AERODYNAMICS OF BLASTS

by

I. I. Glass

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SUMMARY

For the past decade theoretical and experimental investigations have been conducted at the Institute of Aerophysics on shock-tube flows. Recently, this work was extended to include the analogous flows generated by spherical and cylindrical explosions. Glass spheres and cylinders are pressurized by means of compressed gases or combustible mixtures and are shattered to generate an explosion. Similar methods can be used for implosions, underwater explosions, and wave interactions. The finite mass, strength, and breaking time of the glass diaphragms impose some limitations on certain experiments where this technique is used to generate a blast wave. Nevertheless, the method has proved very valuable in the study of many basic properties of spherical and cylindrical blast phenomena that have been investigated using piezophy pressure gauges and several schlieren and shadowgraph techniques. Some consideration is given to intense explosions from concentrated energy sources for spherical, cylindrical, and planar blasts, and explosions and implosions generated from finite sources with the same geometries. Blast-wave simulators for aerodynamic tests and the dynamic testing of structural components are briefly discussed.
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### NOTATION

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<tr>
<td>$a$</td>
<td>sound speed (ft/sec, mm/μsec)</td>
</tr>
<tr>
<td>$\alpha (\gamma)$</td>
<td>function of $\gamma$</td>
</tr>
<tr>
<td>$C_v$</td>
<td>specific heat at constant volume (ft-lb/slug°R, cal/gm°C)</td>
</tr>
<tr>
<td>$C_p$</td>
<td>specific heat at constant pressure (as above)</td>
</tr>
<tr>
<td>$E_0$</td>
<td>total energy in spherical flows (ft-lb, equivalent gm of TNT)</td>
</tr>
<tr>
<td>$E$</td>
<td>$E_0/\alpha (\gamma)$, i.e. $E$ is proportional to $E_0$</td>
</tr>
<tr>
<td>$\xi$</td>
<td>$E_0/p_1$, an energy parameter (ft³, ft², ft depending on $\gamma$)</td>
</tr>
<tr>
<td>$\xi'$</td>
<td>$\sqrt[3]{E_0/p_1}$ ft, for spherical flows</td>
</tr>
<tr>
<td>$f$</td>
<td>flow quantity at a given radial distance $r$ or $R$</td>
</tr>
<tr>
<td>$G$</td>
<td>$G (r/R)$ a function of the reduced radial distance</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>$c_p/c_v$ specific heat ratio</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>$r/\xi$ nondimensional energy reduced distance</td>
</tr>
<tr>
<td>$\lambda'$</td>
<td>$r \left( \frac{E/p_1}{(E_0/p_1)^{\frac{1}{2}} + \frac{n}{2}} \right)^{\frac{1}{2}}$ nondimensional distance</td>
</tr>
<tr>
<td>$M_s$</td>
<td>$(S/a_1)$ shock Mach number</td>
</tr>
<tr>
<td>$N$</td>
<td>number of grid zones in shock transition</td>
</tr>
<tr>
<td>$n$</td>
<td>a power index</td>
</tr>
<tr>
<td>$\nu$</td>
<td>1, 2, 3 for planar, cylindrical, spherical flows</td>
</tr>
<tr>
<td>$p$</td>
<td>pressure (lb/ft² or dynes/cm²)</td>
</tr>
<tr>
<td>$\Delta P_s$</td>
<td>peak-overpressure at the shock front (atm)</td>
</tr>
<tr>
<td>$\Pi$</td>
<td>3.1416, also nondimensional parameters</td>
</tr>
<tr>
<td>$q$</td>
<td>artificial viscosity { nondimensional form Eq. (17) }</td>
</tr>
<tr>
<td>$R$</td>
<td>shock wave radius (in, ft)</td>
</tr>
</tbody>
</table>
(iii)

r  radial distance (in, ft)

r_1  Lagrangian or initial radius (in, ft)

r_0  diaphragm radius (in)

\rho  density (slugs/ft^3, gm/cm^3)

S  shock velocity (ft/sec, mm/\mu sec)

t  time (sec)

\mathcal{U}  a_1 t/\varepsilon  nondimensional energy reduced time

T  temperature (°K)

\mathcal{U}  p_1^{5/6} t/\bar{E}_0^{5/3}  nondimensional time

u  particle velocity (ft/sec)

U_1  free stream velocity in steady flow (ft/sec)

V  volume (ft^3, cm^3)

X  1/3 (r_1/\varepsilon )^3, a nondimensional Lagrangian variable in spherical flows

\triangle X  grid spacing in numerical computation

Subscripts

0  a reference atmosphere 14.7 psi, 0°C

1  ambient or atmospheric conditions

2  conditions immediately behind the shock wave

3  conditions immediately behind the rarefaction wave

4  conditions in the diaphragm

P_{21}  p_2/p_1 shock pressure ratio

P_{41}  p_4/p_1 diaphragm pressure ratio
(iv)

$T_{21}$  $T_2/T_1$ shock temperature ratio

$T_{41}$  $T_4/T_1$ diaphragm temperature ratio

$SS$  forward and backward facing shock waves (particles enter from right and left, respectively)

$RR$  forward and backward facing rarefaction waves

$C$  contact surface

$Air/\text{Air}$  diaphragm separating interior air at high pressure (and temperature) from exterior air at low pressure; similarly for He/Air
1. INTRODUCTION

Blast waves are familiar phenomena. They occur in nature in a relatively mild form during thunderstorms or they may become very intense during volcanic (steam) explosions. It is estimated that the Krakatoa explosion of 1883 resulted in an energy release equivalent to 5000 megatons of TNT (Ref. 1). However, man was also able to generate controlled or uncontrolled shock waves of increasing intensity when he learned how to crack a whip (Ref. 2), discovered propellants and explosives, made use of coal mines and grain elevators, and finally when he invented nuclear weapons (Ref. 3).

The aerodynamics of blasts is not only of interest in itself, but it is also closely related to supersonic and hypersonic flight and its now familiar shock wave patterns and sonic booms. It is of interest to note, for example, that a pound mass, at the earth's escape speed of 7 miles per second, possesses a kinetic energy equivalent to over 14 pounds of TNT (see Figure 1). Consequently, a ballistic re-entry at such speeds is very much like a powerful explosion. It is fortunate that most of this energy is absorbed through the bow shock in the denser layers of the atmosphere by heating the air which is left behind in the wake of the vehicle. Only a very small percentage of this energy is finally transferred to the vehicle itself, otherwise it would quickly vaporize. In a similar manner, the finite amount of energy in an explosion spends itself through shock-wave heating of an ever increasing mass of air until the shock becomes vanishingly weak.

Mechanical, chemical, electrical or nuclear blasts all dissipate their energy through shock waves. In the latter, however, about half of the energy is dissipated through thermal and nuclear radiation, although at very early times the thermal energy leakage is small (Ref. 3). Large flow velocities, temperatures, and pressures are induced behind a shock wave and it is the pressure and drag forces that cause the structural damage. The flow quantities decay in value with time and distance and when the shock wave is far enough away from the point of the explosion it has attenuated to a sound wave and the physical quantities behind the wave are then only vanishingly different from those in the ambient atmosphere. A similar type of decay applies to the shock system surrounding a supersonic aircraft so that when it flies at a sufficiently high altitude its effects on the ground are negligibly small.

The properties of both idealized intense explosions from concentrated constant energy sources and very weak explosions can be predicted analytically (Refs. 4, 5, 6). On the other hand, the analysis of actual explosions from finite sources must be treated by numerical methods (Refs. 7, 8). Such analyses have only become possible in recent years with the advent of high-speed electronic computers and the increased knowledge of the thermodynamic properties of explosives and of the air itself.
Some of the analytical solutions for intense explosions can also be applied to steady hypersonic flight through the so-called blast wave theory. For example, the solution for the intense cylindrical blast wave carries over to steady hypersonic flow over axisymmetric blunt-nosed slender bodies, and the planar blast to two-dimensional flows (Refs. 9, 10, 11, 12).

The method of generating cylindrical and spherical explosions, implosions and wave interactions that has been developed at UTIA, consists of bursting glass spheres or cylinders from 1 to 6 in diameter. For explosion studies these glass "diaphragms" are pressurized by means of compressed gases or combustible mixtures and exploded in a facility which consists of a 3 ft. diameter steel sphere whose ambient atmosphere can also be varied. For implosion experiments the steel sphere is pressurized and the glass spheres and cylinders are evacuated and implode owing to the existing pressure differential or they can be broken mechanically. In the case of an underwater blast the sphere is exploded through overpressure in a small tank filled with water. A few preliminary experiments of exploding spheres in a supersonic flow at $M = 2.5$, have also been tried (Ref. 13). The head-on collision of relatively weak spherical shock waves has been successfully investigated (Ref. 14).

An explosion generated from a 2 in. diameter glass sphere pressurized to 400 psi is driven by a blast energy equivalent to about 50 milligrams of TNT. Although the scaling of strong explosions in a facility of this type is aerodynamically quite possible it would only apply to very small models and at relatively small overpressures (up to several atmospheres). Consequently, shock tubes, sector tubes and other devices that are driven by TNT or other chemical explosives must be used to produce high-pressure pulses of long duration (fractions of a second) which are required for the proper simulation of the flow over large models with relatively long structural response times. The present facility is best suited to basic studies of the gasdynamics or the aerodynamics of the blast itself or the flows induced over small models by explosions.

2. INTENSE EXPLOSIONS FROM CONCENTRATED ENERGY SOURCES - SPHERICAL, CYLINDRICAL AND PLANAR BLASTS

The instantaneous release of a finite amount of energy in a concentrated form at a point, line, or plane gives rise to an intense blast wave in a spherical, cylindrical, or one-dimensional geometry, respectively. All of these blast waves possess the property that the profiles of any thermodynamic and dynamic flow quantity, $f$ (pressure, temperature, density and flow velocity) relative to the corresponding value immediately behind the shock front remain invariant with time ($t$) when the distances ($r$) are expressed as fractions of the shock wave radius from the point of the explosion; ($r/R$). That is, as the decaying blast
wave engulfs an even greater mass of gas, at a given fractional distance the physical quantities possess the same ratio, or $f(r, t)/f(R, t) = G(r/R)$. This similarity is predicted on the assumption that the shock wave is so strong that the ambient pressure and temperature are negligibly small in comparison to those behind the shock wave. Consequently, the similarity solution applies to the intermediate region between the origin of the explosion, where $r \to 0$ and $\tau \to \infty$, and that radius of the shock front where the shock wave has attenuated to an extent that the strong-shock assumption is invalid.

This type of problem was considered independently and almost simultaneously for the spherical case by Taylor (Ref. 4), Sedov (Ref. 5) and von Neumann (Ref. 6). The cylindrical case was considered later by Lin (Ref. 10), who also noted that his solution should be applicable to the analysis of a steady flow over an axisymmetric blunt-nosed slender body at zero angle of attack at hypersonic speeds, (where $r$ is equivalent to $y$ and $t$ is equivalent to $x/U_1$ (Ref. 11). An observer viewing a passing hypersonic body through a slit normal to the flight velocity will see very significant changes in the radial flow velocity as the body appears to drive the shock wave in a piston-like manner. Consequently, the flow in the $(y, x)$-plane appears like a cylindrical explosion in the $(r, t)$-plane. The flow in transverse planes exhibits a self-similarity in both cases when the shock wave is very intense and can be treated as having one independent variable. In a hypersonic flow the energy per unit length is equal to the total drag of the body. The planar, cylindrical and spherical blast waves were treated by Sedov (Ref. 5) and later by Sakurai (Ref. 12).

In solving this type of problem it may be seen that the solution will depend on the following six quantities $\gamma$, $p_1$, $f_0$, $E_0$, $r$, and $t$. The first three quantities describe the gas, $E_0$ is the instantaneous energy release, and $r$ and $t$ are the independent variables in the space-time plane of interest. From dimensional analysis, (using length, mass, and time as the three basic quantities) it is known that five minus three or two nondimensional ($\overline{\tau}$) functions can be formed that will describe the subsequent motion ($\gamma$ is already dimensionless). In the spherical case, for example, these functions are, $\mathcal{S} = (r/E_0)^{1/5} r/t^{1/5}$ and $\overline{\tau} = (r^{5/6} t)/E^{1/5} r^{1/2}$. Since it is assumed that for the strong blast wave $p_2 \gg p_1 \sim 0$, the nondimensional time parameter ($\overline{\tau}$) becomes zero and the motion is independent of time and is self-similar as noted above, and only two dimensional constants $E_0$ and $f_0$ are essential for a solution of the problem.

