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TITLE **Laser-Induced Shock Wave Effects in Materials**

AUTHOR(S) R. S. Dingus and B. P. Shafer

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Los Alamos

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

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Laser-induced shock wave effects in materials

R. S. Dingus and B. P. Shafer
Los Alamos National Laboratory, Los Alamos, NM 87545

ABSTRACT

A review of the effects of pressure pulses on materials is presented with an orientation toward laser-induced shock wave effects in biological tissue. The behavior is first discussed for small amplitudes, namely sound waves, since many important features in this region are also applicable at large amplitudes. The generation of pressure pulses by lasers is discussed along with amplitudes. The origin and characteristic properties of shock waves is discussed along with the different types of effects they can produce. The hydrodynamic code techniques required for shock wave calculations are discussed along with the necessary empirical data base and methods for generating that data base.

1. INTRODUCTION

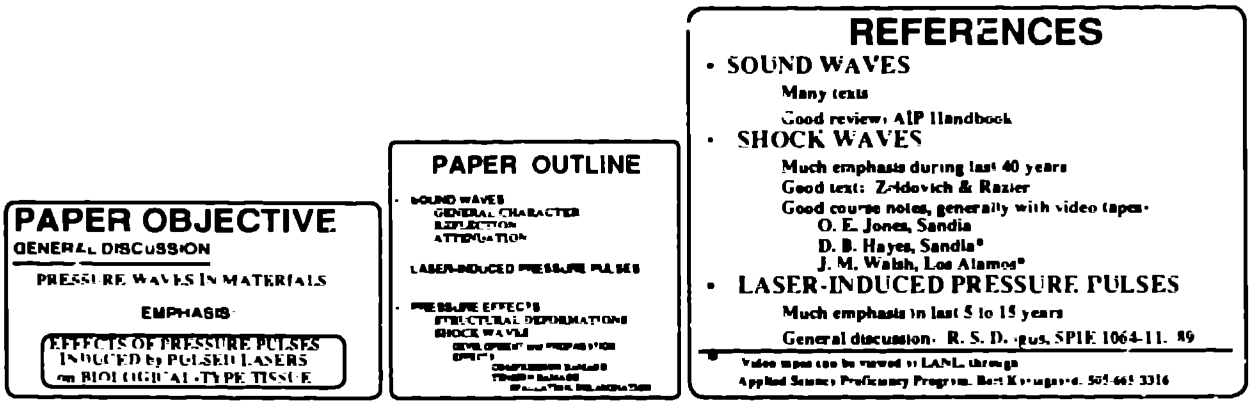

Figure 1. Objective, outline and general references for this paper.

A general discussion of pressure waves in materials is presented in this paper, as indicated in Fig. 1. Although the subject is treated in generality, it is oriented toward the effects of pressure pulses induced by pulsed lasers on biological-type tissue. The emphasis is upon pressures large enough to cause prompt and substantive changes in the tissue; however, the basis is first laid for low amplitude pressures, namely sound waves, for which the mathematics is simpler due to the linearity and associated applicability of superposition. Even for small amplitudes, many of the important features exist that are also associated with shock waves; also, certain aspects of the behavior for large amplitude pressure pulses can frequently be usefully approximated by assuming linearity. A brief discussion of the generation of pressure pulses by lasers is included.

A thorough review of the properties of sound waves is given in the American Institute of Physics Handbook[1]; more detailed references can be found there. A good treatment of shock waves is given in the two volume text by Zeldovich and Raizer[2]. Also, video tapes and/or lecture notes exist of informative courses given on shock waves by O. E. Jones and by D. B. Hayes both from Sandia National Laboratory and by J. M. Walsh from Los Alamos National Laboratory. These are probably available from the authors but are also available at the Applied Science Proficiency Program at Los Alamos National Laboratory (contact: Bert Kortegaard, Phone 505-665-3316). Information relating to laser-induced pressure pulses can be found in a review of pulsed-laser effects phenomenology by R. S. Dingus[3].

2. SOUND WAVES

2.1. General Character

Acoustic waves are small-amplitude, cyclic, elastic vibrations with frequencies, f, in the range from 15 to 20,000 Hz that propagate with a characteristic velocity called the sound speed, c, that depends on the properties of the transport medium. In normal water, the velocity is about 1.6 mm/μs. Waves of lower frequency are referred to as infrasound and waves of higher frequency are referred to as ultrasound. Ultrasound with frequencies of 2 to 20 MHz have wavelengths,

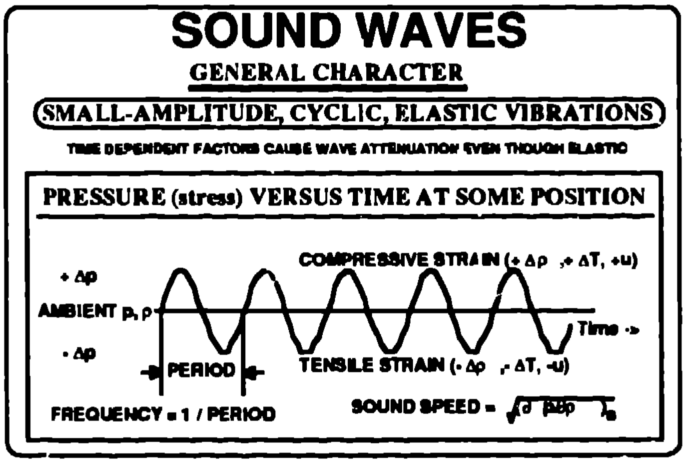

Figure 2. General character of sound waves.

