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TRANSLATION

SHOCK WAVES

By

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FOREIGN TECHNOLOGY DIVISION

AIR FORCE SYSTEMS COMMAND

WRIGHT-PATTERSON AIR FORCE BASE

OHIO

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SHOCK WAVES

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ANNOTATION

Sometimes we hear unexpected, loud booms, reminding us of the sound of a shot or an explosion, much more abrupt than peals of thunder. This is the unique signal of the flight of a supersonic aircraft; it is called a shock wave caused by an aircraft. This book is concerned with how shock waves appear and spread their actions useful and harmful to man, and the various sources of these waves (from aircraft and rockets to atomic and hydrogen bombs).

Shock waves are a new subject, almost unexplored in popular scientific literature. This book is simply intelligibly written and does not require special knowledge of the reader, although it does require thoughtful and leisurely reading.

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INTRODUCTION

At the end of the war, newspapers reported about our pilot, who during an air battle, had to jump from a burning plane. The parachute did not open, and the pilot would have perished unavoidably, but at the last second an aerial bomb exploded on the earth just under him. The blast wave turned out to be, in the words of the report, an excellent shock absorber, braking the drop, and the doomed pilot landed safely.

This case later depicted in a movie, could have been called fantastic, if it had not concerned the rescue of a human life. Unfortunately, blast (or shock) waves until now have destroyed many more lives than they have saved. But the forces of nature per se are not "evil" or "good" -- it all depends on their application by man. Thus, shock waves also find application not only in war, but also for large explosions for ejection which considerably facilitate construction of dams and channels, or for surface mining of useful minerals. Shock waves are used for extinguishing fires of petroleum and gas wells: with powerful bursts of air gigantic flames are blown out like candles. Shock waves accompany the flight of space rockets during flight through the atmosphere. They hinder during takeoff, but they then help during landing. Therefore, the study of shock waves is a necessary part of a new field of science and technology - stellar navigation, or cosmonautics. Shock waves can play a decisive role in the matter of peaceful releasing of thermonuclear energy, which will forever solve the energy problem for mankind for any level of consumption.

What then is a shock wave? There was a time when only a few were interested in this subject--military men and, in general, those specialists who were necessarily concerned with explosions. Certainly, not all physicists had a clear understanding of shock waves, and even now not all higher educational institutions teach about them.

On these questions there is little popular literature. This book is written for the reader, who has some, however vague, recollection of a school course in physics. He will remember many things more distinctly, will recognize some anew, and will perhaps become interested in a field of knowledge whose practical applications are all increasing--gas dynamics.

CHAPTER I

WHAT IS GAS DYNAMICS?

1. Sound Waves

A continuous medium solid, liquid or gas - can transmit oscillatory motion in the form of sound waves. Any nonuniform, and that also means oscillatory, motion is necessarily connected with some forces: in the absence of forces, bodies can move only in straight lines and evenly. Oscillations of the medium are caused by forces of elasticity in it. Thus, if we were to compress a volume of air and to allow it to be expanded, its elasticity will result in motion of the surrounding air. Here initially compressed air will be expanded not to its initial volume, but to larger volume: being expanded, it will obtain acceleration. The work, initially expended on compression, will become kinetic energy of motion; the latter, in turn, will be expended on the work of compressing the surrounding air medium. But, also, it will not remain compressed - being expanded, it will also turn work performed on it into kinetic energy and will compress a new, adjacent layer of air. Thus a sound wave will run along the air.

It is known that liquids and gases resist change in volume only, not change in shape: with respect to various misalignments or torsions they possess no elasticity. Therefore, during spreading a sound wave in the air it is necessary to consider only the expansion and compression of each volume.

In free space a sound wave runs from the source in all directions; for further reasoning it is more convenient for us to consider that the sound runs along a tube: then all volumes are compressed and expanded similarly. From one end of the tube let us assume there is an oscillating piston, which creates alternate compressions and rarefaction. First, let us consider piston displacements very small in amplitude. But no matter how small they are, as many compressions and evacuations per second will occur in any cross section of the tube aa in fig 1. At times the piston creates them by its reciprocating motion.

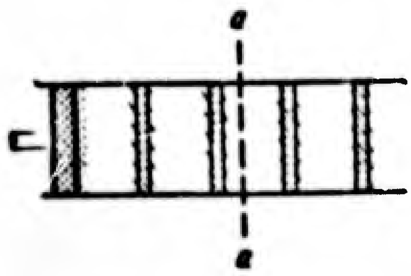

Fig 1.

The speed of the piston is directly proportional to two quantities: amplitude and frequency of oscillation. Consequently, for very low amplitude its speed will be very low even for a high frequency, or number of oscillations per second. But the speed of propagation of sonic oscillations has nothing in common with the speed of the piston. For oscillation frequencies perceived by the human ear (from 20 to 20,000 per second), from a barely audible rustle to the roar of a plane motor, the speed of propagation of a sound is the same: at "room" temperature (near 20° C), sound travels through the air with a speed of 330 m/sec.

This speed is determined only by the properties of air itself and depends on how fast motion in it is transmitted from one volume to another. As was already said, here the work of compression of one volume is expended on particle acceleration in a neighboring volume.

We will not derive the expression for the speed of sound, although it is easy to see how it may be constructed for known properties of gases. Acceleration is even greater the greater the force, or elasticity, of the air and is smaller the greater the mass of a unit volume, that is the density of air. Therefore, we should expect that the speed of sound should increase with its pressure and decrease with its density. And in fact, it turns out that the speed of sound is directly proportional to the square root of the pressure divided by the density. Those who remember the dimensions of physical quantities can be easily convinced that this quantity indeed is of the dimensions of speed and that it is impossible to construct other quantities with such dimensions from constants characterizing a gas.

Under the root here is still a coefficient of proportionality equal to the ratio of the heat capacity of air for constant pressure to its heat capacity for constant volume. This ratio is approximately equal to 1.4.

Its origin is curious. If we were to compress a certain volume of air very slowly, then its temperature would become equal to the temperature of the surrounding air. Such compression is called isothermal. Sonic oscillations occur comparatively quickly, so that the temperature of the compressed volume does not quite level off with the temperature of surrounding volumes; part of the work of compression is expended on its heating. Such compression is called adiabatic.

It is obvious that inasmuch as work here is expended not only on compression but also on heating of the air, then, for an equal degree of compression the adiabatic method requires greater pressure than the isothermal method. Adiabatic elasticity is greater than isothermal; therefore, in the expression for the speed of sound, the coefficient $\sqrt{1.4} = 1.19$ appears. For very low frequencies of piston oscillations, compression of the air would be isothermal. The speed of propagation of such a sound (a low frequency sound), inaudible to the human ear, is lower than the speed for a normal sound; for very low frequencies the ratio is exactly 1.19.

2. The Appearance of an Abrupt Change

The propagation of a sound will interest us not as a periodic process occurring in a gas, but quite from another point of view.

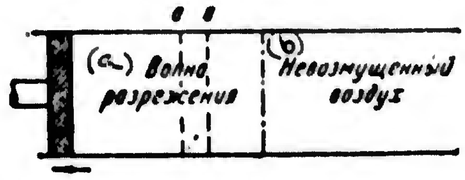

Fig 2.
KEY: (a) Wave of rarefaction; (b) Undisturbed air.

In order to explain it, we will imagine that the piston in Fig. 1 does not make periodic motions, but is simply smoothly extracted from the tube, starting from a certain initial position (Fig. 2).

Air rushes after the piston, but of course not simultaneously in the whole tube. At first, this will be a very thin film adjacent to the piston, then the neighboring layer etc. The boundary between motionless and moving air will run to the right along the gas with exactly the speed of sound. Right of this boundary the air will still not be touched by motion; to the left it will flow behind the piston. The distance between planes a and a, through the same particles, continuously increases.

Expressed graphically, the air to the right of the boundary of disturbances still "does not know" that the piston has started to move out of the tube. The speed of sound is like the speed of transmission of a signal in a gas - a signal reporting motion. Here is the meaning of the speed of sound for gas dynamics, which, unlike acoustics, usually has something to do with nonperiodic processes, such as, for instance, extraction or insertion of a piston.