If we assume that the gas is perfect and inviscid, the equations of continuity, motion and energy (particle isentropic) which are valid in the region bounded by the blast wave are given by,

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial r} + (\gamma-1) \frac{\rho u}{r} = 0 \quad (1)$$

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial r} + \frac{1}{\rho} \frac{\partial p}{\partial r} = 0 \quad (2)$$
\[
\frac{\partial}{\partial t} \left( \frac{\rho}{\rho^2} \right) + u \frac{\partial}{\partial r} \left( \frac{\rho}{\rho^2} \right) = 0 \tag{3}
\]

where, \( \nu \) = 1, 2, and 3 for planar, cylindrical and spherical flows, respectively.

In general, this set of nonlinear partial differential equations is too difficult to solve and recourse must be made to numerical techniques. However, in the case of intense blasts where only two dimensional quantities \((E_0, \rho_1)\) affect the motion, the two independent variables \((r, t)\) are so related that the equations can be reduced to ordinary differential equations and exact self-similar solutions are possible (Ref. 5). The boundary conditions that have to be satisfied are that the particle velocity at the origin is zero and that the following Rankine-Hugoniot equations are satisfied across the shock wave at a radius equal to \(R\),

\[
\begin{align*}
\mathcal{U}_2 &= \frac{2}{\gamma+1} \left( 1 - \frac{1}{M_S^2} \right) \tag{4} \\
\rho_2 &= \frac{\gamma+1}{\gamma-1} \rho_1 \left( 1 + \frac{2}{\gamma-1} \frac{1}{M_S^2} \right) \tag{5} \\
p_2 &= \frac{2}{\gamma+1} \rho_1 \left( 1 - \frac{\gamma-1}{2\gamma} \frac{1}{M_S^2} \right) \tag{6}
\end{align*}
\]

For intense blasts, \(M_S\) is very large and the above relations reduce to,

\[
\begin{align*}
\mathcal{U}_2 &= \frac{2}{\gamma+1} \tag{4a} \\
\rho_2 &= \frac{\gamma+1}{\gamma-1} \rho_1 \tag{5a} \\
p_2 &= \frac{2}{\gamma+1} \rho_1 \left( 1 - \frac{\gamma-1}{2\gamma} \frac{1}{M_S^2} \right) \tag{6a}
\end{align*}
\]

The solution of Eqs. 1 to 3 subject to the above boundary conditions are given in detail in Reference 5 for planar, cylindrical and spherical flows and the results are illustrated in Figure 2. It is seen that the pressure behind the shock wave is a maximum and falls off quite rapidly near the shock wave to level off to a nearly constant value for radial positions \(r/R < 0.5\). As expected, the fall-off in pressure is greatest for the spherical case with its greatest freedom for expansion, and least for the planar case. The same tendency is even more accentuated
in the density profiles where it is seen that nearly all of the mass of gas engulfed by the blast is concentrated close to the shock front itself. The pressure and density profiles are reflected in the temperature profiles where it is seen that (subject to the assumption of an inviscid nonconducting gas) enormous temperatures are developed towards the centre of the blast as a result of the prevailing vanishingly small densities and finite pressures. This is particularly marked in the spherical case. The particle velocities decrease from their maximum value behind the shock front to zero at the origin of the blast. It is seen that the curves differ only slightly in the range \(0.5 < r/R < 1\), but here at a given \(r/R\), the spherical flow velocity is the lowest and the planar velocity the largest.

The motion of the shock wave is of course also found from the solution. However, an insight into this can be obtained from the dimensional considerations noted above. Since \(E_0\) represents the total energy released in the spherical case, per unit length in the cylindrical case, and per unit area in the planar case, it has dimensions of \(ML^{\nu-1}T^{-2}\), where \(M, L,\) and \(T\) represent the usual basic quantities of mass, length and time. Consequently, the nondimensional distance noted above can be expressed as

\[
\mathcal{L} = \frac{r}{(E/p_1)^{\nu/(2+\nu)} t^{2/(2+\nu)}}
\]  

(7)

where \(E = E_0/\alpha(\gamma)\). The function \(\alpha(\gamma)\) is a constant and is determined from the solution of the equations of motion. With the above notation the shock wave path can be obtained from Eq. (7), as

\[
R = \left(\frac{E}{p_1}\right)^{\nu/(2+\nu)} t^{2/(2+\nu)}
\]  

(8)

where, for convenience \(\mathcal{L}\) was set equal to unity. Using Eqs. (8) and (6a), the quantities in Table 1 can be derived. From the shock radius \(R\), shock speed \(S\), the pressure behind the shock \(p_2\), or the overpressure \(\Delta p\), it can be seen that the spherical blast wave decays most rapidly with time or shock radius.
TABLE 1

Some Properties of Intense Blast Waves

<table>
<thead>
<tr>
<th>Geometry</th>
<th>( R, E_{\text{eq}}(8) )</th>
<th>( S = -\frac{\Delta P}{P_{\infty}} ) or ( \frac{P_{\infty}}{P} \propto S^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spherical</td>
<td>( \left( \frac{E}{P_1} \right)^{\frac{1}{5}} t^{\frac{2}{5}} )</td>
<td>( \frac{2}{5} \left( \frac{E}{P_1} \right)^{\frac{1}{5}} t^{\frac{3}{5}} = \frac{2}{5} \left( \frac{E}{P_1} \right)^{\frac{1}{2}} R^{\frac{3}{2}} = \frac{1}{R^3} )</td>
</tr>
<tr>
<td>Cylindrical</td>
<td>( \left( \frac{E}{P_1} \right)^{\frac{1}{4}} t^{\frac{1}{2}} )</td>
<td>( \frac{1}{2} \left( \frac{E}{P_1} \right)^{\frac{1}{4}} t^{\frac{1}{2}} = \frac{1}{2} \left( \frac{E}{P_1} \right)^{\frac{1}{2}} R^{-\frac{1}{2}} = \frac{1}{R^2} )</td>
</tr>
<tr>
<td>Planar</td>
<td>( \left( \frac{E}{P_1} \right)^{\frac{1}{3}} t^{\frac{2}{3}} )</td>
<td>( \frac{2}{3} \left( \frac{E}{P_1} \right)^{\frac{1}{3}} t^{-\frac{1}{3}} = \frac{2}{3} \left( \frac{E}{P_1} \right)^{\frac{1}{2}} R^{-\frac{1}{2}} = \frac{1}{R} )</td>
</tr>
</tbody>
</table>

It is worthwhile considering some actual applications of the above equations. Equation (8) was used by Taylor (Ref. 4) to deduce the energy yield of the atomic explosion in New Mexico. Measurements of shock radii with time from high-speed photographs gave the points shown in Figure 3, which is a plot of Eq. (8) for the spherical case, that is,

\[
\frac{5}{2} \log R \text{ (cm)} - \log t \text{ (sec)} = 11.915
\]

The value 11.915 is the intercept of the 45° line with the ordinate axis at \( \log t = 0 \), and is equal to \( \frac{1}{2} \log E/P_1 \). For \( P_1 = 1.25 \times 10^{-3} \) gm/cm³, \( E = 6.76 \times 10^{23} \) ergs = \( 8.45 \times 10^{20} \) ergs. For \( \gamma = 1.4 \), the solution for the spherical blast yields \( C(\gamma) = 0.851 \) or \( E_0 = 7.19 \times 10^{20} \) ergs, or using a value of the energy content of TNT as 1000 cal/gm, this is equivalent to a yield of 17 kilotons of TNT. It should be noted that an upward translation of the straight line in Figure 3 would be indicative of a stronger or higher energy yield spherical blast and vice versa. The answer obtained in this manner is only approximate considering the simplifying assumptions of a point source, constant energy, and a perfect, inviscid gas. In an actual case a significant portion of the energy is dissipated through thermal radiation at later times (Ref. 3). Nevertheless, the method shows that a great deal of insight can be obtained from this type of analysis.

An example of an intense cylindrical blast wave is the sudden explosion of a fine cylindrical metal wire caused by the sudden input of a heavy electrical current pulse. The analysis of the motion of the shock wave is made more difficult by the complex manner in which energy is added and the change of phase of the wire from a solid to a vapour that occurs at very small times. In addition, the imperfect equations of
state for the metal and the ambient gas into which the blast propagates must be taken into account. In fact, the exploding wire becomes analogous to a hot, pressurized cylinder that is suddenly ruptured, rather than a line source. Consequently, imploding shock waves and wave interactions occur that invalidate the similarity assumptions.

A recent survey of exploding wires is given in Reference 15, where Bennett's experimental results indicate a variation favouring $R \propto t^{0.6}$ rather than $t^{0.5}$ as given by Eq. (8). For this case $\dot{x}(\gamma) \approx \dot{x}(1)$ (see References 5 and 10). One of the best results for a 5 mil exploding copper wire with a rated energy of 60 joules/cm ($\sim 15$ milligram TNT/cm) is shown in Figure 4. Here, the shock wave is advancing into air at half an atmosphere at a rate of $R \propto t^{0.7}$. However, in the range of 1.5 to 1 atmosphere, a single plot of $R \propto t^{0.6}$ appeared to fit the remaining results even better. The fact that all of these experiments at different ambient densities gave an apparently constant $E/\rho$, or that a decreasing $\rho$ could apparently decrease the energy added to the copper wire is surprising. However, when this result is considered from the viewpoint of the cylindrical analogue to the shock tube noted above, it might be explained by the fact that a diaphragm pressure ratio that changes by a factor of 5 (as in this case) would hardly affect the strength of a strong shock wave (Ref. 16). Some critical comments regarding this problem by Bennett and by Rouse can be found in Reference 15.

A planar type of blast wave may be generated by the sudden addition of electrical energy to a gas by means of an electrode or electrodeless discharge. The so-called T-tube developed by Fowler and by Kolb is a typical example (see Ref. 16 for a brief survey). Such a device for adding energy to a gas in a plane (ideally), as investigated at UTIA is shown schematically in an insert in Figure 5. Energy during a discharge is added to the gas across a gap from two 1.5 microfarad, 30 kilovolt, low inductance capacitors by means of ohmic heating and through the magnetogasdynamic ponderomotive force applied as a consequence of the rigid back-strap. During an experiment the current, rate of current, and voltage inputs are monitored across the gap by means of oscillograms. The energy input is therefore known as a function of time. The sudden addition of electrical energy coupled with the ponderomotive force generates a blast wave in the 22 mm. pyrex tube whose path is illustrated in Figure 5, in an (r, t)-plane schlieren record.

The initial conditions are noted on the figure, and from the oscillograms a computation has indicated that about 20, 8 and 5 joules/cm$^2$ were added to the gas in three damped half-cycles at about $3\mu$ sec. intervals. The latter two probably did not contribute very much to driving the blast wave as there was no apparent strengthening of the shock wave after the first half-cycle. Figure 5 shows the hot, luminous, expanding gas driving the shock wave in front of it. During the first $25\mu$ sec. it is difficult to separate the shock front from the luminous gas on the schlieren record. Some typical shock paths are shown in Figure 6 as solid lines and the dashed lines show the planar blast wave decay given by Eq. (8). In this instance $\dot{x}(\gamma) \sim 1.08$, for $\gamma = 1.4$ and $\dot{x}(\gamma) \sim 0.60$ for $\gamma = 5/3$.
Also in this case as well similarity is not achieved during the early phase of the flow because the assumption of energy addition at a plane is not met. A finite source is probably closer to reality. At higher pressures (5 mm. Hg) and after about 20 $\mu$ sec, $R \propto t^{2/3}$ appears to be a reasonable approximation for subsequent small time intervals. Below 20 $\mu$ sec, the shock waves are weaker than predicted by this power law. However, for the case of air at a pressure of 0.2 mm. Hg, a power law profile appears to be entirely inadequate. The blast wave is considerably stronger at the low pressures, which would result from a higher effective diaphragm pressure ratio. Further details are given in Reference 17.

It is worthwhile to note at this point that in the analysis of an intense blast at times when shock wave attenuation no longer permits the assumption that the pressure in front of the shock wave may be neglected by comparison with that behind it, the exact Rankine-Hugoniot shock conditions must be satisfied and that the solution is no longer self-similar. Equations (1) to (3), must now be solved numerically. This has been done by Brode (Ref. 7), who made use of the concept of an artificial viscosity in order to overcome the difficulty of flow discontinuities at the shock wave. The artificial viscosity spreads the shock front over about 6 mesh lengths and a continuous transition results, analogous to an actual shock transition. The results are shown in Figure 7 for air considered as a perfect gas and an imperfect gas. It is seen that for shock wave peak overpressures, in atmospheres, in the range $\Delta P_s > 10$ atm, $\Delta P_s \propto 1/\lambda_s^3$ (a slope of 72 degrees) and at very low overpressures, $\Delta P_s \propto 1/\lambda_s$, the acoustic result for a spherical wave (a slope of 45 degrees). In the intermediate range $\Delta P_s$ can be fitted with a polynomial in $1/\lambda_s^6$.

The perfect gas solution lies above the imperfect gas case and is indicative of the energy that is bound in vibration, dissociation, electronic excitation, and ionization, and is not available for driving the blast wave. Brode estimates that the imperfect point-source explosion is only about 50 percent as efficient as that in perfect air ($\gamma = 1.4$) (Ref. 8).

