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A 17-Inch Diameter Shock Tube for Studies in Rarefied Gasdynamics

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A shock tube for studying problems in rarefied gasdynamics is described. The motivation for operating at low density (to increase the length and time scales of certain interesting flows) and the effect of low density on the performance and design of the shock tube are discussed. In order to guarantee uniform and reproducible shock waves of moderate strength, the configuration of the tube is conventional. However, innovations are introduced (for example in the suspension, the pumping system, and the diaphragm loading and rupturing mechanism) to simplify the operation of the large facility. Care in the design of the tube as a vacuum system has resulted in a leak rate of less than 0.01 μ Hg per hour. A series of shakedown runs at relatively high pressures has shown, for example, that the reproducibility of a given shock Mach number is $\pm 0.6\%$.

I. INTRODUCTION

STUDIES in rarefied gasdynamics have generally been directed toward the understanding of processes such as those operative in boundary layers, shock waves, and reaction zones. The length and time scales of such dissipative flows are determined by the mean free path and mean collision time, respectively. At sufficiently low densities these scales become large enough that details of the flow can be observed, and this fact has been used frequently in wind tunnels (e.g., in the measurement of shock wave profiles in the Berkeley low density wind tunnel[1]). Similarly, orifice flow at reduced pressures has proven to be an interesting dissipative flow which can be easily studied.[2]

The shock tube[3] is capable of generating many nonsteady dissipative flows at elevated temperatures, and it is for the purpose of examining such flows at low density that a 17-in.-diam shock tube has been constructed at the Graduate Aeronautical Laboratories of California Institute of Technology (GALCIT). Since the scale of the flows in the tube is generally larger than in standard shock tubes, the size of the facility must also be larger to keep the flows geometrically similar. In order to maintain a well-defined plane shock, for example, the tube diameter should be, say, 50 times larger than the shock thickness.

As the density is decreased in a tube with fixed diameter, the increased scale of the dissipative regions has a strong effect on the behavior of the shock tube flow. Three of the most important thickening regions are the shock wave, the boundary layer behind the shock, and the contact region. The major effect of boundary layer thickening is to decrease the distance between the shock wave and the contact region.[4] Thus three adjacent regions (the shock wave, the shocked gas region, and the contact zone) change radically with decreasing density. These changes are important in the transition from nearly ideal behavior at high pressures to the extreme low-pressure limit of a free cloud of driver gas expanding into a highly evacuated tube. For, as the shock and contact zone thicken and the region between them decreases in size, it is evident that driver gas eventually penetrates into the shock and, ultimately, the features of the diffusively thickening contact zone dominate.[5]

Two measures of the departure of the flow in a shock tube from ideal are the ratio of shock thickness to tube diameter, δ/d, and the ratio of shock-contact separation to tube diameter, ℓ/d. The presence of the boundary layer behind the shock waves causes a loss of mass from the shocked gas to the wall. By continuity, this loss results in a decrease in ℓ from the ideal value. The contact surface adjusts its distance from the shock wave until, if the tube is long enough, a steady state is reached in which the mass loss into the underlying boundary layer is just equal to the rate of mass capture by the shock wave, i.e., until ℓ is constant $=\ell_m$. This asymptotic state is reached after the shock has traveled 10 or 15 times ℓ_m from the diaphragm station.[4] Since we will be concerned with ℓ/d of order 1 and the shock tube is 50 diameters long we can always use ℓ_m for ℓ. The asymptotic value ℓ_m, calculated in reference 4, can be written in the functional form

$$\ell_m/d=f(M_s,\gamma)(a_1d/\nu_1), \quad (1)$$

where M_s is the shock Mach number, γ the ratio of specific heats, and a_1 and ν_1 are the speed of sound and the kinematic viscosity in the undisturbed gas.