It is possible to show that if the piston does not change direction in its own motion, then the front boundary of disturbance always moves with constant speed. For this it is necessary and sufficient, that it not overtake the sonic signals coming from the left, from the region of flowing, rarefied gas. If these signals do not arrive at the front boundary, then the gas at it "does not know" when and how the piston began to move after it came into motion for the first time. The boundary extends through the gas just as if the piston continued to retreat from the gas with the same speed as that with which it started its motion.

Why cannot a sonic signal from the rarefied region catch the front boundary? For this there are two causes. The speed of sound, as was already shown, is proportional to the square root of the pressure divided by the density. But this quotient is determined, according to the well-known Clapeyron equation, only by the absolute temperature of the gas (absolute temperature is equal to the centigrade temperature plus 273°; for instance, absolute "room" temperature is equal to $273° + 20° = 293°$). Expansion of the gas occurs adiabatically (see section 1). Consequently, it is cooled. Therefore, at every point of the gas moving after the piston, the speed of sound is lower than at the front boundary of disturbance.

Already for this one reason a sonic signal from a rarefied gas cannot overtake the front boundary of disturbance. But this is still not all. The gas moves after the piston, that is, to the left. Therefore, sonic signals are carried also to the left by moving gas. The speeds are subtracted, so that relative to the tube a sound from the rarefied region travels still slower than relative to the gas itself. This is the other cause why it cannot catch the front boundary of disturbance traveling along a motionless gas.

The disturbed region of the gas, flowing behind the piston, is called the wave of rarefaction. Since the piston moves to the left and the boundary of the wave to the right, the region of the gas behind the wave of rarefaction is continuously increased. The speed of every particle caught by the wave increases. On the actual boundary of the disturbance, it is still equal to zero; to the left, it increases and at the actual piston is equal to its speed if only the piston itself does not move too fast.

It turns out that if there is air in the tube but the speed of the piston is greater than five times the speed of sound in undisturbed air, then the flow does not keep up with the piston, so that a vacuum forms between the piston and the gas. In proportion to the expansion of the gas in the vacuum, the speed of each of its parts tends to five times the speed of sound. To avoid misunderstandings, let us note that we are not discussing specific molecules of a gas, which move in a disorderly manner, but about the ordered, normal rate of gas motion relative to the tube.

For sound waves, which are studied in acoustics, the velocities of particles (again of small volumes, not of molecules!) are always very low as compared to the speed of sound. In a wave of rarefaction, the relationship is exactly the inverse: the gas travels faster than sound. Such a situation is characteristic for gas dynamics, studying the motion of gases with high speeds.

The velocity of particles is usually compared not with the speed of sound in undisturbed air, but with the "local" speed of sound, that is, with its speed in a given small area. On the boundary with a vacuum in a wave of rarefaction, the pressure of a gas is equal to zero, and the temperature is equal to zero. Certainly, this refers to an imaginary "ideal" gas, which at low temperatures does not turn into a liquid; we will now study the dynamics of just such a gas. But at absolute zero even the local speed of sound is equal to zero, since it is proportional to the square root of the temperature. Consequently, at this place, or, more exactly, this particle of gas the speed of flow is an infinite number of times greater than the speed of sound.

Thus moves a gas when the piston is extracted from the tube. What will occur if the piston is inserted and thereby compresses the gas in the tube? It turns out that quite a different picture appears.

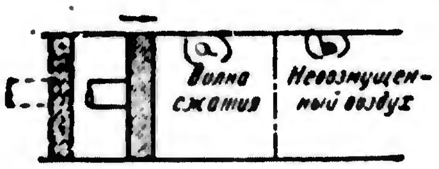

Fig. 3.
KEY: (a) Compression wave; (b) Undisturbed air

Let us assume that we start to insert a piston very slowly. Then the front boundary of the compressed gas will travel with the speed of sound along the uncompressed gas. Gradually the piston will be accelerated. A compression wave will be formed in which the air is adiabatically heated and moves to the right (Fig. 3). Therefore, the disturbance from the compression wave will certainly catch its front boundary: in heated air the speed of sound is higher, and furthermore, it accumulates with the speed of the flow. Consequently, the front boundary of the compression wave will certainly "find out" that the piston accelerates, compressing the gas.

It is possible to depict the profile of a compression wave, that is, the distribution of pressure in it depending on the coordinate (Fig. 4a). Let us assume that on this profile there is a small "protrusion" of pressure a. It cannot remain in place even relative to that volume of gas in which it appeared, but like any gas compression it will travel in the gas with the speed of sound, variable on the profile, from point to point. But any point, for instance, b, can be considered a protrusion above the chord designated by a dotted line.

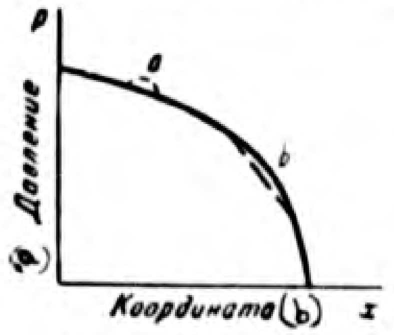

Fig. 4a.
KEY: (a) Pressure; (b) Coordinate.

Thus, every gas compression extends through it with the local speed of sound, while, on the profile depicted in Fig. 4,a, greater pressure will overtake and even, one would think, surpass the lesser. But if that happened the profile depicted in Fig. 4a would be reconstructed to correspond to Fig. 4b, which corresponds physically to an absurd situation when, at the same point, for instance A, the pressure of the gas has two or even three values on the profile (p_1, and p_2, in Fig. 4b, p_1, p_2, and p_3, in Fig. 4c). It is obvious that, in fact, this is not possible and something quite different will happen.

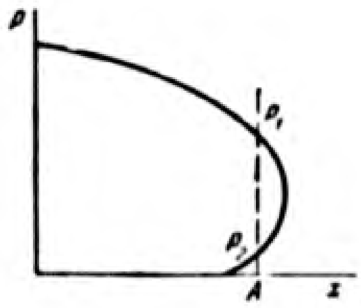

Fig. 4b.

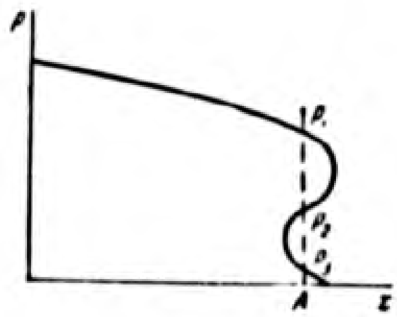

Fig. 4c.

Before studying what will occur in the gas it is useful to turn to another, very similar case of wave motion - sea surf. It turns out that the laws of propagation of waves along the surface of the water in a shallow reservoir are very similar to the laws of propagation of compression waves in a gas. One wave, so to speak, is the model of the other. Everyone, probably, knows that an electrical oscillation mesh due to capacity and self-inductance simulates the oscillations of a load suspended on a spring. The role of an elastic link is played by capacity; the role of mass is played by self-inductance.

In spite of the completely different physical natures of the phenomena, they obey regularities of identical form. This is simulation.

No wave motion in a liquid simulates a compression wave in a gas. For instance, a shallow ripple on a surface has another law of propagation. An analogy appears only if the wave length is comparable to the depth of the reservoir. Then the height of the water level at a given point is a quantity analogous to the pressure in a gas. The profile of pressure in a gas corresponds to the visible profile of a wave in water.

Let us study how waves similar in profile to that depicted in Fig. 4b appear in surf. If waves run onto a sloping shore, their crests have higher speed than their troughs. It is easy to prove that this should be so: under the crests the local depth is greater than under the troughs. But the speed of the waves can depend only on two quantities: depth and acceleration due to gravity. And from them it is possible to construct only one quantity having the dimensions of speed: the square root of the depth multiplied by this acceleration. The expression for speed of drop of a body from a given height has the same form. But if the crests travel faster than the troughs they have to overshoot in the front, so that the waves first obtain the vertical section of the leading front, which is then inclined as in Fig. 4b,c. Having such a form, waves cannot travel, and they collapse in the form of surf.

