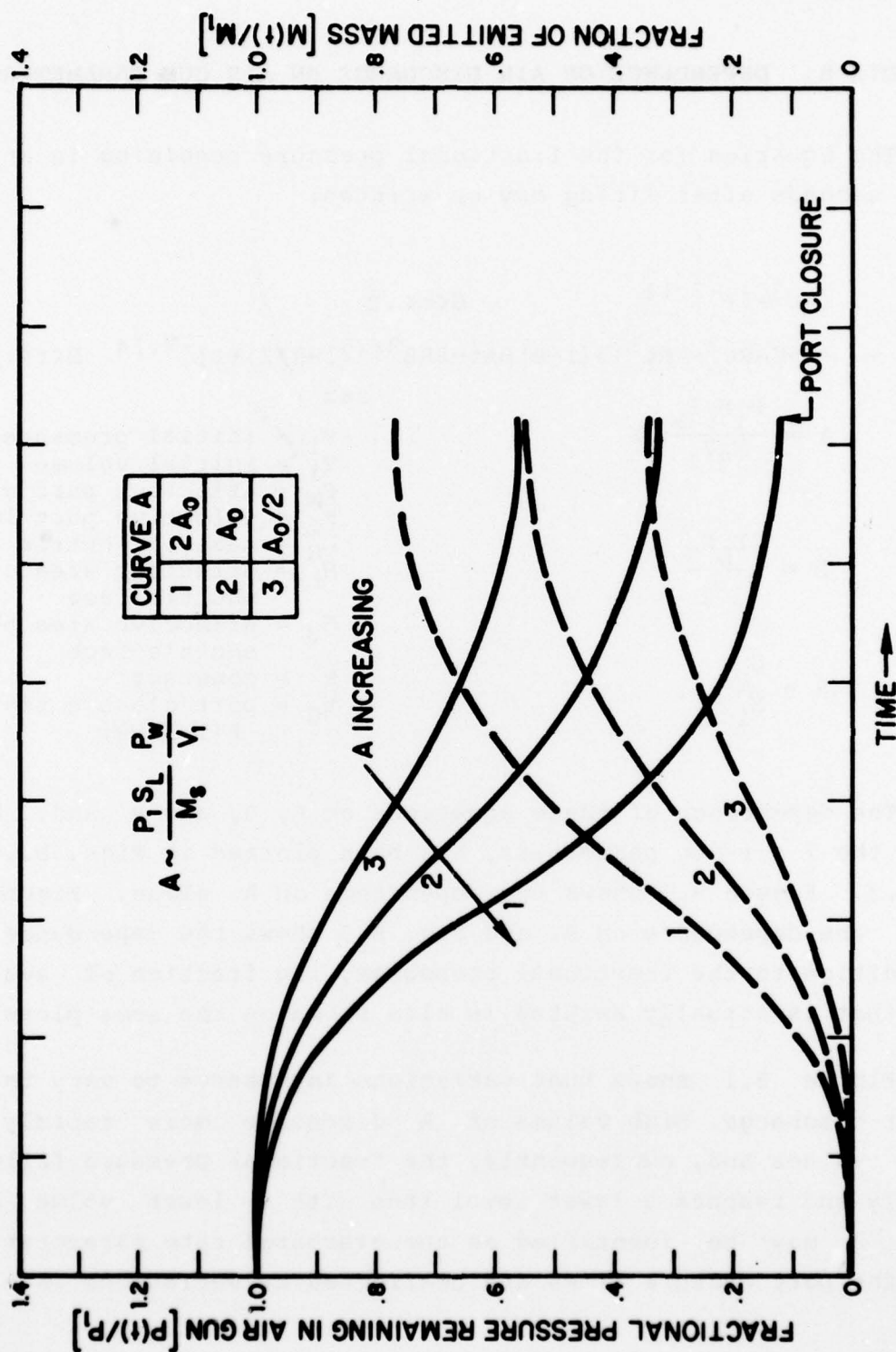


FIG. B.1.1. DEPENDENCE OF AIR DISCHARGE ON RATE OF DISCHARGE.

