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TARGET DYNAMICS AND THERMONUCLEAR BURN

PART I

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Introduction

Impact fusion appears at first sight to make possible a very attractive fusion reactor system. An accelerator, capable of many repetitive shots, drives projectiles at high velocity into a reactor volume where they hit targets placed there before each shot. Fusion fuel is heated by the impact to thermonuclear temperature and contained inertially to produce fusion energy greater than the energy required to accelerate the projectile by a factor q. The accelerator can stand off at a large distance from the reactor volume so that it is not exposed to blast and radiation from the fusion reaction. The reactor volume contains no complicated structures, but is simply a blast container with tritium breeding blanket and heat store.

When we look at details, we find a number of problems with impact fusion that may interfere with its realization. Projectiles must be accelerated to very high velocities, tens to hundreds of times the present state-of-the-art. The accelerator must be efficient and durable. Suitable projectile-target systems must be developed capable of producing a high q. I intend here to concentrate on projectile-target problems rather than those of the accelerator. We must keep in mind, however, that there are serious accelerator problems so that systems requiring modest projectile velocities and energies are highly desirable. Also, we would like to avoid systems requiring large fusion yield per shot because of the economic cost of large blast containment.

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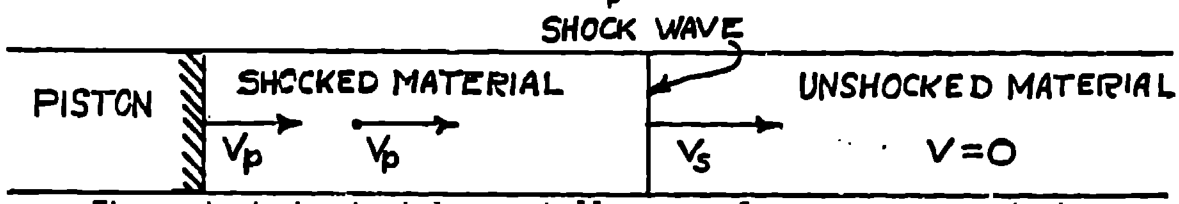
Shock Waves

Shock waves are frequently visualized as being generated in a hard-walled cylinder filled with unshocked material. A piston is driven into the cylinder from one end accumulating material ahead of it. The velocity of the piston is v_p.



The unshocked material, we shall assume for our purposes to have

pressure = 0
density = ρ_0
velocity = 0

A shock wave moves ahead of the piston into unshocked material at velocity

velocity = $v_s > v_p$

Material that has passed through the shock has

pressure = p_s
density = ρ_s
velocity = v_p

The shocked material has the same velocity as the piston. Using conservation of material and a pressure vs. rate of change of momentum equation, we can derive

$$p_s = \rho_0 v_p v_s$$
$$\rho_s = \rho_0 \left(\frac{v_s}{v_s - v_p}\right)$$

If the shock is energetic enough that the energy required to ionize the material can be neglected, and if the resulting electron plus ion plasma obeys the perfect monatomic gas law, with $\gamma = 5/3$, i.e., the internal energy per unit volume is 3/2 times the pressure, then the density of the shocked material is 4 times the unshocked density.

$$\rho_s = 4\rho_0$$

With a $\gamma = 5/3$ gas, the shock velocity is given by

$$v_s = 4/3\ v_p$$

and the pressure by

$$p_s = 4/3\ \rho_0 v_p^2\ .$$

These gas shock formulae would be be modified somewhat for $\gamma \neq 5/3$. For instance, if γ were 1.4, approximately the value for weak shocks in air, the density ratio would be 6 instead of 4.