$\lambda = c/f$, of 0.8 to 0.08 mm; this small wavelength makes short bursts of ultrasound in this range useful for medical diagnostics by timing reflections from boundaries where density or modulus changes occur. Since these waves cause only elastic vibrations, it would seem that there would be no attenuation during transport through the medium; however, as will be discussed, there are time dependent effects that leave residual energy behind in the transport medium and cause attenuation.

Figure 2 illustrates the pressure as a function of time at some position in a material and indicates important features associated with the pressure wave. If the transport medium is a solid, the pressure in the solid is more properly referred to as stress because of material strength; this is especially important at low amplitudes (for simplicity of discussion, this distinction will not always be made in this paper). The material has ambient pressure p and density ρ. During positive pressure increments, the material is compressed to higher density and thus is slightly raised in temperature. During negative pressure increments, the density and temperature are below ambient values. While the pressure is rising the particles are being accelerated in the same direction as the propagation of the sound wave. Similarly, while the pressure is falling the particles are decelerated so that the particle velocity is zero when the pressure returns to zero and becomes negative when the pressure (stress) is below ambient. For sound waves, the particle velocities are negligible compared to the sound speed; however, for shock waves, the particle velocity can be large.

2.2. Amplitude

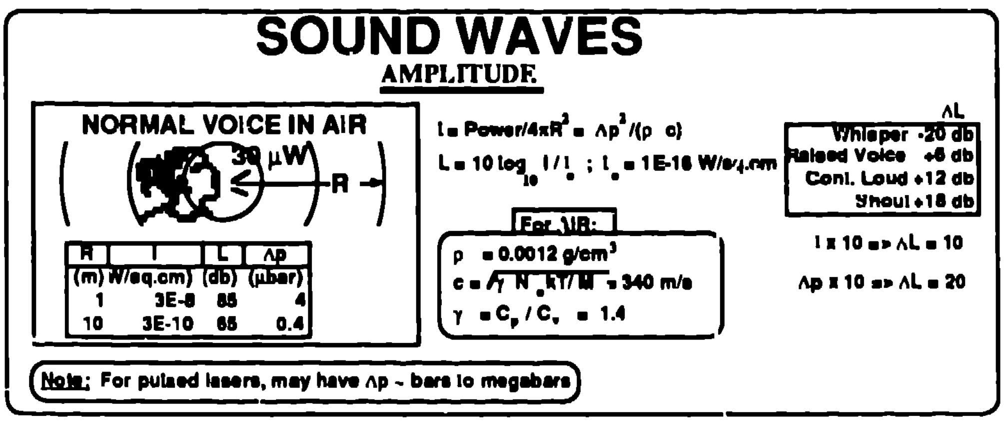

Figure 3. Typical amplitudes of sound waves in air.

For perspective, Fig. 3 indicates typical amplitudes of sound waves and relates intensity to pressure. The power (averaged over many cycles) emitted by a normal voice is of the order of 30 microwatts[1]. Since the signal generally propagates uniformly in all directions, the intensity or flux (watts/cm^2) decreases with the radius squared from the source. The intensity is proportional to the pressure difference squared. The bell has been defined as a logarithmic level of sound based on a reference level of 10^{-16} W/cm^2 but the decibel, db, (one tenth of a bell) is the common value used. Thus, as shown in Fig. 3, a normal voice in air at a distance of one meter has an intensity of 3×10^{-8} W/cm^2, has a level of 85 db and causes a pressure increment of 4 μbar (1 bar= 10^{-6} dyne/cm^2 ~ 1 atmosphere). At 10 meters the intensity is down by a factor of 100, the level is down by 20 db and the pressure increment is down by a factor of ten from that at one meter. A whisper is down about 20 db from a normal voice and a shout is up about 18 db from a normal voice. A pulsed laser incident on a solid might generate pressures pulses with amplitudes of bars to megabars (see Sections 3 and 4.2.6; these amplitudes are many orders of magnitude larger than that of sound waves and will generally result in shock waves.

