THE INTERACTION OF CO_2 LASER RADIATION AND WATER

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ABSTRACT: The output of a CO_2 laser was focused upon the surface of water to study the generation of sonic waves for air to water communication. A rotating mirror Q-switch system and an electrical pulsing system were used to obtain laser pulses. Continuous wave output was also investigated.

In each case, there were three obvious effects from the interaction: (1) generation of an acoustic wave in air, (2) generation of an acoustic wave in water, and (3) generation of a circular surface wave. The best efficiency for producing a water acoustic disturbance was about 10^{-6}. One part in 10^4 of the generated acoustic energy couples into the water, while the balance is dissipated in the air. Placing a transparent window on the surface enhanced the water acoustic wave so that it was comparable in energy to the air acoustic wave.

It is concluded that though the process is inherently very lossy, further improvements in laser engineering may yield better results.

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The characteristics of CO_2 laser-induced acoustic pulses in water
reported here were made by the Infrared Group of the Solid State
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                              GEORGE G. BALL
                              Captain, USN
                              Commander

                              W. W. SCANLON
                              By direction

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THE INTERACTION OF CO_2 LASER RADIATION AND WATER

I. INTRODUCTION

The purpose of this study was to investigate the interaction of a CO_2 laser, both focused and unfocused, with the surface of a body of water. The ultimate intent was to produce an acoustic pulse in the water of sufficient amplitude and low enough frequency so that it could be detected by an underwater acoustic system.

Work done previously at the U. S. Naval Ordnance Laboratory by Bell and Christian[1] with neodymium and ruby pulsed lasers showed that high pressure acoustic shock waves could be generated by the interaction of impurities in water and the laser radiation. However, because of the high frequencies generated by the very short laser pulses, the acoustic waves did not propagate well through water. Since the frequency of acoustic radiation tends to decrease with an increase of the interacting volume, laser radiation was sought which would be absorbed by the water itself in a proper amount to yield acoustic waves of low frequency. Because of the high absorption coefficient of water for CO_2 laser radiation (10.6_μ) and the high average powers obtainable with CO_2, it was felt that the present study might be fruitful.

Previous attempts[1] in the area of CO_2 laser-water interactions were not complete either experimentally or theoretically, and the hope of this study was to add to the knowledge of the interaction in both respects. Work had been carried out with a 100 watt CO_2 laser, both Q-switched and modulated continuous wave, but the results were insufficient to allow an analysis of the problem. The intent, therefore, was to investigate as thoroughly as possible the various effects of the interaction and to determine the coupling efficiency for conversion of incident radiation to acoustic energy. In order to control the amount of incident energy and the time in which it is delivered, pulse techniques were considered applicable.

II. EXPERIMENTAL PROCEDURES

The two methods of pulse generation used were Q-switching and electrical pulsing of the laser. As wide a range as possible of pulse amplitudes and lengths was desired with our systems in order to determine the parameters of the interaction.

Initial work was done with a 120Hz Q-switched laser shown in Fig. 1. The discharge tube was 1.8 meters long with a 1.5 inch bore and was water cooled. Continuous wave operation at about 30 watts was possible with internal mirrors. To convert to Q-switched operation, the 100% mirror was replaced with an antireflected germanium window and an external rotating mirror was added. The lens used for focusing the laser beam was made of antireflected Irtran II and it reduced the beam to a spot of approximately 0.6 mm^2 area. The motor was a 60rps synchronous motor and, since the Q-switch mirror was plane parallel and gold coated on both sides, the output was 120 pulses per second.

Subsequently, the 60 rps motor was replaced with a variable speed motor so that the pulse length and height could be varied. This replacement gave a variable Q-switching pulse rate of 12 to 120 sec^{-1}. The major difficulty in using much faster motors was that the vibration of the mirror disturbed cavity alignment to the point where no Q-switching occurred.

Later work was done with a one meter, 10 watt c.w. laser made at the Naval Ordnance Laboratory. A smaller Q-switching system was used with it since its bore was only about 1.0 cm. This could be operated with a 200 rps motor without excessive vibration. The laser was cooled with a circulating refrigerant.

Finally, pulses were produced electrically by discharging a capacitor across the laser tube, which had been optically aligned beforehand. The system is shown in Fig. 2. The spark gap was an EG&G GP14A and the trigger and EG&G TM-11. It was possible to obtain 20 pulses per second with the power supply available. An aperture was used to vary the output power.

Two methods were used to measure the laser pulses. First, a power meter was used to measure the average power coming from the laser. Second, a HgCdTe detector cooled to 77°K was used to display the output pulses on an oscilloscope as a function of time. The 50 nsec response time of the detector was more than adequate for the pulses obtained.

To measure the acoustic pulses, two hydrophones were used at different times. The first was a USRL H17 with a sensitivity of -99db re 1 volt/μbar and linear response to 50 kHz. The second, smaller in size, was an SSQ-23 Goulton hydrophone with a sensitivity of -90db re 1 volt/μbar and linear response to 20 kHz. In all cases the detectors were placed 5 cm. from the source.