Now, whereas ℓ_m/d decreases with decreasing initial pressure, the shock thickness increases, and is given by the function form

$$(\delta/d)=g(M_s,\gamma)(\nu_1/a_1d). \quad (2)$$

[1] F. S. Sherman, National Advisory Committee for Aeronautics, Tech. Note 3298 (1955).
[2] H. W. Liepmann, J. Fluid Mech. **10**, 65 (1961).
[3] For a description of shock tubes, cf., for example, I. I. Glass and G. N. Patterson, J. Aero. Sci. **22**, 73 (1955).
[4] Cf. R. E. Duff, Phys. Fluids **2**, 207 (1959); and A. Roshko, Phys. Fluids **3**, 835 (1960).
[5] Of course, the extent to which the departure of the shock tube flow from ideal can be tolerated depends on the experiment, and blanket statements cannot be made about the utility of shock tubes at low pressures. In studies of chemical reactions in hot, uniform gases, say, the requirements for uniformity are strict because of the sensitive temperature dependence of reaction rates. On the other hand, there are no requirements on flow duration in the study of an expanding cloud of driver gas or of the approach to that limit from high pressures.

Therefore

$$\delta/d\cdot\ell_m/d=f\cdot g=\text{fnc}(M_s,\gamma)\quad\text{only.}\tag{3}$$

Note that if for some reason one of the quantities δ/d or ℓ_m/d is fixed (say $\delta/d=0.02$ to insure shock planeness) then the other is determined by M_s and γ and *is independent of tube diameter*. With shock waves of $M_s=6$ to 10 in argon, if $\delta/d=0.02$, then $\ell_m/d\doteq1.0$. Equations (1) and (2) are plotted in Fig. 1 for argon in the 17-in.-diam shock tube. In this case $\delta/d=0.02$ corresponds to a shock wave about 1 cm thick obtained at about $p_1=20\ \mu$ Hg.

II. DESCRIPTION OF TUBE

The GALCIT 17-in. shock tube facility is designed to take maximum advantage of the flexibility inherent in shock tubes as tools for basic experimental research in gasdynamics. It was felt from the beginning that reproducibility of operation and simplicity could best be achieved in a tube of conventional type, in spite of the unconventional requirement of operation at very low pressures. Most of the innovations in design, therefore, have arisen either through application of standard vacuum techniques to a device intended for alternate exposure to high and low pressures, or through efforts to provide for one-man operation.

The shock tube is not mounted on the floor of the laboratory, but is suspended from the ceiling (Fig. 2). A clearance

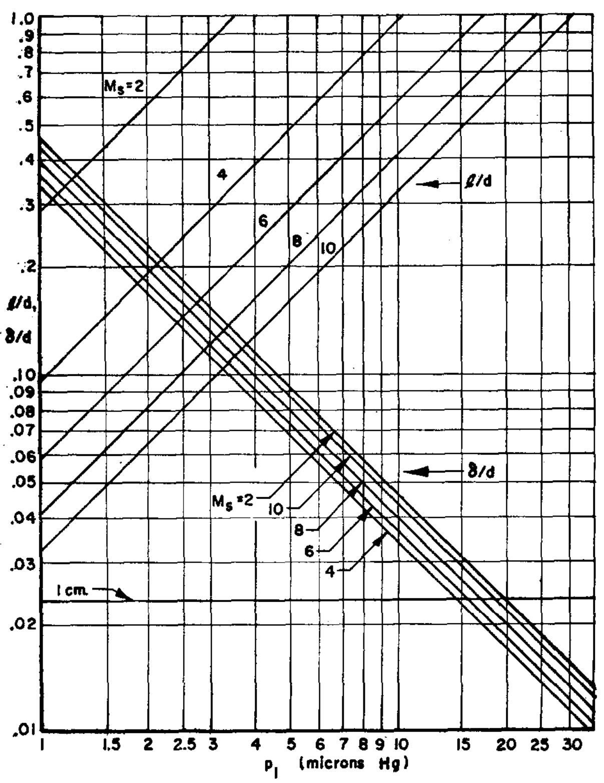

FIG. 1. Variation of shock thickness (δ) and shock-contact separation (ℓ) with P_1 and M_s in the 17-in. shock tube ($d=17.10$ in.).

of about seven feet is maintained except near the diaphragm, this clearance being sufficient for a fork lift used in assembly and disassembly of the tube. Such an arrangement not only simplifies the supporting structure but also frees valuable floor space for other equipment (such as a ping-pong table sometimes used for unsponsored research in low-speed aerodynamics). The basic driven section is 67.9 ft long and consists of five $12\frac{1}{2}$-ft lengths and one 6-ft length (the "anchor section"). It can be extended to a maximum length of 72.0 ft by adding shorter lengths of pipe. The only section of the shock tube rigidly fixed to the building is the anchor section which incorporates the downstream half of the diaphragm joint and is also fitted with two 6-in. ports leading to the vacuum pumping system. Axial recoil during firing is transmitted laterally from this anchor section to an I-beam structure which also supports two of the four pumps.