2.3. One-Dimensional Longitudinal Waves

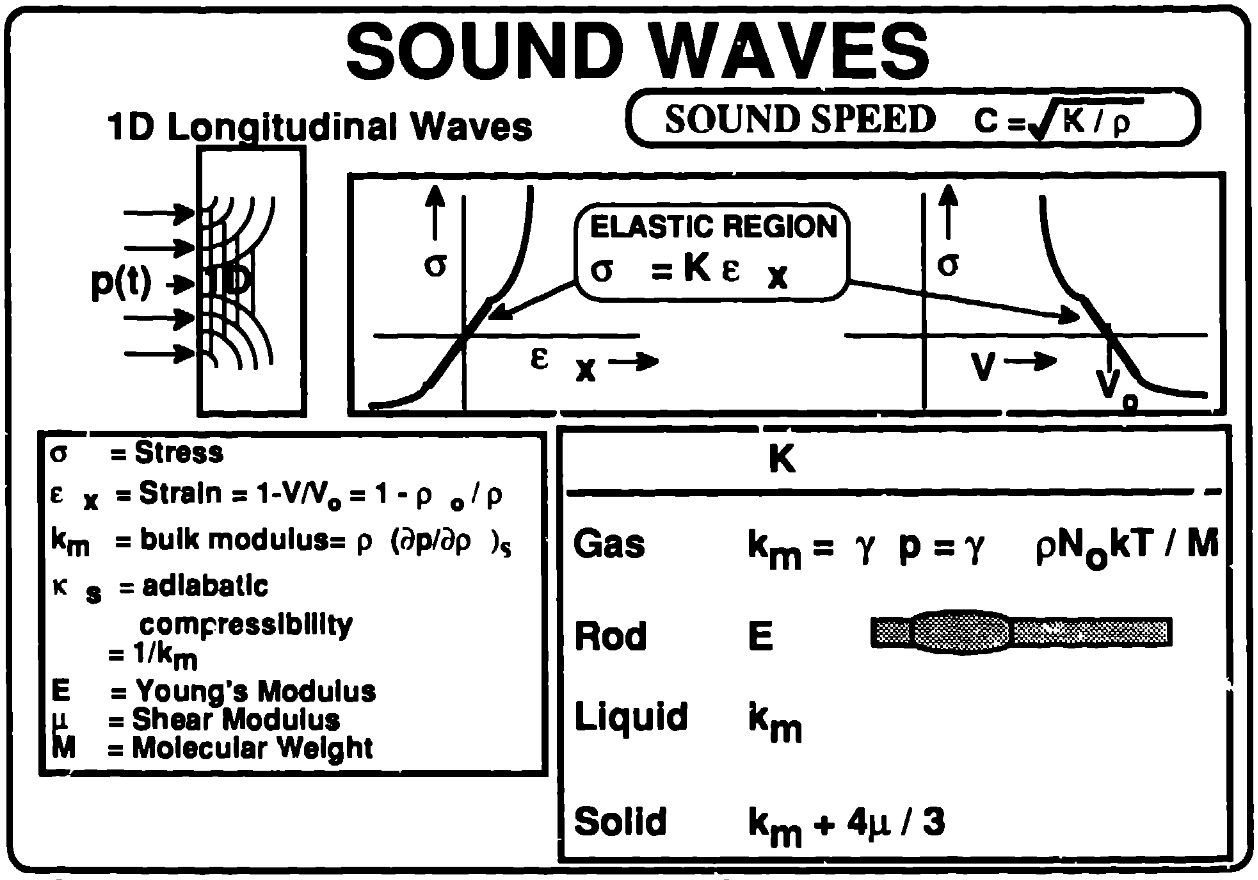

Figure 4. The speed of sound in different types of materials for one-dimensional longitudinal sound waves.

It has so far been assumed that the pressure changes cyclically; however, the discussion is also applicable to a single pulse of pressure. For example, suppose a pressure as a function of time, p(t), which simply rises to a peak and falls to zero is applied to a surface over a limited area. Throughout this paper, it will generally be assumed that one-dimensional longitudinal pressure waves exist in the region of interest; that is that release waves have not had time to propagate from the edge over which the pressure was applied into the region of interest (see Fig.4). A typical stress (σ)-strain (ε_x) curve for a 1D longitudinal wave in a solid is plotted in Fig. 4 (for illustrative purposes, the shape of the curve is exagurated); this curve is also repotted in Fig. 4 using specific volume (V) instead of strain (ε_x), which is a common form for shock wave considerations. For sound waves, the strain varies linearly with the stress, $\sigma = K\,\varepsilon_x$, that is, the material is in the elastic region. In the elastic region, the sound speed is independent of stress and is equal to the square root of the modulus K over the density. As shown in Fig. 4, the physical meaning of K for solids differs from that for liquids or gases; this is because solids have shear strength. For a pressure wave that has traversed far into a rod, the release wave condition stated above is not satisfied and the rod expands radially as the pressure wave passes; this causes the quantity K to have yet another physical meaning, namely, Young's Modulus. For large compressive stress, the stress-strain curve generally becomes concave upward which causes the sound speed to increase with stress instead of remaining constant: as will be discussed, this causes a shock wave to occur for large stresses.

