LASER-GENERATED ULTRASONIC BEAMS

M. P. Felix
University of California, San Diego
La Jolla, California

I have noticed throughout the day that most of the speakers from the so-called real world, as Mr. Caustin termed it earlier, have been speaking at length for about a half hour or 45 minutes, whereas most of us from the research community who are, I must conclude, speaking from the unreal world, more or less by default, are speaking for 15 minutes or so. I don't know if there is any significance or not to it. I will continue to speak to you from the unreal world. What I am going to present to you this afternoon is one phase of a larger study undertaken at the University of California at San Diego under AFOSR sponsorship on the effect of high-power laser radiation on solids and liquids.

Now, it is well known that when the radiation from a high-power laser (a Q-switched laser) is focused onto a specimen, very large stresses are generated within the specimen primarily by thermo-elastic means as well as others. Generally, in this focused configuration, damage results. "Damage" is a bad word in the context of this workshop, so consequently we were concerned with harnessing this potential for lasers to generate large stress waves and thereby produce a stress wave of a more useful nature. In particular, we wanted to generate plane compressive stress pulses and sinusoidal wave trains to be used in subsequent wave propagation experiments from a nondestructive point of view. These waves may be used wherever a compressive stress pulse or a sinusoidal wave train with a very large amplitude might be needed. In particular, they may be used for flaw detection through materials that might be very dissipative where signals from piezoelectric crystals might not get through.

I will show that we were successful in doing this. I will also show how we used the laser to generate high-intensity, short-duration plane stress pulses, and how we used the waves to generate moderately high amplitude, high frequency sinusoidal wave trains.

I will demonstrate one or two examples of how we put this to use. Figure 1 shows what I was talking about earlier. This is what happens when you focus the laser radiation from a Q-switched laser down into a sample. This sample is polymethyl methacrylate (Lucite). The laser radiation is focused in from the left and the sample is more or less destroyed. This is typical. This is what everyone does when they get their hands on a high-powered laser for the first time. They flex their muscles over the material. After you do an experiment like this, you stand back and realize that you didn't learn much. The only thing you really learned from this experiment is that you are going to have to make another sample. That is not in keeping with, as I said, the philosophy of this workshop. So consequently, we wanted to use the laser in the nonfocused configuration in an attempt to generate useful stress waves.

Figure 2 shows a schematic diagram of how we did that. The laser radiation is incident from the left, as the arrows show, and is nonfocused. It is a very intense burst of light. We used a Q-switched laser with peak powers of tens to hundreds of megawatts. As shown in the figure, the laser radiation passes right through the fused silica block because it is transparent to this radiation. The radiation is totally absorbed in the thin absorbing liquid. Now, this liquid is a special liquid that totally absorbs the radiation in a very thin layer. What occurs is more or less like a controlled explosion of that layer. Since the radiation deposition time (typically 30 nanoseconds) is much shorter than any thermal conduction time or wave propagation time in this liquid, the liquid is instantaneously heated and a pressure gradient is instantaneously developed which manifests itself as a compressive stress wave propagating both to the right and also to the left in the specimen.