Each pipe section is supported by coil springs from trolleys on an overhead rail. After a new section has been raised by the fork lift and attached to its trolleys, the height is adjusted so that the flanges are one foot below the rail. The new section is then rolled into position next to the previously assembled tube, the outside diameters of the mating flanges are aligned by a compression strap, and the flanges are bolted together. Any small deflection which results from this alignment procedure is absorbed by the spring suspension. Experience has shown that a section of the shock tube can be added or removed in about 30 min, if necessary by one man.

The shock tube is made from 17-in. i.d. welded type-304 stainless steel pipe with a wall thickness of $\frac{1}{2}$ in. Seamless extruded tubing was originally specified but after difficulties encountered in fabrication by the manufacturer had caused a delay of about nine months, the original order was canceled at the request of the supplier. Welded pipe was then ordered from Swepco Tube Corporation of Clifton, New Jersey, and this pipe has proved to be satisfactory in every way. The pipe was fabricated in $12\frac{1}{2}$-ft lengths, each length being leak tested with a mass spectrometer and the welds being ground smooth by the manufacturer before delivery. After the pipe arrived in Los Angeles in late 1960, the inside was honed to a surface finish of approximately 40 μin. by Industrial Hydraulics, Inc. (Fig. 3), and the outside was sandblasted. All further machining was done at Caltech by its Central Engineering Services.

One of the most difficult problems arising in fabrication, and one which may not have been solved in the best possible way, was the attachment of the mild steel flanges at the ends of the pipe sections. Because it was originally expected that this would not require welding, the honing operation was carried out first. Several methods of flange attachment were considered and discarded, and one trial weld was made. A full circumferential weld, however, caused unacceptable local shrinkage of the pipe and flange,

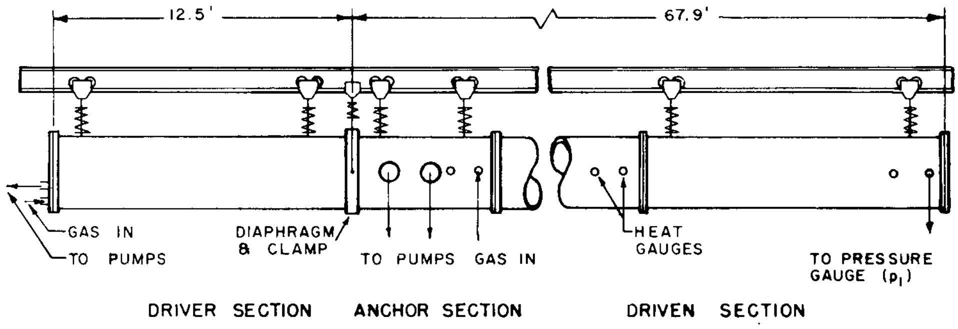

FIG. 2. Schematic layout—17-in. shock tube.

with very large residual stresses. The scheme finally adopted was to turn grooves in the pipe and flange for a single-acting circumferential wire key of $\frac{1}{4}$-in. diameter. This key transmits axial tension loads to the flanges, while axial compression loads are carried by the ends of the pipe directly. A number of small nonstructural tack welds hold each flange in close contact with its key. Slight local distortions can be detected inside the pipe under these welds, but are hardly noticeable from the aerodynamic point of view. An alternative procedure might have been to attach the flanges with continuous welds and to stress-relieve the sections before honing; but this procedure could well have proved to be as troublesome as the one actually used.