2.4. Reflection

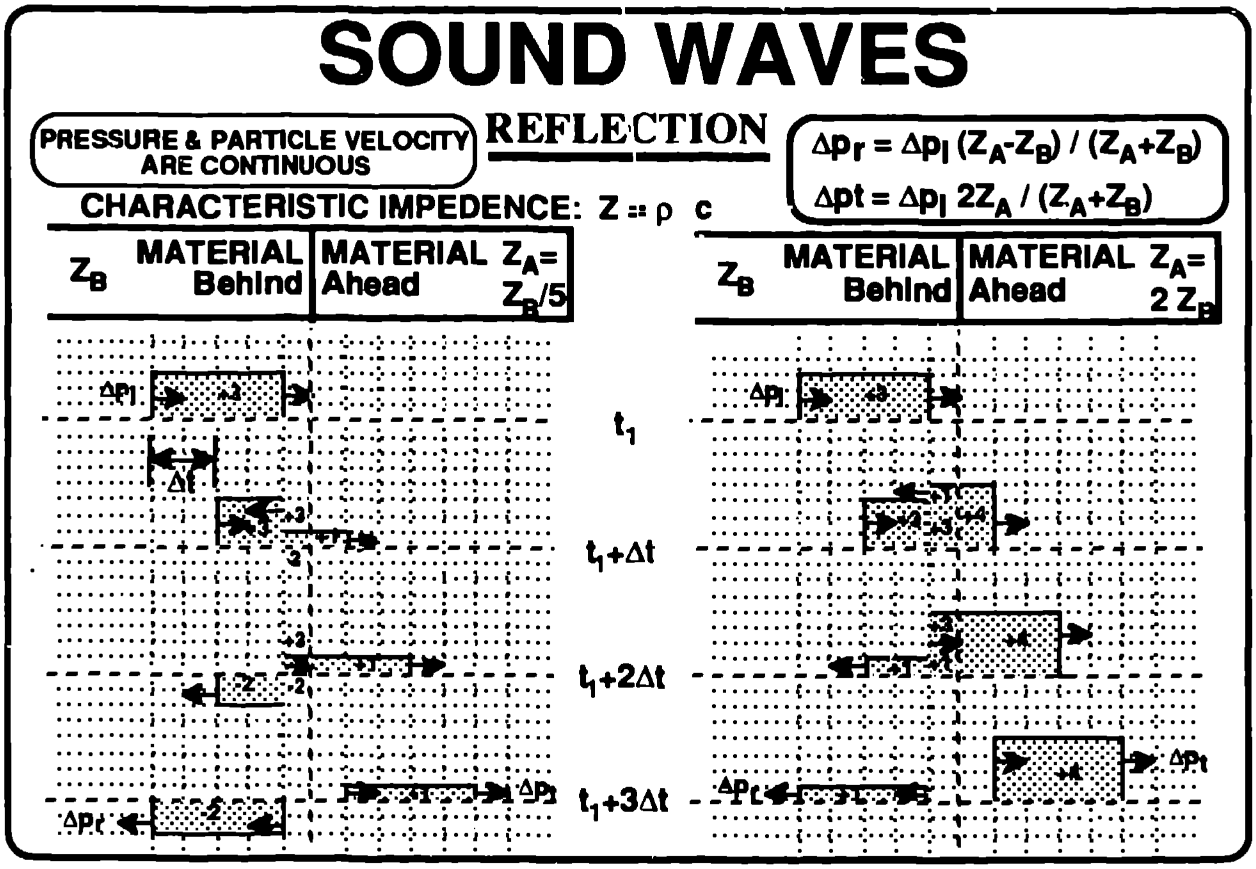

Figure 5. Reflection of sound waves from impedance mismatches.

Figure 5 illustrates what happens when a sound wave encounters a boundary. To simplify illustration of the reflected and transmitted waves in Fig. 5, the sound wave incident on the boundary is assumed to be a single square pulse (actually the square nature is generally unrealistic). The amplitudes of the reflected and transmitted waves are given in Fig. 5 in terms of the relative characteristic impedances (density times sound speed) on either side of the boundary, Z_A and Z_B . These amplitudes are the result of the fact that the pressure and particle velocity must be continuous within the transport medium. If Z ahead is less than Z behind, than the reflected wave is negative and the transmitted wave is smaller in amplitude than the incident wave. For $Z_A = Z_B/5$, the reflected amplitude is -2/3 of the incident amplitude and the transmitted amplitude is +1/3 of the incident amplitude. During times while the incident wave is still incident on the boundary, the amplitude at the boundary on the behind side is the linear superposition of the incident and reflected amplitudes. If Z ahead is greater than Z behind, then the reflected wave is positive but smaller than the incident wave and the transmitted wave is larger in amplitude than the incident wave.

2.5. Attenuation

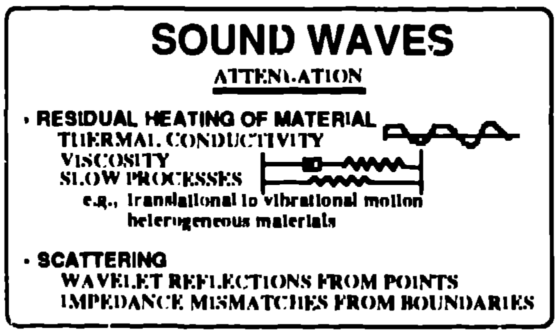

Figure 6. Attenuation of sound waves.

Because of the small amplitude, the sound wave produces only elastic deformations, which means that during cycles the energy alternates back and forth between translational kinetic energy and potential energy of compression, like a spring in simple harmonic motion. For this purely elastic behavior, one might think that there would be no attenuation. However, there is attenuation because of time dependent effects which cause some of the compression energy to be converted to thermal energy which remains behind as residual heat in the material..

As indicated in Section 2.1, the material is heated during compression which causes a temperature gradient and resulting in heat flow. Materials have viscosity, which can be thought of as a dashpot (representing internal friction) in combination with elastic springs; depending on the rate of deformation, some work is done on the dashpot resulting in deposited heat (see Fig. 6). Translational compression can be relatively slowly converted to vibrational motion and left behind as heat. For heterogeneous materials, the different constituents can have different moduli which respond at different rates, which also leaves energy behind as a pressure pulse passes.

Scattering from point discontinuities in the transport medium or from impedance variations in the material can also cause attenuation or extinction of the wave.

3. LASER-INDUCED PRESSURES

LASER-INDUCED PRESSURES

- INTERNAL DEPOSITION: SEMI-TRANSPARENT MATERIALS
  IMPULSE: $I = \int p\,dt \sim \sqrt{2\,m\,KE}$
  GRUNEISEN PARAMETER, $\Gamma = (\partial p/\partial E)_V / \rho = \beta / (\rho\ C_V\, \kappa_T)$
  Short-Pulse: $\Delta p = (\Gamma\ \rho)\,\Delta E$

  β = EXPANSION COEFFICIENT = $\rho\ (\partial V/\partial T)_p$
  C_V = SPECIFIC HEAT AT CONSTANT VOLUME
  κ_T = COMPRESSIBILITY = $-\rho\ (\partial V/\partial p)_T$

- SURFACE VAPORIZATION: PRESSURE APPLIED TO SURFACE
  PRESSURE DEPENDS ON TRANSPORT MEDIUM OVER SURFACE
  VACUUM
  $I \sim \sqrt{2\,m\,KE} \sim 2\,p\,\Delta t$
  GAS–LSC or LSD WAVES
  Larger Impulse, longer pulse
  LIQUID/VAPOR–CONTAINED VAPORIZATION
  (NON-CONDENSIBLE LONG TERM PRESSURE)

Figure 7. Manners in which pressures are induced by pulsed laser deposition

As indicated in Fig. 7, pressures can be induced by lasers by internal deposition within semi-transparent materials or by surface vaporization on opaque materials[3]. The (specific) impulse or momentum per unit area imparted to the target is equal to the integral of pressure over time and, because the impulse is insensitive to the distribution of kinetic energy within the blowoff mass, it is also approximately equal to the square root of 2 times the mass ejected from the surface times the kinetic energy of this mass.