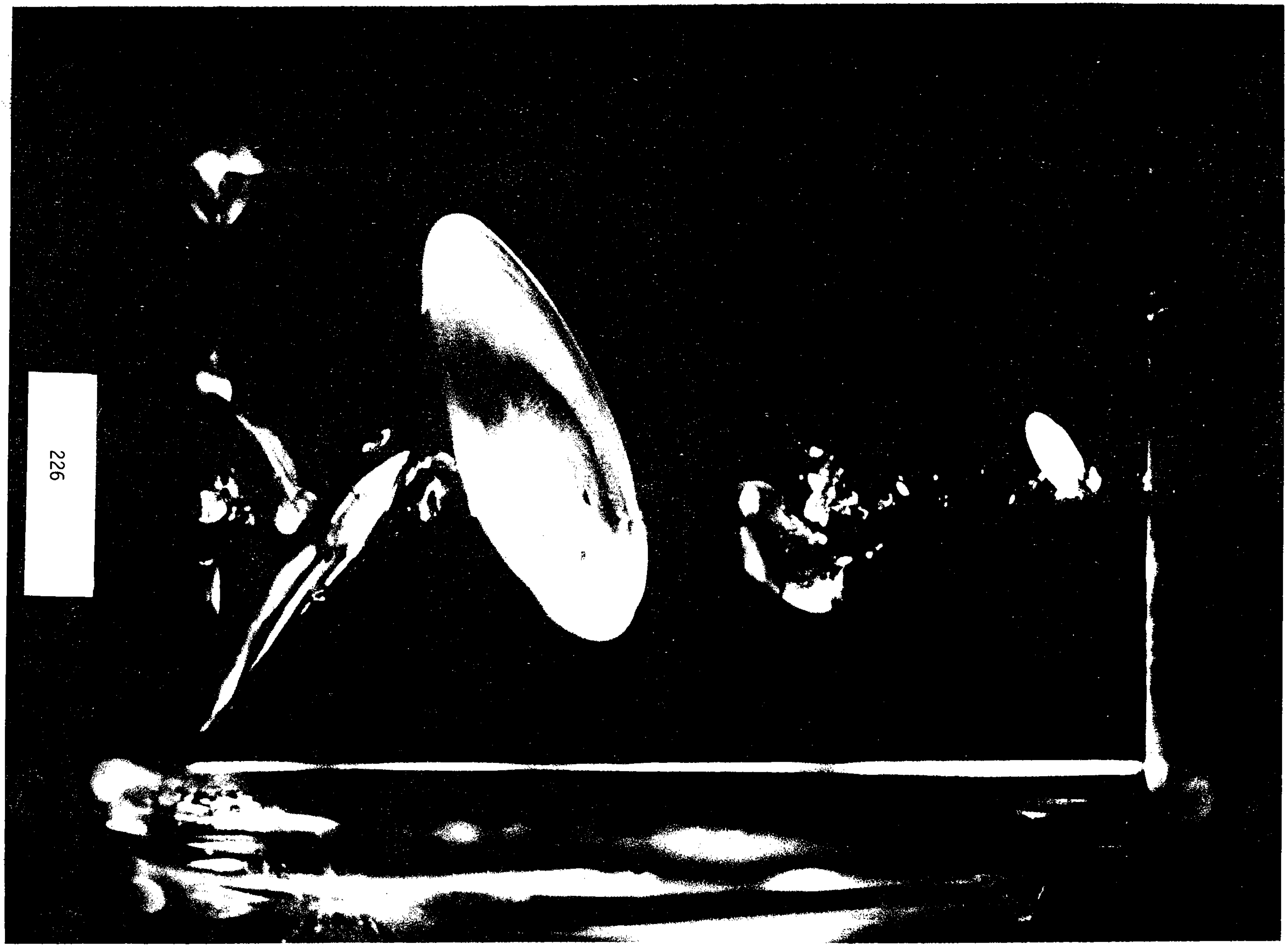


Fig. 1 Visualization of Laser Damage in Lucite

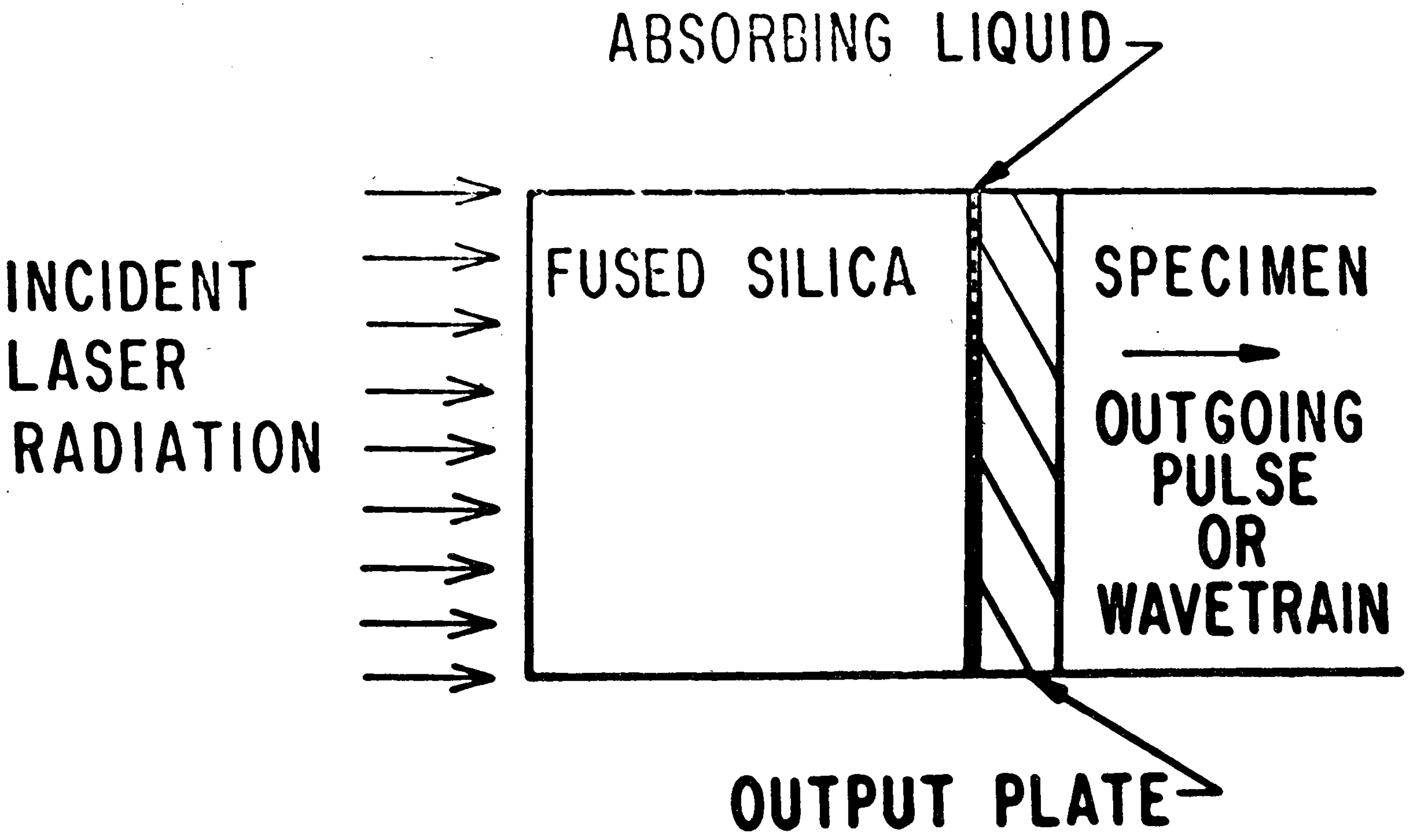


Fig. 2 Experimental Arrangement for Generating Sound Waves from Laser Irradiation

We were interested in generating a single pulse which would propagate to the right into the specimen. Consequently, we had to get rid of any reflections that might come about from interfaces. The following technique was used. Look at the fused silica block. While one stress wave is going to the right, one is also going to the left. If the block is very long, the stress wave is effectively delayed so that by the time it hits the left surface, turns around and comes back, the phenomenon of interest in the specimen going to the right is completed. This technique works well if your experiment is short, and in most of our work in wave propagation, this was realized.