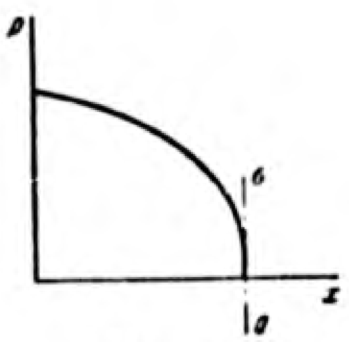

Fig. 5a.

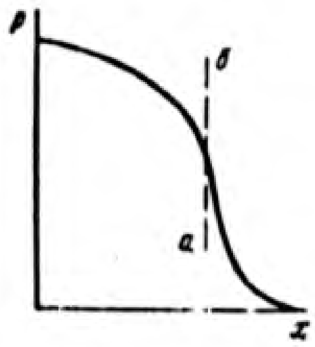

Fig. 5b.

We will now trace the way in which the profile of a compression wave in a gas will change.

Before physically impossible overlash will appear, at a certain point of the profile a very small vertical section should be formed (Figs. 5a, b). Depending on the law of motion of the piston, this vertical section can be obtained both at the front point of the compression wave and also at its middle. The pressure from the left side of this section will continue to increase due to signals arriving from the direction of the piston. But as if it did not increase the vertical tangent ab to the profile will not be inclined to the right, so that it will not start the impossible profile depicted in Fig. 4b.

Consequently, the only exit is formed when a break in the pressure will be developed from the vertical t ngent (Fig. 6a, b).

The place of the break can be considered a section of a curve with any large slope, so that indeterminacy of pressure will arise.

We started our reasoning, by assuming that all quantities in a compression wave change continuously in the sam way as in a wave of rarefaction. But it turned out that in a compression wave there must come a moment when motion can no longer remain continuous. However, displacement of the piston, in

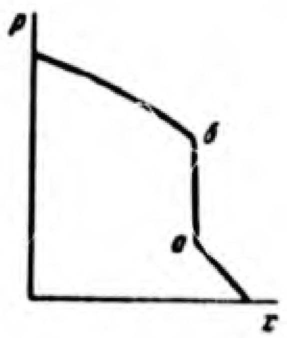

Fig. 6a.

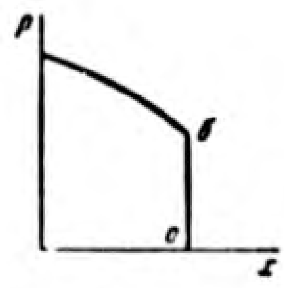

Fig. 6b.

principle, can be located arbitrarily so that the gas should find some natural exit. The only possible assumption is that an abrupt change will appear in the gas.

Such a change is called a shock wave. Gas dynamics came to the conclusion of the necessity of shock wave formation from a compressional wave not from qualitative reasonings, but from strict equations. But those who came to this conclusion first actually did not believe it, proceeding from the metaphysical prejudice that "nature does not make abrupt changes". Probably, at the basis of this false principle lies the assumption that an abrupt change is something lawless, disturbing the natural pattern of things. In fact, however, a shock wave is directed by the same strict regularities as a smooth, continuous flow of gas. It appears, develops and spreads in the same agreement with the mechanical and general properties of a gas as a sound wave.

3. Conditions at Shock Wave Discontiniuty

The motion of a gas with shock wave discontiniuty is one of the particular cases of mechanical motion. Consequently, no matter which quantity changes abruptly in a shock wave--the pressure, density or speed of the gas--change always should occur in such a way that the general laws of mechanics are not disturbed.

One of the basic laws of motion in Newtonian mechanics is the law of conservation of mass: no matter how a material particle moves, its mass remains the same. The law of conservation of mass is approximate; in the more exact equations of mechanics of Einstein, it is not confirmed. Thus, for nuclear transformations the total mass of particles can change by approximately 0.1 - 0.4%. But we will dwell a while on shock waves of such great force that here it is necessary to take in account nuclear transformations.

Thus, it is necessary to require that the mass of a substance flowing in one second into a shock wave discontiniuty from the left be equal to the mass leaving it on the right. Otherwise, mass would be accumulated in the actual change, thus obtaining infinite density, which it is impossible.

Besides the law of conservation of mass, the law of conservation of momentum is very important. This is the term, as is well known, for the product of the mass of a particle times its speed. According to the second law of Newton, if forces act on a particle then the change in momentum for a unit of time is equal to the forces applied.

Let us study a particle of a gas passing through a discontiniuty. The force applied to it is equal to the difference in the pressures on the right and on the left of the discontiniuty; it is obvious that these pressures act on opposite sides so that the resultant is found by subtraction.

We will now calculate the momentum of a gas passing through a discontiniuty. For this, we will mentally construct in the gas a cylinder whose axis is perpendicular to the shock wave discontiniuty (Fig. 7), and the area of whose base is equal to 1 cm^2. On the left we will construct along the axis of the cylinder a section numerically equal to the speed of the flow of gas from this side, and we will construct an analogous section on the right. Then according to our construction it is clear that all the gas located in the left section of the cylinder will overflow through the break into the right section in a unit of time. How will the momentum of the gas in the cylinder be changed during that time? The mass of the left section is equal to the density on the left multiplied by the speed there, because the volume of this part of the cylinder is numerically equal to its length (the area of a cross section = 1), so that mass = density x length. Momentum is equal to the product of mass times speed, which is finally equal to the product of the density times the square of the speed. An analogous expression is equal to the momentum of the right section of the cylinder.

Fig. 7.
KEY: (a) Shock wave discontiniuty.

When a gas passes from left to right through a shock wave discontinuity, its momentum for a unit of time is changed by the amount of the difference between these expressions.

But according to the second law of Newton, change in momentum for a unit of time is equal to the resultant of the applied forces, that is, according to what was just now said, the difference in pressures for faces of the entire cylinder. This is the second condition at discontinuity. It is most convenient of all to express them assuming that we move along with the discontinuity relative to the gas. Then the law of conservation of mass states:

The product of density times the speed of the gas is equal for both sides.

The second law of Newton yields:

The difference in products of the density times the square of the speed is equal to the difference, taken with reverse sign, in pressures.

In the actual discontinuity density, pressure and speed change abruptly. Let us study their known values for one side of the discontinuity. What should be given in order to determine them for the other side?

First of all, let us note that, besides these three quantities, the actual velocity with which the discontinuity spreads relative to particles of the gas, is also unknown. It is clear that it is in no way connected with those same particles; after all, the gas will overflow through it. If it is assumed that gas ahead of the wave is at rest, then the speed of wave is that superfluous unknown which it is necessary to know, along with the state of the gas behind the wave.

The state of the gas ahead of the wave is usually given, so that for total determination of the wave it is necessary to know four more quantities; for this, we have two more conservation laws. If, for instance, we knew the pressure and density also for the other side of the discontinuity, then already the speed of propagation of the discontinuity and the speed of the gas along its other side will be simple to calculate. Note that these quantities are not at all equal to each other, just as the speeds of sound and of the gas are not equal in a sound wave.

The laws which we used are universal and do not depend on the nature of the substance in which the discontinuity occurs—whether it is solid, liquid, or gas, or even friable, like sand.

In nature there is, however, one more law universal in content-that of conservation of energy. It essentially differs from the preceding two in that they are also universal in form: the expression of momentum of any body in terms of its mass and speed is always the same. But it is impossible to record in ordinary form the energy of an arbitrary body. The difference is connected with the fact that the momentum of a body pertains to its displacement, as an integer, but the energy is also connected with internal, thermal motion of separate atoms and molecules.

The energy of a body is always formed from two parts: the purely mechanical part, which, in general, is equal to the sum of kinetic and potential energy, and the energy of internal molecular motion, which is sometimes called "thermal". The law of conservation of energy pertains to the sum of kinetic, potential and internal energies of a substance. But the potential energy depends on the position of a particle in space and cannot endure a discontinuity on a shock wave. Therefore, on a wave the sum is simply that of kinetic and internal energy.