Since the wide band signal output of the hydrophone was nearly equal to the ambient noise level when Q-switching a frequency analyzer was used for recording the hydrophone output with a preamplifier of gain 100x. The output was the

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main frequency component of the signal, determined by the difference between the analyzer signal with and without the acoustic pulse present.

III. EXPERIMENTAL RESULTS

When the unfocused laser beam was aimed at the water, no discernable acoustic signal was obtained for any case, i.e. Q-switched, electrically pulsed, and c.w. However, upon focusing the beam on the surface, for every case, three effects were noticed: First, there was a small water wave set up on the surface, second, there was an acoustic wave generated in the water, and third, there was an audible acoustic wave or "buzz" generated in the air. These effects resulted from the boiling of the water c/er a very small area on the surface of the water at the focal point of the lens. The following is a quantitative description of the water acoustic wave generated by the various laser pulses.

The output pulse of the laser Q-switched at 120 sec^{-1} was approximately $2\mu sec$ in length, 1 mJ in energy, and 1 Kw peak power. Its shape was approximately triangular as shown in Fig. 3. Correspondingly, there was an acoustic pulse train of central frequency of 3.6 kHz and peak pressure of about 10 μbar at a distance of about 5 cm from the source. It decayed away over a period of several milliseconds, the major portion disappearing in about one millisecond.

By varying the pulse rate and consequently the laser pulse length and amplitude of the Q-switch pulses, the experimental points shown in Fig. 4 were obtained. They are a plot of the peak pressure and calculated energy in the acoustic pulse as a function of the energy in the incident laser pulse. (The relations used to calculate the energy in the acoustic pulse are discussed in the following section.) The pulse lengths, T, pulse rates, R, and peak amplitudes, W, for the laser pulses are shown in Table I:

TABLE I

T(μsec)	R(sec^{-1})	W(KW)
2	60	1
4	30	.9
10	12	.8

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Since for the long pulses, the shape became complicated, the values are not related by a single geometric relation to the total energy of the pulse.

After switching from the Q-switch system to the electrical pulsing system, the data shown in Fig. 5 were obtained for the peak acoustic pressure and acoustic pulse energy as a function of the amplitude of incident pulse energy. For each case, the pulse repetition rate was 20 sec^{-1}. Photographs of both laser and acoustic pulses appear in Fig. 6. Since the shape of the acoustic pulse in Fig. 6 is about the same for the acoustic pulses generated in every case, the photograph is representative of all the data. Although it is not clear in the photographs, there was a delay of approximately eighty microseconds between the beginning of the acoustic pulse and that of the laser pulse; thus, only the initial part of the optical pulse contributes to acoustic generation.

In the case of c.w. output focused at the water surface, similar acoustic pulses were obtained, since the water boiled spontaneously. Fig. 7 shows the peak acoustic pressure and pulse energy as a function of the laser power. The repetition rate of the acoustic pulses was between 50 and 100 sec^{-1} and sporadic within this range. As before, their main frequency was about 3.6 kHz and their duration about 1 μsec, but there was an additional large frequency component at 2.7 kHz. A time delay of about a second was noticed between application of the c.w. radiation and the beginning of acoustic output, probably because of the heating of a relatively large amount of water before boiling.

IV. THEORETICAL CONSIDERATIONS

In this section we attempt to interpret the experimental results. Although a complete analytic solution of the problem is very difficult, it is possible for the theory to give reasons for the interaction and plausible relations which govern the efficiency of the process.

First, consider the thermodynamic effects when the laser pulse impinges upon the water surface. The intensity distribution of radiation in the focal area of the lens on the water surface is $I(x, y, t)$, where x and y are mutually perpendicular horizontal directions parallel to the water surface and t is time. $I(x,y)$ will be largest at the origin or focus, $(0,0)$, and decrease to approximately 10% of $I(0,0)$ at a distance $r = (x^2 + y^2)^{1/2} = 0.5$ mm for our lens. Although the intensity distribution will depend on the optical mode pattern of the laser beam, this effect is not easy to measure and will be neglected.

Since water is almost totally absorptive at 10.6 μ, the intensity of radiation below the surface of the water is:

$$I(x, y, z, o) = I_o(x, y, o)e^{-\alpha z}$$

where z is the depth beneath the surface and α is the absorption coefficient of the water at 10.6 μ ($\approx 0.1\mu^{-1}$).

According to Gournay[3], the temperature distribution beneath the surface of the water is

$$\theta(x, y, z, t) = \frac{\alpha \int_o^T I_o(x, y, t) dt e^{-\alpha z}}{J\rho S} \tag{1}$$

where T is the pulse length, J is the reciprocal of the fraction of incident radiation turned into heat, ρ is the density of water, and S is its specific heat. Eq. 1 assumes that thermal conduction may be neglected.

