

STRONG SHOCK WAVES

Strong shock waves can create very hot plasma. What temperatures can shock waves produce? What physical phenomena become important with increasing shock speed? What is the present state of our understanding of shock waves, where do they occur in nature, and how strong a shock wave can now be produced in laboratory devices? These are the questions discussed below.

By Robert A. Gross

To put strong shock-wave research in perspective it is appropriate to recall its origins. In 1848, Stokes and Challis observed that simple sound-wave theory will break down when the disturbance amplitude becomes large. Subsequent work by Earnshaw, Riemann, Rankine, and Hugoniot placed the early theory of large-amplitude gas dynamic waves, or shock waves, on a firm theoretical basis. Laboratory experiments with shock waves began about 1899 with the work of Vielle. About 1900, detonations and explosion research by Chapman and Jouguet revealed that supersonic propagation of combustion waves have shock-like behavior. From that time on, basic research in physics, chemistry, mathematics, and aerodynamics has accelerated our state of understanding of shock waves, and the scope of this research field now encompasses nearly all of physics.

In the 1940's, as a result of the need for an expanded knowledge about explosives and supersonic flight, experimental shock-wave research was undertaken by Bleakney at Princeton, Kantrowitz at Cornell, and Laporte at Michigan. In 1950, deHoffman and Teller studied theoretically for the first time shock waves in gaseous plasmas with attendant magnetohydrodynamic and relativistic effects. Pioneering experimental work with strong, plasma-producing shock waves in a variety of electromagnetically driven shock devices was begun, principally by Fowler, Kolb, and Patrick. Present high-speed (above Mach 50) shock-wave research is primarily motivated by controlled thermonuclear

fusion research and the desire for understanding astrophysical phenomena.

The major physical feature of a shock wave is that it separates two regions in space, the upstream, cold, low-pressure and low-density gas and the downstream, hot, high-pressure gas. The shock-wave structure is the region of very steep gradients which separates the uniform states of matter on each side of the shock wave. Shock waves move at supersonic speed (i.e., greater than the acoustic speed) relative to the preshocked gas. A shock wave propagating through a gas at a speed of several times the speed of sound is only a few mean free paths thick, so the gradients are very large. At higher speeds where chemistry becomes important the shock thickness may be much larger. The postshock gas temperature increases rapidly with the wave speed, roughly as its square, or more appropriately as the square of the Mach number, which is the ratio of the shock to upstream acoustic speed. For low-speed shock waves (below about Mach 5) in a given gas, the jump in physical conditions across the wave depends solely on a simple quantity, the Mach number. The extent of the uniform postshock hot-gas region depends upon how the shock wave was created; i.e., by an explosive release of energy, a rapidly (supersonic) moving object, in a shock tube, etc. The determination of this extent of the uniform shocked gas is a boundary-value problem.

As the shock speed increases, new physical effects become manifest in the postshocked gas, bringing to the fore interesting and important phenomena. The postshock gas dissociates and then becomes ionized. The flow field can then interact with electromagnetic fields. The plasma radiates and, at very high speed, behaves relativistically. At relativistic shock-wave speeds the gas energy can become of the order of the rest mass of the electron ($kT = m_e c^2 = 0.5 \times 10^6 \text{ eV} = 6 \times 10^9 \text{ }^\circ\text{K}$). Such hot plasma will exhibit pair produc-

The author is professor of engineering science at Columbia University. A specialist in plasma physics and high-temperature gas dynamics, he received his PhD in applied physics from Harvard University in 1952. In June of this year, he presented an invited paper on strongly interacting shock waves at a session of the American Physical Society's Division of Plasma Physics during the APS summer meeting in New York City. A more detailed and fully referenced review paper entitled "Strong Ionizing Shock Waves" is to be published in the October 1965 issue of *Reviews of Modern Physics*.

tion where collisions create electrons and positrons. Somewhat analogous with slower-speed shock waves, where dissociation and ionization are important, very high-speed shocks have their particular high-energy chemistry.