After installation of the flanges, the ends of the sections were faced square and parallel, an O-ring groove was cut in the exposed pipe end, and the flange o.d.'s were turned concentric with the pipe i.d. The final concentricity is not completely perfect, and some of the joints assembled with the o.d.'s of the mating flanges flush show lateral displacements of the inside surfaces of as much as 0.015 in. If necessary, however, this displacement can be reduced by rotating one or both pipe sections. Finally, instrumentation pads were machined on the pipe wall of most of the pipe sections at points 20 and 70 cm from the O-ring end. These pads consist of a $1\frac{3}{8}$-in.-diam access hole through the wall, a $2\frac{7}{8}$-in.-diam flat on the tube o.d. for an O-ring seat, and four blind tapped holes for bolting instrumentation plugs to the shock tube. The finished inside diameter of the shock tube is 17.097 ± 0.005 in. throughout the length of the low-pressure section except near the center of the anchor section, where some distortion occurred during welding of the pump flanges. This diameter was selected in the course of the honing operation as the smallest value which would allow machining the inside of the pipe completely. The tolerance mentioned includes out-of-roundness, variations from point to point along the tube, and miscellaneous distortions during fabrication. The pipe sections are not perfectly straight, however, being curved in some cases by as much as $\frac{3}{16}$ in. in $12\frac{1}{2}$ ft.

The driver section is made of the same pipe as the driven section, except that the inside surface is not honed and the flanges are attached by continuous circumferential structural welds. Although the maximum design pressure for this section is 15 atm, a static test was carried to 33 atm in order to prove the integrity of the driver as a pressure vessel.

III. THE TUBE AS A VACUUM SYSTEM

Some care was taken in the design of the facility as a vacuum system. The material from which the tube was made was specified to be stainless steel primarily because of its good performance under vacuum. The number of instrumentation access holes in the five $12\frac{1}{2}$-ft sections of the tube was kept to a minimum, and their design was standardized to insure complete interchangeability. There are two pads in each section (Fig. 2) except in the anchor and extreme downstream driven sections, which have four pads each. Five short test sections ranging in length from 2 to 5 ft are available for the installation of further instru-

FIG. 3. Interior of shock tube showing surface finish.

mentation at any point in the tube; it is not intended to make further alterations in the basic tube.

Neoprene O-ring seals were used exclusively and the number of welded joints exposed to vacuum was minimized. The O-ring grooves and faces at the ends of the tube were cut into the stainless steel tubing material so that the tube-flange joint is outside of the vacuum system. In fact, provision of sufficient thickness for these O-ring grooves was the main reason for specifying a $\frac{1}{2}$-in. wall. In addition to the longitudinal seam made during the fabrication of the tubing, the only exposed welds are those joining the two 6-in. ports to the anchor section. Furthermore, all valves on the driven section are gate or bellows vacuum types.

Honing the inside of the tube contributed immensely to its performance as a vacuum system. Not only is the tube easy to clean, but adsorption on the smooth surface and consequent degassing are probably reduced. The quick diaphragm change method described below also probably reduces degassing by minimizing the time that the interior surfaces are exposed to atmospheric pressure during diaphragm changes.

The above precautions have resulted in a measured leak rate in the nearly 70-ft long driven section, complete with plumbing and 12 thin film heat gauge instrumentation plugs, of less than 0.01 μ Hg per hour. (If this entire leak were through a single orifice from the atmosphere, the orifice diameter would be 2×10^{-4} mm.) The tube is always maintained under vacuum except during diaphragm change. The leak rate is observed to decrease continually, so it is probably largely due to degassing.

IV. PUMPS

The primary pumping system (Fig. 4) consists of two German Heraeus pumps in series. The fore pump is a type E225 (pumping speed 132 cfm, inlet port 3 in. in diameter, ultimate pressure 20 μ Hg), and the vacuum pump is a Roots-type blower VPR-1600 (pumping speed 400 liter/sec, 8-in. port, ultimate pressure 0.5 μ Hg). The pumps are separated by a 3-in. pneumatic gate vacuum valve, Consolidated VST-33, in a 3-in. all metal line, and the Roots blower is connected to a 6-in. port in the anchor section through an 8-in. bellows and elbow and a Consolidated VST-62 6-in. toggle gate valve. The inlet ports enter at the side of the tube to reduce the chances of foreign particles dropping into the pumps.

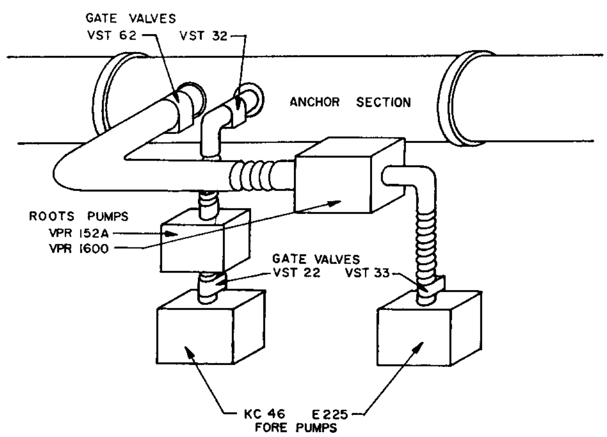

FIG. 4. Schematic diagram of pumping system.