To determine the effect of thermal conduction, consider the basic heat equation:

$$\frac{\partial \theta}{\partial t} = \frac{k}{\rho S} \nabla^2 \theta + H \tag{2}$$

where k is the thermal diffusivity and $H = Q/\rho S$ where Q is the heat absorbed.

For the case of an infinitesimally thin disc of absorbed heat on the surface of water at an air-water interface, which is an idealization of the case at hand, the solution of 2 is:

$$\theta = \frac{2\int_0^T I(x, y, t)dt}{J(P_a S_a \rho_a + P_w S_w \delta_w)\pi 1/2} \cdot e^{-z^2/\delta_a^2}, \qquad z > 0$$

$$\tag{3}$$

$$\theta = \frac{2\int_0^T I(x, y, t)dt}{J(P_w S_w \delta_w + P_a S_a \delta_a)\pi 1/2} \cdot e^{-z^2/\delta_w^2}, \qquad z < 0$$

It is assumed that T, the duration of the radiation, is also infinitesimal and

$$\delta = \frac{4kt}{\rho S} \qquad (4)$$

The a's refer to air and w's refer to water. For water, $k=1.4 \times 10^{-3}$ (cal/cm^2-sec)/($^{\circ}$C/cm), $\rho =1.3$ mg/cc, S=1.0 cal/g/$^{\circ}$C. For air, $k=6.1 \times 10^{-5}$ (acl/cm^2-sec)/($^{\circ}$C/cm, $\rho =1.3$ mg/cc, S=.24 cal/g/$^{\circ}$C.

Thus, δ_w is $\sqrt{5.6 \times 10^{-3}t}$ and δ_a is $\sqrt{7.5 \times 10^{-1}t}$. Thus, as long as δ_a and δ_w are much less than the absorption depth, $1/\alpha$, 10^{-3}cm, thermal diffusivity will not change the temperature profile given by Eq. 1. However, as the laser pulse length increases, δ_a and δ_w will become important parameters. Although the solutions of Eq. 2 and Eq. 3 are valid only for laser pulses short compared to the time needed for significant thermal diffusion, it is an approximation of the exact solution, which is not a simple task to ascertain in general. The general solution can be found by an appropriate integration using the Green's function, which we have not performed since the laser intensity distribution $I(x, y, z, t)$ is not well enough known. If T is taken to be about 100 μsec, which is a reasonable laser pulse length, then $\delta_a(T)$ is about 10^{-2}cm and $\delta_w(T)$ is about 10^{-3}cm. Thus, during the application of radiation to the water surface, there will be conduction to the air and water sufficient to change the temperature profile of Eq. 1. Therefore, a loss factor which is a function of the pulse length must be included in Eq. 1.

The temperature profile which results from the interaction will cause both stresses in the water and, if the energy density is greater than about 2.5×10^3 J/cc, boiling, Gournay[3] has solved the thermal stress equations for the case where the water is stressed, but not boiled, and found that for water at a free surface, the efficiency η is:

$$\eta = \frac{E_{acoustic}}{E_{laser}} = 1.83 \times 10^{-11} I_0 F(\alpha cT) \qquad (5)$$

where I_0 is expressed in watts/cm^2 and $F(\alpha cT)=0.1$ when $\alpha cT=1$. F decreases sharply as [αcT] deviates from unity. As usual, α is the absorption coefficient, c is the velocity of sound in the medium, which for water is 1.5×10^5 cm/sec, and T is the length of the laser pulse. An efficiency η greater than 10^{-7} can not be obtained with the parameters of the present system. Since this optimal efficiency occurred for the shortest pulses, 0.2 μsec, for which the average power was only 50 mw, we may conclude that the acoustic signal generated fell far below the wideband ambient noise level so that no signal was detected.

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However, at higher pulse energies, the condition was reached where there was sufficient ene gy to cause boiling. Whe the water vaporized, the resulting high ressure gas bubble caused a reverberation which generated n acoustic wave in the water and in the air, and also a small wate wave.

The relations describing his explosive process at the interface between air and water are too difficult for an analytic solution. However, the interaction may be idealized as a point pressure source. Although the frequency of oscillation was fairly constant for all the pulses, the behavior does not appear to be mode generation because the signal falls off with increasing distance. Also, the signals are not of a single frequency, but rather spread out over a band of 1.5 kHz at a center frequency of about 3 kHz.

In order to determine the amount of energy associated with the acoustic pulses, the relation derived by Davis[4] for a point pressure source was used. Since the dimensions of the source of the pressure pulse were small compared to the distance at which they were measured, the point source idealization was proper. The acoustic impedance Z of the water at a distance r from the point source, where Z is the ratio of the pressure p to particle velocity ξ at r, is

$$Z = \rho c$$
$$c = \text{speed of sound in water} \qquad (6)$$
$$\rho = \text{density of water}$$

The power associated with the water acoustic pulse is $\frac{p^2}{Z} 2\pi r^2$; and the energy contained in the pulse $\frac{2\pi r^2}{Z} \int_0^T p^2 \, dt$, where T is the estimated cutoff for the acoustic pulse.