For purposes of generating a compressive stress pulse of fairly high amplitude, you want to select the material for the output plate (shown in the figure) such that you maximize the compressive stress transmitted from absorbing liquid to output plate and into the specimen. You want to maximize the stress transmitted into the specimen. What this means is that you select the acoustic impedence of the output plate equal to the square root of the product of the acoustic impedence of the absorbing liquid and the specimen. This is not easy to do for all kinds of specimens, but we used Lucite for most cases. Also, the thickness of the output plate is selected by the same delay time criterion previously described for the fused silica block. You can make the delay time many, many microseconds if you like.

Figure 3 shows the results of our stress generator and oscilloscope trace. What you see is the stress-time profile generated by this device using the Q-switched laser. The vertical component is stress; the horizontal component is time. This is measured by an impactducer (a quartz stress gauge). The vertical amplitude in this case is about 15,000 psi, a very large stress. The time here is 200 nanoseconds per centimeter. This is about a quarter of a microsecond duration, so the pulse is very close to a delta function in stress. The only other way I know of to get something like this is with very large gas guns impacting thin flyerplates into specimens but that is a mess.

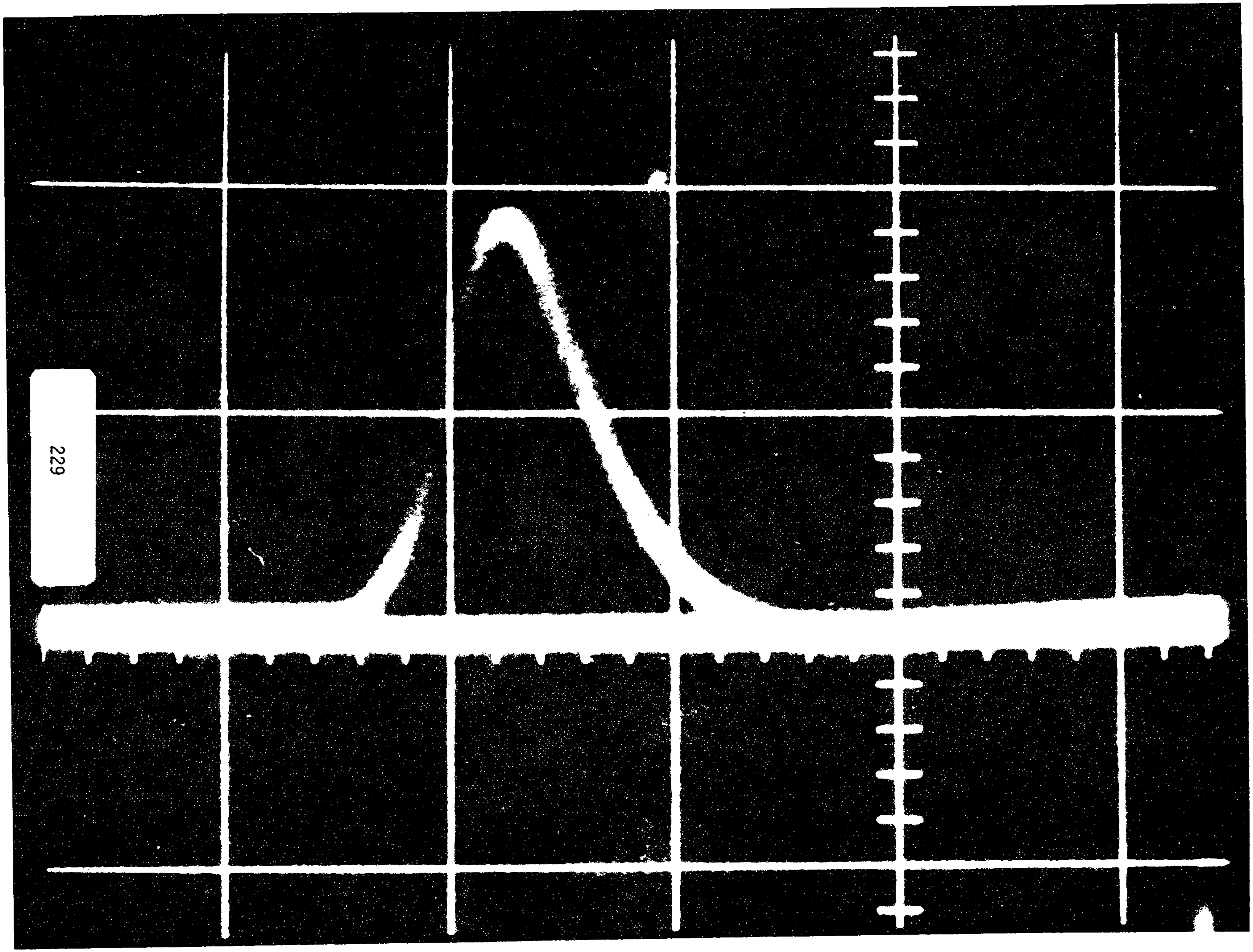
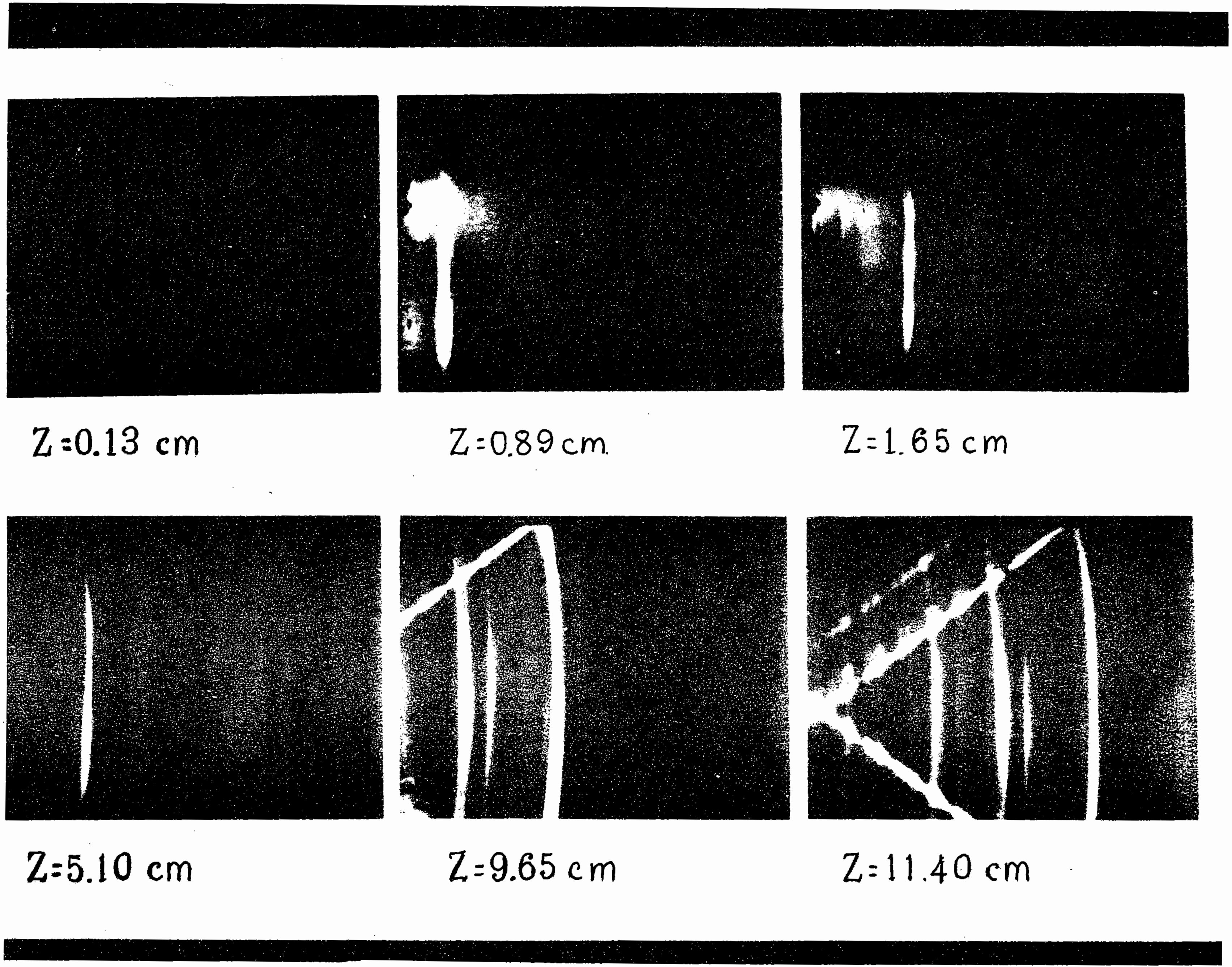


Fig. 3 Stress-Time Profile of Laser Generated Stress Pulse

I think it is much easier to do it with a laser because you don't have to realign the experiment each time. You merely need our transducer bonded to the specimen with a liquid bond to transmit the stress wave.

