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SOME ACOUSTICAL CHARACTERISTICS of UNDERWATER EXPLOSIONS of HYDROGEN-OXYGEN MIXTURES

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Some Acoustical Characteristics of Underwater Explosions of Hydrogen–Oxygen Mixtures

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The acoustic characteristics of a hydrogen–oxygen explosive mixture are investigated in an attempt to find a substitute for solid explosives (e.g., TNT) which will achieve a simple underwater acoustic pulse uncomplicated by bubble oscillations. Data are shown relating the intensity and form of the acoustic signal to the proportions and amounts of gas mixture, point of ignition, hydrostatic pressure, length-to-diameter ratios of chambers, and various chamber appendages and terminations. It is shown that for certain conditions the bubble pulse can be almost suppressed or dissipated. Some experimental techniques and difficulties associated with practical application are included.

INTRODUCTION

UNDERWATER acoustic studies and the geophysical investigation of the substructure of the sea bottom require powerful broad-band sound sources. TNT is frequently used as an explosive sound source. However, in some TNT applications, problems arise in achieving high-repetition rates of detonation under carefully controlled conditions. These have led to investigations into the use of explosive mixtures of gases. Varying degrees of success have been attained.

The purpose of this investigation was to study experimentally the conditions under which a mixture of hydrogen and oxygen could be detonated under water at reasonable repetition rates to give acoustic pulses of sufficient power, simplicity of character, and breadth of frequency spectrum to permit a detailed study and the differentiation of various signal arrivals in multipath propagation. Early in the study, consideration led to the choice of rugged chambers, open at the lower end, as containers for the explosive mixtures. The following results are limited to such containers.

EQUIPMENT AND EXPERIMENTAL CONDITIONS

Although the exact conditions varied from time to time, all acoustic measurements were made at sea in water depths of 30 to 400 m. The receiving system used consisted of two pressure-sensitive hydrophones, with associated amplifiers, connected to two separate tracks of a multichannel magnetic tape recorder. The response of the system was essentially flat from 30 to 10 000 cps. The hydrophone nearest the chamber, besides providing an additional check on the change in acoustic waveform with distance, gave a signal which could be used as a trigger in the analysis. Great care was taken to ensure that no spurious signals or distortions were introduced into the system by virtue of the hydrophones and their cables being situated in the strong sound field.

DESCRIPTIONS OF CHAMBERS USED AND SOME MECHANICAL DETAILS

Six experimental chambers were used. Photographs of two of them are shown on the same scale in Fig. 1. The first model, later referred to as chamber A, is shown on the left. The larger chamber shown on the right will be referred to subsequently as chamber B. Chamber B was used in many trials. The top part of this chamber is detachable. It contains electromagnetic valves for controlling the filling and scavenging of the chamber, and an ignition device employing an automobile spark plug. This interchangeable cap was used with all chambers except A. At the lower end of chamber B is a removable deflector. The two smaller side chambers, situated near the open end, are part of an alternative system for filling the chamber with explosive gas mixture.

A flexible system of filling the various chambers with the desired gas mixtures was required. In most cases, this was achieved by simultaneously injecting the two gases through calibrated orifices. The gases were stored under high pressure in normal cylinders carried on board

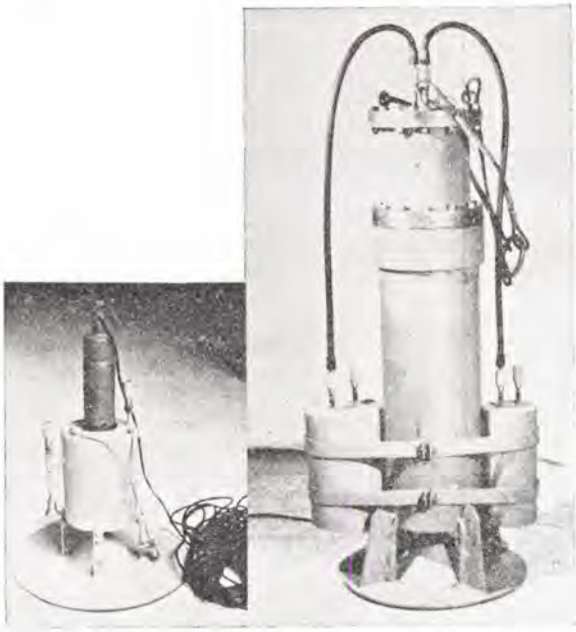

Fig. 1. Experimental chambers A and B (same scale).