This arrangement of pumps, requiring no bypass lines or valves and no oil warm-up time, has definite advantages in systems such as shock tubes which are repeatedly pumped down from atmospheric pressure. In the roughing phase the Roots blower merely windmills until a pressure of 6 mm is reached, at which time it automatically turns on. The system is further simplified in that no traps or baffles are required to prevent backstreaming of oil vapors, since rotor clearances eliminate the need for lubrication. The high cut-in pressure (compared with 10–100 μ Hg for oil diffusion pumps) eliminates the usual valley in the pumping curve and thereby reduces the pump-down time. The relatively low pumping speed at low pressures compared with that of a diffusion pump of equivalent cost is a potential disadvantage of the Roots blower in a leaky system, but in the 17-in. shock tube the pumping speed is more than adequate (10 min to pump the 110 cu ft driven section from atmospheric pressure to $\frac{1}{2}$ μ Hg). The VPR-1600 pumps the whole tube to about 0.2 μ Hg, less than half of its guaranteed ultimate pressure of $\frac{1}{2}$ μ Hg.

For attaining higher vacuum, another independent pumping system is mounted at the other 6-in. port in the anchor section. It consists of a Kinney KC 46 in series with a smaller Heraeus Roots blower, the VPR-152A (pumping speed 40 liter/sec, 3-in. inlet port, ultimate pressure 2×10^{-6} mm Hg). In addition to permitting studies in high purity rarefied gases other than air, this system serves as a spare in case of breakdown. The pump-down time from atmospheric pressure to 10^{-5} mm Hg using both pumping systems is about $\frac{1}{2}$ h.

V. DIAPHRAGM CLAMP AND CUTTING DEVICE

A quick opening clamp is used at the diaphragm station to join the driver section to the anchor section. It clamps the two mating flanges uniformly around their circumference and is opened or closed with one motion of a cam locking device (Fig. 5). To open the clamp a solenoid-driven locking pin must be withdrawn. This pin is interlocked by a pressure switch so that the clamp can not be opened if the driver is pressurized or if electrical power fails. In fact, an attempt to energize the solenoid when the driver is under pressure opens a dump valve in the driver. A diaphragm assembly, consisting of the diaphragm bolted at its circumference between two heavy rings, nests between the mating flanges. Seals are made by two O-rings in the anchor section flange and one in the diaphragm rings. The advantage of this system is that diaphragms can be bolted into the rings during pump down or when the facility is shut down. Then, all that remains for the actual diaphragm change is to open the clamp, roll back the driver section, remove the old ring and diaphragm, load the new, and reclamp the driver; a simple 30-sec job for one man. This arrangement helps make it possible for a single member of the research staff to operate the tube without technical assistance.

A cruciform blade cutting device (Fig. 5) is used for bursting the diaphragms.[6] The blades, which are on the low pressure side of the diaphragm, cut it as it bulges under pressure. A given blade setting and diaphragm thickness give accurately reproducible bursting pressures and, more important, shock Mach numbers (Sec. VII). However, a development program is still continuing on the device because at high pressures (near the free bursting pressure of a given diaphragm) the petals tear away from the rings, an effect not observed in the test rig of reference 6. In most cases the fragments are found in the far end of the *driver* section, so they are apparently torn off by the reflected shock wave (diaphragms that are intact are usually found to have their petals pointing into the driver). This effect becomes serious with thin diaphragms for which the free bursting pressure is only a few pounds above the minimum p_4 (reference 6, Fig. 4). In fact, the 0.006 and 0.010 in. 1100-0 Al diaphragms tested in reference 6 suffer petal loss over their whole p_4 range. The use of materials with better fatigue resistance and a redesign of the cutter are being investigated at present.