Brode has reported three explosions from very hot spheres of gas where the interior density is assumed as that at standard conditions but at pressures of 122, 2000, and 20,000 atmospheres (Refs. 7, 8). In the latter case the required uniform temperature is about 386,000°K. The 122 atm. sphere approaches the perfect gas point-source solution at $\Delta P_s \sim 20$ and $\lambda_s \sim 0.2$ and the 2000 atm. sphere when $\Delta P_s \sim 300$, $\lambda_s \sim 0.8$. The 20,000 atm. sphere approaches the imperfect gas solution when $\Delta P_s \sim 2500$ atm. and $\lambda_s \sim 0.035$, as shown in Figure 7. The latter then diverges somewhat from the imperfect point-source curve and is brought closer to it by the overtaking of the second shock and finally the third shock. After an overpressure of 10 atm. the hot-sphere solution runs almost parallel to the imperfect gas point-source solution. The circled points are the data from a nuclear explosion as reported in
Reference 3, and are seen to agree very well with Brode's calculations, except at low overpressures when the explosion energy is small compared with the ambient energy of the air engulfed by the blast wave and the accuracy in the calculation of maintaining a constant blast energy is reduced.

The TNT curve on Figure 7 exhibits a decay in $\Delta P_S \propto 1/A_S$ initially (Ref. 18). Later, it cuts across the other three curves, and at low overpressures lies closest to the imperfect gas solution. As Brode points out, every explosion is affected by its initial history to some degree and consequently they are difficult to compare or scale accurately. He indicates that a rough rule is that the peak overpressure in an explosion will decay in a manner similar to a point source when the shock wave has engulfed a mass ten times the mass of the initial explosive. Furthermore, although the peak overpressure may be scalable the flow quantities within the blast interior may differ for each source, and identical scaling becomes very difficult (Ref. 8).

Three profiles of overpressure to peak overpressure ratio ($\Delta P/\Delta P_S$), density ratio ($\rho_1/\rho_2$) and particle velocity ($u/u_2$) from the blast centre to the shock front for the point source, perfect gas explosion have been drawn on Figure 7, for $\gamma = 0.00147$, 0.1436, and 0.745. These have been included to illustrate how, in time, the blast wave profiles depart from Taylor's solution for the strong shock wave and develop positive and negative phases when the overpressure drops. A hot spot remains near the origin even at late times, as indicated by the persistent near-zero densities and finite pressures.

An important conclusion that one might draw is that a finite source explosion will eventually decay very much like a point source blast. The effects of the wave interactions appear to vanish quickly if the source is hot (high sound speed). Since the cube of the inverse radius type of shock-decay relation applies to the spherical-shock overpressures long after the strong shock conditions really cease to be accurate, the corresponding attenuation relations would also be expected to apply to the cylindrical and planar blasts. However, this is not entirely borne out by the exploding-wire or T-tube experiments noted above. In these cases it is possible that a modified type of similarity solution based on a decreasing energy input with time might yield a more realistic type of power profile for the shock path at early times. Later on the decay may well be represented by that from a finite source explosion in a manner exhibited by the nuclear blast points on Figure 7.

3. EXPLOSIONS AND IMPLOSIONS GENERATED FROM FINITE SOURCES

The results of Sec. 2 indicate that a realistic approach to the propagation of blast waves would be to consider an energy source of finite extent for spherical, cylindrical and planar explosions. Once a finite source is assumed then the complementary problem of implosions may be considered simultaneously. In order to simplify the analysis it
is assumed that no energy is lost through radiation and that the flow is inviscid. The problem is then to determine the resulting flow properties when a plane, cylindrical, or spherical diaphragm, which separates a gas at higher or lower pressure (and temperature) from that of the external atmosphere, is suddenly ruptured generating an explosion or an implosion, respectively (Figure 8). In the case of a planar flow one assumes a very small length of chamber \( r_0 \) relative to the channel in the case of an explosion. On the other hand, in the case of an implosion the channel is made very short.

For very small times, less than the time it takes for the head of the rarefaction wave or the shock wave to reach the origin in the case of an explosion and implosion, respectively, Eqs. (1) to (3) can be solved by using a power series solution or the method of characteristics (Refs. 19, 20). The results are illustrated schematically in Figure 8. The planar case is the familiar shock-tube case, which has been treated in great detail by many authors (Ref. 16). Here state (4) is at high pressure (and temperature) and state (1) at low pressure. Since the flow is symmetrical about the origin, consider that the right diaphragm is ruptured. Immediately a shock front (S) moves into region (1), compressing and heating the gas in region (2) in an irreversible manner. At the same instant a rarefaction wave (R) moves into state (4) and isentropically expands and accelerates the particles in the opposite direction to form state (3). This gives rise to a contact surface (C), which separates the uniform state (2) existing at a high entropy level from that of state (3).

For the cylindrical and spherical explosions the picture is changed. States (2) and (3) are no longer uniform. The shocks and contact surfaces decelerate. Consequently, state (2) is a region of decreasing entropy behind the shock path. The characteristic lines in the expansion fan accelerate towards the shock front (Ref. 13), and it will be shown that the existence of an imploding shock wave turns state (3) into a nonisentropic region. These effects are even more pronounced in the spherical case than in the cylindrical case (Figure 8).

When an implosion occurs, the shock accelerates towards the origin and it is followed by an accelerating contact surface. The characteristic lines in the expansion wave decelerate in a direction opposite to the shock front. State (2) is now a region of increasing entropy behind the shock path. The effects are again accentuated for the spherical flow. As expected, for the same diaphragm pressure ratio \( P_{41} \), a finite-source explosion generates a stronger rarefaction wave for the spherical and cylindrical blasts than for the planar explosion, and vice versa for the implosion. Furthermore, it might have been anticipated that since in cylindrical and spherical flows the contact surface decelerates and it also behaves as a massless piston it would send expansion pulses to decay the main shock wave and compression pulses to form a second shock at the tail of the rarefaction wave in the case of cylindrical and spherical explosions. In implosions the reverse takes place. Here the
compression pulses reinforce the main shock and the expansion pulses reinforce the main rarefaction wave. Consequently, a second shock wave does not occur in an implosion. This will be verified subsequently.

Although the above approach for small times is of interest, it does not solve the problem. A solution has to be obtained from a numerical integration of a set of stable, finite-difference equations that approximate the nonlinear partial differential equations Eqs. (1) to (3). The boundary conditions of zero velocity at the origin and the Rankine-Hugoniot relations across shock waves must also be satisfied. It might be noted that although a solution is possible by using the method of characteristics for the planar case, it is complicated by the additional term in the continuity equation for the cylindrical and spherical cases. This term leads to a singularity at the origin and causes the planar Riemann invariants \( \frac{2a_0}{(\gamma - 1) \pm c} \) to vary along characteristic lines so that the method becomes complex especially when unique values for the flow quantities no longer exist as a result of the formation of shock waves from steepening compression waves.

The method of numerically integrating Eqs. (1) to (3) has been developed by Brode (Ref. 7), and successfully applied to a number of problems (Refs. 8, 18, 21). For convenience, Eqs. (1) to (3) are written in Lagrangian form (Ref. 13). The independent variables are time \( (t) \) and the initial radial position of a gas element \( (r_i) \). The dependent thermodynamic and dynamic variables are made nondimensional by using the ambient gas properties (for example, \( \bar{p} = p/p_1 \), \( \bar{u} = u/a_1 \), etc., and the bars can be omitted for simplicity). Similarly, the independent variables are made nondimensional by using the pressure-reduced energy of the gas contained in the interior of the diaphragm. For example,

\[
\frac{\varepsilon_0}{\bar{p}_1} = \frac{\bar{V}}{\bar{p}_1} = \frac{\sqrt{\bar{f}_4 \bar{C}_v \bar{T}_0}}{\bar{p}_1} = \sqrt{\frac{\bar{p}_{41}}{\gamma_4 - 1}} \tag{9}
\]

where

- \( V = \frac{4}{3} \pi r_o^3 \), spherical flows, \( \nu = 3 \)
- \( V = \pi r_o^2 \), per unit length, cylindrical flows, \( \nu = 2 \)
- \( V = 2 \pi r_o \), per unit area, planar flows, \( \nu = 1 \)

For spherical flows in particular,

\[
\frac{\varepsilon^3}{4/3 \pi r_o^3} = \frac{\bar{p}_{41}}{\gamma_4 - 1} \tag{10}
\]

From Eqs. (9) and (10) it is seen that the reduced energy per unit volume (reduced energy density) depends only on the diaphragm pressure ratio \( \bar{p}_{41} \) and the specific heat ratio \( \gamma_4 \) in all blast cases, and approaches infinitely large values when \( \bar{p}_{41} \rightarrow \infty \) or \( \gamma_4 \rightarrow 1 \).
The usefulness of Eq. (10) will be considered subsequently. The follow­
ing dimensionless quantities are now formed,

\[ \lambda = \frac{r}{\epsilon} \]
\[ \zeta = \frac{a_1 t}{\epsilon} \]  

(11)

With the above notation, the Lagrangian equations of motion in non­
dimensional form can be expressed for the spherically symmetric case, 
as follows (Ref. 7),

\[ \frac{\partial \lambda}{\partial \zeta} = \frac{1}{\rho \lambda^2} \]  
\[ \frac{\partial \rho}{\partial \zeta} = -\frac{\lambda^2}{\gamma} \frac{\partial}{\partial \lambda} (\rho + \sigma) \]  
\[ \frac{\partial \sigma}{\partial \zeta} = \frac{1}{\rho} \frac{\partial}{\partial \zeta} \left[ \gamma \rho + (\gamma - 1) \sigma \right] \]  
\[ u = \frac{\partial \lambda}{\partial \zeta} \]  
\[ X = \frac{1}{3} \left( \frac{\gamma}{\epsilon} \right)^3 \]  

(12)  
(13)  
(14)  
(15)  
(16)

The quantity \( X \) is a Lagrangian variable expressing the nondimensional volume per steradian for a spherical shell of radius \( r \). The quantity \( \sigma \) is the dimensionless form of the artificial viscosity that provides the means of automatically spreading the shock wave into a thin, continuous trans­
tion (Ref. 22). Brode has found that the following form of \( \sigma \) produces the required results without significantly distorting the rest of the flow field,

\[ q = \frac{9 \gamma (\gamma + 1)}{4} \left( \frac{N}{11} \right)^2 \rho \left( \Delta X \right)^2 \frac{\partial u}{\partial X} \left[ \frac{\partial u}{\partial X} - \frac{\partial u}{\partial X} \right] \]  

(17)

Where, \( \Delta X \) is the grid size (\( \sim 1/100 \) distance traversed by the shock wave), \( N \) is the number of grid zones in the shock front (\( \sim 6 \)) and, is neg­
avtive for shock waves so that \( q \propto (\partial u/\partial x)^2 \) for shocks and \( q = 0 \) for expansion waves or for contact surfaces. Equations (12) to (17) provide five 
equations for the five unknowns \( \lambda, \rho, \sigma, u \) and \( q \) in terms of \( X \) and \( \zeta \). A discussion of the finite difference equations that have been used by Brode to approximate the above partial differential equations and the required stability conditions in the time interval \( \Delta \zeta \) can be found in Reference 23.
3.1 Spherical Explosions and Implosions

Explosions have been produced by bursting 1 in. diameter to 5 in. diameter pressurized glass spheres. Compressed air, helium, argon, sulfurhexafluoride, and combustible mixtures of oxygen-hydrogen diluted with helium were used as driver gases. However, extensive numerical solutions by Brode were done only for the following two cases, 2 in. diameter spheres containing air at 22 atmospheres and helium at 18 $-1/4$ atmospheres and $300^\circ$K. These cases were checked experimentally in some detail (Refs. 24, 25). It should perhaps be emphasized again that the shock-tube problem only has a simple analytical solution as long as the diaphragm separates chamber and channel sections of sufficient length to eliminate immediate wave interactions. The amount of work required to obtain a solution for a single spherical or cylindrical blast problem is rather extensive and it is for this reason that the investigation was limited to the above two cases. Under the conditions noted above the air and helium spheres contained an energy equivalent to 88 and 44 milligrams of TNT (1040 cal/gm), respectively. The nominal 50 mm. diameter glass spheres were about 1 mm. thick and weighed approximately 20 gm. The spheres were blown individually of pyrex or soda lime glass with stems about 65 mm. long, 6 mm. diameter and 1 mm. thick.

The original computations, as described in Sec. 3, for the Air/Air and He/Air blasts were done in the nondimensional radius-time $(\lambda, \tau)$-plane and on several graphs, have been converted for convenience to units used in the experimental work. The conversion factors for the $(r, t)$-plane are $\lambda = 0.2$ corresponds to $r = 0.11$ in. and $\tau = 0.2$ corresponds to $t = 90\mu$sec. for Air/Air and $0.2 \lambda \equiv 0.94$ in. and $0.2 \tau \equiv 72\mu$sec. for He/Air. A standard atmosphere of 14.7 psi and $0^\circ$C (subscript 0 ) was used by Brode as a reference atmosphere rather than the ambient conditions.