ship and were fed in metered amounts through rubber hoses to the submerged chamber. The filling of the chamber was controlled by the electromagnetic valves, mentioned previously, operated remotely from the surface. A scavenging valve provided an opening from the top of the chamber to the sea. With this system, hydrogen and oxygen could be metered into the chamber at any depth of submergence up to 100 meters with an accuracy of about 5%. In many instances, it is possible to make use of a less critical system of filling. When this system is employed, the two side chambers mentioned above are first filled, the larger with hydrogen, the smaller with oxygen, until it is certain they overflow. Subsequently, the gases are pushed into the explosion chamber by hydrostatic pressure when the valves inside the cap are operated.

In all cases, ignition was achieved by charging a number of condensers in parallel and discharging them in series through the spark plug. Sea water was used as a return conductor. The interchangeable filling and ignition cap are shown in Fig. 2. Obviously it must be extremely robust in construction for an operational device.

Figure 3 shows, in schematic form to the same scale, all the different chambers employed in the investigation and their internal dimensions. As can be seen, the length-to-diameter ratios vary over a considerable range, i.e., from 1.5 to 160. All chambers were made of soft steel. Some were fitted with various terminations, and for most such parameters as gas-mixture ratio, volume of mixture, depth of operation or hydrostatic pressure, etc., have been varied. These results are based on approximately 400 explosions.

EXPERIMENTAL RESULTS

The experimental results that follow are discussed in connection with the particular parameter being studied. Sound-pressure levels are given in decibels referred to one microbar at a distance of one meter from the source. The value at one meter has been found by extrapolating the distance from the measuring hydrophone to the chamber back to one meter, assuming a spherical spreading loss. It is possible that finite-amplitude waves exist and may result in higher losses. Finite-amplitude effects have been investigated for solid explosives, but their existence in the present investigation is probably negligible. It is worth noting that the peak pressures involved in the explosive gas-mixture investigation are much smaller than those encountered with solid explosives.

Except where specifically mentioned, the reproducibility of the waveforms was excellent for explosions made under the same conditions. Identical oscillograms have been observed months apart.

Point of Ignition

The influence of the location of the spark plug has been investigated. Usually it was situated at the top of

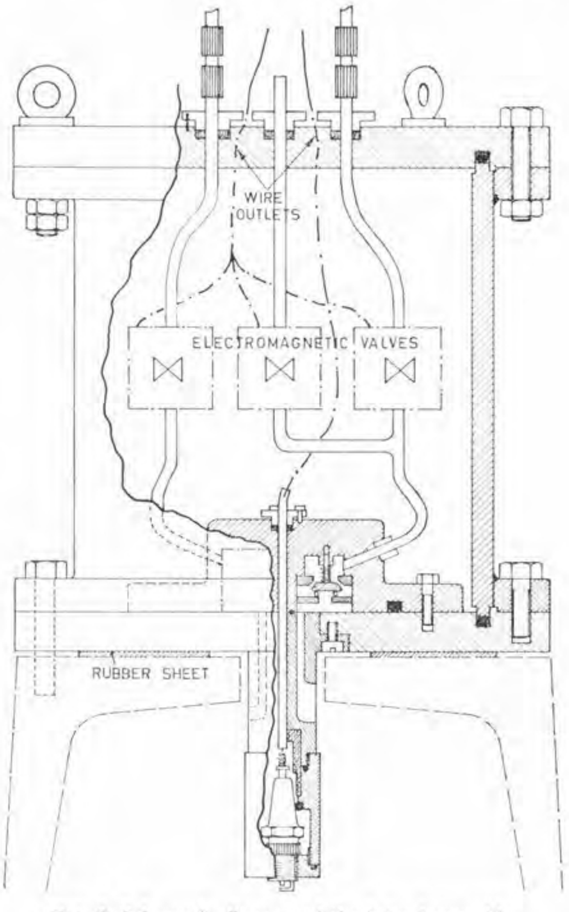

Fig. 2. Schematic diagram of the interchangeable filling and ignition cap.

the tube or chamber, but with tubes B and C results were obtained with the ignition near the middle or the bottom of the column of gas, according to the filled volume, by means of an additional spark plug. The location of this plug is shown on the left-hand side of the tube B and C diagrams in Fig. 3. No appreciable difference was found in the acoustic pulse produced.