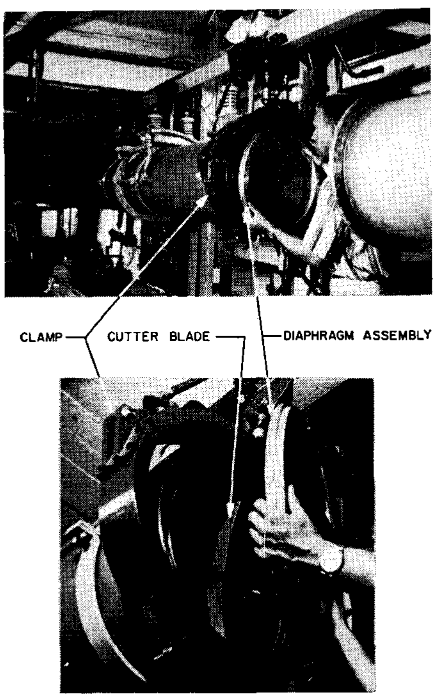

FIG. 5. Diaphragm assembly, clamp, and cutter.

[6] A. Roshko and D. Baganoff, Phys. Fluids 4, 1445 (1961).

VI. CONTROLS

In order that the tube can be easily operated by one person in the course of an experiment, a complete set of controls is mounted on a console at the test section (the pumps and associated valves can also be operated from a switchboard on the pump stand). In this way all operations other than diaphragm change can be performed at the test section. The initial driven section pressure p_1 is measured at the test section by a battery of gauges (aneroid, Pirani, and McLeod) mounted on the console and connected to the tube through a 1-in. bellows. A special valve which closes flush with the i.d. of the tube isolates the gauges from the test section during a run. A system of bellows vacuum valves on the console controls the admission of test gas or air to the driven section. This gas is carried through a 1-in. vacuum line from the console to the anchor section where it is admitted through a Veeco solenoid valve. The test gas inlet and pressure measuring lines are at opposite ends of the tube to insure that the gauges measure test section pressure rather than local pressures near the gas inlet. Also, in changes of tube configuration only one line between the console and test section needs to be changed.

Either of two driver gases (usually nitrogen and helium) can be admitted to the tube from the console. Two regulators and toggle throttle valves on the console join to a high pressure line that runs to the driver. A pressure gauge mounted on the console and connected to the driver through a separate line measures p_4, the driver pressure.

Also mounted on the console is some electronic equipment that is considered a permanent accessory to the tube; 2 Berkeley counters, 6 special fast-rise, high-gain preamplifiers (RHS Electronics model 201), and 6 junction boxes, each containing heating circuits, differentiators, and outputs for 2 thin film heat gauges.

VII. SHOCK TUBE PERFORMANCE

A series of 130 runs at relatively high initial pressures (1–10 mm) was made during the trials and shakedown of the facility. Certain features such as the diaphragm clamp, the cutting device, the feasibility of one-man operation, etc., were checked out, and some measurements of tube performance were made. The shock velocity was measured at 6 stations with thin film platinum heat gauges mounted in the instrumentation access holes (Fig. 6). Side wall heat transfer measurements and an indication of diaphragm opening time were obtained. These measurements were made simultaneously, with all amplification and recording done at the test section. The signals were led from the

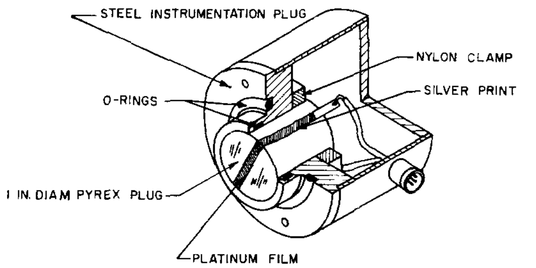

FIG. 6. Thin film heat gauge.

185-Ω films to the console through heavily shielded double 96-Ω coaxial cables up to 80 ft in length. With this arrangement it was possible for a single operator to obtain data on 5 timers and 2 oscilloscopes while averaging 2–3 runs per hour. The materials cost in a typical run was $1.65 for the diaphragm ($.50 material, $1.15 labor) and $5.00 for helium.