Even if there is no ejected mass, a pressure can be generated but in this case, the pressure pulse must have both positive and negative components because the impulse must be zero (the momentum of the photons is negligible). For short laser pulses, the induced pressure is equal to the Grüneisen parameter, G, times the density times the deposited energy per unit mass; this pressure is the result of the material having been heated so fast that it did not have time to expand. As the material eventually expands the pressure will drop. This expansion can result in the ejection of solid or liquid material even without any vaporization.

When the blowoff from the target involves vaporization, the induced pressure depends strongly on the transport medium over the surface. If the transport medium is a vacuum, the pressure drops to zero rapidly after the laser pulse ends. If there is a gas, for example air, in front of the target, then there will be a laser supported combustion or laser supported detonation wave and the impulse will be larger due to the added mass of the air and the pressure will last longer because the expansion is held up by the surrounding air. If there is a transparent liquid or solid in front of the target, then the vapors are tamped even more strongly; this contained vaporization can produce large structural deformations. If the vapors are condensible at temperatures above ambient, they will condense on the walls as the temperature drops and, depending on the conditions, this can relieve the pressure, thus reducing the structural deformation. If thermal- or photo-decomposition has produced non-condensable vapors, then the condensation process is not available for relieving the pressure; for certain conditions, this will result in much larger structural deformations.

4. PRESSURE-WAVE EFFECTS

The effects of pressure pulses can be separated into two classes: structural deformations caused by work done on relatively long time scales and pressure wave effects. Usually, the latter involves shock fronts, or their reflection from boundaries, where sharp, positive or negative pressure gradients exist.

4.1. Structural Deformations

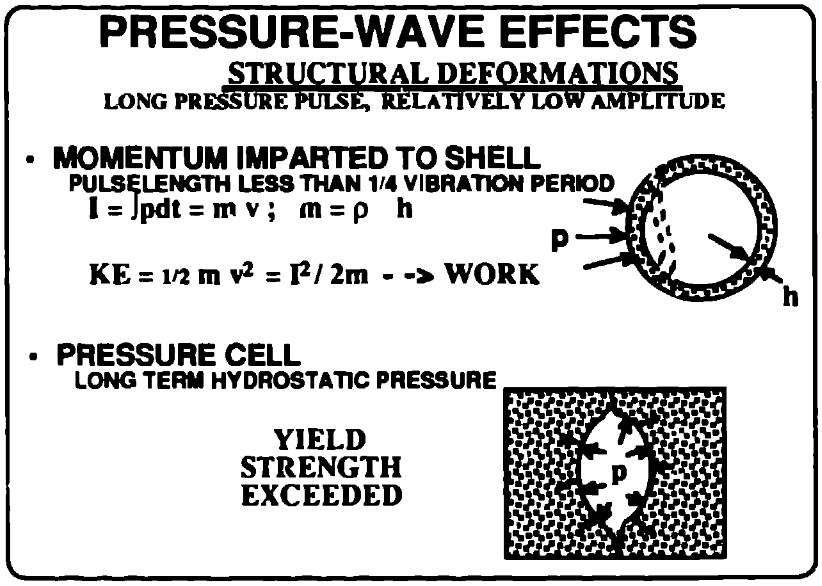

Figure 8. Structural deformations caused by pressure pulses.

Structural deformations can result from pressure pulses even with a relatively slow rise and fall and with a relatively low amplitude. As illustrated in Fig. 8, if impulse is imparted to a hollow shell (or membrane) in a time of less than about one-quarter of the natural period of vibration of that shell, then the impulse (per unit area) will give the shell a kinetic energy (per unit area) equal to the impulse squared divided by two times the mass per unit area of the shell. This kinetic energy will go into work done on the shell either as heat or permanent (ignoring biological healing) deformations depending of the conditions. For contained vaporization, a pressure cell can exist with essentially a long term hydrostatic pressure inside; if the pressure is sufficiently large, it will expand, possibly causing permanent deformations.

4.2. Shock Waves

4.2.1. General Character

Figure 9 illustrates important features of shock waves. Shock fronts occur when sound speed increases with stress, which occurs at high stress in materials. In Fig. 9, the stress is plotted as a function of propagation distance for a pressure pulse. The pulse shape is plotted at three different times, $t_1 < t_2 < t_3$. At time t_1, the pulse shape (initial disturbance) is assumed to be slowly rising and slowly falling with a flat top. The propagation speed of any point on the pulse is equal to the particle velocity plus the sound speed for that point. Because of the positive curvature of the stress strain relation shown in Fig. 9, the points at higher stress have higher propagation speeds than those at lower stress (some materials, such as fused quartz, have different shapes leading to different consequences). This causes the rising side to develop into a shock front which is nearly a discontinuity from ambient pressure to peak pressure (heat conduction and viscosity prevent it from being a perfect discontinuity) and it causes a rarefaction fan to spread out the pulse on the falling side. At the peak of the pulse, the rarefaction fan is propagating faster than the shock front and eventually overtakes it, after which the peak amplitude of the shock front begins to decrease. If instead in Fig. 9, the stress was plotted versus time at different locations, the general character would be similar to the Fig. 9 plots and the area under the pulse ($\int \sigma dt$) would remain constant because of momentum conservation; thus, after the rarefaction fan catches the shock front, the shock front amplitude decreases approximately in inverse proportion to the increase in length of the rarefaction fan. The Hugoniot is the name assigned to the locus of points attainable by a shock; this is