Although a detailed integration needs to be carried out to arrive at the exact energy value, estimated calculations were made. There was also the possible error due to the fact that the size of our detectors was on the order of the distance between them and the source.

The acoustic pulses generated in the air were measured to determine how much energy was going into the air from each vaporization. These had a frequency about double that of the water acoustic pulse and lasted about the same amount of time. In amplitude they were about half as large as the water acoustic pulses at the same approximate distance from the source. Since the acoustic impedance Z_m of a medium is $\rho_m c_m$ where m refers to the medium, the impedance of the air is much less than that of water: for air $\rho = .13$ mg/cc, $c = 3.3 \times 10^4$ cm/sec whereas for water $\rho = 1$ g/cc, $c = 1.5 \times 10^5$ cm/sec. Thus, $Z_{air} = 42.9$ g/sec/cm^2, $Z_{water} = 1.5 \times 10^5$ g/sec/cm^2. Therefore, the air absorbs on the order of 10^4 times as much energy as the water does from the interaction.

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In order to reduce the effect of the air, an Intran II 10.6μ window was placed on the surface of the water. The water acoustic pulse increased by a factor of about 100 and the air acoustic pulse was cut in half. Thus about 10^4 times as much energy goes into the water when the air does not have the effect of "shorting out" the water acoustic pulse with its low impedance.

The third noticeable effect of the interaction, the water wave, which was extremely difficult to measure, was shown to carry off a negligible amount of energy from the interaction when reasonable estimates were used in the equations for water waves as derived by Stoner.[5]

V. CONCLUSIONS

The results of these experiments show that there are two major parameters of interest in the interaction of CO_2 laser radiation and water, namely the energy delivered to the water surface and the time in which it is delivered. The quantity which must be known to determine the amount of acoustic signal generated is the amount of energy which actually enters into the vaporization. Since the data show that only a fraction of the incident energy absorbed ever goes directly into vaporization, it is important to control the length of time for the energy to be absorbed. There is an optimum pulse width, depending upon the peak powers and optics, for which the largest volume of water vaporizes while losses to the air and the water outside of the volume vaporized are minimized.

In general, the efficiency of the process improves with shorter pulses and higher peak powers since losses are minimized. However, if the energy is delivered too quickly, a relatively small volume vaporizes and efficiency decreases. In the future different optical systems should be investigated for increasing the efficiency.

Improvements in laser Q-switching systems should also aid in making the system more efficient. Sequentially electrically pulsing and Q-switching the laser has shown to yield higher energy output pulses and should be useful in the future as the system is perfected. The effect of the air, however, is the fundamental difficulty. As its acoustic impedance is so low, it will always absorb a great deal of energy from the process and thereby greatly reduce the overall efficiency of transducing.

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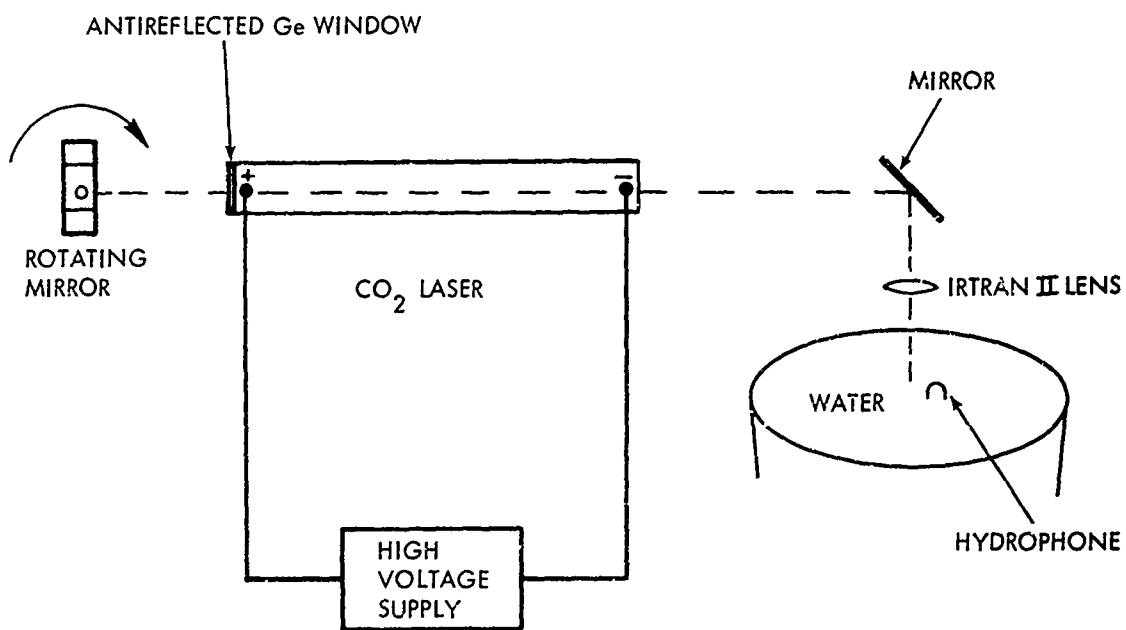Been Removed