To gain perspective, consider a shock wave propagating through room-temperature hydrogen at a pressure of 0.1 torr. Dissociation of the postshock gas begins at a shock-wave speed of about 6×10^3 m/sec (about Mach 5), and all the postshock hydrogen is monatomic at a wave speed of 25×10^3 m/sec (about Mach 20). At this latter wave speed the postshock gas begins to become lightly ionized, and at a wave speed of 70×10^3 m/sec (Mach 56; $25,000^\circ\text{K}$) it is an ionized hydrogen plasma consisting solely of electrons and protons. At about Mach 20, where ionization of hydrogen becomes significant, electromagnetic phenomena become important, and it is here that the study of strong, ionizing shock waves begins. Figure 1 shows the postshock temperature produced by a shock wave in hydrogen.

Let there be an applied magnetic field perpendicular to the plane of the shock wave. Such waves are called normal ionizing shocks. The variety of phenomena caused by the presence of a magnetic field interacting with a shock wave has generated a whole new vocabulary of shock terminology which as yet hasn't become standardized. One might expect that with a dielectric medium in front and a highly conducting plasma behind, the ionizing shock-wave behavior would be a mixture of an ordinary gas-dynamic shock (dielectric both up and downstream) and a pure magnetohydrodynamic shock (high electrical conductivity on both sides). This is only partially true since ionizing waves have some unique properties of their own. The unique effects arise from the fact that a transverse electric field can, and often does, exist in the cold gas ahead of the ionizing wave. The electric field, even when small, causes important ramifications in the shock behavior. In magnetohydrodynamic shock theory it is assumed that the gas conductivity is large, and consequentially in the preshock plasma there is no electric field. The failure to take into account the electric field in early studies of ionizing shock waves has caused considerable confusion.

Kulikovskii and Lyubimov, in the USSR, first recognized the importance of the upstream electric field, but their brief paper did little to give any physical insight. Recently Chu and Taussig at Columbia University have extensively investigated ionizing shock-wave properties. They have shown that for ionizing shock waves one cannot arbitrar-

ily specify the preshock electric field. This electric field is determined by the solution of an initial-value, boundary-value problem. The ionizing shock-wave solutions are bounded for a given initial electric field, and below a certain speed (determined by the preshock conditions) there are no steady-state solutions.

In Fig. 1 is shown a numerical solution of the appropriate shock equations when there is an initial transverse electric field. Besides the gas-dynamic solution, which is the single curve beginning at the lower left corner of the figure and proceeding toward the upper right-hand corner, the ionizing wave with an initial electric field has a horizontal branch (shown about tangent to the 10^4 °K line) and a vertical branch indicated by the letter *b* on the abscissa. There are three relevant signal speeds for normal ionizing shocks: *a*, the acoustic speed; *b*, the Alfvén wave speed; and, *c*, the speed of light. All three are shown on the abscissa of Fig. 1. The Alfvén wave is charac-