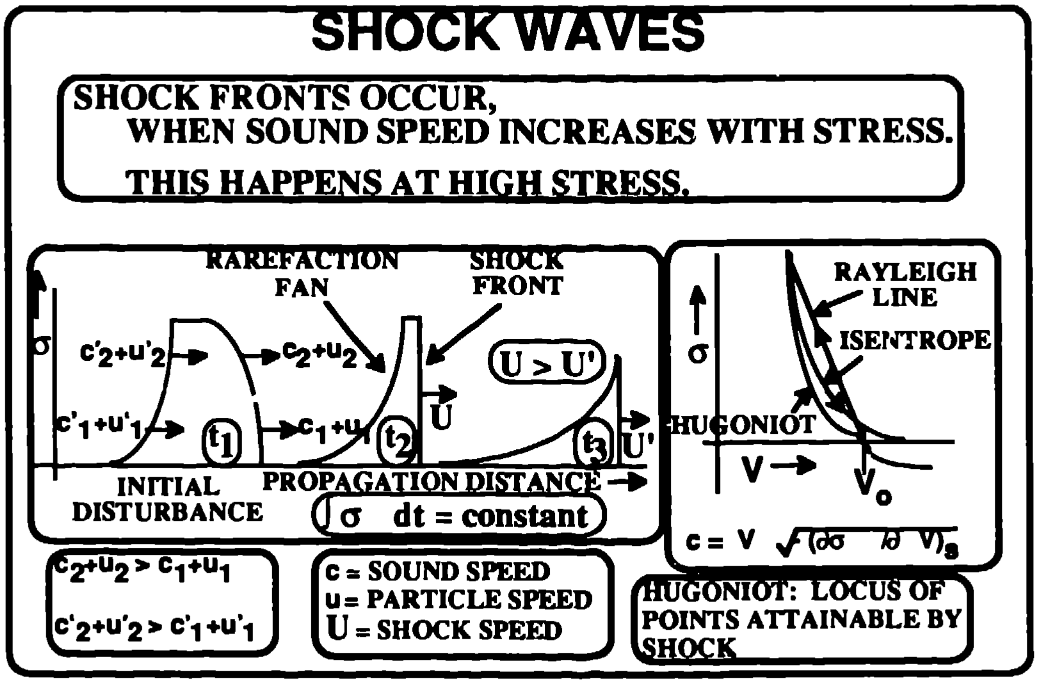

Figure 9. General character of shock waves.

generally an empirical curve obtained from shock wave measurements; it may be a curve of stress versus specific volume or stress versus particle velocity. The line connecting the jump from the initial density to the density associated with the stress at the shock front is called the Rayleigh line; this jump is adiabatic (i.e., no heat flow), but it is irreversible. The return to ambient stress is both adiabatic and reversible, thus, it is an isentrope. The difference in area under the return isentrope and the Hugoniot is the net work done on the material which leads to a residual temperature rise; the associated thermal expansion causes in increase in the specific volume after the wave passes. For pulses with intermediate peak stresses in solids, the Rayleigh line may intercept the Hugoniot in the elastic region, causing an elastic precursor shock front with smaller amplitude that travels faster than the main shock front. The cusp (which exists for solids because of their shear strength) in the Hugoniot is at a stress, referred to as the Hugoniot elastic limit, where plastic yield of the solid occurs; for liquids the stress reduces to a hydrostatic shock pressure and there is no cusp in the Hugoniot.

4.2.2. Calculations

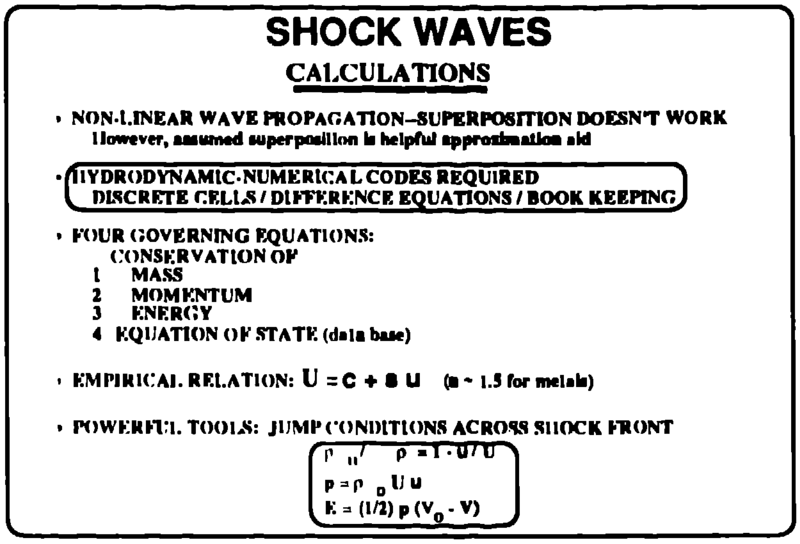

Figure 10. Manner of performing calculations for shock waves.

In contrast to sound waves, the superposition of waves does not give accurate values for shock waves because the wave propagation is non-linear. However, assumed superposition is frequently a helpful aid for estimating approximate behavior. Accurate evaluations require numerical calculations with hydrodynamic codes. Many different kinds of codes have been developed to treat various special circumstances. Generally, these codes involve breaking the material up into discrete cells with specific thermo-mechanical properties assigned to each cell and converting the differential equations into finite difference equations relating the celis. The equations are solved at successive time steps and the code does the book keeping to track the behavior with time.