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ANTIREFLECTED Ge WINDOW

MIRROR

ROTATING
MIRROR

CO_2 LASER

IRTRAN II LENS

WATER
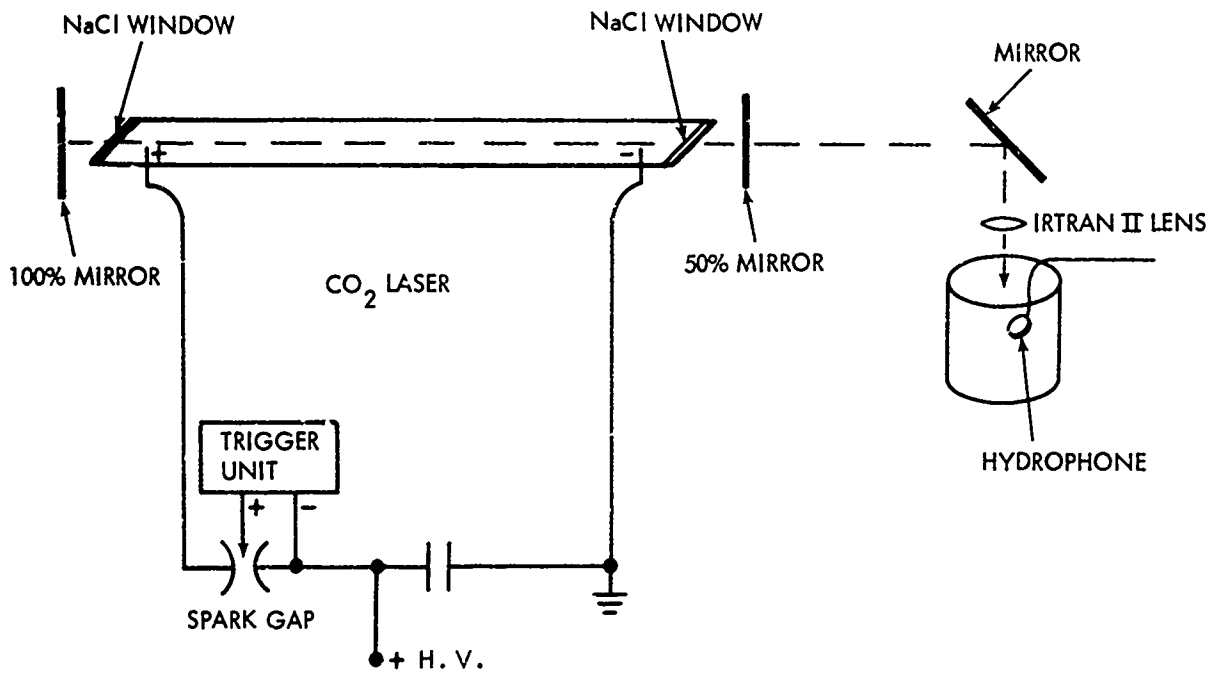
HYDROPHONE

HIGH