The law of conservation of energy was formulated after R. Mayer established mechanical heat equivalent: until this, such a law could not be expressed in quantitative form. General postulations about the conservation of "force" or "motion" of the XVII or XVIII century belong more to philosophy than to physics since they gave no definite numerical ratios. It is impossible to talk about the conservation of a quantity as long as it is not stated exactly what is kept, that is, how the quantity kept is measured physically. This is a part of determination of mechanical equivalent of heat.

The law of conservation of energy, as we have already noted, is universal only in content, but not in form, because the internal energy of various bodies is connected in different ways with their state, that is, with pressure and density. In this case, this is very essential, since it is precisely pressure and density which must be defined for various sides of a shock wave discontinuity.

But if for a certain specific substance the dependence of the internal energy on pressure and density is known, then the law of conservation of total energy makes possible determination of one more quantity after a shock wave discontinuity. Therefore, if pressure, density and speed before the discontinuity are known, then after the discontinuity it is sufficient to know only one pressure, or instead of it is necessary to give the speed of propagation of the shock wave.

The energy of a gas is very simply expressed in terms of its pressure and density. Since the heat capacity of a gas is a constant quantity, its energy is directly proportional to the absolute temperature. The latter, according to the Claperyron equation, in turn, is proportional to the pressure of the gas divided by its density. Therefore, the energy of the gas is also proportional to this quotient.

This simple expression allows us to calculate easily any quantity behind the front of a shock wave in a gas if one of the quantities characterizing the discontinuity is given. Very frequently abrupt changes in pressure occur for given pressure, speed and density in front of the front.

Instead of density we sometimes use another quantity - specific volume of the substance, that is, volume per unit mass, whereas density is mass per unit volume. Obviously, these quantities are the reverse of each other.

Given the initial state of a gas at rest before the front, it is possible to construct the curve of dependence of pressure on specific volume behind the front. It is called Hugoniot adiabat (here we discuss the inertia of incorrect pronunciation of the surname Hugo). According to what has been said, Hugoniot adiabat is especially simply constructed for an ideal gas. Its approximate form is shown in Fig. 8. p_0 and V_0 - initial pressure and volume of the gas; p_1 and V_1 - final pressure and volume after shock compression. AB - vertical asymptote (see below).

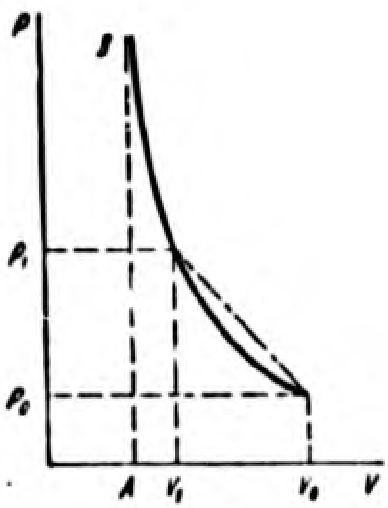

Fig. 8.

We already mentioned in Section 1 two methods of compression of gases - isothermal and adiabatic. The curve in Fig. 8 illustrates a third method of compression - the shock method. The curve here is also called "adiabatic" because during shock compression there is also no heat exchange with the environment, as during the usual adiabatic compression. But one should consider that there is deep distinction in the meanings of the two curves which we will now explain.

For comparison we will depict the curves of isothermal and adiabatic compression (Fig. 9) in the same variables. Externally, they resemble Hugoniot adiabat, but in fact, they have an absolutely different meaning. If pressure smoothly increases from its initial value p_0, then the volume will also decrease smoothly from initial value V_0 along an isotherm or adiabat, from the point of view of the method of compression.

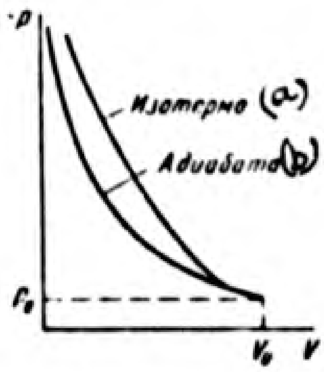

Fig. 9.
KEY: (a) Isotherm; (b) Adiabat

During relief, that is, when the pressure smoothly decreases, the volume of the gas assumes in reverse order the same values which it assumed during loading at the same pressure. In other words, the curve of isothermal compression coincides with the curve of isothermal expansion and at the same time relates to the curve of adiabatic compression. Conversely, during shock compression the volume abruptly decreases from its initial value to its final value. But it is essential that this final state by all means should lie on a Hugoniot adiabat.

Expressed more technically, it is necessary to say that the Hugoniot curve is the locus of points on a volume - pressure graph reached by shock compression from the given initial state. But one should not think that the process of shock compression itself proceeds along the curve of Fig. 8, as isothermal or adiabatic compression proceed on the curves of Fig. 9. This becomes especially clear when one considers relief. Further it will be shown that shock, abrupt relief in a gas, in general, is impossible. Relief occurs in a wave of rarefaction. If we were to relieve a state compressed by a shock wave to initial pressure p_0, then the gas would by no means return to its initial state (before compression).

We are now disregarding the molecular structure of the substance, and only the initial and final states during shock compression can be of importance physically. During calculation of this structure one can also determine the intermediate states (we will do this in Section 6). With the first two laws of conservation, it is possible to show that the state is changed along a chord connecting points before and after the shock transition. It is essential that this conclusion does not depend at all on the specific nature of the substance and that it follows only from the laws of conservation of mass and momentum.

4. Limiting Compression in Shock Waves

One more difference between shock compression and nonshock is that for the shock method the volume cannot be made as small as desired. Conversely, during isothermal compression the volume is inversely proportional to the pressure. Therefore, if the pressure is as great as desired, then the volume is as small as desired. We were distracted from the fact that molecules in fact, are not points, but this is of influence only during compression by several hundred times. The law of adiabatic compression is different, but even here, zero volume is reached at infinite pressure. The curve of shock compression (Fig. 8) is quite different for large pressures. The existence of vertical asymptote AB shows that here the volume cannot decrease by more than six times, no matter how great the pressure in the shock wave. Therefore, the curve of shock compression tends to the vertical tangent AB when the volume tends to one sixth of its initial value (for air).

The product of the volume of gas times its pressure is proportional to the absolute temperature. Since the pressure at six-times compression of the air tends to infinity but the volume remains finite, the temperature of air in a very strong wave tends to infinity proportional to the pressure.

It is necessary to note that, during strong heating, the properties of air are greatly changed; molecules of nitrogen and oxygen break up into atoms; from the atoms burst electrons, so that, in fact, the limiting compression of air with normal initial density is not six times, but approximately ten times. This occurs in a wave with pressure of the order of one thousand atmospheres. Meanwhile, for isothermal compression of air by ten times, total pressure of ten atmospheres is necessary.

During adiabatic compression, air is also heated, but significantly less than during shock compression. For instance, in order to compress air adiabatically ten times, pressure of twenty-five atmospheres is necessary. Then from the Clapeyron equation it is clear that the temperature will increase 2.5 times. If the initial absolute temperature was 300° Absolute, then after compression it will be 750° Absolute, or 477° C.

A shock wave in which the pressure is equal to one thousand atmospheres heats air to 14,000° C. Let us remember that the temperature of the radiating layer of the sun is 5700° C. One square centimeter of the surface of such a wave radiates 36 times more energy per second than an equal surface on the sun.

During nuclear explosion brightly luminescent shock waves, fiery spheres are formed. If a fiery sphere with temperature 14,000° is seen at an angle 5.3 times larger than the solar disk, then it shines brighter than a thousand suns

$(36\times 5.3^{4}>1000)$ in accordance with the name of the famous book by R. Young. But such a bright glow does not last long, (less than a fraction of a second).

We will return to the general properties of shock compression. If we were to remove the pressure, then a substance compressed by a shock wave would not return to it initial state before compression. Meanwhile, during isothermal or adiabatic compression, after discharging the gas returns to the initial state. Both these processes of compression pertain to the class of reversible processes, but shock compression belongs to the class of irreversible processes.

Irreversibility of shock compression is already conspicuous from the fact that a wave of rarefaction essentially differs from shock wave. In Section 2 it was shown that in a rarefaction wave gas is expanded adiabatically, that is, by another law entirely than it is compressed in a shock wave. Therefore, if one were to at first insert a piston in a pipe in such a way as to compress gas by a shock wave, and then to extend the piston to its initial position, the gas will not at all come to the initial state. Since the volume became equal to the initial, and mass was not changed, density became equal to the initial value, but pressure will be higher, because adiabatic cooling during expansion does not compensate shock heating during compression.