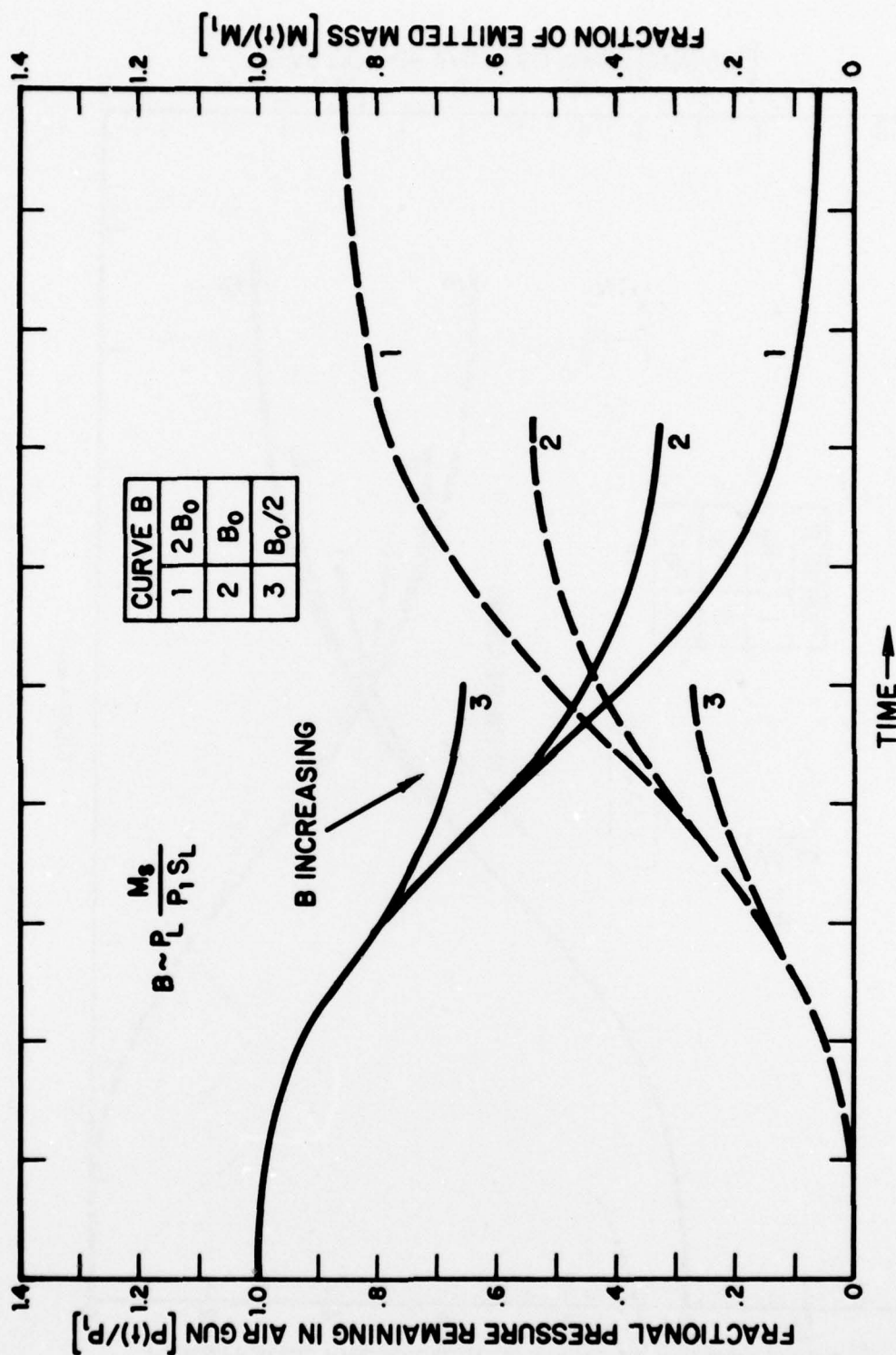


FIG. B.2. DEPENDENCE OF AIR DISCHARGE ON DURATION OF DISCHARGE.