VOLTAGE
SUPPLY

FIG. 1 Q-SWITCHING SYSTEM

FIG. 2   ELECTRICAL PULSING SYSTEM

TIME IN 1.0 μ SEC/DIV., AMPLITUDE IN 500 WATTS/DIV.
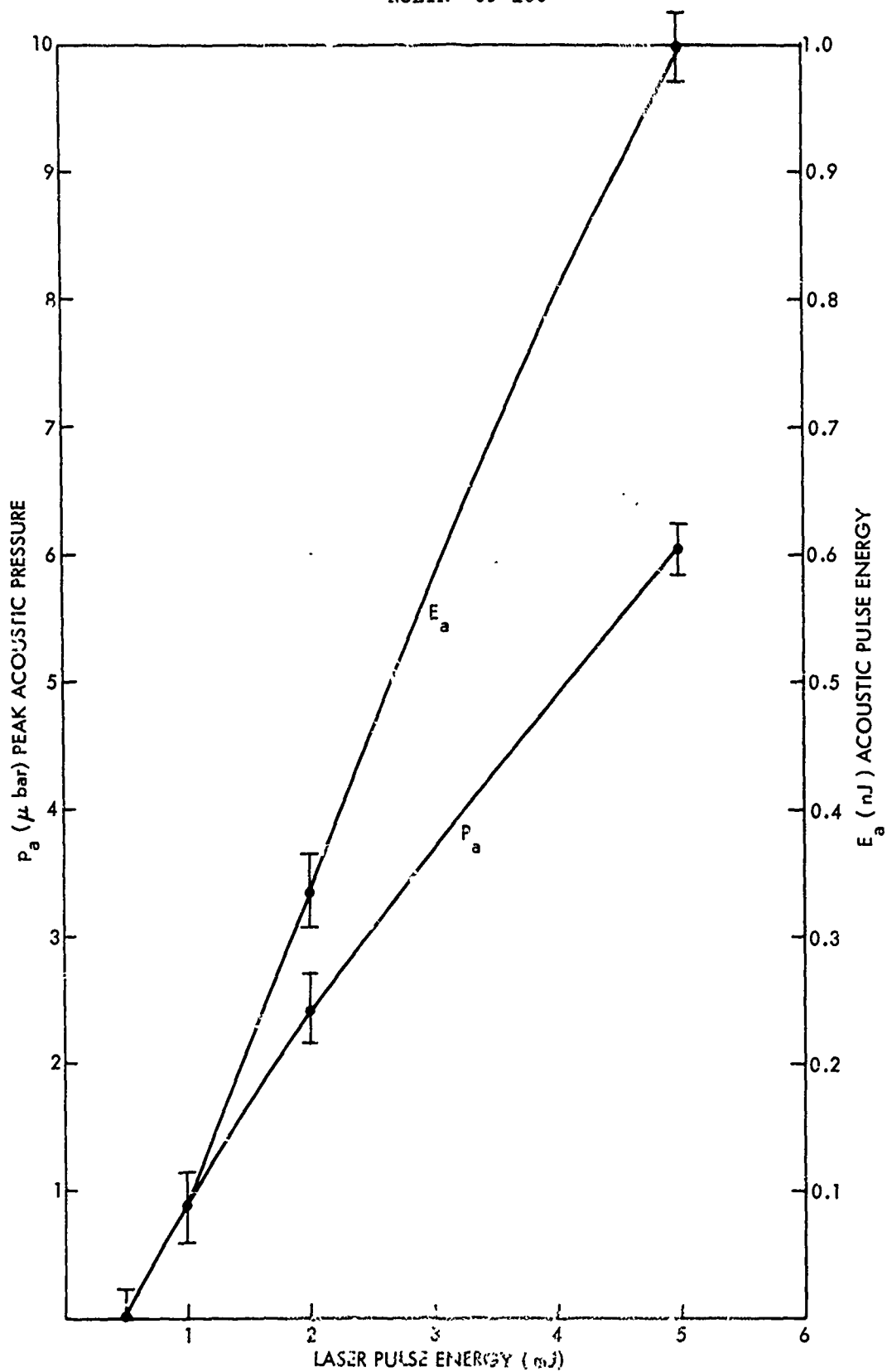
FIG. 3   Q-SWITCH PULSE