Effect of the Length of Mixture in Long Tubes

The position of the gas–water boundary in the chamber will be discussed first because it produces, in many cases, a predominant effect which may mask the influence of the parameter of primary interest. In a given chamber at a given depth, varying the length of the gas mixture (i.e., the position of the gas–water boundary) also varies the mass of gas; however, any resulting differences in intensity were found to be negligible in most cases.

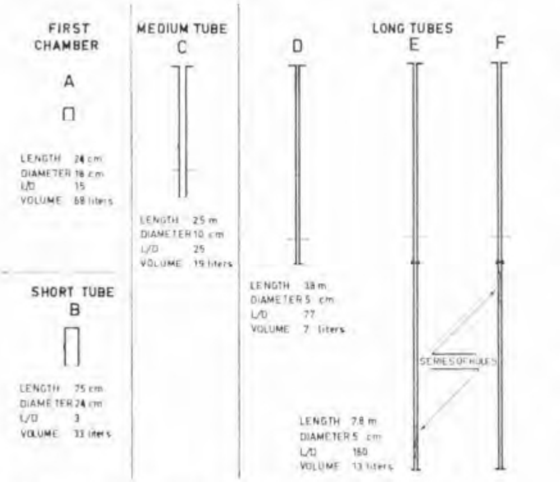

FIG. 3. Scaled sketches of the various experimental chambers used.

Some considerations relating to securing rapid detonation and, hence, a sharper, more intense, initial acoustic pulse suggested that a certain length-to-diameter ratio had to be exceeded by the volume of gas mixture. Consequently, chamber D, a tube of 3.8 m long, 5 cm in diam was tried. The results differed from those expected, and pressure versus time oscillograms are shown on the left of Fig. 4. Below a certain length of mixture in the tube, the signal is weak, irregular, and composed of an incoherent series of rather high-frequency pulses; also, its reproducibility is poor. For a length mixture of 2.5 m, some low-frequency oscillations begin to appear, but this condition turns out to be unstable. For a greater length of mixture, e.g., 3 m, a steeper shock wave is achieved, but strong oscillations occur. The latter is associated with the pulsations of the bubble (herein caused by unburned gases and/or water vapor), a phenomenon well-known from studies involving solid explosives.

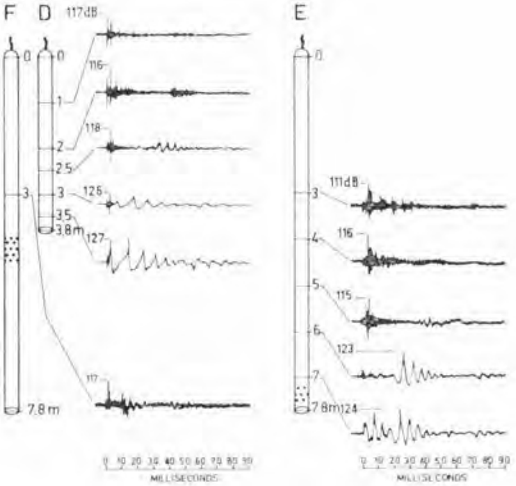

FIG. 4. Variation in character of acoustic pulse with quantity of $2H_2+O_2$ mixture for long tubes (explosions at 40 m).

Since the expected intensification of the shock wave was masked by these oscillations, longer tubes of the same diameter as chamber D were tried (chambers E and F, length each 7.8 m). The results for chamber E are shown in Fig. 4 on the right. When filled with the same length of mixture as chamber D (e.g., 3 m), it produces, instead of a clear shock wave, the same results as with the shorter length of mixture in the shorter tube (D), although the condition is more reproducible. Increasing the length of mixture again produces oscillations, but, as the end of the tube approaches, they become more intense, and the interval between the shock pulse and their onset decreases.

Chamber F, of the same length as chamber E but with a series of holes around its middle, gives a waveform with 3 m of mixture, which is somewhat intermediate to those obtained with tubes D and E. This waveform includes weak oscillations as shown in the bottom oscillogram on the left of Fig. 4.