One quite important piece of information obtained from the measurements was the repeatability of the shock Mach number. Over the course of more than a month the velocity of the shock wave generated by one particular blade setting, diaphragm material, etc., was measured 28 times in the test section. In this case p_1 was 5 mm (air), p_4 about 18 psig (helium), the diaphragm was 0.020 in. thick 1100-0 aluminum and the mean shock Mach number was 4.28. The rms deviation in the time for the shock to traverse 50 cm was 2 μsec out of 337, or ±0.6%. This means that the temperature and pressure ratios were reproduced to about ±1%. Actually, at least as much scatter was introduced in the measurement of p_1 as in the rupture of the diaphragm. The use of a 0–50 mm absolute pressure dial gauge to measure $p_1=5$ mm resulted in an estimated standard deviation of at least 0.1 mm or ±2%. Now, from the shock tube equation,

$$\frac{d(p_4/p_1)}{p_4/p_1} \doteq \left[2+\frac{2\gamma_4}{\gamma_4-1}\frac{M_s}{\dfrac{\gamma_1+1}{\gamma_4-1}\dfrac{a_4}{a_1}-M_s}\right]\frac{dM_s}{M_s} \tag{4}$$

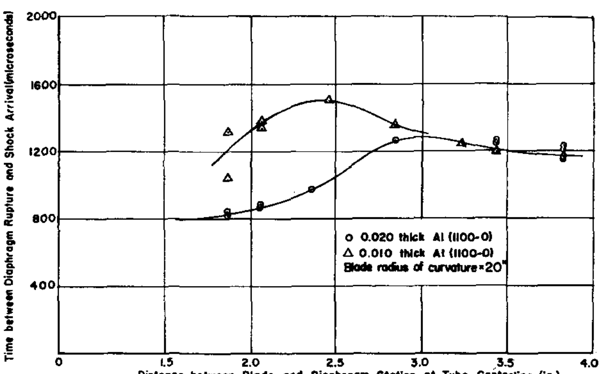

FIG. 7. Time between diaphragm rupture and shock arrival 2.6 diameters downstream vs blade setting ($p_1=5$ mm, helium driver).

so that for the conditions considered here the deviation in Mach number from p_1 variation alone is at least $\Delta M_s/M_s \geq \pm 2/6.3\% \doteq \pm 0.3\%$.

Under the above conditions, the shock reaches a maximum velocity about half-way down the tube, 20 diameters from the diaphragm. The attenuation in the last $12\frac{1}{2}$ ft of the tube is 0.03%/ft. This figure is 50% larger than the value predicted for laminar boundary layers and one tenth the value predicted for turbulent boundary layers.[7] (Laminar-turbulent transition is observed to occur 4.4 ft behind the shock.) A maximum attenuation of 0.1%/ft in $12\frac{1}{2}$ ft is observed just after the shock goes through its maximum velocity and may be associated with the shock formation process.[8]

At the first measuring station, 2.6 diameters from the diaphragm, a well-defined shock wave moving at 70–80% of the final velocity and followed by a highly nonuniform flow is observed. As a measure of the diaphragm opening time, the time interval between initial rupture of the diaphragm (determined by a shorting device mounted on the cutter blade) and the arrival of this shock at the first film gauge was measured. This quantity is plotted in Fig. 7 against cutter blade setting for two different diaphragms. It is evident that the diaphragm behaves differently at small blade settings than at large. Indeed, it seems plausible that when the blades are close to the diaphragm and the bursting pressure is relatively small the details of the diaphragm slicing determine the opening time, whereas at large settings the brute force of the pressure swamps other effects. Now, as the blade setting increases, the end of the blade at the perimeter of the tube recedes from the fixed diaphragm, so the diaphragm is not sliced all the way from its center to its outer edge by the blades but must partially tear. It seems reasonable that the increasing opening time for increasing but small blade settings reflects the increasing amount of tearing in the opening process. If so, this result graphically illustrates the effectiveness of cutting blades in decreasing opening time. In fact, a new method of adjusting the blade setting is being incorporated in which one of three different blades with different radii of curvature is inserted at the diaphragm station, rather than a single movable blade as at present.

Near the free bursting pressure of the diaphragm, on the other hand, the opening time τ is presumably determined by acceleration of the petals by the pressure force p_4. One can then argue from a simple model that, *for a given blade setting*,

$$\tau \sim d\left(\frac{\rho}{\sigma_{\mathrm{ult}}}\right)^{\frac{1}{2}}, \tag{5}$$

where ρ is the density of the diaphragm material, σ_{ult} its

[7] H. Mirels, National Advisory Committee for Aeronautics, Tech. Note 3278 (1956).
[8] D. R. White, J. Fluid Mech. 4, 585 (1958).