I indicated that we wanted to generate a plane compressive stress pulse. Figure 4 shows that we were successful. This is a sequence of pictures of the pulse in Pyrex glass taken at very short intervals. Optically this is a darkfield polariscope setup. Now, Pyrex glass is birefringent so that in a darkfield polariscope setup, you see a white band indicating the stress pulse going through. Each of these frames was taken with a high-speed camera we developed at U.C. San Diego. The effective exposure time of each frame is 20 nanoseconds, so even though this wave is travelling at the dilatation speed of sound in glass (530,000 centimeters per second) you see it essentially stopped in time. You see the compressive stress pulse moving on, with a relatively straight-front. Over a small region it can be assumed to be a plane wave. Beyond five centimeters you see noticeable curvature of the front and mode conversion at the boundary.

We developed this tool initially to generate stress pulses in composite materials and to look at the way the pulses propagate. We next made a composite material of sort. In Fig. 5 is shown a block of Pyrex glass, two inches by three inches by 1 inch, with an array of six cylindrical holes ultrasonically bored through with about an eight-inch diameter. We impacted the compressive stress pulse on the left side and took a picture with the very short-duration camera to see what the stress situation was after the pulse propagated past the holes. The results are shown in Fig. 6. This figure is more magnified than the previous pictures. This picture represents the transient stress situation frozen in time. In the array of six holes, you only see about four of them due to the magnification. The picture was taken after the pulse had propagated past the holes, and you start to see somewhat of a deterioration or change in the shape of the straight front of the pulse. You can also see there is a very complicated dynamic stress field around the hole.