Thus, when the initial gas–liquid boundary is near the open end or an opening of the chamber, the oscillations of the gas bubble (burned or unburned) which are

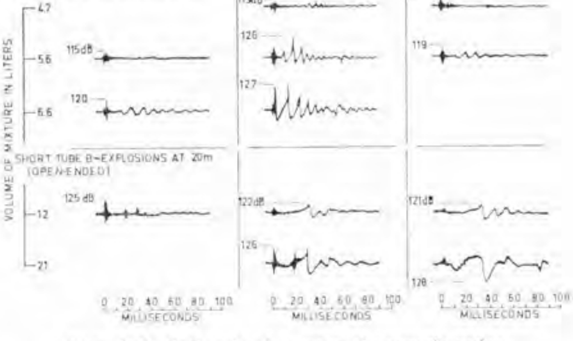

FIG. 5. Variation in character of acoustic pulse with gas–mixture ratio.

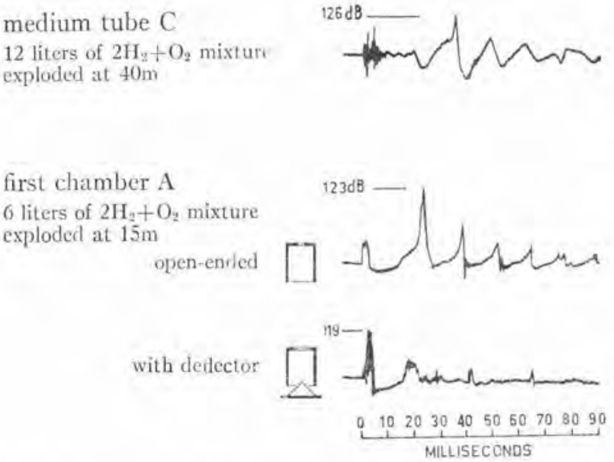

FIG. 6. Character of acoustic pulse produced by several chambers.

forced out are the most important feature following detonation.

Effect of the Proportion of Gases

Different ratios of hydrogen–oxygen mixture have been tried in various chambers. No improvement in the intensity nor simplification of the character of the acoustic pulse has been found by departing from the stoichiometric mixture. For example, a one-to-one hydrogen–oxygen mixture gives a poorer result than a three-to-one mixture, which in turn is not so good as the stoichiometric ratio. The aspect which the stoichiometric ratio produces generally has sharp peaks in the waveform, and all further results concern only this two-to-one mixture of gases. Examples of the effect of different proportions are shown in Fig. 5. Oscillograms are reproduced at the same scale of pressure and time.

Effect of the Shape of the Chamber and of Various Appendages

It was found that no useful waveform could be obtained with long narrow tubes. The signal has a low intensity if the gas–liquid boundary is far from the opening and is highly oscillatory if it is close to it. Also, only small volumes of mixture can be fed into the long thin chamber. A shorter and wider tube, such as chamber C (2.5 m long and 10 cm in diam), allows a greater quantity of gases to be ignited but gives, after a stronger though ragged shock pulse, prohibitive gas-bubble oscillations. The top of Fig. 6 shows a sample oscillogram produced by exploding 12 liters of a two-to-one mixture.

Other chambers, on which measurements have been made, have a much smaller length-to-diameter ratio and have been fitted with several different terminations at their lower end.

The lower part of Fig. 6 shows the results obtained with the small experimental chamber A. Owing to its shape, the gas level inside the chamber is very near the open end, and oscillations are again present. However, the first pulse appears better defined. A deflector at the open end of the chamber damps the oscillations.

Still better results have been obtained with chamber B, which, for this reason, was more extensively investigated. The dimensions of this short chamber are such that, when a reasonable amount of gas is injected, the column of mixture has a length approximately equal to the diameter, and the gas level is not too near the open end of the tube. Various appendages or terminations were tried with this chamber in an effort to simplify the acoustic signal it produced. The results achieved are summarized in Fig. 7. The familiar slowly decaying oscillations accompany detonations in the open-ended condition. If a cone-shaped deflector, having a 25-cm-diam base welded to a circular plate of 50-cm diam, is attached to the lower end of the chamber, the oscillations appear to be broken up although they are of the same frequency, and their onset occurs at about the same time interval after the initial shock wave. When the lower end of chamber B is closed with a thick plate, perforated with 40, 14-mm-diam holes, the resulting