The paths of the various wave elements are shown in the $(r, t)$-plane in Figure 9 for the case of Air/Air and in Figure 10 for He/Air. It is seen that when the sphere is ruptured a decelerating shock wave $(S_1)$ moves into (1) followed by a decelerating contact front $(C)$. A rarefaction wave $(R)$ propagates into (4) and a second shock wave $(S_2)$, which forms at the tail of the rarefaction wave but faces in the opposite direction to $(S_1)$, is swept outward by the expanding high-pressure gas. However, as the second shock wave gains strength, it overcomes this flow velocity and finally implodes on the origin. Refractions at the contact front produce secondary waves (rarefaction and shock waves in the case of the air explosion, but only shocks for the case of the helium blast) (Ref. 16) and cause it to oscillate as indicated, and after some time several shock waves $(S_1, S_2, S_3)$ move away from the explosion. Unlike similarly-facing shock waves in the plane case these waves do not overtake (Ref. 16) at the times and distances considered here. For example, $(S_2)$ is caught in the negative-pressure phase of the primary shock wave where it encounters a low sound speed and opposing particle velocity that slows it up. In the case of the hot sphere shown in Figure 7, $S_2$ does not encounter
such conditions and does overtake to strengthen $S_1$, and this is repeated again by a third shock $S_3$. Unlike the planar flow, regions (2) and (3) are not uniform or isentropic owing to the existence of these shock waves of continuously varying strength.

It has been shown by Brode (Refs. 7, 8, 24), that various types of blasts approach and have a decay rate like the limiting point-source solution for shock overpressure versus radius after the primary shock ($S_1$) has engulfed a mass of air of about tenfold that of the original explosion. For a hot or light gas this occurs much more rapidly than for a heavy gas for a given initial volume. Therefore, for the same size sphere ($r_0$) and diaphragm pressure ratio ($P_{41}$) the combination He/Air gives initially a much stronger shock than SF$_6$/Air say (shock tube effect) (Ref. 16). However, SF$_6$ is a more efficient explosive when the point source solution is finally reached and the scaling laws can be applied approximately (energy loading effect - Eq. (10)). That is, the same shock overpressure would take place at a larger physical radius for the case of SF$_6$. These effects are illustrated in Figure 11 for the cases of He/Air and Air/Air blasts used in the present experiments. It is seen that the He/Air case approaches the point source solution faster owing to the lower mass of helium or since the sound speed in helium is much greater the effects produced by the wave interactions vanish sooner. Initially, the helium gives a larger peak overpressure ($\Delta P_S$) at a given radius (R) than the air case. However, for the same initial diaphragm pressure ratio ($P_{41}$) the air sphere contains $5/3$ as much energy as the helium sphere and if both explosions would coincide with that of the point-source solution, $\Delta P_S$ at a given R would be larger for the air blast than for the helium blast. From Figure 11 it is seen that the initial history of a given blast is not "forgotten" and no curve is coincident with any other. Consequently, identical scaling using different sources is not possible, although as noted above for many purposes the close proximity of the curves may be quite sufficient for scaling.

It is worth noting from Eq. (10) that once a spherical flow solution has been found for a given $P_{41}$ and $\gamma_4$ (this fixes the type of explosive), then it does not matter if $r_0$ or $\xi$ (mass of explosive) is increased or decreased. The same solution applies as this only increases or decreases $\lambda$ and the explosion is magnified or reduced in the physical $(r, t)$-plane.

The Air/Air and He/Air explosions approach the point source curve at positions when $\Delta P_S$ decays in a more complex manner than $\Delta P_S \sim 1/\lambda_S^3$ since the shock front is neither strong nor weak. The helium blast approximates the point source imperfect-air attenuation when the shock is at $\lambda_S \sim 0.5$ or $R \sim 2.4$ in., at a shock overpressure $\Delta P_S \sim 1.8$ atm. If one considered a 20 kiloton point source blast, then, applying the energy scaling relation such an overpressure would exist at a distance $R \sim (20 \times 10^6 \times 10^3 \times 10^3)^{1/3} \left(\frac{44}{1/3} \times \frac{2.4}{12}\right) = 1540$ ft, or 0.29 miles. The Air/Air blast cuts the point source imperfect-air
solution when $\gamma_s \sim 1.1$ or $R \sim 6$ in. and $\Delta P_s \sim 0.35$ atm., but it has a more gradual attenuation. The equivalent scaled distance for a 20 kiloton blast when $R$ is at the same overpressure occurs at $R \sim (2 \times 10^{13}/88)^{1/3} \times 6/12 = 3050$ ft, or 0.58 miles. Consequently, only shock wave effects at large distances from very intense explosions with correspondingly small models could be simulated by using the present shock-sphere apparatus.

In addition to the wave traces in the $(r, t)$-plane it is also possible to plot all the thermodynamic and dynamic properties of the explosions (see References 7, 8, 18, 21 and 24), for example) as functions of time or radial distance. Contours of constant particle velocity and density are shown in the $(\nu, \lambda)$-plane in Figures 12 and 13 respectively. The decrease in density behind the incident and reflected rarefaction waves is quite apparent. The particle velocity however is increased through the incident rarefaction wave and decreased through the reflected rarefaction wave until it is zero at the origin. The density in front of the imploding shock wave near the origin is very small. The imploding shock also induces large negative velocities as it nears the origin. The effects are felt over the entire flow field and it is seen that a line of zero particle velocity exists behind the exploding primary shock wave. This is the beginning of the negative phase and the pressure becomes subatmospheric to the left of this contour. It is of interest to note that the constant density lines in the $(\nu, \lambda)$-plane resemble their steady flow hypersonic counterpart in the $(x, y)$-plane for a body whose axisymmetric shape is given approximately by the contact surface locus in the $(t, r)$-plane (the blast wave analogy would really apply to the cylindrical explosion since the spherical blast involves four dimensions and it has no analogue in steady flow).

A second shock wave is also usually observed in the steady flow case. However, it always appears to be coupled with some overexpansion at the shoulder of a flat plate with a cylindrical nose say, where the boundary layer thins and a recompression is necessary for the streamlines to match the body contour. Unlike an explosion, the second shock wave in supersonic flow appears to be caused by viscous effects, but this has not been verified analytically.

As an example of a typical profile the variation of pressure from the main shock front to the centre of the explosion is shown in Figure 13. (Any number of such profiles or of density, temperature, particle velocity, dynamic pressure, and the static and dynamic pressure impulses can be drawn from the detailed tabulated results). The pressure profiles are shown for times of 130, 195, 310 and 420 $\mu$ sec. The contact surface is identified by a bar. At 130 $\mu$ sec, the rarefaction wave has already reflected from the origin where the pressure is quite low. The second shock $S_2$ is imploding on the origin and the main shock $S_1$ has covered over 2 inches. As time goes on the pressures behind the main shock and in front of the second shock are dropping, giving rise to a weaker first shock and a stronger second shock wave, respectively. At 420 $\mu$ sec.
$S_2$ has reflected from the origin and is very much stronger than $S_1$, which it is now following.

The variation of temperature with time at the origin for the air blast is shown in Figure 15. It is seen that the temperature undergoes extreme changes from the reflected rarefaction wave to the reflected imploding shock wave ($20^0K$ to $3000^0K$). The origin is a singular point and Guderley (Ref. 26) has shown that the imploding shock wave in a perfect gas approaches infinite strength when it reaches the origin. For an imperfect gas (or perfect gas) considering viscosity and heat conduction this would hardly occur, furthermore the continuum equations may not apply very close to the origin. However, this is not the reason why the temperature (or any other thermodynamic quantity) remains finite on the present graph. It is due to the artificial viscosity that spreads the shock wave over about 6 mesh points and consequently it is not possible to approach the origin to within a few hundredths of an inch. For all practical purposes this is quite sufficient. The experiments conducted at UTIA indicate a finite shock velocity at the origin within the limits of resolution of the $(r, t)$-plane schlieren records for cylindrical and spherical flows.

The question why the second or imploding shock wave occurs is often asked. It arises as a result of the spherical or cylindrical nature of the flow and can be understood by observing the path of the contact front, which indicates the manner in which the interior high-pressure gas expands to its nearly stationary value at a pressure somewhat below the ambient atmosphere. As this front decelerates, it sends out ahead of itself rarefaction pulses that overtake and decay the primary shock. However, behind it compression pulses are sent out that steepen into the second shock wave. (The behaviour is qualitatively similar to the one-dimensional problem of impulsively accelerating a piston to a uniform velocity and then decelerating it instantaneously). Such an effect does not occur in the planar case where initially the contact front moves at a uniform velocity before it interacts with the shock or the rarefaction wave.

It might be noted that in the case of an implosion the motion of the contact front is such as to generate in front of it compression pulses or Mach waves to further increase the strength of the imploding shock wave. However, behind it rarefaction pulses are produced. Consequently, a second shock cannot occur in an implosion. Furthermore, these rarefaction pulses make it possible to have a weaker initial rarefaction wave for a spherical implosion than in a shock-tube flow. The inward motion of the contact front is stopped by the reflected imploding shock wave.

Although explosion experiments have been made using spheres from 1 in. to 5 in. diameter, the 2 in. diameter spheres have proven most satisfactory for the present 12 in. diameter field of view.
schlieren system. The 1 in. diameter sphere shrinks the phenomena at the origin while the 5 in. diameter magnifies it too much in many cases. Consequently, most of the blast effects will be illustrated with the results from the 2 in. diameter spheres.

Figure 16 shows a sequence of four shadowgrams that illustrate the bursting process of a 2 in. diameter glass sphere pressurized at 300 psi when it is hit with a 1/2 in. diameter mallet head and the subsequent development of the flow and the shock wave. The mallet head is attached to the slender rod which is part of a solenoid actuated breaker mechanism. At the top of the photographs appears the rubber coupling that holds the stem through which the sphere is pressurized. The foil or wire at the right side forms part of the triggering circuit. It is seen that the gas rushes out through the fractured glass to generate compression waves which coalesce to form the shock wave. The contact region exhibits turbulence owing to its passage over the jagged glass fragments and its front is therefore irregular. Although this has an effect on the shape of the shock front at small times, the wave soon stabilizes and becomes perfectly spherical as shown in (c). The mallet blow affects the collective shape of the glass fragments so that they assume an ellipsoidal form as in (d), where the appearance and diffraction of the second shock wave can also be seen (Refs. 24, 37). The glass fragments are not small. It is only when they strike the wall of the steel sphere that they are pulverized.

Figure 17 is a schlieren record of the bursting of a 2 in. diameter glass sphere taken with a high-speed multi-source spark camera (Ref. 28). In this case the sphere was ruptured through overpressure alone. A band of conducting paint circled the sphere and when the paint was severed it supplied the pulse for triggering the spark sources. The central frame, which is on the optical axis, is circular (1 in. diameter) and is used for alignment purposes only. The remaining 8 frames are on a 2-7/8 in. diameter pitch circle and undergo vignetting owing to the off-axis location of the spark light sources of the schlieren system (Ref. 29), whose 12 in. diameter beams also transilluminate viewing windows of identical size. All the 9 frames are taken on standard 4 in. x 5 in. Kodak Royal Pan cut film. The framing sequence is from 1 to 8, at intervals noted on Figure 17. The growth of the explosion is illustrated very well in this series. Especially noteworthy is the second shock wave in frame 6, and its disappearance in frame 7.

The same type of blast is shown in Figure 18, which is a schlieren photograph of the (r, t)-plane. The paths of the main shock wave, the second shock waves, the front of the contact region, and the glass fragments are readily seen. From this and many other records it can be concluded that the imploding second shock and its reflection at the origin advance at finite speeds. The glass sphere breaks up in about 50 to 60 μsec. and the fragments accelerate to velocities of over 200 ft/sec. As a result the shock front does not form instantly but as a consequence of
coalescing compression waves as noted above. This can be seen in Figure 18 at small times and is similar to the formation process of plane shock waves in a shock tube (Ref. 30).

A comparison of theory and experiment for the case of the air blast is shown in Figure 19. Owing to the finite duration of the breaking process of the glass sphere the actual primary shock takes some time to form and to achieve full strength and consequently it falls behind the theoretical wave. The glass fragments are quickly accelerated to a uniform velocity ($\sim 250$ ft/sec) and represents an equivalent loss in energy available to drive the explosion ($\sim 20\%$). These effects cause the second shock to implode about $15 \mu$ sec late. However, it races on and soon does match the theoretically predicted shock trace. The oscillations of the contact front are much milder than predicted by theory and this no doubt arises from the fact that the actual contact front becomes quite turbulent as it passes over the glass fragments. Consequently, the expected refraction process is more gradual. The large scale mixing at the contact front also causes the cold gas to occupy a larger (and asymmetrical) volume than predicted by theory. Some detailed discussions of the blast generated by an exploding glass sphere can be found in Reference 24, and more recently in Reference 25.