Z=0.13 cm

Z=0.89 cm

Z=1.65 cm

Z=5.10 cm

Z=9.65 cm

Z=11.40 cm

Fig. 4 Stress Pulse as a Function of Propagation Distance in Pyrex-glass

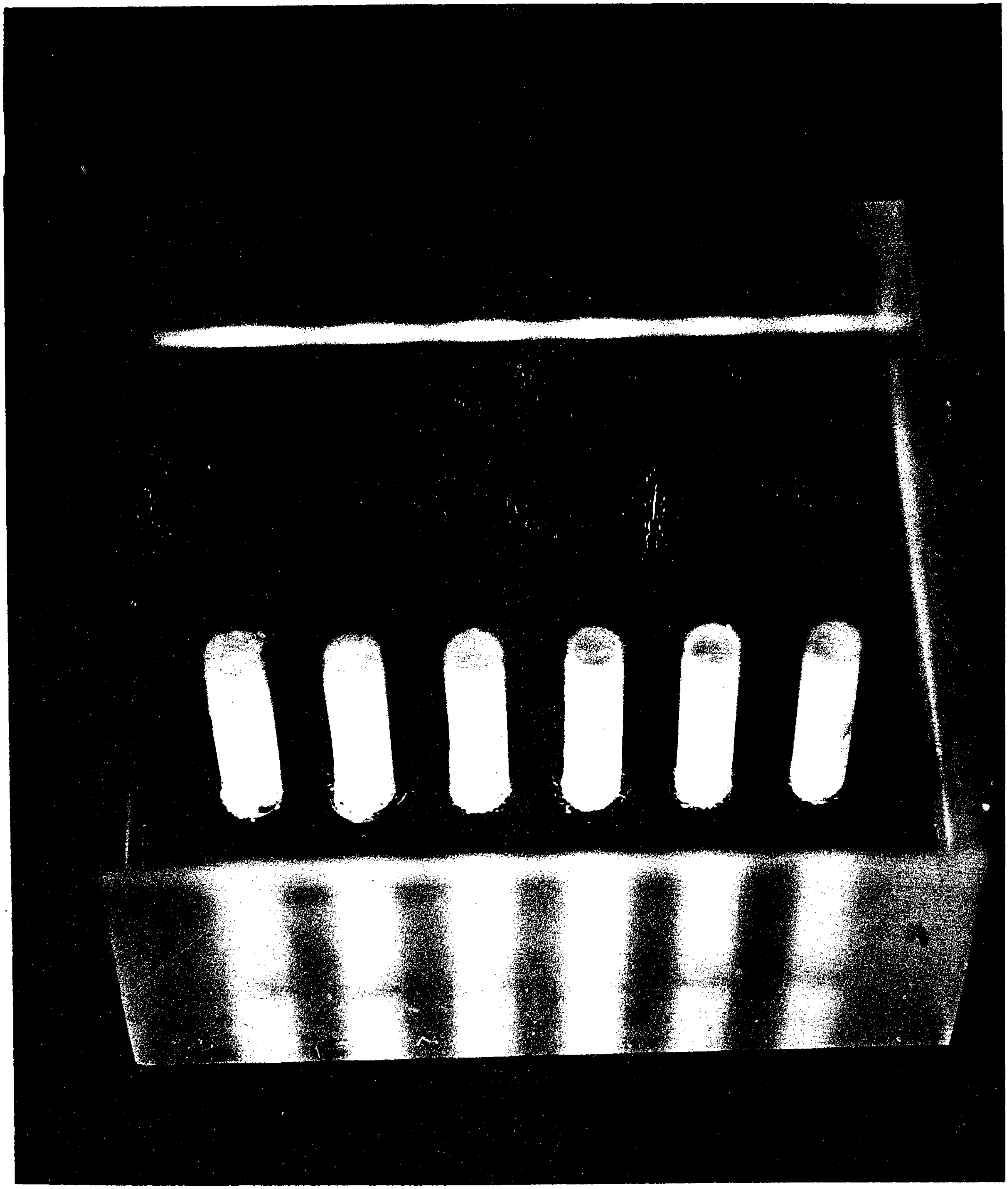


Fig. 5 Sample Array of Six Holes Bored in Pyrex-glass

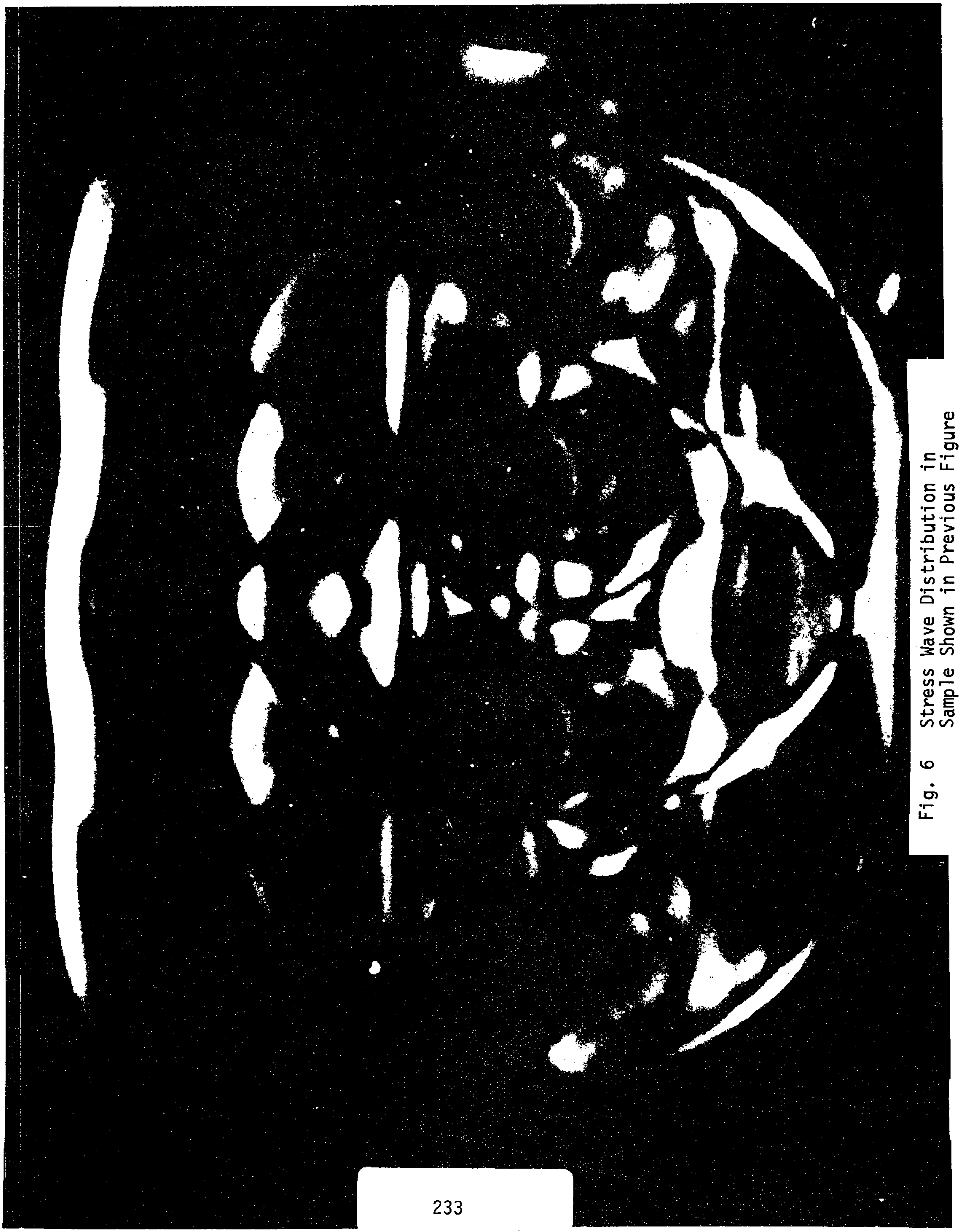


Fig. 6 Stress Wave Distribution in Sample Shown in Previous Figure

What we are currently doing at UCSD is making more composite specimens with many holes in them, both systematically arranged and randomly arranged, and observing how this pulse (generated by the Laser) is more or less smeared out and deteriorated. This work was the motivation of the study. We weren't initially motivated to demonstrate techniques for nondestructive testing. We were primarily interested in generating techniques for monitoring stress wave propagation in all kinds of materials. However, this technique definitely could be used wherever you need a high amplitude, short duration stress pulse.

The next phase of the study dealt with generating sinusoidal wave trains. I mentioned that when generating a single pulse, you select the material for the output plate such as to maximize the stress going into the specimen. If your goal is to generate a sinusoidal wave train, you make the output plate of a material that has a very high acoustic impedence ρc much higher than both the specimen and the liquid. If the output plate is very, very thin in addition to having a high ρc, the stress pulse "rings" back and forth in this high acoustic impedence thin material between the liquid and the specimen. The stress transmitted into the specimen on each pass is essentially a sinusoidal wave. The material we used in this case is a thin sapphire window. It has a ρc of 44×10^5 versus, say, quartz which is 15 and 17; water is about 1 or 2.

With this technique we were able to generate arbitrary frequencies. The frequency is dependent only upon the thickness of the crystal. Now obviously, the amplitude is going to be much less in this case because a lot of energy is trapped just ringing back and forth. However, each time the stress wave hits the specimen, some stress is transmitted. I will show that even though the amplitude is reduced, we have been able to generate sinusoidal wave trains in solids and liquids with amplitudes much higher than is currently possible using piezoelectric transducers.

I want to show you one example of this effect. Figure 7 shows a stress-time profile measured by a pressure transducer of a portion of the six megahertz wave train propagating in water. Now, the time scale here is 100 nanoseconds per centimeter. The wave is therefore about a six megahertz wave train. This train has propagated about four centimeters in water already, and the amplitude