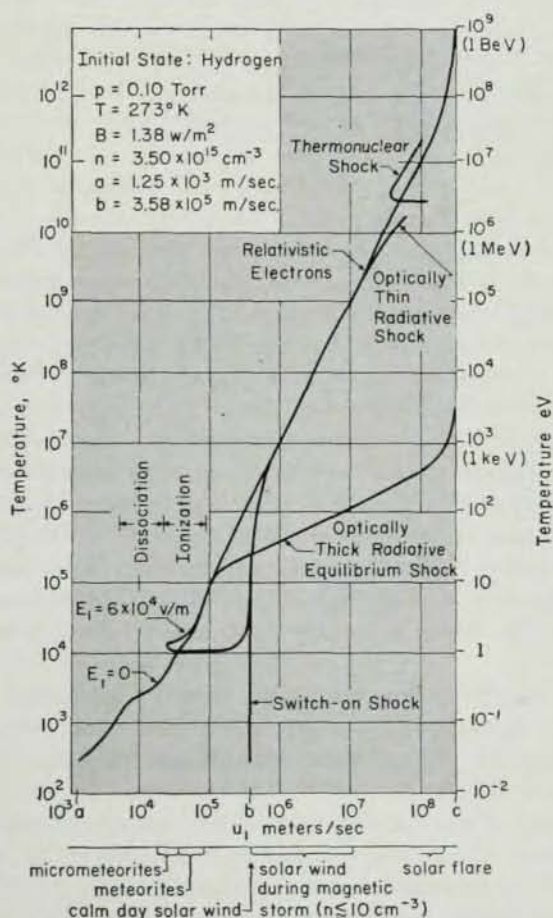


Fig. 1. Temperature produced by a shock wave propagating through hydrogen. The closed triangular loop in the lower left is the ionizing shock wave with a transverse electric field.

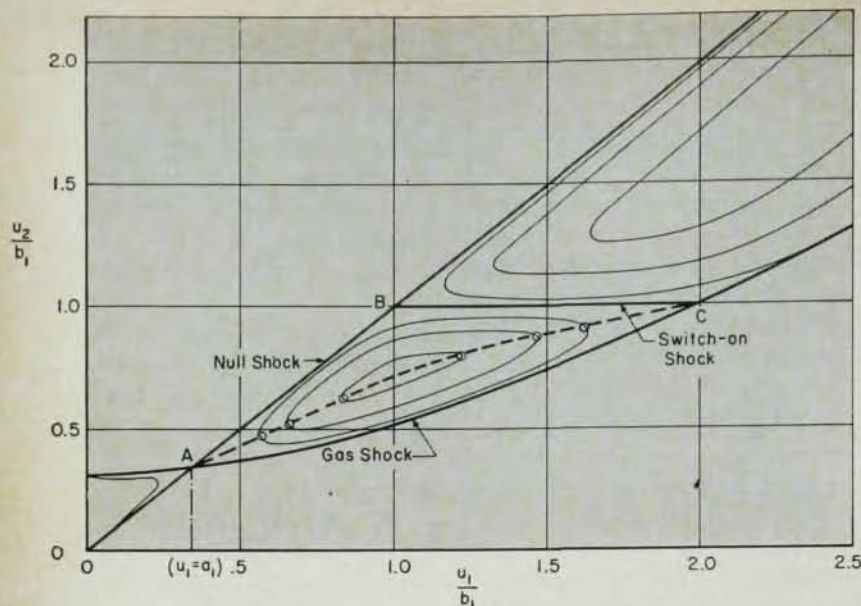


Fig. 2. The bounding curves are magnetohydrodynamic shock waves. The enclosed nested solutions represent ionizing shock waves with a transverse electric field. The dotted line is the locus of the extremal points.

teristically found in hydromagnetic problems. The horizontal branch of the ionizing-wave solution is analogous to the null ($u_1 = u_2$) gas-dynamic solution. In magnetohydrodynamic shock-wave theory there is a special type of wave, first predicted by Friedrichs, called a switch-on (or off) shock wave. It is characterized by the property that momentum transverse to the plane of the shock wave is switched on (or off) as the wave swallows plasma. This component of momentum results from an impulse imparted to the plasma by the Lorentz force present in the shock-wave structure. Current flows through the shock wave, interacts with the normal magnetic field, and imparts a transverse force on the plasma. Such a pure switch-on shock is shown in Fig. 1 as the nearly vertical curve beginning at u_1 (the shock speed) equal to b (the Alfvén speed). In magnetohydrodynamics, switch-on waves are only found in the speed range $b \leq u_1 \leq 2b_1$. Ionizing shock waves have a branch analogous to the switch-on wave in magnetohydrodynamics. For a given wave speed the post-ionizing shock temperature is higher than that produced by the corresponding zero electric-field wave. There is also a value of the electric field, above which there is no steady solution for ionizing waves.