Two $(r, t)$-schlieren records for a He/Air explosion appear on Figure 20, where $S_1$, $S_2$, and $S_3$ are clearly seen. The implosion of $S_2$ is masked by the glass fragments since it occurs sooner than in air. The excellent reproducibility for the two runs for the 6 in. and the 12 in. radii are shown in (a) and (b) and is quite typical of all runs. The experimental results for the helium blast appear in Figure 21, and are seen to be qualitatively similar to those described for the air case. Owing to the initial formation delay the second experimental shock wave appears where the calculated third shock occurs.

It is worth noting that the final results shown in Figures 19 and 20 were obtained in a very much improved apparatus (Ref. 25), as illustrated in Figure 22, whereas the original explosion runs were made in a simple wooden box (Ref. 24). The glass spheres and cylinders were housed in a spherical shell of 3 ft. diameter that could be pressurized or evacuated for explosions, implosions, or wave interaction studies.

Some experiments were also conducted at the same diaphragm pressure ratio ($P_{41}$) but at half the absolute pressure level in order to verify Eq. (10), and to simulate an altitude explosion where the explosive energy density has been reduced in the same ratio as the ambient atmosphere. This is simple to do in the present case but is not so easily done with TNT, for example. The runs were in good agreement in every detail with those taken at ambient conditions (at sea level). However, this should not be misconstrued as a verification of scaling at high altitude where sizeable excitation of internal modes can take place which are both density and temperature dependent. Under such conditions it is not
possible to use the blast data obtained at sea level in order to extend it to high-altitude by means of the energy parameter ($E$) in a simple manner. It should be noted that TNT cannot be scaled identically at altitude because by analogy with Eq. (10) the diaphragm pressure ratio ($P_{41}$) is changed as a result of the reduced ambient pressure $p_1$. To reproduce identical scaling a solid explosive of lower energy density would have to be used to match the new pressure $p_1$ (see Reference 18).

Piezo pressure records taken at given radii as a function of time for these types of explosions are discussed in some detail in Reference 25. As these gauges effectively measured the unsteady pitot pressure they were useful for determining the instantaneous overall Rankine-Hugoniot pressure jump across the incident and reflected shock waves. Miniature blast type gauges for measuring flow-pressure profiles have as yet not been developed. Two representative pressure records for Air/Air and He/Air explosions are shown in Figure 23. Good agreement was obtained between the pressure records and those of the $(r, t)$-plane schlieren photographs regarding shock arrival and shock strength.

It is worth noting that the head of the spherical rarefaction wave can also be seen when a gas with a high index of refraction, such as sulfurhexafluoride is used in a large glass sphere which also helps to decrease the opacity, as shown in Figure 24. The imploding head moves at a constant sound speed of about 450 ft/sec until it reflects from the origin and then the speed decreases through the rarefaction wave. The second shock is also seen to implode and reflect from the origin about 1.3 milli­-sec after the sphere breaks and illustrates that the wave interaction effects persist for a relatively long time in a low sound speed gas.

The effect of increasing the charge size or sphere diameter is well illustrated in Figure 25a when it is compared with Figure 18. For example, the corresponding distance between $S_1$ and $S_2$ is reduced in half in Figure 25a. Cranz (Ref. 31) discovered that times and distances in spherical blasts of a given explosive, for example, scale directly with the radius of the charge. Consequently, if the charge radius is doubled or the mass increases eightfold a given peak-overpressure say will occur at twice the distance and time than those for the original charge. This property is already inherent in the present numerical solution because of the definition of $\tau$ and $\chi$, which were made nondimensional by the total explosion energy.

The effect of a high diaphragm pressure ratio ($P_{41}$) is illustrated in Figure 25b where the shock is propagating into the 10 mm. Hg atmosphere at 2600 ft/sec with almost negligible attenuation. Consequently, very strong spherical shocks can be produced by using a hot, high-pressure driver and a low ambient atmosphere. This result might have been expected since at the instant of rupture conditions at a spherical or cylindrical diaphragm are as in an ordinary shock tube. That is, the planar solution applies at the instant of rupture but immediately after the
cylindrical or spherical geometric decay takes effect. However, with combustion runs significant improvements in the production of strong shock waves should be possible if they are coupled with a low pressure atmosphere.

Experiments using combustion drivers for 2 in. diameter to 5 in. diameter spheres have recently been performed at UTIA, using a stoichiometric mixture of oxygen and hydrogen diluted with 70% helium (partial pressures) (Ref. 32). The combustible gas was initially premixed in two stages, the hydrogen and helium from one tank was admitted first and oxygen from another was used to complete the charge. The three gases are now premixed (strict safety precautions must be taken) in a single high-pressure cylinder to improve combustion through the homogeneity of the mixture. The mixtures are ignited at the centre of the sphere from a small spark obtained from a pulse transformer using a 300 volt primary and 6000 volt secondary. The combustion process is illustrated in Figure 26a, where for convenience it is taking place in a 4 in. diameter cylinder, 4 in. long, so that it may be observed through the optically transparent end plates. The moment the spark occurred is shown by the horizontal light line. This timing marker was put on using another spark source. It is seen that the flame builds up in velocity during the first 200 ft/sec and then maintains an almost constant speed of 50 ft/sec up to 1700 ft/sec when it starts to decelerate (Ref. 33) as a result of reflected compression waves generated by the piston-like flame front, and at 2800 ft/sec the cylinder bursts. From these and other results it can be concluded that only a slow moving deflagration front occurs since the spark is very weak. The full pressure and temperature (theoretically nearly an order of magnitude greater than at ambient conditions) (Ref. 16) is not realized in any of the present spheres (or cylinders) as they will normally not withstand more than about 600 psi. As a result, the spheres burst at each particular maximum strength and the combustion process is quickly extinguished by the incident and reflected rarefaction waves. Consequently, although a noticeable improvement in shock velocity is obtained the full benefit of combustion is not realized. Figure 26b illustrates this point. It is seen that the second shock wave reflects from the origin very early (less than 100 μ sec. after rupture) owing to the predominantly hot helium in the driver-gas mixture. An acceleration of the main shock wave occurs after about 50 μ sec. and its maximum speed is only 2000 ft/sec. Therefore the most significant improvement in shock strength would be obtained if the combustion drives were coupled with stronger spheres bursting in a low pressure atmosphere. Further details will be found in Reference 32.

Some earlier attempts to generate spherical implosions may be found in Reference 25. In the present experiments the 3 ft. diameter steel sphere was pressurized up to 125 psi, which is the limiting pressure of the existing windows in the sphere. The glass sphere, up to 5 in. diameter, was either evacuated and broken with the solenoid-operated breaker or the sphere failed automatically at its weakest section owing to the crushing effect of the ambient atmosphere. Two representative results are shown in Figures 27 and 28.
Figure 27 is a high-speed schlieren record taken at 50 μ sec. intervals of an implosion from a 5 in. diameter glass sphere. It is seen that when the mallet hit the sphere the fragments that formed the lower cap were carried inside the sphere by the inrush of high-pressure air. Unlike the explosion cases the glass sphere did not fragment instantly illustrating that a compressive load tends to keep it intact. The very interesting fringe pattern that covers the field appears to consist of Mach waves. It has not been settled whether their origin is aerodynamic (inflow) or elastic (oscillation or rippling of glass surface). (The knife edge in the schlieren system was vertical and to the right looking from the camera. Therefore, light areas on the left of any frame are indicative of expansions and dark areas of compressions and vice versa on the right hand side.) The low pressure region around the periphery of the broken sphere caused by the inflow is clearly seen in frames 1 and 2 in the region of the lower cap. The shower of glass fragments soon impinged on the remainder of the sphere and broke it up and then emerged through the upper cap of the sphere. The resulting flow was completely non-uniform.

Figure 28 illustrates a similar implosion run, but this time the sphere was broken by the crushing load of the external pressure. The painted conducting ring which is clearly seen, supplied the trigger pulse for the camera. The right hand side of the sphere failed first as shown in frame 1. This time it is evident that the entire sphere has cracked since there is an efflux of gas from the sphere cracks on the left hand side. It must be concluded that compression or shock waves were formed by the piston action of the inrushing air such that the pressure and temperature inside the broken glass sphere locally exceeded the ambient pressure. The density of the gas however is still lower than ambient (white). The glass fragments formed a "shaped charge" that completely penetrated and obliterated the left side of the sphere, as seen in the remaining frames.

A similar type of implosion is shown in Figure 29, which is a schlieren photograph of the (r, t)-plane. A 5 in. diameter sphere containing air at 300 mm. Hg was used under an external pressure of 65 psi of 30% SF₆ and 70% air in order to get a high index of refraction for the schlieren flow visualization. Rarefaction wave pulses are seen for about 800 μ sec. to the left of the record (black lines) and when the glass fragments started moving towards the origin the expansion appears stronger. About 400 μ sec. later the fragments have reached their minimum collective apparent diameter and were then swept outward by the compression wave (broad black band on the right). The inner compressed air also is seen to be moving out at the left as a lower density (black) flow. Qualitatively therefore, the correct type of implosion record is obtained except that the shattering process does not take place instantly, and the waves form gradually. The interior flow is completely hidden by the opaque glass fragments so that it is not possible to tell whether any sharp imploding shock wave existed.
In view of the high-speed schlieren records of the \((x, y)\)-plane and those of the \((r, t)\)-plane it must be concluded that this method of generating spherical implosions will not prove successful until a type of glass diaphragm is found that will shatter uniformly and very rapidly and even then interior observations may prove impossible. The present results substantiate those obtained previously in Reference 25.

In summary, one can state that the use of pressurized glass spheres for generating spherical explosions has proved quite successful. The agreement with theory is satisfactory considering the limitations that are imposed when a physical diaphragm, which has mass and takes a finite time to break up, is introduced. The motion of the second shock wave in the interior and exterior gas has been established. There is little doubt from the schlieren records that the second shock wave does not reach infinite strength as it implodes and reflects at the origin as expected for a viscous, heat-conducting gas. Attempts were made to photograph the luminosity that might have been produced at the origin in argon and air but without success. This substantiates that even if strong imploding shocks were generated the amount of gas affected by excitation at the origin is negligibly small.

3.2 Cylindrical Explosions and Implosions

During the past few months glass cylinders have been used to generate explosions and implosions (Refs. 32, 34). Open and sealed-end cylinders have been used for this purpose (Figure 30). The sealed-end cylinders were made by the Corning Glass Co., with glass end plates fused to the cylindrical body with a minimum of optical distortion. Both types of cylinders were held quite rigidly in a frame between two approximately 12 in. x 12 in. x 3/4 in. glass plates in order to assure that a cylindrical flow geometry was maintained.

The cylinders were either pressurized and ruptured using a solenoid-operated mallet or they were ruptured by overpressure when filled with a gas or combustible mixture of oxygen-hydrogen and helium (as for spheres) and an exploding wire was used for ignition in case of open-end cylinders. Rubber gaskets and O-rings held the cylinders against the glass plates which were drilled and fitted with two 1/8 in. diameter copper electrodes. A 0.0025 in. diameter copper wire was stretched across the electrodes in the centre of the cylinder and it was exploded by discharging an energy of 50 joules stored in a 25 \(\mu\)f capacitor at 2000 volts. The wire ignited the gas mixture and at a later time the cylinder ruptured and generated an explosion.

A blast from a 2 in. diameter closed-end cylinder appears in Figure 31. It is seen that the wave system is very similar to the spherical explosion. The head of the rarefaction wave \((H)\) is easily visible now through the flat end plates. The first shock \((S_1)\) and the imploding and exploding motion of the second shock \((S_2)\), as well as the path of the contact front \((C)\), can readily be distinguished.
Figure 32 shows a much stronger explosion from an open-end cylinder. The rarefaction wave and the main shock wave are very clear in this record. The second shock wave is obscured by the internal flow and reflected shock waves. Sound pulses are seen in the interior of the pressurized cylinder (50 µ sec.) prior to its complete collapse. The pulses which arise from the initial cracks in the cylinder are not seen in the exterior atmosphere owing to its low density perhaps, or the asymmetry of the break.

Figure 33 shows a cylindrical blast, using a stoichiometric mixture of oxygen and hydrogen diluted with 70% helium at a total pressure of 88 psi, which was initiated by an exploding wire. The moment the wire exploded is indicated by the luminous streak across the schlieren record. The shock wave from the exploding wire and its attached rarefaction wave move back and forth within the cylinder and distort the motion of the flame front. The burning mixture appears as a white region, and is finally extinguished by the expansion waves about 1100 µsec. after initiation. The black line through the centre is the position of the electrode. It can be seen that the shock wave was accelerating and finally was moving at 1700 ft/sec at a radius of about 5 in. from the centre of the explosion. Since every cylinder has its own bursting pressure, which is below the calculated constant-volume pressure conditions, combustion will continue for a short time after rupture and will help to accelerate the shock front, but because the breaking strength of a cylinder is relatively low the full benefit of the high-pressure and temperature due to combustion is not attained. The motion of the second shock is rather obscured in the combustion runs and it is difficult to distinguish.