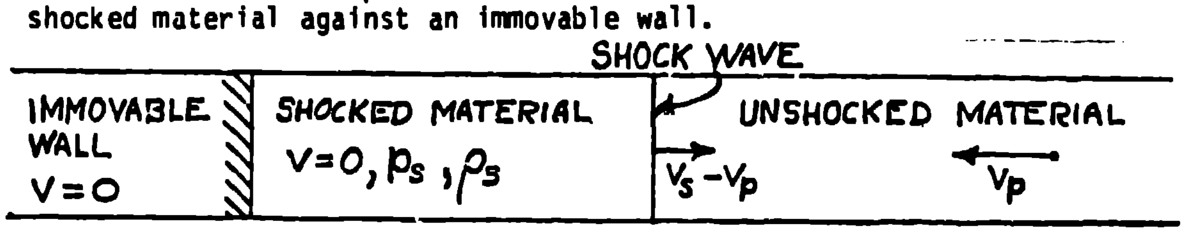
We might inquire as to the reason for being interested in the behavior of a monatomic perfect gas when the problems we face concern shock waves in solid materials, solid frozen DT and various metals. The case of solid DT with a density

$$\rho_0 = 0.2\ \text{gm/cm}^3$$
$$n_0 = 4.82 \times 10^{22}/\text{cm}^3$$

is particularly easy to justify. The energy required to dissociate and ionize a hydrogen molecule is 29.5 eV. Once it is ionized, it has become 4 particles instead of 1 particle, 2 electrons and 2 ions. The dissociation plus ionization energy per particle is then about 7.4 eV. We are inte[illegible]ed in shocks producing temperatures of at least several hundred eV. As an example, a temperature of 400 eV would imply a thermal energy of 3/2 kT for each electron and ion or 600 eV, 80 times the dissociation-ionization energy, which would thus appear to be negligible.

Impact Against an Immovable Wall

A simple coordinate transformation on the shock wave diagram given above, namely subtracting v_p from every velocity, puts the shock in a system in which the piston does not move. In other words, it describes a system in which the material streams from the right at velocity v_p, accumulating as a lengthening cylinder of shocked material against an immovable wall.



The equations applicable to the moving piston case apply equally here. In addition, in this system it is particularly easy to calculate the temperature of DT. Assume a cylinder of DT, containing N D+T atoms, impacts at velocity v_p against a hard wall. The initial kenetic energy is

$$U = 1/2\ NMv_p^2$$

where M is the DT ion mass

$$M = 2.5 \text{ atomic mass units}$$
$$= 4.15 \times 10^{-24} \text{ gm}$$

A shock wave moves through the DT cylinder until, when it reaches its back surface, the velocity is zero everywhere and all of the kinetic energy has been turned into thermal energy,

$$1/2\ NM\ v_p^2 = 3\ N\ kT$$

3 instead of 3/2 because there are now 2N particles, including electrons. From this we get

$$kT = 1/6\ Mv^2$$

Putting numbers into this

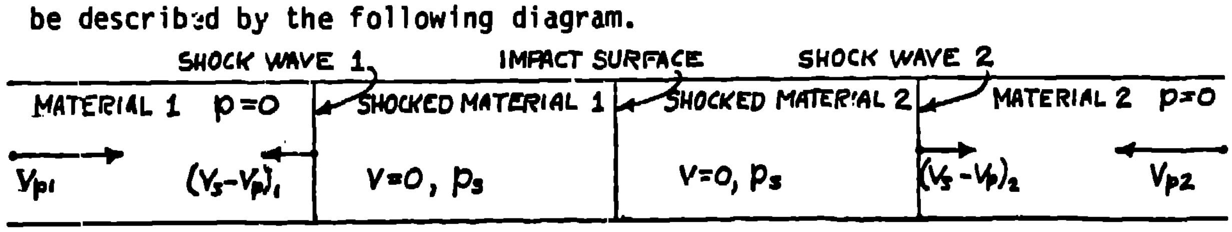
$$T = 4.32 \times 10^{-13}\ v_p^2 \text{ (T in eV, } v_p \text{ in cm/sec)}$$

To achieve a shock temperature of 10 keV in DT, we need a relative velocity between DT and an immovable wall of

$$v_p = 1.52 \times 10^8 \text{ cm/sec.}$$

<u>Impact Between Two Different Materials</u>

If disks of two materials collide with each other with relative velocity normal to their surfaces, a plane impact surface is formed with a shock wave moving away from it into each material. The shocked material is at rest with respect to the impact surface, and the pressures of the two shocked materials are equal. If we examine this system in the frame of the impact surface, we see that it can be described by the following diagram.