Figure 2 shows another view of solutions of the shock-wave jump properties. The outer bounding dark curves represent the gas-dynamic, null, and switch-on wave solutions with no electric field. These correspond to the magnetohydrodynamic (zero electric field) case. The curves to the left of $u_1 = a_1$ are not physically relevant. Within the points ABC all the ionizing waves (nonzero electric field) form closed nested curves. The extremal points of these curves, indicated by circles, are analogous to the Chapman-Jouguet condition

in detonation theory. At these points, the entropy is stationary, and the postshock plasma speed u_2 is equal to the plasma slow-wave*, small-disturbance speed. Such a condition in aerodynamics is descriptively called choking. In the upper right-hand part of Fig. 2, the ionizing waves are open-ended curves with only one extremal point.

From these ionizing-wave solutions an interesting and physically appealing picture has evolved for the switch-on shock-speed regime ($b \leq u_1 \leq 2b_1$) which helps to explain the multitude of puzzling observations of laboratory electromagnetically driven ionizing shock waves. Consider a metallic-wall, coaxial, electromagnetic shock tube containing a cold, nonconducting gas. When a high voltage is placed across the shock tube, a series of electromagnetic waves propagate, back and forth along this wave guide. These waves die down in a few nanoseconds to produce a radial electric field in the cold gas just equal to the impressed field. Then the gas in the tube begins to break down electrically, and current starts to flow across the tube. Electric charges along the tube walls redistribute themselves with some flowing through the gas, and the newly formed ionizing shock wave starts to accelerate into the cold gas, which contains an initial electric field that is continually changing (decreasing). The postshock plasma speed increases until it attains the slow, small-disturbance signal speed. The flow behind the ionizing wave is then choked, and further acceleration is no longer possible. The ionizing wave continues to propagate at a steady speed with conditions representative of the extremal points of ionizing shock-wave theory in the switch-on speed

* The slow wave speed is the slowest of three acoustic speeds that are found in plasmas containing a magnetic field.