From the above it can be concluded that it is quite feasible to generate cylindrical explosions using glass cylinders by any of the three methods noted above. The combustion runs are more desirable when strong shock waves are required and for their reliability in obtaining a successful break. However, their initial conditions are not as well known as in explosions initiated with a mechanical breaker. Comparing the cylindrical and spherical explosions it can be stated that the spherical bursts are much more reliable and symmetrical. They do not suffer from gasket leaks and are much simpler to set up. In addition, the cylindrical explosions are not free from side-wall boundary layers.

For the analysis of the cylindrical explosions Eqs. (12) to (17) may again be solved, employing the method developed by Brode. This has not yet been done, since it was felt necessary to establish first a successful method of generating such explosions prior to undertaking extensive calculations.

It was noted previously that a real difficulty with spherical implosions from ruptured glass spheres is that the interior flow is obscured by the opacity of the fragmented glass. To overcome this difficulty some cylindrical implosions were initiated using sealed-end and open-end
cylinders (Ref. 34). The sealed-end cylinders were not found to be useful for this work, as the end plates shattered and the net effect was an obstructed interior view nearly similar to the spherical implosions seen above. Large open end cylinders appear to offer some promise and their use is presently being investigated. Analyses also in this case will not be attempted until a feasible experimental method has been established. It should be noted that Payne (Ref. 35) has solved numerically a number of cases for the cylindrical implosion. No second shock wave was found for the reasons given in Sec. 3.1. Payne used a form for the artificial viscosity that did not prove as useful as the one employed by Brode (Eq. (17)), since it appeared to affect the entire flow field to some extent. It would be quite worthwhile to repeat this work using an equation of the form given by Eq. (17) for the artificial viscosity. Such calculations would be initiated at UTIA if a successful method of generating cylindrical implosions were developed.

3.3 Planar Analogues of Explosions and Implosions

If a very short chamber relative to the channel is used to establish a shock-tube flow, then the rarefaction wave will quickly reflect from the closed end, interact with the contact region, overtake the shock wave, and establish a process of shock decay. A peaked type shock wave profile is then formed which resembles a blast wave. If the initial shock wave is very strong then the shock motion may perhaps have a type of strong planar blast wave decay similar to Eq. (8), after it had engulfed a certain mass of air, corresponding to the spherical cases shown on Figures (7) and (11). In the planar case a graphical or numerical solution using the method of characteristics would be quite feasible, especially since many of the interaction problems can be solved in closed form (Ref. 16).

In a similar manner, when the channel of a shock tube is made very small compared with the chamber then a flow analogous to an implosion can be generated. The shock wave "implodes" on the origin with uniform strength (end of channel), reflects from the closed end with an increased uniform strength, interacts with the contact surface, and then with the rarefaction wave where it is decayed. Of course, it is only the attenuation of the shock wave that bears an analogy with the cylindrical and spherical blast waves in the explosion or implosion cases. Before that time the waves and states are uniform in the planar case and nonuniform in the cylindrical and spherical cases. It would be of some interest to investigate these two problems analytically and experimentally in a shock tube such as the Wave Interaction Tube at UTIA, which is well suited for this purpose.
4. BLAST WAVE SIMULATORS

The effects of blast waves can be simulated by different methods and to different degrees. Each method has its own inherent advantages and drawbacks. The following methods have been used: full scale tests (Ref. 3), chemical explosions in open ranges (Refs. 36, 37), chemical explosions in closed ranges (Ref. 31), shock tubes, conical sector tubes (Ref. 38), and explosively-driven (Primacord) pressure vessels (Ref. 39). A full discussion of these facilities is beyond the scope of the present paper. However, it is worth noting that complete simulation can only be achieved in a full-scale test but with the inherent disadvantages of hazards, expense and the lack of laboratory type of control and repeatability. The other facilities may simulate various properties of explosions and some of these better than others. For example, the blast from pressurized glass spheres or cylinders is most useful for the investigation of the shock wave and the flow properties since the overpressures and their durations are comparatively small for significant size model tests. Shock tubes are very useful for the determination of aerodynamic loads on rigid models in a blast (Ref. 40) and for proving structural components. Typical schlieren photographs of the flow over slender (Ref. 41) and gable models with relatively short and long shock transit times are shown in Figure 34 a and b. In both cases the shock diffraction over the models gives rise to Mach-type shock reflection which includes a vortex and a slipstream (contact surface). In Figure 34a the flow behind the shock wave is just supersonic and in b, it is subsonic and contains a series of Mach waves generated in the flow. For a slender solid model (34a) with a short shock-transit time or rapid pressure equilization, aerodynamic drag may be predominant. However, for a sizeable panelled structure (34b) with a long transit time, then peak pressures and the pressure impulse may cause the most severe damage.

For dynamic testing of sizeable structural components a shock-tube facility would become enormously large and expensive. For such tests high overpressures and long flow durations (of the order of the response time of the structure) are required and explosively driven simulators such as specially designed high-pressure vessels (Ref. 39) or sector tubes (Ref. 38) appear to be very useful. It is worth noting that since all of the blast energy in a sector tube can be concentrated over a small solid angle rather than over $4\pi$ steradians very large amplification factors are theoretically possible for very small cone angles $(4/d\theta)^2$, or $5.25 \times 10^4$ for a one degree cone angle. Consequently, relatively small charges can be used to produce effectively large explosions. In practice, such high magnification factors are not obtained owing to losses that arise from elastic and viscous effects. However, the experimentally obtained gain is still very impressive (Ref. 38).
A blast from relatively small hemispherical TNT charges exploded in a steel hemisphere of about 50 to 100 ft. in diameter, for example, would only have a magnification factor of two for the same charge weight. However, it would be more versatile than a narrow sector tube with regard to the number of models that might be tested per run at different radii, and it would have the advantage of simulation of terrain and water surfaces as well as the possibility of testing at low pressure (high-altitude) testing. With a 7 lb. hemisphere of TNT (1060 cal/gm) it would be possible to obtain an over-pressure of 25 psi at 11 ft. from the origin, about 3.4 millisec after the initiation of the blast. The positive phase would last about 2.2 millisec and the negative phase about 5.6 millisec. At a 50 ft. radius the overpressure behind the blast wave is down to 1.5 psi and should not present any structural difficulty. On the other hand, a pressure of 25 psi is reached at about 1560 ft. in a 20 kiloton TNT blast giving pressure profile durations of about 140 times as great as for the 7 lb. hemisphere. Consequently, for dynamic structural tests flow times of several hundred milliseconds would be required.

5. SOME RESEARCH APPLICATIONS OF EXPLOSIONS GENERATED FROM PRESSURIZED GLASS SPHERES AND CYLINDERS

It was noted in Sec. 3 that successful explosions can be generated from pressurized glass spheres and cylinders. Blasts produced in this manner are relatively safe in comparison with chemical sources and the initial conditions are well known. The spherical explosions have the added advantage of the absence of any viscous boundary layer effects and are even simpler to generate than cylindrical blasts. Consequently, spherical explosions produced in this manner can be applied to a variety of interesting research problems such as underwater explosions, blasts in a supersonic flow (Ref. 13), shock wave collisions (Ref. 14), shock wave diffractions over various models, shock wave refraction at gaseous and liquid interfaces and shock waves at extremely low densities without boundary layer interference. Properties of cylindrical and spherical deflagration and detonation waves may well be investigated using the same techniques.

In the following subsections a few of the problems noted previously will be considered. As soon as the flow loses complete spherical symmetry, the analysis becomes very complex. It is necessary to introduce an additional space variable and more difficult boundary conditions. Consequently, problems on spherical shock wave collision, diffraction and refraction have as yet not been solved numerically using the methods developed by Brode, as they tax the capabilities of present day high-speed computers. It is hoped that such solutions will become possible in the near future. In the meantime experimental feasibility studies have been made of some of the problems outlined previously.
5.1 Underwater Explosions

It is quite feasible to study underwater blasts generated from pressurized glass spheres using compressed gases or combustible mixtures as drivers. Some preliminary runs have just been conducted in a commercial aquarium (8 in. x 16 in. x 10 in. deep) filled to a depth of about 8-1/2 in. of water. Distilled water is most satisfactory as it reduces light absorption and scattering. Pressurized glass spheres, 2 in. diameter containing air over 300 psi were used to produce the blasts, which were recorded with the high-speed schlieren camera. One run containing 200 psi of a combustible mixture (0.2 H₂ + 0.1 O₂ + 0.7 He) was also photographed and a schlieren record of the (r, t)-plane was obtained. All the runs were self-breaks due to overpressurization. A trigger pulse to the spark light sources was provided by a painted circuit circling the glass sphere which was severed when the sphere burst.

High-speed schlieren photographs of an underwater explosion generated from a 2 in. diameter glass sphere at 310 psi are shown in Figure 35a. In this experiment the schlieren system was not perfectly adjusted for the water but rather for the air as the working medium. The record also suffers from a slight accidental double exposure which accounts for the flake-like background in some frames. Nevertheless, it does illustrate the blast phenomena quite well. In frame 1, the air-water contact surface appears as a black band and above it is the wider band of the aquarium metal framework. The sphere and its metal pipe holder are also seen. Tap water was used in the tank for this run. Frame 1 was taken 15 μsec. after the sphere ruptured. The hydrodynamic blast wave appears well-formed but somewhat displaced below the ruptured sphere, which still appears intact. Unlike an air burst the glass fragments are constrained by the water from flying off. Taking half of the difference between the shock and glass sphere diameters for a distance base line gives the shock wave an average velocity of 1.84 in. in 15 μsec. or 12,300 ft/sec. Using a sound speed in water of 4800 ft/sec results in an apparent shock Mach number \( M_s \approx 2.12 \). Employing the calculated shock wave properties in water given in Reference 42, a corresponding pressure of nearly 35,000 atm. would exist behind a blast wave at this shock velocity. Consequently, it must be concluded that the electronic timing, any optical refraction effects that might produce an enlarged shock-wave image and the encasement effect of the glass sphere will have to be carefully investigated before the actual velocities of the shock wave are accurately established.

Since vertical knife edges (to the right, looking from the camera) were used, the upper and lower portion of the shock do not appear so well defined. The left portion of the shock also suffers from the removal of light from an already weakly illuminated background. Many overtaking compression waves are seen behind the shock wave in the white area (compression) to the right of the frame. Unlike an air burst, the characteristic change from a white to a black area, as the gradients from the rarefaction zone of the peaked profile take effect behind the shock wave,
is not seen here. The reflected rarefaction pulses generated at the air-
water contact surface as the main blast wave and overtaking compression
or Mach waves refract at the contact surface are seen in frame 2. These
waves do travel with the sound speed in water at about 4800 fps, as will
be noted later.

The compressed air bubble is seen to emerge in frame 4
and does not appear to have changed in frame 5. In frame 6 it has grown
to a 3.0 in. diameter, in frame 7 to a 3.9 in. diameter, and in frame 8
to a 4.6 in. diameter, giving an average velocity of about 60 ft/sec. and
40 ft/sec, respectively. The air bubble appears effectively opaque, as a
result of the spherical lens action of the surrounding water which deflects
the light rays very much like the glass sphere itself. In frame 7 the ex-
panding bubble is now raising the water surface and in frame 8 this effect
is still more apparent. Even in this last frame after a flow duration of 2
millisec, the glass sphere still appears intact and its diameter is almost
unchanged.

Figure 35b contains frames from three additional under-
water explosions taken in similar aquariums (the glass side plates in-
variably broke during a run) all filled with distilled water. The schlieren
system was adjusted for the water as the working medium. The improved
quality of the schlieren photographs is quite noticeable. The advance of
the blast wave and its refraction at the contact surface are well illustrated
in row no. 1. The apparent average shock speed from frame 1 is 2 in. in
11 \( \mu \) sec. or 15,200 ft/sec; from frame 2, 3.1 in. in 30.4 \( \mu \) sec. or
8500 ft/sec. The difference between frames 2 and 3 gives 1.16 in. in
19.4 \( \mu \) sec. or a rapid decay to nearly 5000 ft/sec. The advance of the
reflected rarefaction wave head in frames 2, 3 and 4 gives it a speed very
close to the sound velocity of 4800 ft/sec.