But internal energy of gas is proportional to its absolute temperature, so that shock compression leads to irreversible loss of energy; work expended on compression will not be returned during expansion.

It is possible to see that as a result of any irreversible processes energy can only be wasted. Thus, for example, effective work, performed above the piston during shock compression of gas was not completely returned to the piston during adiabatic expansion. Part of the energy "stuck" in the gas. It is easy to prove from the opposite that it cannot be otherwise. Actually, if adiabatic expansion cooled gas stronger than it was heated during shock compression, then after discharging the gas would turn out to be at a temperature lower than the environment, and we would get back certain excess work. Waiting somewhat, until gas again is heated to ambient temperature, we could repeat the whole process and again obtain the same work, and so on an arbitrary number of times. As a source of energy, moreover inexhaustably large, would serve the whole environment. Owing to this energy a certain imaginary motor could work. In science it even received a special name, a perpetual motor of the second kind.

Perpetual motors are, and more exactly are not, of two kinds. The motor of first kind, according to the idea of its unfortunate inventors, had to obtain energy directly from nothing. That such motor is impossible to construct follows simply from the law of conservation of energy.

Designs of perpetual motors of the second kind do not encroach on this universal law. They only have to borrow internal energy without limit from the environment and to transform it into effective work. But it is impossible to erect them the same way as motors of the first kind.

One should not, of course, confuse the imaginary perpetual motor of the second kind with the so-called free motor, such as the turbine of a hydro-electric power plant. Energy of flowing water is borrowed in the end, from the sun, that is, a body much hotter than the medium surrounding the electric power station. In this case sun replaces heating of steam boiler.

As is known, constant failures of inventors of a perpetual motor of the first kind led, finally, to formulation of law of conservation of energy, which otherwise is called the first beginning of thermodynamics.

The same fate befell inventors of a perpetual motor of the second kind, and just as inevitably. Therefore, the second law of thermodynamics was formulated: it is impossible to construct a thermal machine working because of internal energy of surrounding isothermal medium. Later the second law of thermodynamics was strictly founded by Boltzmann from statistics of molecular motions. Boltzmann showed that concentration of internal energy of medium in motor is all the more so an improbable event the longer the motor is assumed to be operating.

In proposed projects sometimes not everyone can recognize that they in essence lead to eternal motors of the second kind; in any case, this is more difficult than detecting dissent with principle of conservation of energy. Therefore authors of such projects are not always just as bitter failures in life, as inventors of perpetual motors of the first kind.

Proceeding from the second law of thermodynamics, it is possible to explain that shock waves of rarefaction are possible, that is shocks on which pressure of gas would drop. On front of such a shock it would have been possible to satisfy the same three laws of conservation, as on the front of shock wave compressing gas. But if shock of rarefaction existed, then gas would be cooled in it stronger than during adiabatic process with the same change of volume. Then it would have been possible to construct a perpetual motor of the second kind compressing gas adiabatically and rarefying it like a shock wave; and this is impossible. This is an example of proof founded on general principle of physics.

But in reference to the given specific case the very same may be seen from simple gas-dynamic reasoning. Namely, analysis of Hugoniot adiabat shows that shock wave of compression moves faster than sound in relation to uncompressed gas and slower than sound in relation to compressed gas. Then for rarefaction shock the reverse would be obtained: it had to move slower than sound with respect to gas lying ahead. What would stir it to radiate forward sonic waves until it will not be blurred in space? In other words, it would be unstable relative to radiation of sonic waves. Conversely, a shock wave is not able to radiate sound forward since it moves faster. Hence its stability is seen. In initially smooth compression wave sonic perturbations catch one another and lead to formation of a shock.

Comparison of adiabatic and shock compression, founded also on properties of adiabat of Hugoniot, shows that with help of these processes it is impossible to construct a motor working because of internal energy of environment. Thus, is revealed the unsoundness of one specific project. Inasmuch as it always appears, the impossibility of construction of a perpetual motor of the second kind was raised to the rank of a principle. But as we already said, this principle does not carry the character of a postulate, that is, something taken on trust, and it is impossible to trust that although a million projects did not succeed, the million and first well work. A perpetual motor of the second kind cannot work, just as a tossed coin an infinite number of times in succession cannot fall with one and the same side upwards.

The impossibility of a shock wave of rarefaction shows that in the Hugoniot adiabat only that part of it which lies higher than the initial state has physical meaning. Only it responds to compression.

Thus we see that only some conservation laws are insufficient, in order to completely construct theory of shock transitions: it is necessary to include either considerations connected with stability or the second law of thermodynamics. It is possible to add that positions of thermodynamics in general, comprise an integral part of gas dynamics.

5. Weak Shock Waves

In the preceding paragraph we explained, how an irreversible shock wave is similar to a smooth, reversible wave of rarefaction. But this pertains to strong shock waves, in which pressure changes considerably. If pressure changes not very strongly, then the relation between magnitudes in shock wave start in many respects to resemble the relation in wave or rarefaction.

Let us assume that the piston creating the shock wave is inserted in gas very slowly as compared to speed of sound in undisturbed gas. Then compression wave will be very weak. Sonic disturbances from the plunger travel through the very lowly compressed gas. Flow of gas will weakly carry them forward.

As a result a shock wave of small amplitude will appear, that is, with excess pressure, composing a small fraction of the pressure in undisturbed gas. If, for instance, speed of plunger is ten times less than the speed of sound, then excess pressure in air will constitute 0.14 of the initial pressure. Both small relations, 0.1 and 0.14 have, as is assumed, one order of magnitude.

But if amplitude of pressure in wave is small, then such wave spreads through the gas like small protuberance of pressure on profile (Fig. 4a). Therefore, weak wave travels along profile approximately with speed of sound. In limit such wave is transformed simply into a sonic wave. The same pertains, of course, also to weak wave of rarefaction. Therefore, general relations for weak shock wave and for weak wave of rarefaction - in limit coincide.

But what wave is considered strong, and what still weak? Everything, obviously, is in that accuracy which is assumed to be sufficient. Let us assume that, for instance, shock wave and wave of rarefaction respond to pressure drop an identical number of times with respect to initial. Then it is possible to agree to consider their speed identical, if difference is less than one percent.

It turns out that here coincidence is much better than it would have been possible to expect. Even when ratios of pressures constitute 2.5, that is, in shock wave pressure increases, and in wave of rarefaction - drops as many times; speeds which air obtains in both waves are distinguished by approximately one percent. But a shock wave with such pressure drop in no way can be called "weak", if one judges its action. All the better, of course, is coincidence for an actually weak wave.

An essential qualitative distinction in the course of magnitudes in wave of rarefaction and in shock wave appears during pressure drops larger than 2.5

times. It is necessary to say, however, that if one were to calculate speed of propagation of shock according to approximation formulas corresponding to the same approximation by which speed of gas was calculated, then error with that same amplitude of shock will constitute around 6 %.

The main difference of a shock wave from a wave of rarefaction is the irreversibility of shock compression. How do we measure degree of this irreversibility? In Section 4 it was shown that measure of this irreversibility can be the residual internal energy of gas after discharging. It shows what fraction of the initial work of compression is expended.

It turns out that for weak shock waves this fraction is proportional to the cube of ratio of excess pressure to initial pressure. Thus, for instance, if this ratio decreases from 0.1 to 0.05, which is by two times, then degree of irreversibility decreases by eight times. This same degree of irreversibility corresponding to a relative amplitude of 0.1, is less than 0.0001. Therefore role of irreversibility is great only at great amplitudes.

6. Structure of Front of Shock Wave

Till now we considered a gas through which runs a shock wave as a solid continuous medium, that is, we completely disregarded its atomic molecular structure. The expression "particle of gas" which we used, signified a volume large enough to contain still very many atoms or molecules, but at the same time small enough that pressure, density, and speed of gas inside it can be considered constants. In rarefaction wave it is always possible to select a small enough volume or particle of gas.