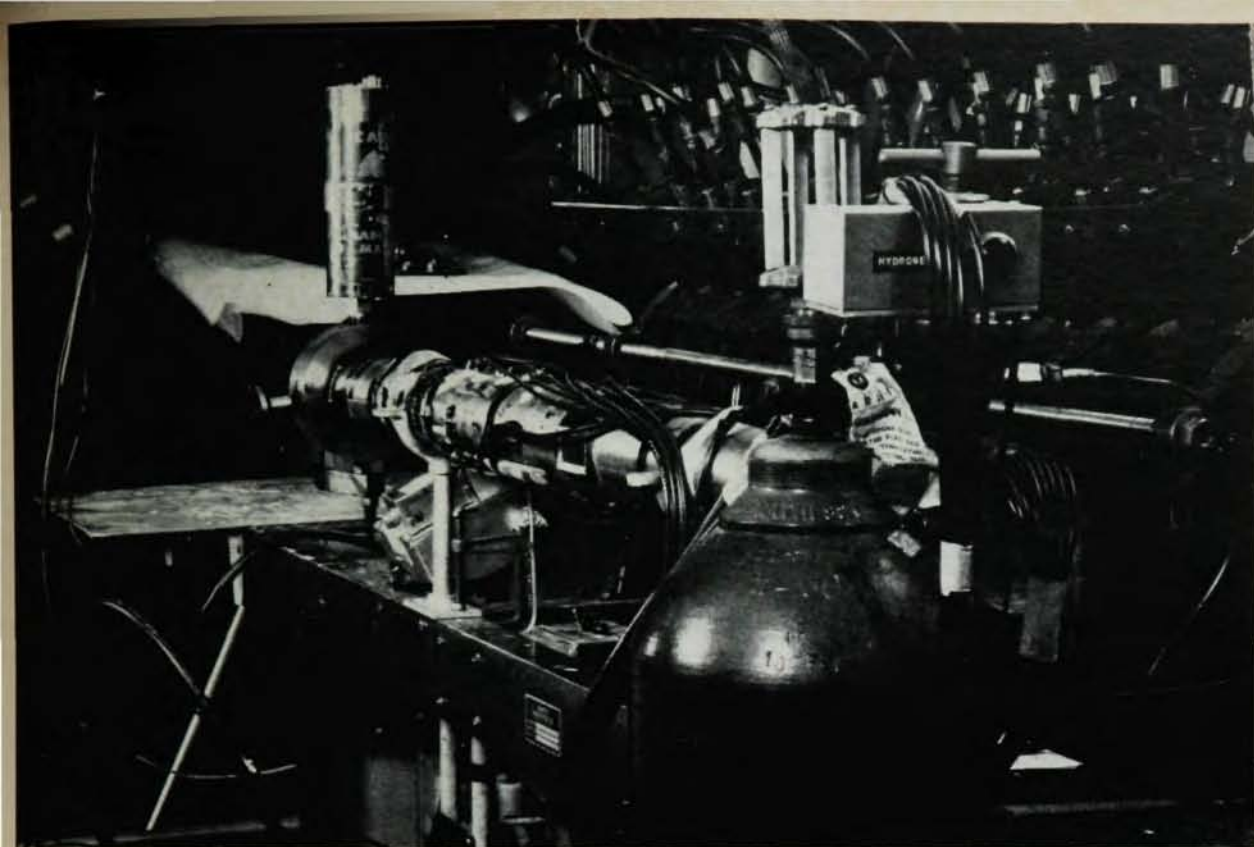


Fig. 3. Electromagnetic shock tube at Columbia University. Longitudinal magnetic-field magnet is at right. The shock tube, removed from the magnet, is the metallic cylinder pointed toward the shaped-pulse capacitor in the background at left.

regime. It is a property of the extremal points that the driving current moves contiguous to the shock front. This helps to explain the previous frustrations of numerous investigators who failed to find the uniform plasma sample behind an ionizing shock wave. At shock speeds greater than $2b$, the initial electric field appears to be essentially zero, and gas-dynamic shock-like behavior is expected.

In recent laboratory experiments at Columbia University, performed with the electromagnetic shock tube shown in Fig. 3, B. Miller found reasonable agreement between measurements and the choking theory just described. He has been able to clearly identify ionizing switch-on shock waves by means of magnetic-field probes. A very small (one- to two-centimeter-thick) uniform plasma sample was found under some conditions between the ionizing shock wave and the drive-current expansion fan. On the other hand, Patrick and Pugh of AVCO Research Laboratories have made measurements in an electromagnetic shock tube that are very suggestive of the null branch of ionizing waves. The conditions necessary to produce either the gas-dynamic ionizing shock or the null ionizing wave remain confused among different experimental devices.

Laboratory experiments with hydrogen ionizing shock waves in shock tubes have produced wave speeds up to about 4×10^5 m/sec and temperatures of the order of a million degrees Kelvin.

Experiments with theta pinches in thermonuclear research have generated wave speeds in excess of 10^6 m/sec. Such ionizing waves must be similar to those I've described, but the details for cylindrical geometry are of course different.

With an increased understanding of ionizing shock waves, what are the possibilities of producing higher wave speeds, and hence higher plasma temperature, by strong shocks? I think that shock tubes can and will be built in the near future that will produce plasma temperatures in the range 10^7 to 10^8 °K. Fortunately, they will not require larger and more expensive capacitor banks or energy storage systems.

What new physical phenomena lie ahead in research with strong shock waves?

Radiation plays an important role, and at higher wave speeds it dominates. Two limiting cases of radiative shock waves have been recognized: the optically thick and optically thin cases. If the photon mean free path is short compared to the shock thickness it is called an optically thick shock, and vice versa. Unfortunately, the photon absorption cross sections are strongly dependent upon frequency, and most photon mean free paths are

many orders of magnitude larger than laboratory apparatus. Some astrophysical shocks may be optically thick, but all laboratory shocks are essentially optically thin over most of the spectrum. Radiation from the shocked plasma, which at high temperatures is principally bremsstrahlung, is absorbed by the walls of the device. Hence, this energy loss from very strong shock waves prevents a truly steady-state situation in the laboratory.