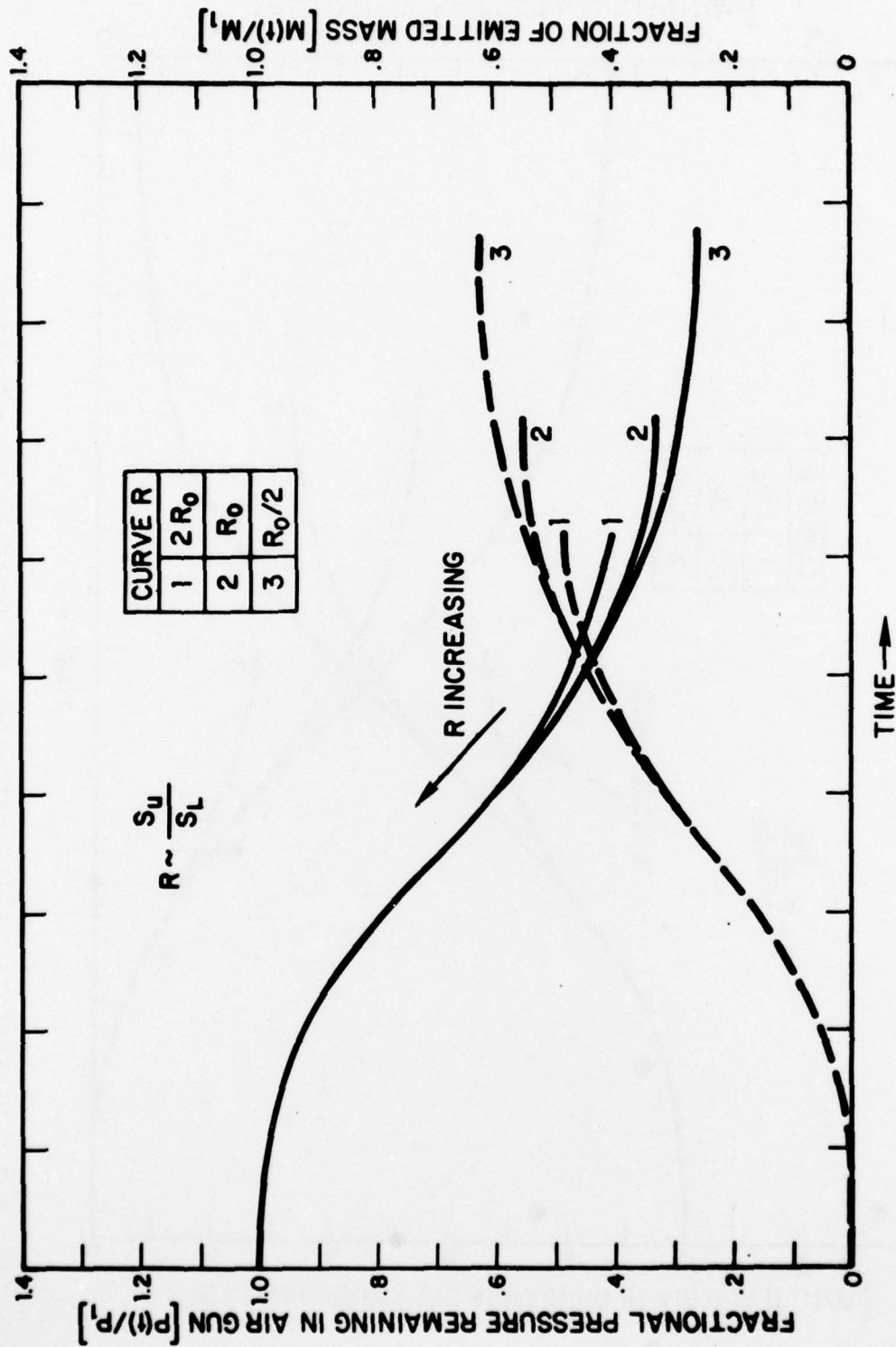


FIG. B.3. DEPENDENCE OF AIR DISCHARGE ON PORT CLOSURE.

B is essentially a measure of the duration of the air discharge.  $\sqrt{B}$  is the time until the shuttle reaches its maximum height and  $\sqrt{B}/\sqrt{R}$  is the time it takes the shuttle to return. As illustrated in Fig. B.2, large values of B imply a long discharge time; consequently, the fractional pressure continues to fall. Note that beyond a certain point further increases in B have little effect on the fractional pressure, since the curve is very flat for large t; i.e., all the air has already been exhausted and keeping the ports open longer is of no value.

R, the ratio of effective shuttle face areas, reflects the ratio between the upward and downward travel times of the shuttle. From Fig. B.3, we see that the main effect of R is on the duration of port opening. Unlike B, however, R has relatively little effect on the fractional pressure or the fractional emitted mass. Since R will not be too different from unity, its effect on pressure will be slight.

Thus, we have loosely identified A with the rate of air discharge, B with the duration (hence, the amount) of air discharge, and R with the duration of port opening (but not greatly affecting air discharge). Note that one gun parameter may affect one or more of the three parameters. In particular, the grouping  $P_1 S_L / M_S$  appears directly in A and inversely in B. Thus, for example, decreasing  $M_S$ , the shuttle mass, will increase A and decrease B; thus, the gun will discharge air at a higher rate for a shorter time. The net effect may be positive or negative, depending on the amount of change. Also note that while in some cases the fraction of emitted mass may decrease with a parameter change (increasing  $V_1$ ), the total amount of mass emitted will increase because of the greater initial mass (proportional to  $P_1 V_1$ ).