These codes have four basic governing equations: conservation of mass, momentum and energy and an equation of state. The equation of state basically determines the pressure from the temperature and density; however, for convenience, this relation is frequently combined with the conservation equations to produce a rather different, but equally valid, form. The equation of state is frequently based upon experimental data. Empirically, it has been found that for many solids and liquids, a valid form for this equation, which is frequently referred to as the Hugoniot, is: the shock speed equals the sound speed at near zero stress plus a constant times the particle velocity, where the constant is in the vicinity of 1.5 for metals. As indicated in Fig. 10, the conservation laws can be used to specify the jump conditions across a shock front; these are powerful tools for making useful evaluations. In order to perform laser-tissue interaction calculations that include the generation of the pressure pulses, it is sometimes necessary to add thermal radiation transport to the hydrodynamic analysis; this becomes necessary when plasmas are formed that absorb the laser beam producing high temperatures and consequent strong reradiation, which becomes an important secondary energy transport mechanism.

4.2.3. Measurements

SHOCK WAVES

MEASUREMENTS

- APPLY PRESSURE PULSE TO SAMPLE
- MEASURE TWO OF THE FOUR QUANTITIES:
  - p–pressure
  - u–particle velocity
  - U–shock velocity
  - ρ –density
- USE JUMP CONDITIONS TO CALCULATE OTHER TWO
- REPEAT FOR SERIES OF EXPERIMENTS TO MAP HUGONIOT
- MORE DATA NEEDED FOR DISSIPATION AND DAMAGE CALCULATIONS
  - THERMAL CONDUCTION
  - VISCOSITY
  - RELAXATION PHENOMENA
  - PERMANENT (PLASTIC) STRAIN
  - SPALL STRENGTH

SHOCK WAVES

MEASUREMENT TECHNIQUES

- PRESSURE PULSE GENERATION
  - PULSED LASER HEATING w/ or w/o ablation
  - FLYER PLATES
    - MAGNETIC DRIVER
    - GAS GUNS
    - EXPLOSIVE FOILS
  - SHEET HIGH EXPLOSIVE
- PRESSURE GAUGES:
  - PIEZOELECTRIC
  - PIEZORESISTIVE
- PARTICLE VELOCITY (at free surface or other boundary)
  - LASER INTERFEROMETER--DISPLACEMENT/VELOCITY
  - CAPACITOR
  - EMF
- SHOCK VELOCITY
  - ARRIVAL TIMES

Figure 11. Measurement approach and techniques for shock waves.

Figure 11 lists measurement approachs and techniques for shock waves. Measurements of material behavior needed for shock wave analysis are generally made by applying a pressure pulse of desired amplitude to a sample and measuring two of the four quantities: pressure, particle velocity, shock velocity, or density. Then the jump conditions are used to calculate the other two. This is repeated for a series of experiments to map out the Hugoniot. If dissipation and damage processes are important for the calculations, then additional thermo-mechanical data may be needed such as: thermal conductivity, viscosity, relaxation phenomena, permanent strain, and spall strength.

Many diagnostic techniques have been developed for measurements designed to obtain the necessary data base to perform shock wave calculations. To perform these measurements it is necessary to apply a pressure pulse of interest to the target. Techniques for applying this pressure pulse include: pulsed laser heating, with or without ablation; flyer plate impact with the target driven by pulsed magnetic fields, gas guns, or explosive foils; and sheet high explosive. Various types of piezoelectric and piezoresistive transducers have been developed for pressure measurements,; also, fiber optic techniques are becoming available. Particle velocity is generally measured at a free surface or other boundary using such techniques as a laser interferometry, either in the displacement or velocity mode; capacitor gauges; or emf gauges. Shock front velocities can be measured by observing time of arrival through different target thicknesses.

4.2.4. Compressive Strain Damage

Figure 12 illustrates the idea behind types of compressive strain damage that might be produced during passage of a shock front. The figure supposes that there are fibers embedded in a matrix material such as collagen in water but the idea could also apply to, say, cells in water. The point is that as the shock front passes, the fibers or cells are subjected to a steep strain gradient which might cause breakage or deformation. Even if the shock front propagates in a direction perpendicular to the fibers, breakage might occur if the fibers are not perfectly straight.

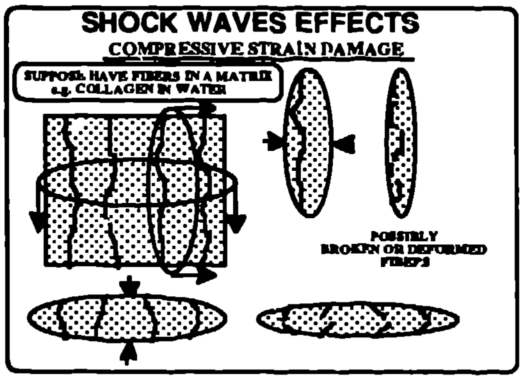

Figure 12. Compressive strain damage.