To get the relative velocity between the two materials, we add the streaming velocity (v_p) in one material, required to produce the pressure p_s against an immovable wall to the v_p in the other material, required to produce the same pressure. For example, if the impact is between DT and DT, the required relative velocity is twice the velocity required in DT collision against an immovable wall. The velocity required of a projectile striking a stationary target is just the relative velocity between the two materials. Clearly, we would like to minimize that velocity, and to do that we need an impact between DT and some material capable of producing the required shock pressure at much smaller velocity.

Extensive investigations of pressure and density in strong shocks have been carried out, using explosives to produce the necessary high pressures. Pressures up to 2 megabars (Mb) have been studied at LASL, while the work of Al'tshuler, et al., in the USSR has gone as high as 10 Mb. The experimental results are summarized in LLL report UCRL 50108 (1977), "Compendium of Shock Wave Data." The results are mostly displayed as "Hugoniots," plots of shock velocity or pressure vs. particle velocity. In Fig. 1 we have plotted pressure Hugoniots for a number of substances as log p_s vs. log v_p. The substances cover the range of densities from that of uranium to that of gaseous DT and cover pressures over 6 orders of magnitude from 100 kb. All pressures covered are above the strength of materials. The substances are U, Cu, Al, CH_2 (polyethylene) Li and DT, solid and gas. The sections of the curves in the lower left corner, where individual points are plotted, are the results of experiment. They are confined to pressures less than 10 Mb and particle velocities less than 10^6 cm/sec. Some of the points represent individual experiments and some are taken from smoothed curves. The straight lines in the upper right are Hugoniots calculated on the assumption that the shocked materials behave like $= 5/3$ gases.

$$p_s = 4/3\, \rho_0\, v_p^2$$

The dashed sections in between are sketched in by eye.

Chemical effects on the Hugoniots are limited to velocities less than a few times 10^6. It is obvious that the overriding effects on pressure are density and velocity. Above $v_p = 10^7$ cm/sec, all shocked materials behave like monatomic gases, for instance having a shock compression ratio of 4.

If we read from the Hugoniots, the particle velocities required in 2 materials to produce some given pressure, and if we then add those 2 velocities, we get the relative velocity in a head-on impact between the materials required to produce the pressure. For example, to produce 1000 Mb (10^{15} dynes/cm^2) shock pressure in the impact between solid DT and U, the uranium velocity is 6.2×10^6 cm/sec, while the DT velocity is 6.3×10^7 cm/sec. The relative velocity is then the sum of these velocities or 6.9×10^7 cm/sec. We could use either a DT projectile of this velocity striking a heavy target or vice versa.

Burn After Shock Heating

We have been discussing heating by plane shock waves in DT. The burn to be expected after this depends on how long the temperature remains high enough and how long before the DT compressed to 4 times its original density decompresses to low density. Heat is lost from the hot plasma by bremsstrahlung and by thermal conduction. Expansion will take place through the sides of a slab of DT and by rarefaction waves after the shock wave reaches the surface of the DT. Expansion through the sides can be reduced either by heavy materials there or simply by making the slab wide relative to its thickness. The burn can take place either through ignition or simply because of the high temperature produced by the shock. Ignition is the condition where the 3.6 MeV alpha particles, produced in the fusion reaction, return their energy to the plasma so as to maintain or increase the reaction rate. It depends on the hot DT plasma being thick enough so that the range of the alphas is smaller than or comparable to the thickness. This problem does not normally arise in magnetic fusion where the alphas are assumed to be contained with the plasma by the magnetic field. The range depends on the electron temperature of the plasma, being larger at high temperature, but the rate of reaction, and thus the alpha particle power, also increases with temperature. The necessary thickness for alpha particle heating to be effective is usually taken to be from 0.2 to 1.0 gm/cm^2, and is referred to as the $\rho\ell$ of the system. For a simple shock system in a wide slab, the disassembly time might be estimated to be the time for the shock wave to traverse the slab once. To shock heat to 10 keV, we need a particle velocity in the DT shock of