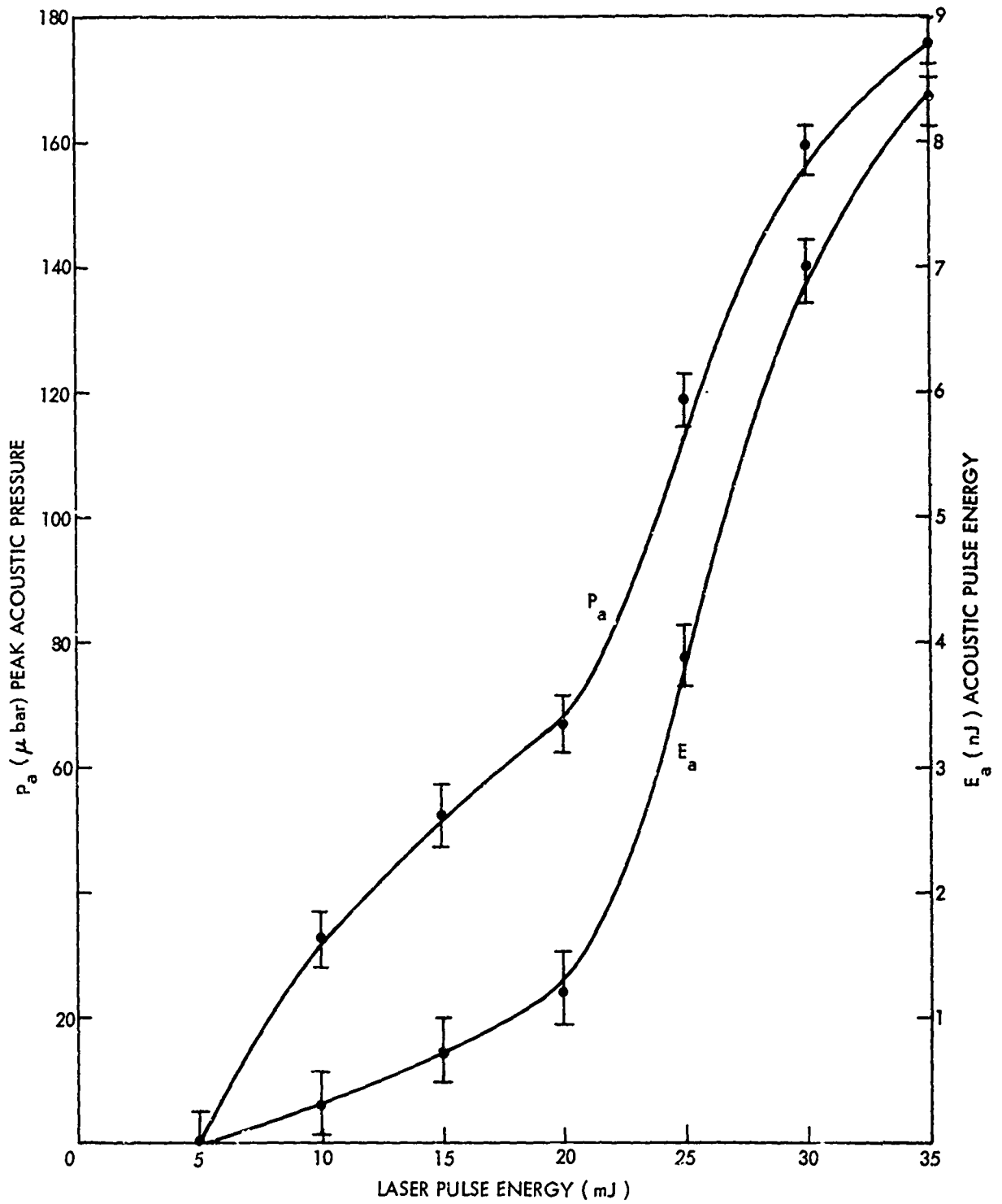FIG. 4 ACOUSTICAL PULSE PRESSURES AND ENERGIES FROM Q-SWITCH PULSES

FIG. 5 ACOUSTICAL PULSE PRESSURES AND ENERGIES FROM ELECTRICALLY PRODUCED PULSES
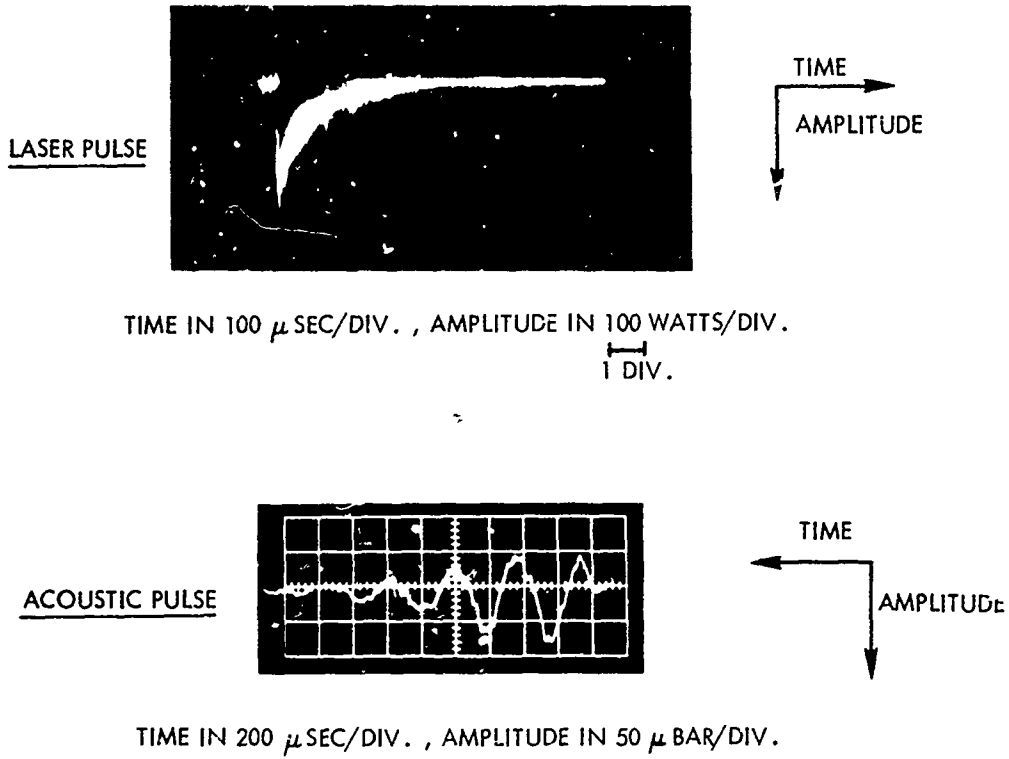
LASER PULSE