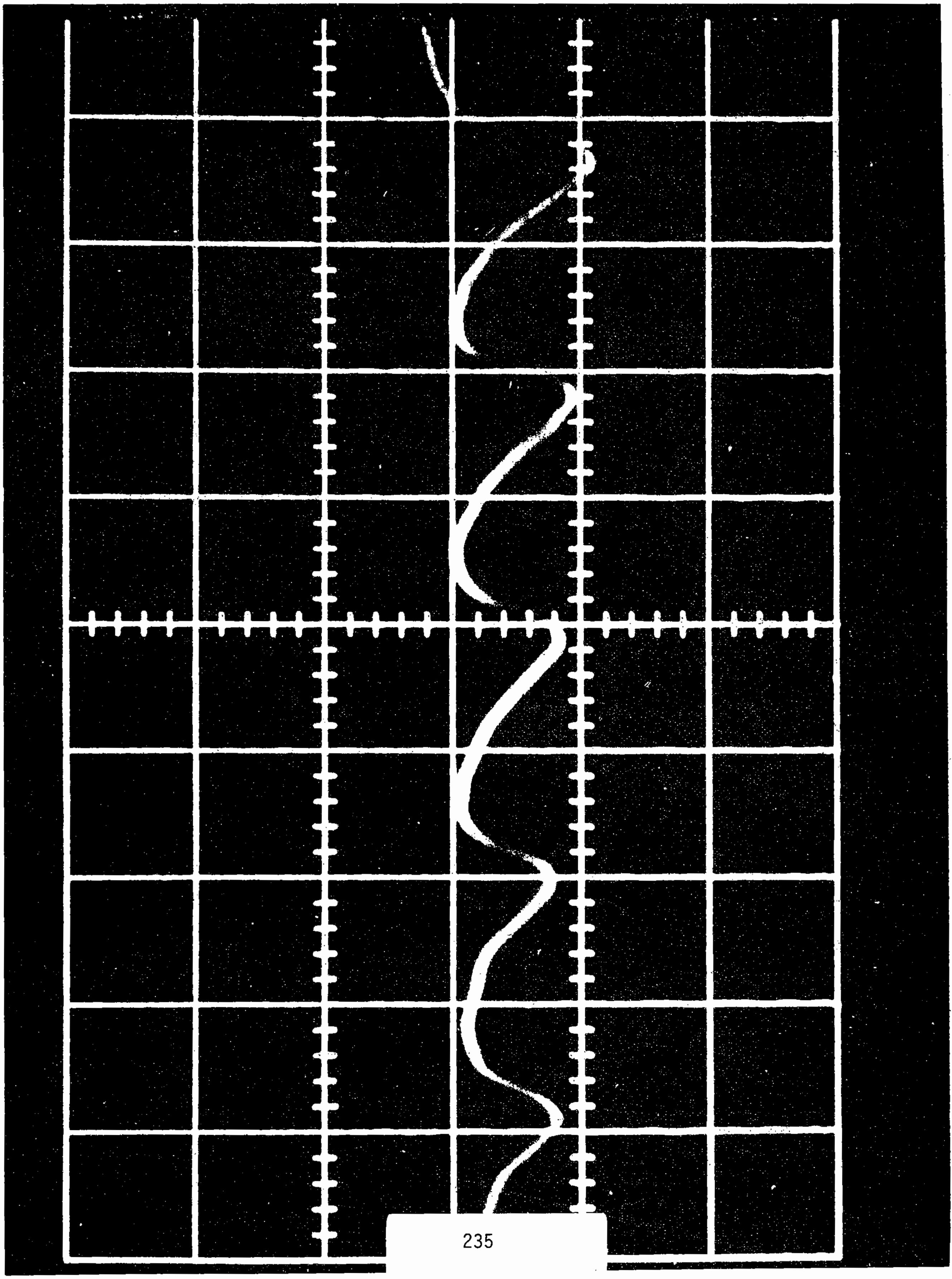


Fig. 7 Six MHz, High Amplitude Stress Wave Propagating in Water

is 25 atmospheres, which is very, very large. Piezoelectric crystals are very seldom driven above one atmosphere, and most of the time in ultrasonic work are driven below a tenth of an atmosphere. This is an incredibly high amplitude wave train, and it, of course, doesn't look sinusoidal now because a wave train of this high amplitude will convert very rapidly to a sawtooth shape due to the nonlinear propagation in the various liquids, especially water. Therefore, it appears sawtoothed in shape, but it is extremely high amplitude.

In Fig. 8 is shown a darkfield Schlieren photograph of the above wave train propagating through water made with a 20 nanosecond exposure. The laser beam and our transducer generated the stress wave train which then propagated through the water. We took a Schlieren photograph of a portion of it. Here you see this nice, straight-fronted train which lasts for about 30 cycles or so. This train has a 25 atmosphere peak-to-peak amplitude which is very, very high.

I feel we have made a contribution in two ways. First of all, we have shown that the laser can generate stress waves in a controlled fashion and not merely in an uncontrolled fashion as shown in the first slide. Secondly, I think I have shown that this device could be used in almost any situation where you need a high intensity, short-duration pulse or a very high intensity sinusoidal wave train.

Obviously, some of the questions in your minds right now concern the need for real time instrumentation. In this context, our device would not be good for real time work because you can't fire the laser as rapidly as you can pulse piezoelectric crystals. It takes time to recharge the laser. However, for applications where you might be satisfied with taking a recording and analyzing it later, this would be good.