But in a shock wave it is impossible to do this, if its front exactly passes through the particle. In this meaning the shock is sharp in any amount.

But this is true only as long as we disregard the structure of gas or in general, any such medium in which spreads wave.

In this paragraph we will consider in a more detailed way the structure of the shock front. Comparatively simple and general relationships are obtained for gaseous medium, by which we will be limited.

In order to describe transmission of motion in gas, it is necessary to consider interaction of its molecules. If gas was "ideal" in the literal meaning, that is, the molecules did not interact at all, then each of them would move absolutely independent of the others, imparting to them neither momentum nor energy.

But it follows from this that any transmission of motion in gas can be depicted only with the help of a detailed picture of intermolecular interaction. Considering, for instance, a wave of rarefaction, we found the force with which each of the volumes, or "particles", of gas interacts with neighboring volumes, in the form of resultant pressure. Certainly, pressure also has a molecular nature, but if volume of gas consists of sufficiently large number of molecules, separate collisions between them can be replaced, by average magnitude of momentum transmitted by them per unit of time and through unit of surface dividing the volumes. Momentum per unit of time is by definition a force, but a force in reference to a unit of surface, is called pressure.

But not always can one determine the corresponding volume if motion includes shock wave discontinuity. If we are interested exactly in those sections of gas through which passes the discontinuity, they no longer can be considered sufficiently large, in order to bring the whole complicated picture of molecular motion only to average transfer of momentum through surface. And these sections of gas interest us, if we study structure of front. It is necessary to consider, besides, that in an ideal gas momentum is transmitted through the surface only perpendicularly to it. Direct calculation of collision between molecules shows that also the component of momentum tangent to surface can be transfered. Let us consider mechanism of molecular transfer.

Force of interaction between two separate molecules has, in general, a complicated character. At great distances all molecules are very weakly attracted, and at small distances, comparable with their dimensions, are very strongly repulsed. Furthermore, the molecules of a majority of gases are diatomic (O_2, H_2, N_2), so that force of interaction depends not only on distance, but also on mutual orientation of molecules in space. Therefore we usually consider not the real interaction in all its complexity but only the most convenient and simple model of gas, properties of which qualitatively transmit its real behavior. Details of interactions are different for various gases, and if we tried to consider them, the theory of nitrogen, oxygen, and air, would be obtained, but not of gas in general.

In model of gas attraction at great distances we will regard in general, (this model knowingly will not reflect certain properties of real gases, for instance, ability to liquefy, which is not important here). All properties of repulsive forces include in one assumption that molecules interact simply as elastic spheres. Real spheres, like billiards, are able not only to shift, but also to rotate. For molecules this is not taken into account, if their rotation is not specially studies. Inasmuch as we now are interested in transmission of momentum, rotation is simply immaterial.

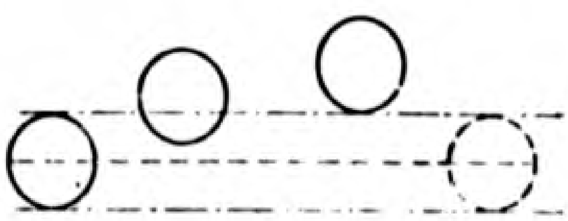

Fig. 10.

In most cases a model of elastic spheres satisfactorily reflects basic feature of transfer of motion in gas.

How does this transfer occur? While two balls are not in contact, they in general, do not interact. From collision to collision they are free.

In Fig. 10. is depicted the approximate location of molecules. While the molecule moves freely, it describes a cylinder in space ("sausage"). It can collide only with those molecules which if only at the border will enter in this cylinder. Centers of such molecules can be removed from axis of cylinder not more than to a distance of double the radius, i.e., the diameter.

Certainly, other molecules fly and leave the cylinder, but on the average a number of them remains constant during that short time which passes between collisions. Therefore, the number of collisions per unit of time equals the average number of molecules in the cyl nder, whose radius equals the diameter of the molecule, and whose length numerically equals the speed of the molecule. If density of molecules is multiplied by the volume of this cylinder, the desired average number of collisions, which any given molecule will experience per unit of time will be exactly obtained. The reciprocal hence is the average time which molecule flies freely from collision to collision. This time, multiplied by the speed of the molecule, equals the average path, which otherwise is called the free path. Following the reasoning, it is easy to see that speed is reduced from the expression for magnitude of free path, which depends, thus, only on radius of molecules and their density in space. Let us note that such a conclusion pertains only to model of elastic spheres.

In air of normal density the free path constitutes approximately 0,00002 cm. Diameter of the molecule equals approximately 0,00000001 cm. At great heights, where air density is small, free path is correspondingly larger.

Using the idea of a path it is very easy to grasp mechanism of transfer in gases. Let us consider first the molecular transfer of energy, that is, thermal conduction of gas.

Thermal conduction signifies transfer of internal energy from a body with a high temperature to a body with a lesser temperature, or simply inside a nonuniformly heated body from a hotter part to a colder part. What sort of minimum dimension should the particle of gas have, so that it is possible to talk about its temperature? Here by the word "particle", as in gas dynamics, is understood by no means a molecule, but a small volume. So that it is possible to talk about temperature of a certain volume of gas, it is necessary that thermal equilibrium be established in it. The only method of its establishment is for the molecules to exchange energy among themselves, until they reach a condition in which there no longer will be further collisions for exchange. If this volume is now insulated from all external influences, then in it no further disproportionation of energy will occur. State of thermal equilibrium is characterized by definite temperature.

So that in certain particle of gas its own temperature is established, molecules composing the given particle, should, as we saw, collide. Consequently, particle of gas should have dimensions of free path. For smaller dimensions, collisions will not occur.

Let us consider now two neighboring sections of gas with different temperatures. According to what has just now been said, they have to be divided by a distance of the order of one run. In a hotter volume molecules possess a larger kinetic energy than they do in a colder volume. Neighboring volumes, of course, are exchanged by molecules. As a result of this exchange part of the energy will pass into a volume with a smaller temperature. This also is the process of heat transfer, or heat conductivity.

Simple calculation, we will not conduct, shows that energy, transferable thus per unit of time through unit of surface, is proportional to the fall of temperature per unit of length. Proportionality factor is called simply thermal conductivity. The greater the length of the free path, the further energy is transferred by the molecules, the greater the thermal conductivity.

Let us return now to the question of structure of shock wave discontinuity.

Far from the discontinuity, on both sides of it, flow of gas can fully be considered smooth. There is meaning talking about definite, constant, temperature and pressure of gas. When we brought in balance of energy and momentum on both sides of the discontinuity, this happened actually somewhat apart from it, on surfaces lying in smooth flow. What occurred among these surfaces, that is, in the actual region of the discontinuity, was not essential, since laws of conservation are always valid.

Here it was possible to assume that one part of gas can transmit energy of other, only accomplishing work on it owing to forces of pressure. Molecular transfer of energy, or thermal conductivity, is carried out in region of smooth flow very slowly, so that it is possible simply to disregard it there. But in shock wave discontinuity the temperature changes so strongly that thermal conductivity becomes determining for structure of shock. Through the surface, conducted somewhere in the actual region of shock transition, is transfered very much energy by molecular means.

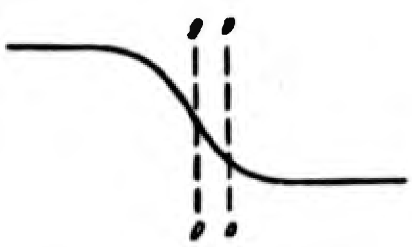

Fig. 11.

In order to make this reasoning to more graphic, we will show the approximate movement of pressure in the region of shock transition (Fig. 11). Now we no longer consider it to be infinitely thin, and we want to follow how the initial state p_oV_o passes into final state pV. Process of irreversible compression is carried out in transitory region.

Let us separate a certain layer between planes aa and bb where the actual shock transition is carried out. Through any of such planes passes the same flow of energy, because if through bb from the layer flowed more energy than flows through aa, then energy would be stored in a layer. Meanwhile we want to consider the already established shock wave: we as it were follow it and move together with it.