TABLE I. Specifications and performance of the 17-in. shock tube.

Internal diameter	17.097 in.
Length basic driven section	67.86 ft (47.5 diam)
Length driver section	12.5 ft
Maximum driver pressure	200 psi
Diaphragm diameter	16.60 in.
Ultimate pressure with VPR 152A	10^{-6} mm Hg
Ultimate pressure with VPR 1600	0.2 μ Hg
Pump-down time, 1 atm to $\frac{1}{2}\mu$	10 min
Leak rate	0.01 μ/h
Mach number deviation, rms ($M=4.28$, $p_1=5$ mm)	$\pm 0.6\%$

ultimate stress, and d the diaphragm diameter. That is, the opening time should be independent of diaphragm thickness and, of course, should decrease with increasing blade setting. This is the behavior observed at large blade settings. It may be surmised that near the free bursting pressure the *action* of the cutter does not contribute to opening time. However, use of the cutter permits larger p_4's to be used than diaphragm scribing does, so the decrease in opening time with increasing p_4 can be utilized to a greater extent.

Some of the features of design and performance mentioned in this paper are summarized in Table I.

ACKNOWLEDGMENTS

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Ultrasonic cw Spectrometer for the Investigation of Electron Spin-Phonon Interactions in Solids*

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(Received February 14, 1962)

A cw acoustic spectrometer operating in the frequency range of 10 to 1000 Mc is described. The acoustic probe, applicable to low temperature measurements, is characterized by its mechanical resonance properties. Several of the novel features of the spectrometer are described in some detail. The apparatus, essentially the acoustic analog of an electron paramagnetic resonance microwave transmission spectrometer, has been applied to the study of electron spin-phonon interactions in solids.

I. INTRODUCTION

THE introduction and increasing use of ultrasonic techniques in the investigation of magnetic resonance phenomena in solids has occurred only in the past few years. The first experiments utilizing ultrasound in magnetic resonance experiments, conducted by Proctor and co-workers,[1,2] were saturation-type experiments, in which the coupling of ultrasound to nuclear spins was detected indirectly, by the effect on the intensity of a normal nuclear magnetic resonance (NMR) line. The ultrasound, in effect, disturbed the equilibrium distribution of spins among the magnetic energy levels; this departure from equilibrium was monitored by an NMR pulse technique. Such experiments did not demand much sophistication in the way of ultrasonic technique; the specimen was purposely made acoustically absorbing at one end so that mechanically nonresonant conditions existed in the specimen. An improvement in this technique was that introduced by Taylor and Bloembergen.[3] In an acoustic saturation experiment on NaCl they prepared the specimen to be mechanically resonant, and attempted to estimate the energy density in the specimen by a capacitor technique.

Observation of direct acoustic excitation of nuclear spins was first made[4,5] by an ultrasonic cw resonance technique. In this technique a marginal rf oscillator was adjusted to "lock-in" to a high-Q mechanical resonance of an acoustic resonator consisting of the specimen and transducer. With the frequency fixed at the value determined by the mechanical resonance, the magnetic field was varied through the value corresponding to nuclear magnetic resonance. The acoustic absorption due to resonant nuclear spin-phonon coupling resulted in a small attenuation additional to the background attenuation. This added attenuation was reflected across the tank circuit of the marginal oscillator as a change in electrical impedance.

* This research was supported in part by the Air Force Cambridge Research Laboratories under U. S. Air Force contract AF 19(604)-8826.

[1] W. G. Proctor and W. H. Tantila, Phys. Rev. **101**, 1757 (1956).
[2] W. G. Proctor and W. Robinson, Phys. Rev. **104**, 1344 (1956).
[3] E. F. Taylor and N. Bloembergen, Phys. Rev. **113**, 431 (1959).
[4] M. Menes and D. I. Bolef, Phys. Rev. **109**, 218 (1958).
[5] D. I. Bolef and M. Menes, Phys. Rev. **114**, 1441 (1959); M. Menes and D. I. Bolef, J. Phys. Chem. Solids **19**, 79 (1961).