TIME

AMPLITUDE

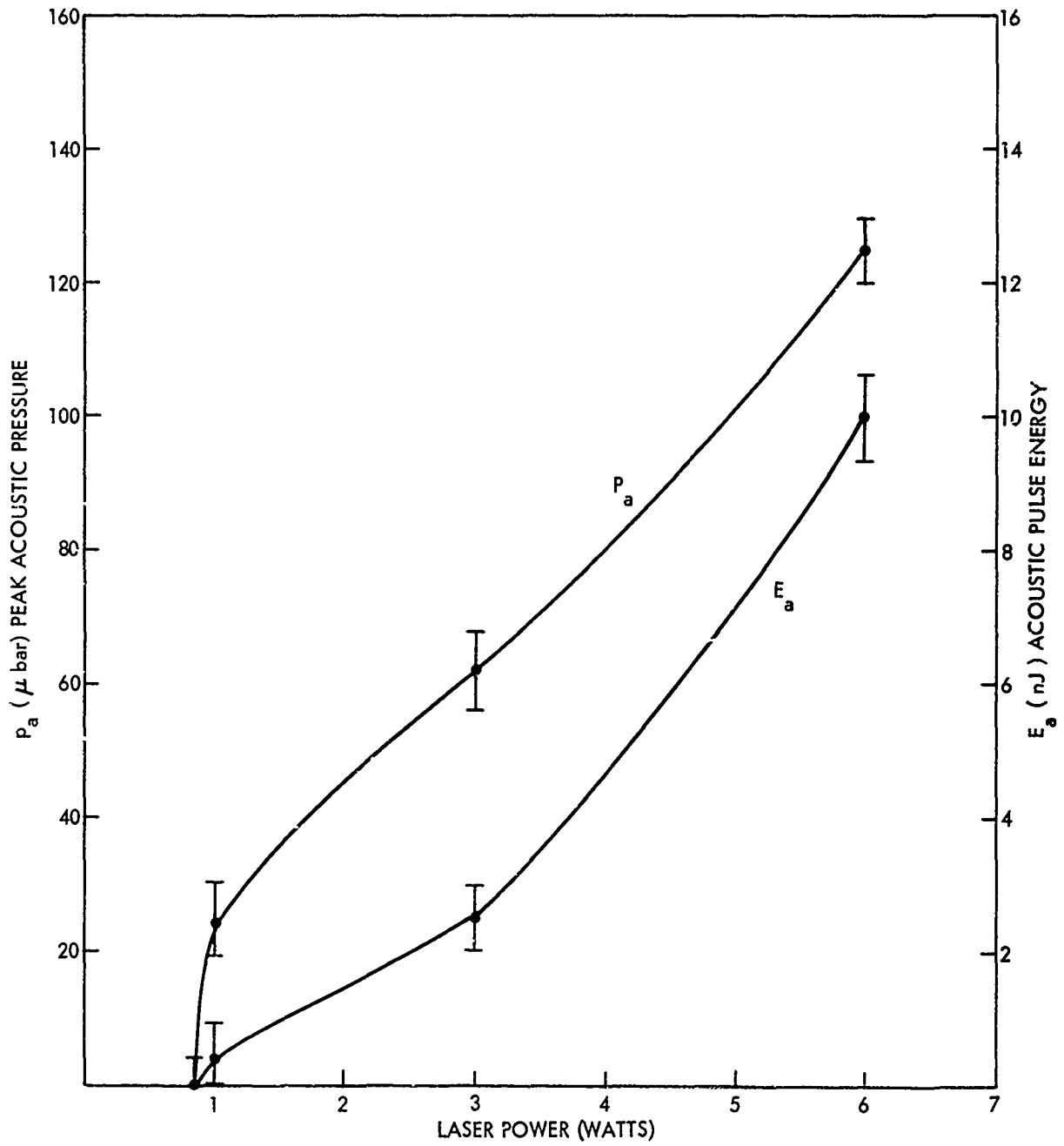TIME IN 100 μ SEC/DIV. , AMPLITUDE IN 100 WATTS/DIV.

|—| 1 DIV.

ACOUSTIC PULSE

TIME

AMPLITUDE

TIME IN 200 μ SEC/DIV. , AMPLITUDE IN 50 μ BAR/DIV.

FIG. 6   LASER AND ACOUSTIC PULSES

FIG. 7   ACOUSTIC PULSE PRESSURES AND ENERGIES FROM C. W. LASER

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13. ABSTRACT

The output of a CO_2 laser was focussed upon the surface of water to study the generation of sonic waves for air to water communication. A rotating mirror Q-switch system and an electrical pulsing system were used to obtain laser pulses. Continuous wave output was also investigated.

In each case, there were three obvious effects from the interaction (1) generation of an acoustic wave in air; (2) generation of an acoustic wave in water; and (3) generation of a circular surface wave. The best efficiency for producing a water acoustic disturbance was about 10^{-6}. One part in 10^4 of the acoustic energy coupled into the water - the balance is dissipated in the air. Placing a transparent window on the surface enhanced the water acoustic wave so that it was comparable in energy to the air acoustic wave.

It is concluded that the process is very lossy, although further improvements in laser engineering may yield better results.

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Interaction of lasers and materials						
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Water-radiation interactions						
Air to water communications						
Laser Communications						

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