In row no. 2, the blast wave appears to have travelled
2.5 in. in 11 \( \mu \) sec. or an apparent speed of 19,200 ft/sec. It is worth
noting that the bursting pressure was also higher here. The reflected
rarefaction wave head again has a velocity of nearly 4800 ft/sec, but some-
what slower. (A measurement of distance does not have the same accuracy
as that of time. However, the velocities quoted are not meant to be defini-
tive as the experiments are only of a preliminary nature). In row no. 3, an
average shock velocity of 7800 ft/sec. is obtained for the first 20 1/8 \( \mu \) sec.
and is consistent with the previous results, as the shock decay is rather
rapid. From frame 2, the average speed over the first 50 \( \mu \) sec. is 6100
ft/sec. The difference between frames 1 and 2 again gives an average
velocity of 5000 ft/sec, which is approaching the acoustic value and is in
agreement with the previous results.

The above preliminary data have shown that this method
of generating underwater blasts offers some very worthwhile possibilities
and a systematic research program is presently underway. The apparent
values quoted for the shock speeds were given for illustration purposes
only and should not be misconstrued as being actual speeds. Further details will be found in future UTIA publications as they become available.

It is perhaps worthwhile to include the (r, t)-plane schlieren record of an underwater explosion, shown in Figure 36. A combustible mixture \((0.2 \, \text{H}_2 + 0.1 \, \text{O}_2 + 0.7 \, \text{He})\) at 200 psi was used as the driver gas. The instant of ignition is shown by the luminous horizontal line and the first shock wave appears about 1400 \(\mu\) sec. later. Poor quality schlieren (due to the flexing of the thin glass plates perhaps) make the passage of the shock wave almost invisible except at the very edges of the film strip. In this case the hot air bubble in contact with the water gives rise to some peculiar spreading and motions of the contact region. The record was included for its qualitative value only but it does illustrate that good quantitative records should be possible. Schlieren photographs of the (r, t)-plane would be much more definitive in accurately computing the shock and air bubble velocities from these continuous-time records.

5.2 Head-On Collision of Spherical Shock Waves

An investigation of this type of interaction, using blasts from 2 in. diameter glass spheres, has proven quite successful. Since numerical solutions existed for Air/Air and He/Air explosions for spheres at 22 and 18 atm., respectively, these were chosen for the initial studies. Consequently, by the time the spherical shock waves collided they were relatively weak. Much stronger collisions can be generated by using low ambient pressures (Figure 25b) coupled with combustible driver gases (Sec. 3.1). The boundary condition at the point of intersection of the spherical shock waves can be determined from planar wave theory (Ref. 16). This type of interaction is illustrated in Figure 37 in the \((x, t)\) and \((u, p)\)-planes. State (1) is a rest state. States (2) and (5) are the states behind the backward and forward facing approaching shock waves. It is seen that after the collision two shock waves that are separated by a contact surface recede from the point of interaction. The new states (3) and (4) have a higher pressure than the previous states and their particle velocity will follow the stronger shock wave. Once the initial shock strengths \(P_{21}\) and \(P_{51}\) and state (1) are known the final wave strengths and states (3) and (4) can be found (Ref. 14).

After the instant of interaction new boundary conditions must be satisfied that involve both regular and Mach type reflections. Consequently, the flow becomes asymmetrical and very complex. A solution would now contain three independent variables (two spatial and one temporal) and the reflection boundary conditions noted above. Such a solution based on the method developed by Brode has not been obtained to date.

However, the collision problem has been investigated using optical techniques and a comparison between the planar theory and the experimental results at the point of intersection was possible. A view of the two 2 in. diameter glass spheres, with their centres 9 in. apart, and of the solenoid-operated, spring-loaded breaker mechanism is shown in
Figure 38. The same technique was employed in generating a double blast as for a single explosion with the exception that the plunger now had two mallet heads to break the two spheres at approximately the same instant. Although there was some variation in sphere geometry and strength of the glass this was usually achieved.

Figure 39a shows a shadowgram of approaching shock waves from He/Air and Air/Air explosions. Some diffracted waves about the breaker can be seen, otherwise, the blasts are as in Figure 16. In Figure 39b the shock waves have collided and penetrated. Only a small change in shock wave curvature is noted owing to the low strength of the colliding shock waves and for the same reason no contact front can be observed in the penetration region between states (3) and (4).

A schlieren record of the (r, t)-plane of the same type of interaction is shown in Figure 40. The left-hand sphere contains helium at 500 psi and the right-hand sphere air at 250 psi. The approximate location of the contact surface is shown in the explanatory sketch. The absolute velocities of the shock waves, measured in laboratory coordinates, divided by the sound speed in state (1) are given in the caption as measured absolute shock Mach numbers. These are in fair agreement with theory. There are some difficulties involved in accurately measuring shock speeds from curved paths and further details are given in Reference 14.

The second shock waves, in both blasts, are clearly visible. The one from the helium explosion appears sooner owing to the higher sound speed. The stationary character of the contact surfaces after about 300 \( \mu \text{sec} \) from the start of the blast is clearly illustrated and is in keeping with the model noted in Subsec. 3.1 for the generation of the second shock wave. In this record the glass fragments attain speeds of 210 and 240 ft/sec. for the air and helium blasts, respectively. The fragments collide about 1500 \( \mu \text{sec} \) after the initiation of the explosions. At approximately this time the shocks reflected from the steel walls of the 3 ft. diameter sphere are also seen and they implode and reflect at the origin. This process is repeated manyfold.

Figure 41 shows the details of the interaction region in the (r, t)-plane for the case of two 2 in. diameter glass spheres under identical conditions, He/Air, 326 psi/14.7 psi, \( T = 295 \degree \text{K} \), except that the left sphere breaks 160 \( \mu \text{sec} \) earlier. As a result a collision of unequal shock waves takes place as shown. Figure 42 shows a typical schlieren record of the head-on collision process, taken at nominal time intervals of 50 \( \mu \text{sec} \), or at a framing rate of 20,000 pictures per sec. In this case, both spheres contained helium at an initial pressure of 326 psi. The series of photographs starts at frame 1, where it is seen that the left sphere breaks first and as a result the shocks when they collide are of unequal strength. The development of the wave systems appears in frames 1 to 8, inclusive, and covers an interval from 100 to 500 \( \mu \text{sec} \). The shocks approach the collision point in frame 5 and have collided in frame 6. In frames 7 and 8 the forward-facing shock is interacting with the contact region from the right sphere. The stationary character of the contact regions beyond frame 4 is quite noticeable.
Figure 43 shows a similar result at a slightly later time of 252 to 605 μsec. Of particular interest in this series is the second shock which has reflected at the origin and is seen to pass through the contact region in frame 4, and appears prominently in frame 6. The second shock wave from the right-hand sphere is more difficult to detect since the schlieren knife edge is on the right and the shock tends to blend into the dark background on the photograph. Further examples and interesting details may be found in Reference 14. The above work has indicated that it is possible to generate head-on collision interactions. The actual experiments were conducted at low shock strength because of the availability of numerical solutions only for the primary blast cases. However, the same methods can be used to generate stronger shock collisions by simply using low-pressure ambient atmospheres. A complete theoretical-experimental comparison was not possible owing to the lack of a numerical solution for an asymmetric problem of this type. Where it was possible to apply planar wave theory, such as to the point of interaction, fair to good agreement was obtained.

5. CONCLUSIONS

Analytical solutions exist both for explosions and implosions when they are very intense and for explosions when they are very weak. For example, Taylor's self-similar solution for an intense point-source blast has been substantiated from shock speed measurements of an atomic explosion at small times when the assumptions of constant energy and a perfect gas do not appear to seriously affect the solution. At later times when the strong shock conditions cease to apply and considerable energy has been lost through radiation the experimental results are in good agreement with the numerical solution for the blast generated from a high-pressure sphere of very hot gas. The analytical extensions to intense cylindrical and planar blast waves do not appear to be well represented by exploding wires or magnetogasdynamically driven shock waves in a T-tube. In these cases it may be necessary to treat the explosion as a finite source with a more complex type of relation for the addition of the blast energy. However, the use of blast-wave theory for the analysis of the related problems in steady, hypersonic, two-dimensional, and axisymmetric flows have been very successful.

The theoretically predicted wave systems from finite source explosions generated by pressurized glass spheres, including the motion of the second shock wave, have been satisfactorily verified from schlieren records of the (r, t)-plane, considering that limitations are imposed by an actual diaphragm of finite strength and mass during the early development of the blast. Ample scope for the measurement of pressure, temperature, density, and velocity profiles still remains in order to fully substantiate the numerical predictions. Various driver gases and combustible gas mixtures have been successfully used to produce explosions of varying initial energy and intensity. As for intensity, a low pressure atmosphere provides a simple means of producing initially strong blast waves.
The technique of using pressurized glass spheres has been successfully extended to the production of cylindrical explosions by using pressurized open or sealed-end glass cylinders. Compressed gases and combustible gas mixtures ignited by exploding wires have been used as drivers. However, the cylindrical explosions are not as consistently symmetrical or as easily generated as spherical blasts. The same methods when applied to spherical and cylindrical implosions have to date not yielded the desired results, owing to the severe asymmetrical bursting properties of glass spheres and cylinders under compressive loading. More sophisticated materials or rupturing methods may be required.

The attenuation of spherical shock waves from various finite source explosions appear to have a decay rate similar to that of a point source explosion, after the blast wave has engulfed a mass of air equal to approximately ten times the initial mass of the explosive. Consequently, it might appear that explosions from different sources would be completely scaleable. However, as Brode points out, the initial history of an explosion persists and identical scaling may not be possible even if the decay rate is similar. However, for the purposes of some aerodynamic simulation even cruder types of explosion generators may be used as long as they supply a blast pressure profile of sufficient duration compared with the response time of the structure.

Use can be made of pressurized glass spheres to generate more complex types of blast phenomena and wave interactions. Some preliminary results of underwater explosions have already substantiated the worth of this method and a detailed study of such blasts is now underway. The head-on collision of spherical shock waves has been successfully produced using this method for weak shock interactions since for this case only were numerical solutions of the initial explosions available. The experimental work could readily be extended to strong shock waves, but a comparison with theory would not be possible because numerical solutions of the interacting flows are too difficult to handle on present day high-speed computers. Such a comparison was only possible near the point of the shock intersection where only the application of planar shock wave interaction theory gave fair to good agreement with the shock-wave paths in the \((r, t)\)-plane.

Similar remarks regarding numerical analyses would also apply to studies of spherical and cylindrical shock diffraction and refraction in gases or in water, or to explosions from pressurized glass spheres and cylinders in supersonic flows. Pressurized glass cylinders and spheres also appear to have useful applications in combustion investigations and for spherical shock wave transition studies in a rarefied atmosphere. The latter would have the advantage of a complete absence of interference from the viscous boundary layer, which is always present in shock-tube flows.
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FIG. 1 VARIATION OF KINETIC ENERGY PER POUND MASS (TNT EQUIVALENT) WITH REENTRY VELOCITY
FIG. 2 SELF SIMILAR PROFILES FOR INTENSE PLANAR (-----), CYLINDRICAL (------), AND SPHERICAL BLAST WAVES (-----) (SEDOV, REF. 5)
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(SHOCK TUBE FLOW REFERENCE: $S = 2110 \text{ f.p.s.}$,

$u_2 = 1250 \text{ f.p.s.}, T_2 = 470 \text{ K}, T_3 = 180 \text{ K}$)
FIG. 10  COMPUTED WAVE SYSTEM OF A BLAST FROM A 2 IN. DIA. SPHERE CASE He/AIR, $p_4 = 18 \frac{1}{4}$ atmos., $p_1 = 1$ atmos., $T_4 = T_1 = 301^\circ$K