We are currently using this device in acoustical holography studies at UCSD because acoustical holography is somewhat limited these days by resolution. Part of that is because high frequencies are attenuated very badly. If you use very high frequencies with piezoelectric crystals, the amplitudes are severely attenuated; however, if you have a device that is capable of developing

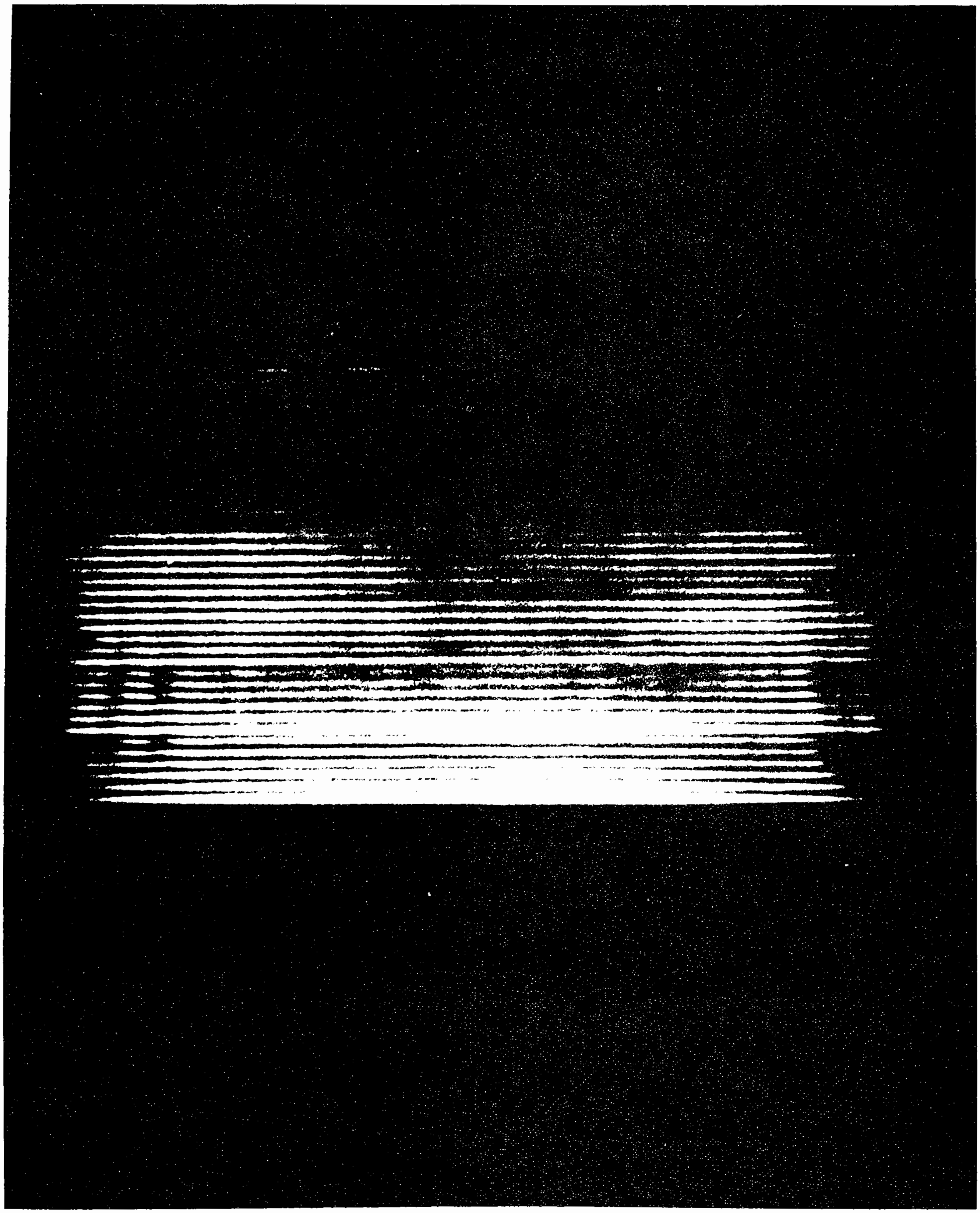


Fig. 8 Schlieren Photograph of Wave Train in Water

tremendously high amplitudes to start with, and go to higher frequencies, more of the signal is going to get through. This should aid resolution in acoustical holography and 3-D acoustic/visual schemes which really should help in nondestructive evaluation.

DISCUSSION

DR. BRUCE THOMPSON (Science Center, Rockwell International): I have a question on an experimental detail. Do you have to replace the absorbing liquid?

PROF. FELIX: No, it stays put at all times. It is sealed in between these quartz plates. In practice we just use a little hypodermic needle to fill it to the top, seal it off, and it stays there. It is like wine, it seems to get better with age.

DR. BRUCE THOMPSON: How long does it take to recharge?

PROF. FELIX: Well, that depends on your laser system. The one we were using would recharge every three or four minutes. Some companies make big, powerful, Q-switched ruby lasers which can be pulsed two or three times a second, but that takes huge power supplies. It depends on what you are after. We were concerned with generating these waves with repeatability. We were not interested in fast repeatability.

PROF. HENRY BERTONI (Polytechnic Institute of New York): Other people have discovered, inadvertently in some cases, that if you hit a surface with a laser, like a metal surface, that, by itself, will generate a sound wave.

PROF. FELIX: Oh, heavens, yes.

PROF. BERTONI: How do the amplitudes compare with using an absorbing liquid, the intensities you can get that way with using an absorbing liquid?

PROF. FELIX: You can get higher intensities with no liquid, but also you damage the specimen. With our device the laser radiation never touches the specimen. If your specimen was a human or something like that, you wouldn't want to get into a lawsuit. Actually, the stress intensities might not be that much higher, because when you focus the laser radiation from a Q-switched laser onto the surface of, let's say, a metal, (we have taken photographs of that) a tremendous amount of energy is used in vaporizing the surface and blowing off a bunch of stuff. You do generate stress waves but they are compressive followed by tensile because you are doing it on a free boundary. You have a relief wave coming instantly and that is a technique that is used, but ours is more controlled, I feel, and doesn't hurt the specimen.