But now no longer can it be considered that energy is transmitted from layer to layer only due to compression: in region of circular fall of temperature certainly an essential role is played also by heat flow. It, as already was said, is proportional to the fall of temperature per unit of length. Already it follows from this that the discontinuity should have a final width. If temperature fell by shocks jumps, it would have had to change to a finite quantity on a length as small as desired. In conversion to final length this would correspond to an infinite drop, that is, also to an infinite flow of heat. But since total flow of energy is final and constant its thermal part also should be everywhere final. Therefore drop of temperature certainly is carried out on a final length.

There exists also a molecular mechanism of transfer of momentum in gas. It consists in the fact that during motion of one volume of gas with respect to another, molecules from moving volume fly into a motionless volume and attract it. This property of gas is called viscosity. Calculation of viscous trnasfer of momentum of gas also leads to blurring of shock front.

Structure of transition region can be considered quantitatively only in that case when the whole shock is weak, that is, when pressure in it is changed by a small part from the initial. Then the whole width (or thickness) of the transition layer equals the free path divided by relative change of pressure. Therefore it is as many times larger than the run, as initial pressure is larger than its change in the shock wave.

But if relative amplitude of shock wave is of the order of unity, then the whole width of the transition region is not larger than one run.

It is necessary to note that if the whole transition is accomplished on one run, then the idea of thermal conductivity and viscosity in significant measure lose their meaning. The fact is that heat flow is proportional to drop of temperature per unit of length only in the case when the actual temperature changes little on length of one run. In a strong shock wave exactly the reverse takes place: temperatures jumps many times on one run. Therefore, the term "thermal conductivity" inaccurately reflects the very complicated irreversible process occurring inside the shock.

Even the actual idea of pressure is strongly changed in narrow transition region. Usually in gas the law of Pascal is in force, according to which pressure on any area is perpendicular to it and does not depend on its orientation in space. To this law also corresponds the term pressure. In zone of shock one volume of gas acts on another in a more complicated manner. The law of Pascal is violated, and it is not only perpendicular, but also tangent to the area of component force.

There occur cases when the shock wave in no way can all be placed on one length of free path, however strong it is. This occurs then, when full change of state of gas cannot occur "from one shock". Let us consider this question in greater detail.

Atoms in molecules are able to oscillate relative to each other rather than the entirety of the molecule being disturbed For instance, in a diatomic molecule atoms shift and are moved apart along the ends of an imaginary straight line conducted between the nuclei. As any motion in gas, oscillation is more intense the higher the temperature. If the initial state of the gas is cold, and the final state has a high temperature, then intensity of oscillations should very strongly be increased in shock.

It turns out, however that oscillations are excited far off not during all collisions between molecules: their migratory motion does not so easily change into oscillatory. Frequently, so that oscillations gather full force, up to 10,000 collisions are necessary. Therefore, it is clear that at a distance of one run oscillations in no way will be excited. At this run all energy of wave will be expended, in order to increase only energy of migratory and rotary motion of molecules. What will occur further? This question is considered purely by the graphic method by our well known physicist Ya. B. Zel'dovich.

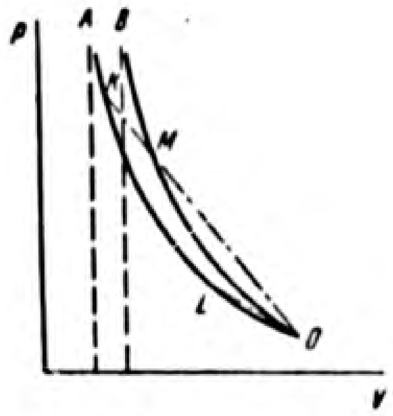

Fig. 12.

It is possible to construct one Hugoniot adiabat, assuming that oscillations of molecules do not exist at all, and another Hugoniot adiabat taking into account oscillatory motion. They are distinguished, by the fact that heat capacity of gas whose molecules are able to oscillate is higher than for gas where there are no oscillations. Oscillations are as it were an additional thermal reservoir, drawing off internal energy; therefore, a great deal of heat is needed in order to heat gas one degree, if heat is expended also on excitation of oscillations.

In Fig. 12 are constructed two Hugoniot adiabats. They are drawn from one and the same initial state O. OB corresponds to the assumption that oscillations are lacking, OA- that they exist.

Will show first of all that OB lies higher than OA. On curve OB for the portion of purely migratory motion there is more energy than on OA. Consequently, with that same degree of compression to points on OB corresponds large density of kinetic energy of gas, and consequently also more pressure. After all from Clapeyron equation it is known that pressure is proportional to absolute temperature of gas, which in turn determines its internal energy. And without calculation of oscillations, temperature is higher since heat capacity is less. Therefore, together with temperature also pressure without calculation of oscillations is higher, which is reflected in Fig. 12 in mutual locations of adiabats.

At the end of Section 3 it was shown that shock transition occurs along the chord connecting initial and final state on Hugoniot adiabat. If the wave is not very strong, then chord OL, from the initial state does not intersect adiabat OB at all. The initial state as a result of shock compression gradually passes into such final state when oscillations of molecules are excited in conformity with portion belonging to them in the total energy of gas. The shock is spread on as many runs as is necessary for energy transfer to oscillations.

If wave is strong then chord OK will intersect also adiabat OB. Then that part of transition which corresponds to segment of chord OM, will occur on one path length that is, will not differ from usual shock wave. But in this wave oscillations of molecules still will not be excited; all energy will be transmitted to migratory and rotary motion. Further its transition into oscillation occurs on section of cord MK, but this already occurs smoothly on such a number of runs necessary for establishment of equilibrium between all forms of motion of molecules. Here temperatures of gas will drop. In Figs. 13a,b are depicted profiles of pressure for both considered cases.

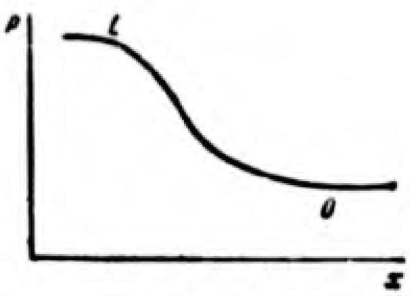

Fig. 13a.

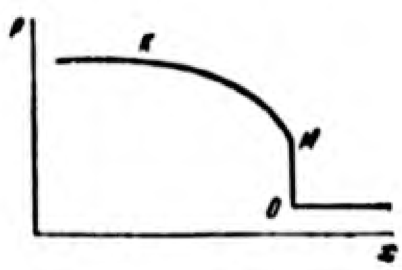

Fig. 13b.

CHAPTER 2

ACTIONS OF SHOCK WAVES

7. Supersonic Motion

We live in a century of growing speeds of movement. It is a risk even to say "great" speeds, because in ten years the present high speeds can appear comparatively small.

The fastest method of movement, as is known, is reactive, and for space flights it is also the only possible one.

In reference to rockets there exist two circles of problems of gas dynamics. First, there is the dynamics of the escape from the nozzle of gases propelling the rocket, and, secondly, the flowing-around of the actual rocket by air, until it abandons the atmosphere of Earth.

In order to impart high speed to a rocket, it is necessary to force gasses to discharge very rapidly. These gasses are formed in a combustion chamber. At first they are motionless with respect to the rocket, but they are under great pressure which drives them through the nozzle. How do we construct the nozzle in such a way as to impart the highest speed to the gases, or, more exactly, to obtain the biggest pulling force owing to the yield of the flowing gases?

Let us consider therefore the outflow of gases from nozzle. Surely, everyone knows that rivers flow the fastest where they are narrowest. This means, that if one were to make the nozzle narrowed, gases will start to be accelerated in it.

We used the words "will start" on purpose, because in a narrowed nozzle it is impossible to reach supersonic speed of flow. Gas can be accelerated only as long as it supports pressure from behind. During a given pressure in combution chamber it is possible to lower the outlet pressure. A certain value of output pressure will then be attained at which the speed of sound will equal speed of gas. Then no "signal" of relief can spread against flow through the nozzle: it will be carried away by the flow. In other words, gas in nozzle will "know" nothing about conditions on output. It is obvious that during further lowering of pressure, gas all the more will not "recognise" what pressure there should be in the output section of the nozzle so that it cannot be accelerated above speed in the output section.