(SHOCK TUBE FLOW REFERENCE: $S = 2700$ f.p.s.,
\[ u_2 = 1850 \text{ f.p.s.}, \quad T_2 = 600^\circ\text{K}, \quad T_3 = 197^\circ\text{K} \])
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POINT SOURCE PERFECT GAS (-- --), IMPERFECT GAS (-- -- -- --),
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CASE He/AIR (SEE FIG. 10)
FIG. 14 PRESSURE PROFILES AT VARIOUS TIMES AFTER AN AIR/AIR EXPLOSION (SEE FIG. 9)
FIG. 15 TEMPERATURE AT THE ORIGIN AS A FUNCTION OF TIME AFTER AN AIR/AIR EXPLOSION (SEE FIG. 9)
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FIG. 17 HIGH-SPEED SCHLIEREN PHOTOGRAPHS OF AN EXPLOSION GENERATED FROM A 2 in. DIA. PRESSURIZED GLASS SPHERE.
CASE AIR/AIR, $p_4 = 370$ psi, $p_1 = 14.5$ psi, $T_1 = 298$ °K,
TIMES IN $\mu$ sec. FROM FRAME NOS. 1 TO 8, 50, 100, 150,
200, 250, 800, 900, 1000
FIG. 18 BLAST FROM A 2 IN. DIA. PRESSURIZED GLASS SPHERE
a) SCHLIEREN RECORD OF THE (r,t)-PLANE,
b) EXPLANATORY SKETCH: G = GLASS SPHERE,
    F = GLASS FRAGMENTS, S1 = MAIN SHOCK,
    S2 = SECOND SHOCK, C = CONTACT SURFACE.
CASE AIR/AIR, p4 = 326 psi, p1 = 14.4 psi, T1 = T4 = 2970K
FIG. 19 COMPARISON OF THEORY AND EXPERIMENT OF THE WAVE SYSTEM FOLLOWING THE EXPLOSION FROM A PRESSURIZED GLASS SPHERE. CASE AIR/AIR, $p_4 = 326$ psi, $p_1 = 15$ psi, $T_1 = T_4 = 300$ °K. NOTE THAT ONLY THE BOUNDARIES OF THE EXPERIMENTAL RESULTS HAVE BEEN GIVEN FOR CONVENIENCE.
FIG. 20  SCHLIEREN RECORDS OF THE (r, t)-PLANE SHOWING THE 
BLAST FROM A 2 IN. DIA. PRESSURIZED GLASS SPHERE. 
CASE He/AIR, \( p_4 = 326 \) psi, \( p_1 = 14.7 \) psi, \( T_1 = T_4 = 300 \) °K 
a) SYMMETRICAL VIEW  b) VIEW FOR MAXIMUM SHOCK PATH
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a) AIR/AIR, $p_4 = 400$ psi, $p_1 = 14.7$ psi, $T_1 = T_4 = 300$ °K,

b) He/AIR, $p_4 = 326$ psi, $p_1 = 14.7$ psi, $T_1 = T_4 = 300$ °K
FIG. 24  BLAST FROM A PRESSURIZED GLASS SPHERE CONTAINING SULFURHEXAFLUORIDE
a) SCHLIEREN RECORD OF (r,t)-PLANE,
b) EXPLANATORY SKETCH: $S_1$ = MAIN SHOCK, $S_2$ = SECOND SHOCK, $R$ = HEAD OF RAREFACTION WAVE, $G$ = 5 IN. DIA. INTACT GLASS SPHERE, $F$ = FRAGMENTS OF SHATTERED SPHERE. CASE SF6/AIR, $p_4 = 70$ psi, $p_1 = 14.7$ psi, $T_1 = T_4 = 300^\circ$K
FIG. 25 SCALING PROPERTIES OF BLAST WAVES
a) MASS SCALING EFFECTS OF A BLAST FROM A 1.0 IN. DIA. PRESSURIZED GLASS SPHERE CASE AIR/AIR, $p_4 = 326$ psi, $p_1 = 14.7$ psi, $T_1 = T_4 = 297^\circ$K,
b) SCALING PROPERTIES AT LOW PRESSURE ATMOSPHERES FOR A 2 IN. DIA. GLASS SPHERE, $p_4 = 326$ psi, $p_1 = 0.013$ psi, $T_1 = T_4 = 295^\circ$K.
FIG. 26 COMBUSTION DRIVEN EXPLOSIONS, a) SPHERICAL COMBUSTION IN A 4 IN. DIA. x 4 IN. LONG GLASS CYLINDER, $p_4 = 40$ psi ($0.2 \text{ H}_2 + 0.1 \text{ O}_2 + 0.7 \text{ He}$), $p_1 = 14.7$ psi (AIR), $T_1 = 300^\circ\text{K}$, b) 2 IN. DIA. GLASS SPHERE, $p_4 = 200$ psi ($0.2 \text{ H}_2 + 0.1 \text{ O}_2 + 0.7 \text{ He}$), $p_1 = 14.5$ psi, $T_1 = 303^\circ\text{K}$
FIG. 27  HIGH-SPEED SCHLIEREN RECORD OF AN IMPLODING 5 IN. DIA. GLASS SPHERE. CASE AIR/AIR, $p_4 = 15$ psi, $p_1 = 100$ psi, $T_1 = T_4 = 300$ °K. TIMES FROM 1 TO 8 IN $\mu$SEC., 900, 1100, 1300, 1600, 1900, 2200, 2500, 2800, MECHANICAL BREAK
FIG. 28 HIGH-SPEED SCHLIEREN RECORD OF AN IMPLODING 5 IN. DIA. GLASS SPHERE. CASE AIR/AIR, $p_4 = 75$ psi, $p_1 = 125$ psi, $T_1 = T_4 = 300^\circ$K. TIMES FROM 1 TO 6 IN $\mu$sec., 600, 800, 1000, 1200, 1800, 1800, AUTO BREAK
**FIG. 29** SPHERICAL IMPLOSION  

a) SCHLIEREN RECORD OF THE $(r, t)$-PLANE SHOWING AN IMPLODING 5 IN. DIA. GLASS SPHERE  
b) EXPLANATORY SKETCH: $G =$ GLASS SPHERE STILL INTACT, $F =$ FRAGMENT OF SHATTERED SPHERE, $p_4 = 65$ psi (0.3 SF$_6$ + 0.7 AIR), $p_1 = 5.8$ psi (AIR), $T_1 = T_4 = 2080^\circ K$
FIG. 30

TYPES OF GLASS SPHERES AND CYLINDERS USED FOR EXPLOSION AND IMPOSION EXPERIMENTS

A) 125 mm. DIA. x 1 mm. WALL, 60 gm., B) 50 mm. DIA. x 1 mm. WALL, 20 gm., IN HOLDER,
C) 50 mm. DIA. x 65 mm. LONG x 65 mm. LONG x 1-1/2 mm. WALL, 40 gm., OPEN END,
D) 50 mm. DIA. x 50 mm. LONG x 1-1/2 mm. WALL, 50 gm., CLOSED END (3.2 mm. WALL),
E) 100 mm. DIA. x 50 mm. LONG x 3 mm. WALL, 200 gm., CLOSED END (3.2 mm. WALL),
F) 100 mm. DIA. x 100 mm. LONG x 3 mm. WALL, 300 gm., CLOSED END (3.2 mm. WALL)
FIG. 31  BLAST FROM A 2 IN., DIA., PRESSURIZED GLASS CYLINDER
a) SCHLIEREN RECORD OF THE (r, t)-PLANE,
b) EXPLANATORY SKETCH: G = SEALED END GLASS CYLINDER 2 IN., DIA. x 2 1/2 IN. LONG, MECHANICAL BREAK, F = GLASS FRAGMENTS, S₁ = MAIN SHOCK, S₂ = SECOND SHOCK, H = HEAD OF RAREFACTION WAVE, C = CONTACT SURFACE. CASE AIR/AIR, p₄ = 115 psi, p₁ = 14.5 psi, T₁ = T₄ = 297 oK
FIG. 32 CYLINDRICAL EXPLOSION FROM A PRESSURIZED OPEN END GLASS CYLINDER 2 IN. DIA. x 2 1/2 IN. LONG
a) SCHLIEREN RECORD OF THE (r, t)-PLANE,
b) EXPLANATORY SKETCH: G = OPEN END GLASS CYLINDER, MECHANICAL BREAK, F = GLASS FRAGMENTS,
H = HEAD OF RAREFACTION WAVE, CASE AIR/AIR,
\[ p_4 = 350 \text{ psi}, \ p_1 = 14.7 \text{ psi}, \ T_1 = T_4 = 300^\circ\text{K} \]
FIG. 33  COMBUSTION DRIVEN CYLINDRICAL EXPLOSION
a) SCHLIEREN RECORD OF THE (r,t)-PLANE,
b) EXPLANATORY SKETCH: G = OPEN END CYLINDER
2 IN. X 2 1/2 IN.; AUTO BREAK, F = GLASS FRAGMENTS,
E = EXPLODING WIRE, W = WIRE GENERATED SHOCK,
B = BURNING FLAME, p₄ = 88 psi (0.2 H₂ + 0.1 O₂ + 0.7 He),
p₁ = 14.7 psi, T₁ = 299°K
FIG. 34 (a) DIFFRACTION OF A PLANE SHOCK WAVE OVER A SLENDER MODEL.
MODEL THICKNESS 1/2 IN., $p_1 = 185 \text{ mm.Hg}$, $P_21 = 5.20$, $M_2 = 1.04$,
2 IN. x 7 IN. SHOCK TUBE, PRIMARY SHOCK MOVES FROM LEFT TO RIGHT
FIG. 34 (b) DIFFRACTION OF A PLANE SHOCK WAVE OVER A GABLE MODEL. PRIMARY SHOCK WAVE MOVES FROM RIGHT TO LEFT AND HAS A SUBSONIC FLOW BEHIND IT.
FIG. 35 HIGH-SPEED SCHLIEREN PHOTOGRAPH OF AN UNDERWATER EXPLOSION GENERATED FROM A PRESSURIZED GLASS SPHERE, AQUARIUM 8 IN. x 16 IN. x 10 IN., WATER DEPTH 8 1/2 IN., 2 IN. DIA. GLASS SPHERE PRESSURIZED AT 310 psi, SURROUNDING CONDITIONS ATMOSPHERIC, FRAMING RATE FROM 1 TO 8 IN μsec., 15, 60, 100, 200, 350, 700, 1300, 2000
FIG. 35(b) HIGH-SPEED SCHLIEREN RECORDS OF UNDERWATER EXPLOSIONS GENERATED FROM PRESSURIZED GLASS SPHERES. AQUARIUMS: 8 in. x 16 in. x 10 in., WATER DEPTH 8 1/2 in. ROW NO.1: 2.1 in. DIA. SPHERE, BURSTING PRESSURE 300 psi, FRAMING RATE FROM 1 TO 4 IN $\mu$ sec., 11, 30 3/8, 50, 70. ROW NO.2: 2.1 in. DIA. SPHERE, BURSTING PRESSURE 365 psi, FRAMING RATE AS ABOVE. ROW NO.3: 2 in. DIA. SPHERE, BURSTING PRESSURE 330 psi, FRAMING RATE 20 1/8 AND 50 $\mu$ sec. AMBIENT, TEMPERATURE 300 $^\circ$K AT 1 atmos.
FIG. 36  UNDERWATER EXPLOSION GENERATED FROM A PRESSURIZED GLASS SPHERE. a) SCHLIEREN RECORD OF THE (r,t)-PLANE, b) EXPLANATORY SKETCH:
G = GLASS SPHERE, 2 in. DIA., FILLED WITH 200 psi (p4) OF A COMBUSTIBLE MIXTURE (0.2 H2 + 0.1 O2 + 0.7 He); AMBIENT CONDITIONS, AQUARIUM 8 in. x 16 in. x 10 in., WATER DEPTH 8 in., SURROUNDING ATMOSPHERE 14.7 psi AT 300 °K, S = MAIN SHOCK WAVE, C = CONSTANT REGION
FIG. 37  HEAD-ON COLLISION OF PLANAR SHOCK WAVES IN THE \((u, p)\) AND \((x, t)\)-PLANES. CONDITIONS IN A SHOCK TUBE BEFORE COLLISION \((t = t_1)\) AND AFTER COLLISION \((t = t_2)\) ARE INDICATED.
FIG. 38 BREAKER MECHANISM USED FOR HEAD-ON COLLISION OF SPHERICAL SHOCK WAVES
FIG. 39 SHADOWGRAMS OF THE HEAD-ON COLLISION OF SPHERICAL SHOCK WAVES
(a) LEFT SPHERE, AIR/AIR, 400 psi/14.7 psi. RIGHT SPHERE, He/AIR, 326 psi/14.7 psi. T = 298°K, 2 IN. DIA. SPHERES, TIME DELAY 297μsec.
(b) LEFT SPHERE, AIR/AIR, 400 psi/14.7 psi. RIGHT SPHERE, He/AIR, 326 psi/14.7 psi. T = 295°K, TIME DELAY = 373μ sec
FIG. 40  SCHLIEREN RECORD OF THE \((r,t)\)-PLANE SHOWING THE HEAD-ON COLLISION OF SPHERICAL SHOCK WAVES.

LEFT SPHERE, He/ AIR, 500 psi/14.7 psi, RIGHT SPHERE, AIR/ AIR, 250 psi/14.7 psi, T = 296⁰K,

- \(S_{21} = 1.04\), \(S_{51} = 1.24\), \(S_{31} = 1.07\), \(S_{41} = 0.91\)
FIG. 41  DETAILED VIEW OF THE COLLISION OF TWO UNEQUAL SPHERICAL SHOCK WAVES. BOTH SPHERES 2 IN. DIA., He/AIR, 326 psi/14.7 psi, T = 295°K, TIME INTERVAL BETWEEN BREAKS 160μsec
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FIG. 43  HIGH-SPEED SCHLIEREN PHOTOGRAPHS OF THE COLLISION OF SPHERICAL SHOCK WAVES.
BOTH SPHERES, 1.9 IN. DIA., He/AIR, 326 psi/14.5 psi, T = 295 °K, TIME DELAYS IN μSEC
FOR FRAMES 1 TO 8, IN 50 μSEC INTERVALS, 250 TO 600 μSEC