Paul Koch of the Columbia Plasma Laboratory has computed the postshock temperature for the optically thick case, and he has also estimated the maximum temperature for the optically thin case. The results can be seen in Fig. 1. The optically thick shock wave has a lower postshock temperature than the nonradiative wave moving at the same speed. The optically thin shock produces a maximum temperature (just behind the shock) that is essentially the same as the nonradiative case up to wave speeds of the order of 10^7 m/sec. This is understandable when we remember that a shock wave is relatively thin, and at high wave speeds there is little time to radiate significant energy while the plasma is in the shock structure itself.

For the optically thin, strong shock wave, a significant number of the plasma electrons become relativistic at a wave speed slightly in excess of 10^7 m/sec ($T \sim 10^9$ °K). The entire plasma behavior is relativistic at wave speeds greater than 10^8 m/sec ($T \sim 10^{11}$ °K). The effect of a relativistically correct equation of state and equations of motion produces postshock temperatures as shown in Fig. 1. At wave speeds in excess of about 10^7 m/sec the plasma may exhibit pair production. Collisions of particles may be accompanied by the production of electron pairs (electrons and positrons), and the number of particles will depend again on thermal equilibrium conditions. The energy density of positrons at relativistic wave speeds becomes important and for $kT \gg mc^2$ is equal to seven-eighths the energy of black-body radiation in the same volume.

If the hydrogen consists of deuterium or tritium, the isotopes of hydrogen, the high temperature created by a strong shock wave will cause thermonuclear reactions. The resulting exothermal thermonuclear shock wave will have dynamic characteristics somewhat like combustion detonation waves. A thermonuclear shock temperature and wave-speed locus are shown in the upper right of Fig. 1. Shock waves heat the ions, which is what is desired for a fusion device. It can be shown, however, that because of the thermonuclear reac-

tion rates an electromagnetically driven shock tube of unreasonable length would be required for fusion.

Experiments with strong, ionizing shock waves are being performed in many laboratories around the world. Electromagnetic shock-tube work is being done at Columbia University, MIT, AVCO, Caltech, University of California, the Naval Research Laboratory, and many other places in the United States. Experiments of importance are in progress at Novosibirsk in the USSR, Nagoya University in Japan, at the University of Sydney in Australia, and elsewhere.

Finally, I must mention that strongly ionizing shock waves are found in nature if one looks to the heavens. Some relevant natural phenomena are shown along the abscissa of Fig. 1. Solar noise of type-II radio bursts have been suggested to originate from plasma created by strong shock waves. The pulsating star W Virginis has been observed and analyzed in terms of shock waves very similar to those now produced in the laboratory. Fowler has recently postulated that very strong shocks play a significant role in his quasar model. Shock waves are thought to play a significant role in heating the upper regions of our sun's atmosphere. Whenever there is a sudden large energy release in a galaxy, surely there is an accompanying strong shock wave. There must be numerous shock waves in the plasma that stretches across our universe; these shocks help redistribute the energy in space.

There is a collisionless shock wave that precedes our earth as it sails through the solar plasma wind. It has many fascinating properties now being measured by satellite probes. It is also attracting the attention of many theoreticians. There is an important difference, however, between ionizing shock waves and collisionless shock waves; the ionizing shocks are collisional. Many researchers have assumed that ionizing shocks become collisionless shocks at sufficiently high speeds. This is not so, and recently it has been pointed out that collisional interactions such as charge exchange dominate strong ionizing shock structure. Collisionless shocks will surely form another branch of shock-wave theory and technology.

In summary, there is a satisfactory theory for ionizing shock waves up to speeds of about 10^5 m/sec and temperatures of the order of 10^6 °K. Laboratory experiments are probing this region. It appears that much higher speeds and temperatures can be generated by strong shock waves. Their creation and study will be helpful in the quest for controlled thermonuclear fusion and understanding important astrophysical phenomena.