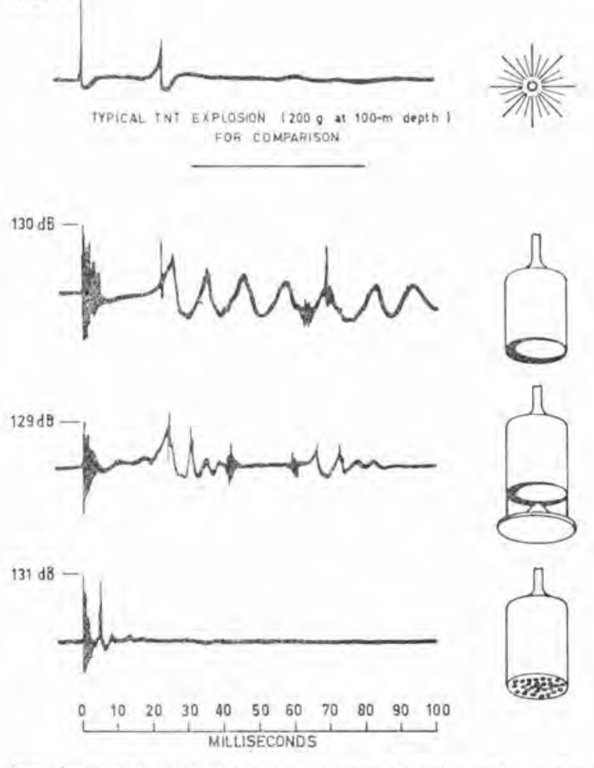

FIG. 7. Variation in character of acoustic pulse with various chamber terminations for short tube B (explosions at 40 m with 12 liters of $2H_2+O_2$ mixture). The acoustic pulse shape from an explosion of 200 g of TNT, recorded at the same distance as for the chamber (40 m) and in the same frequency band, is given for comparison. The indicated peak level of the shock wave has also been standardized to the value at 1 m, assuming this time that between 1 m and the recording range the shock-wave peak pressure varies as $1/r^{1.12}$.

waveform is completely different from all others and is reasonably simple as desired.

Effect of Varying Volume at a Given Depth

In a given chamber, the effect of varying volume at a given depth is usually masked by the effect of the position of the gas–water boundary, as discussed previously. However, in the case of chamber B, terminated by the perforated plate, the character of the acoustic pulse does not change appreciably, and increases of peak pressure accompany increases in volume, as shown in Fig. 8. This is to be expected from energy considerations.

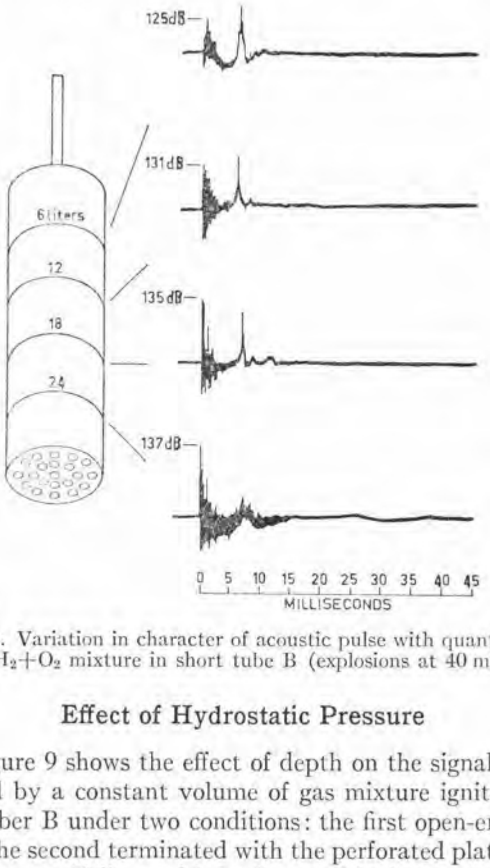

FIG. 8. Variation in character of acoustic pulse with quantity of $2H_2+O_2$ mixture in short tube B (explosions at 40 m).

Effect of Hydrostatic Pressure

Figure 9 shows the effect of depth on the signal produced by a constant volume of gas mixture ignited in chamber B under two conditions: the first open-ended, and the second terminated with the perforated plate. In both cases, 12 liters of 2:1 mixture of hydrogen–oxygen were used. As expected, increasing the depth produces an increase in peak sound-pressure level due to greater mass of gas, a shortening of the time interval between shock pulse and the first bubble pulse, and an increase in the frequency of the bubble pulses.