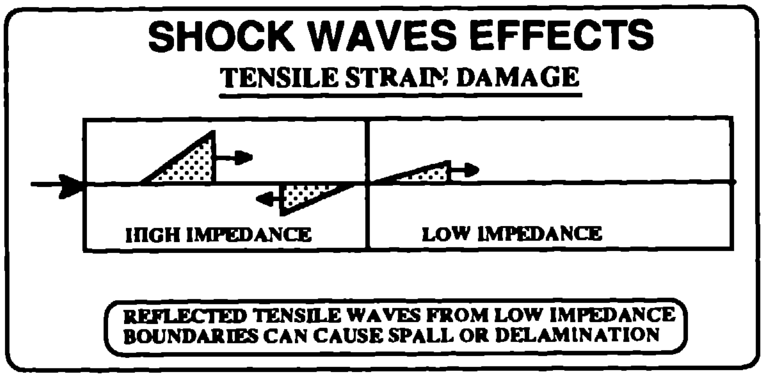

Figure 13. Tensile strain damage

4.2.5. Tensile Strain Damage

Figure 13 illustrates the idea behind types of tensile strain damage that might be produced during reflection of a shock front from a boundary where the impedance of the material ahead is lower than the impedance of the material behind. The figure shows a shock front approaching the boundary and the negative reflected and positive transmitted waves which result from interaction of the pressure pulse with the boundary as discussed in Sec. 2.4. The leading edge of the negative reflected wave is a rarefaction fan because the density is being rarefied as the leading edge passes a region of material. If the negative amplitude (tensile stress) of the reflected pulse exceeds the tensile strength (which is rate dependent because of nucleation growth times) of the material, a partial or complete separation of the material will result. This separation is referred to as spallation (or spall) when the boundary is a free surface, or debonding when a fracture is induced near the boundary.

4.2.6. Example of potential shock wave effects

Figure 14 illustrates conditions relating to the use of pulsed excimer lasers to shape the cornea of the eye. Experiments have been done with lasers having a wavelength 193 nm, a pulse length of 10 ns and a fluence per laser

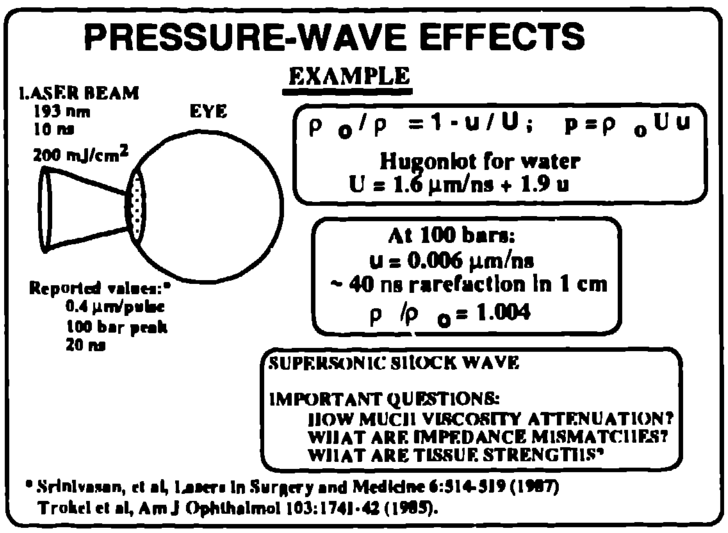

Figure 14. An example of pressure wave effects to the eye.

pulse of 200 mJ/cm^2. Under these conditions, reported values for the ablation[4] and pressure[5] are 0.4 μm per pulse and 100 bar peak amplitude with 20 ns duration. From rough calculations, these reported values appear to be consistent with modeling of the laser-tissue interaction as described in Refs. 3, 6 and 7. Using the Hugoniot for water given in Fig. 14 (which is from high pressure data and may not be too accurate at these low pressures) and conservation laws, simple jump condition calculations for a 100 bar shock front give a particle speed of 0.006 μm/ns, a shock speed of 1.61 μm/ns (compared to ambient pressure sound speed of 1.60 μm/ns) and a density increase to 1.004 times the ambient density. These values imply that after traversing 1 cm in pure water, a 100 bar shock front would out run a low amplitude pressure disturbance by about 40 ns. Thus, over a distance of 1 cm, a laser-induced, 100-bar pulse with 20 ns duration in water would evolve into a shock front (if the initial rise wasn't already sharp) with perhaps some attenuation from a rarefaction fan. Even though a large fraction of the eye is water, the added constituents in the eye would possibly lead to significantly larger attenuation. It seems important to address in detail whether or not this pressure pulse will damage the eye. For hydrodynamic calculations, there are a number of important questions. How much attenuation occurs due to viscosity and material heterogeneity? What are the impedance mismatches at the various interfaces in the eye? What are the compressive and tensile strengths of the tissue and the bonds at the interfaces?

5. SUMMARY

SHOCK-WAVE EFFECTS SUMMARY

- SHOCK-WAVE EFFECTS CAN BE CALCULATED
- MATHEMATICS ARE COMPLICATED
- NUMERICAL HYDRODYNAMIC CODES ARE REQUIRED
- AN EMPIRICAL DATA BASE IS A NECESSITY
- MEASUREMENT TECHNIQUES EXIST TO OBTAIN NEEDED DATA BASE

Figure 15. Summary of shock wave effects issues.

In summary, small amplitude pressure pulses, such as sound waves, produce linear disturbances in materials which follow laws of superposition; however, understanding the low amplitude behavior provides an important base for explaining larger amplitude behavior where pressure pulses evolve into shock fronts with rarefaction tails. The effects of shock waves can be calculated but the mathematics are complicated because of the non-linear propagation behavior. As a result of this complication, numerical hydrodynamic codes are required for these calculations and an empirical data base in these codes is a necessity. Measurement techniques exist to obtain this data base. The effects of pressure pulses associated with laser-tissue interaction can likely be advantageous (e.g., in enhancing ablation) or disadvantageous (e.g., in causing damage to nearby tissue), so that it seems important to develop a thorough understanding of these effects in order to optimize the use of lasers in biomedical applications.

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