$$v_p = 1.52 \times 10^8 \text{ cm/sec}$$

or a shock velocity

$$v_s = 4/3\ v_p = 2.02 \times 10^8 \text{ cm/sec.}$$

If the slab, before compression, is 1-cm thick, the disassembly time would then be $1/v_s$ or 5×10^{-9} sec. At 4 times solid DT density, this would give an $n\tau$ Lawson parameter of 9.6×10^{14}. This would be marginal for nonignition burn, and it appears to be roughly marginal for ignition.

Loss of energy by bremsstrahlung can be compensated by alpha heating. In the absence of effective heating, the bremsstrahlung cooling time is

$$\tau_{br} = 9.04 \times 10^{14} \frac{T_e^{1/2}}{n} \qquad (T_e \text{ in keV})$$

$$= 1.48 \times 10^{-8}\,s \qquad \text{(10 keV, 4 x solid density}$$

This is somewhat longer than the disassembly time in our example, but not by a large factor.

To get ignition in a target such as we have been discussing here, would require a large target and a very fast, energetic projectile.

The result would be a technically difficult, expensive accelerator and an enormous explosive yield on every shot. Altogether, it appears that simple one-dimensional shock heating is unsuitable for fusion power production.

Compression After Shock Heating

An obvious improvement to simple shock heating is shock heating to some lower temperature, followed by further compression. In a one-dimensional situation, we can imagine a high-density projectile moving normal to its surface, colliding with a DT layer, backed up by another high-density slab. Initial heating would be identical to what we have discussed above, except that the velocities and temperatures would be smaller; however, the DT would not start to disassemble when the shock wave reached its rear surface, but would be further compressed by a second shock reflecting from the high-density slab. The temperature would be further elevated by the reflected shock, and compression and heating would continue by shocks and isentropic compression once the sound velocity becomes larger than the relative velocities of the high-density slabs. This subject will be discussed in other papers by Christiansen, Jarboe, and Krakowski so I shall not attempt to cover it here. Suffice it to say that in order to achieve energy gains (q's) large enough to make an impact fusion reactor practical, ignition or near-ignition conditions appear to be necessary and in plane slab systems, this implies large amounts of DT, perhaps one gram or greater and very large explosive yields. A one gram, DT burn produces nearly 400 GJ of energy. Not all of this energy must produce explosive yield, but still the explosion might be equivalent to 50 tons of TNT and would require a very massive containment vessel.

Three-dimensional compression of thermonuclear fuel has the advantage that because of convergence, large effective thickness of fuel can be achieved with modest amounts of DT. A 1-mm radius sphere of solid DT has a mass before compression of 0.84 mg, and after compression by a factor 10 in radius, would have a ρr of 2 gm/cm^2, comfortably above the ρr requirement for ignition. There have been suggestions of ways in which linear motion of a projectile can be turned into strong three-dimensional compression. One method has been published in the open literature by a Polish group under Kaliski. They have done experiments in which linear motion, produced by explosives, has resulted in conical compression of D_2 after shock heating, leading to appreciable neutron yields. This work will be discussed in a later session.