Discussion of Numerical Values and Spectrum

Results obtained with chamber B and its various terminations represent the best and most reproducible data from the investigation. As such, they will be considered in greater detail.

With 12 liters of 2:1 hydrogen–oxygen mixture at 40-m depth, the peak sound-pressure level for the shock wave lies in every case between 130–132 dB. For comparison, 200 grams of TNT gives a level of 167 dB. The energy spectra, corresponding to each of three conditions of chamber termination, are given in Fig. 10. For the open-ended tube, the peak value of energy occurs at approximately 100 cps, which corresponds to the fundamental frequency of the bubble pulse. When the chamber is fitted with the deflector, this peak value is significantly attenuated. When the chamber is terminated in the perforated plate, this low-frequency peak is almost completely suppressed. It should be noted that the portion of the spectrum lying between 200–10 000 cps remains practically unchanged under all conditions. Detailed analysis shows this portion of the spectrum to be due almost exclusively to the shock wave. Its total energy is not altered by the various chamber terminations, but its shape varies slightly.

It is probable that the shock waves include some vibrations of the chamber which is excited by the explo-

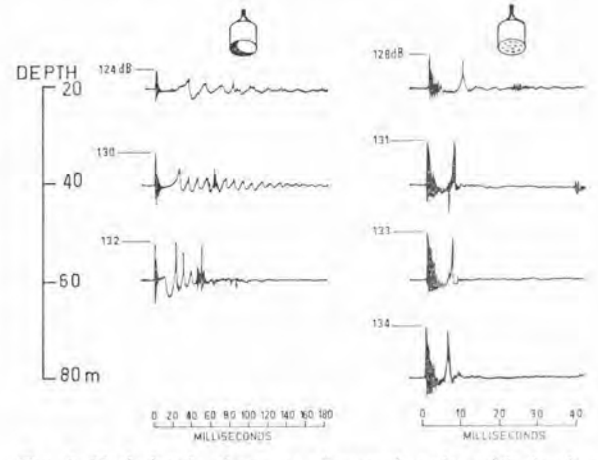

FIG. 9. Variation in character of acoustic pulse with depth of explosion of 12 liters of $2H_2+O_2$ mixture for two types of terminations of short tube B.

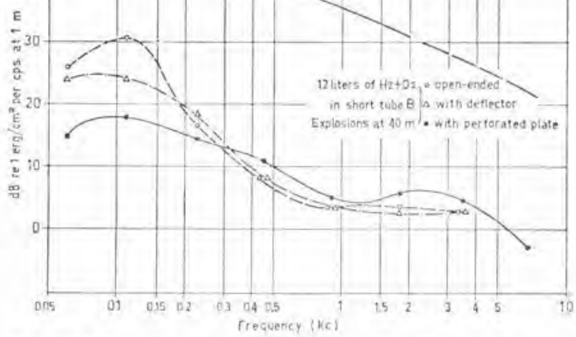

FIG. 10 Energy spectra of the acoustic pulses from short tube B in various conditions. The spectrum from the explosion of 200 g of TNT (the record of which is given in Fig. 7) is given for comparison. Values are referred to the distance of 1 m, using the simplification that the energy e varies with range r as e/r at all frequencies.

sion. Also, some part of the radiated energy may have been transmitted through the walls of the chamber. No attempt was made to confirm these theories.

If directivity effects are assumed to be negligible at these frequencies, the following values for total acoustical energy are found:

(a) For the open chamber: 1600 J of which 300 J are accounted for by the shock wave and 1300 J by the bubble pulses.

(b) Chamber B with deflector: 700 J total.

(c) Chamber B terminated with the perforated plate: 400 J total.

The efficiency of conversion from chemical to acoustical energy is poor, and in no case is it as much as 1%. Solid explosives are considerably more efficient.

CONCLUSION

The study has demonstrated that, by proper design of chamber, it is possible to obtain a simple, relatively clean, acoustic signal and to dissipate interfering bubble pulses without the loss of energy in the remainder of the frequency band.

From this investigation, one must conclude that the efficiency of a sound source, using an explosive mixture of hydrogen and oxygen, will be low in any moderate-sized device. Solid explosives are clearly better.

As a practical sound source for precisely timed repetitive operation under seagoing conditions, the simple chambers investigated suffer from a number of obvious disadvantages. However, it does seem likely that most of these could be overcome with further development and engineering.

ACKNOWLEDGMENTS

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