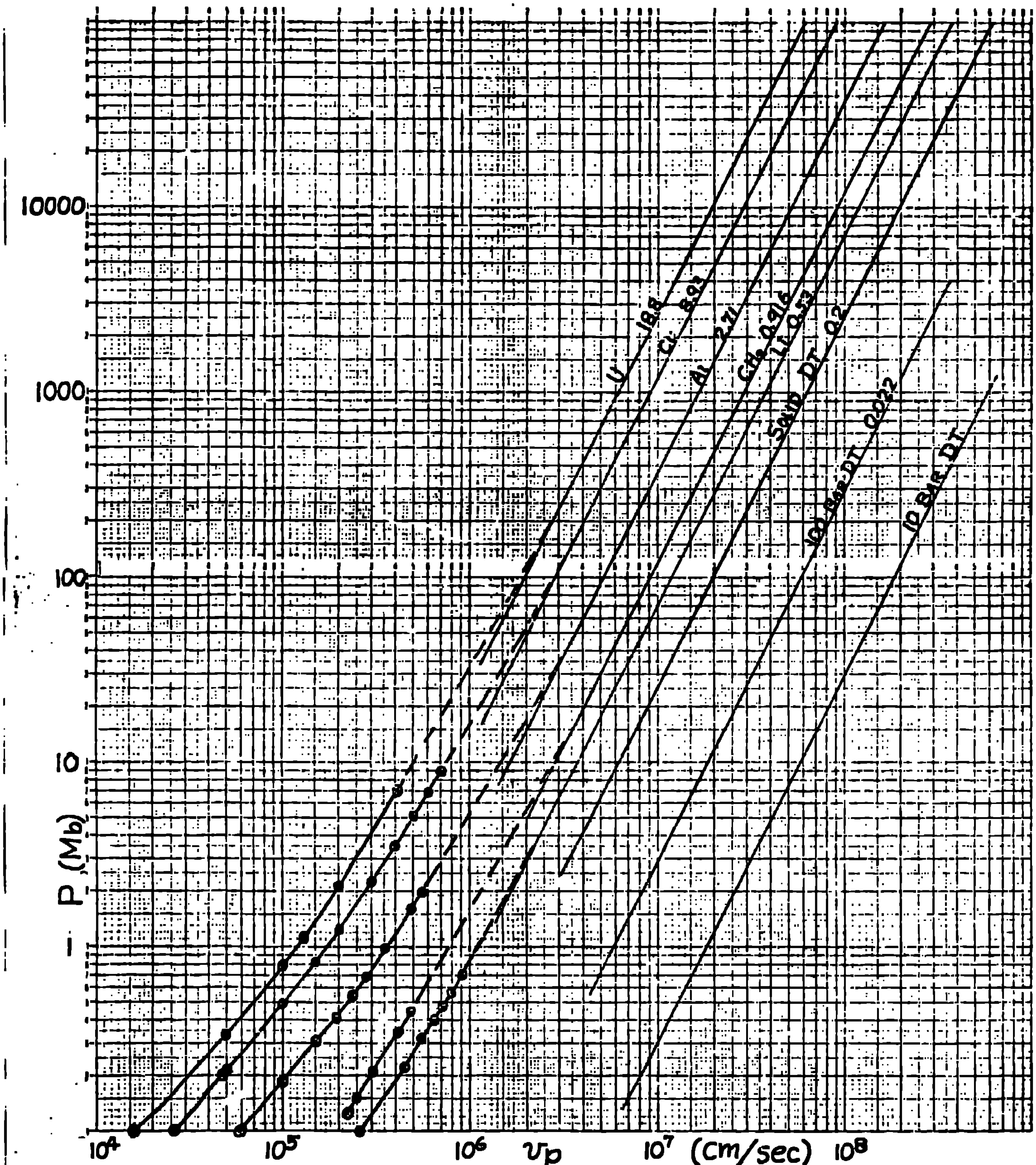


Fig. 1. Pressure vs. particle velocity Hugoniots for representative materials. Hugoniots are experimental below 10^6 cm/sec and 10 Mb. Straight lines at high velocity and pressure assume $\gamma = 5/3$ gas law behavior.