How nevertheless is supersonic flow obtained? It turns out that for that it is necessary again to increase section of nozzle (Fig. 14). Such a nozzle for the first time was constructed by the inventor of the steam turbine, Laval. In distinction from subsonic flow, supersonic flow is accelerated as the opening of the nozzle grows. If one were to reach the narrowest place, the throat, of the nozzle, then the flow becomes audible, and from the mouth will come a supersonic flow of gas.

It is possible to trace, as well as to change pressure in nozzle. In the throat will appear exactly what had to be in external space, so that a sonic out flow from narrowed nozzle is obtained. On getting out of the mouth it will appear still lower.

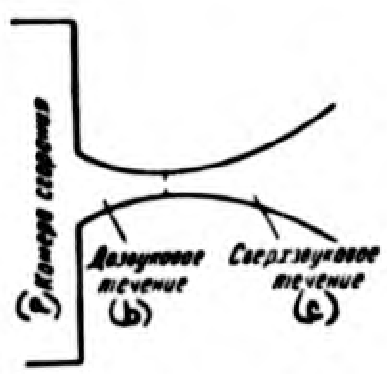

Fig. 14.
KEY: (a) Combustion chamber, (b) Subsonic flow, (c) Supersonic flow.

If it exactly equals external pressure, then a so-called ideal nozzle is obtained, in which gas, being adiabatically expanded, passes from initial state to final without shocks. If however pressure on output is different, a smooth passing over turns out to be impossible. But since gas somehow should flow from combustion chamber into the atmosphere, inside the flow there appear shock wave discontinuities. Depending upon magnitude of external pressure these shocks can be inside divergent section of nozzle or already in outgoing flow. Here they do not stand crosswise to the flow, but branch like films in neck of beer bottle (Fig. 15,a,b,).

However, in this comparison the analogy is purely visual. Liquid films are branched in an absolutely arbitrary form, whereas in case of shock waves branching out and intersection of surfaces occurs with necessity. Further, in Section 9, it will be shown that a shock wave can be reflected from a hard surface, (in this case wall of nozzle) not at an arbitrary angle, but only at an angle smaller than a certain angle. With a large angle of incidence appears a more complicated configuration with branching out, called a Mach configuration. This is observed also in the out flow from the nozzle.

The biggest reactive force is developed during out flow from ideal nozzle, without shocks.

Fig. 15a.
KEY: (a) Boundary of stream, (b) Shock front.

In distinction from shock waves, running along pipe, which we considered in preceding chapter, here are obtained shock waves which stand relative to the nozzle. They appear thanks to the fact that gas flows with variable speed along a pipe having a variable cross-section. In smooth flow pressure and speed are connected uniquely; if, however, compulsorily there is non-correspondence between them and others, then the gas adapts to these conditions by means of shock transitions. It is clear that this can be only shock waves which compress gas flowing in their front; rarefaction shocks, as we saw, are impossible.

Here again is conspicuous the necessity of shock transitions in gas dynamics.

Thus appears supersonic flow in nozzle. How flows external to the rocket until it leaves the air, atmosphere?

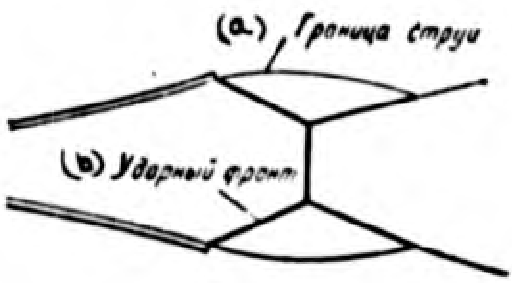

Fig. 15b.
KEY: (a) Boundary of stream, (b) Shock front.

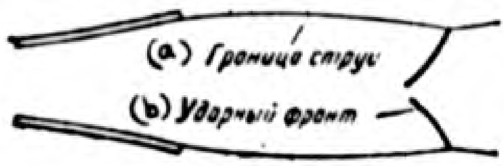

Fig. 15c.
KEY: (a) Boundary of stream, (b) Shock front.

First of all it turns out that the difference between subsonic and supersonic flight is very great. During subsonic motion the body sends forward compression waves, which by the graphic expression of one author "warn" the air about the approach of a body. In unlimited space the air diverges and the body smoothly flows through. In principle, no matter how far one goes ahead of the body there are some weak perturbations. A picture of motion is simple to reproduce, considering that the body rests and air runs against it with a speed equal in magnitude and reverse in direction to the body. At a very large distance from body the flow is almost flat and parallel, and near the flow line they are distorted and pass around it (Fig. 16.). Giving the body a drop-shaped form, it is possible to reach a state such that during the flowing around turbulence will not appear.

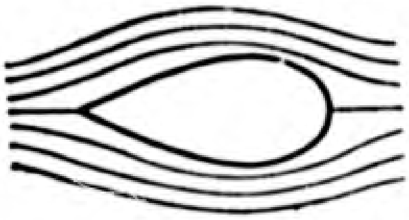

Fig. 16.

During supersonic motion air cannot diverge-it is overtaken by compression waves running behind it. As a result, ahead of the body occurs a shock wave. The faster the body moves, the stronger is the wave. One more wave is separated from the trailing edge (Fig. 17.).

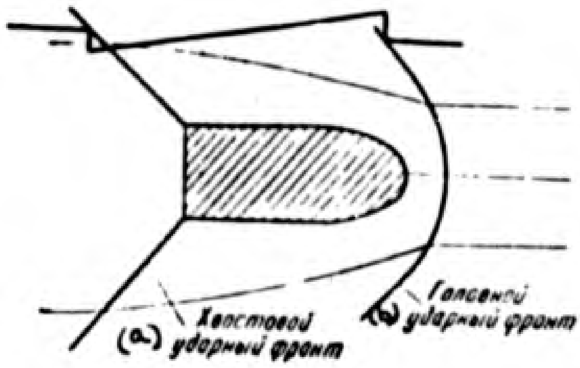

Fig. 17.
KEY: (a) Tail shock front, (b) Head shock front.

This shock wave is called a tail wave. Air originally compressed in the head shock wave, then is expanded to a pressure which less than the initial pressure. In the tail wave it returns to initial pressure. Profile of pressure, shown separately in Fig. 17, from above reminds one of a pulled and unscrewed Latin letter N, which is why this wave is called an N-wave. Let us note that both shocks in the N-wave are, of course, compression waves, as they should be. At a certain distance from the body both these waves have the form of cones inserted one in the other.

Since in shock waves air is compressed, in it there are shocks and index of a refraction using this, the wave can be photographed with proper illumination. Similar photographs were first obtained by the famous E. Mach, using an electrical spark as an instantaneous source of light.

In a shock wave air is heated. That particle of air which encounters the tip of the body is heated still more, reaching the body. This is easy to grasp, applying reasoning to a picture in which the body is stopped, and air flows in on it with a speed equal but opposite in direction to the body. In this picture a particle moving exactly toward body, stops upon reaching it. Consequently, its kinetic energy completely becomes internal. After passage through shock front it continues to be heated further and reaches, as is customarily said, to temperature of deceleration. At a sufficiently high temperature the body begins to melt and to evaporate. The generated glow makes visible the flight of meteors through the air - these tiny particles of cosmic substance create a glow which is visible at a distance of tens of kilometers. They are called figuratively, but incorrectly, falling stars.

The glow of the meteors sometimes is explained by the fact that they are heated from "friction against the air". As to this, the warming up comes not from "friction" (force of viscosity), but in the shock wave, and thus from the subsequent deceleration. The glowing shock wave also accompanies the flight of a rocket in the atmosphere.

Yu. A. Gagarin has already been able to look upon this glow of air from within, through a small heat proof window. He saw, as it were, a raging flame. It is probable that this was still at a great height where the atmosphere is sufficiently rarefied. At a flight speed of km/sec, equal, obviously, to the speed of the tip of the shock wave, the temperature of air in the wave reaches 10,000°! If air would emit heat, as does a dense hot body, not only the human eye but also the whole ship would not be able to stand it. But when a transparent body radiates, it emits much less energy.

It is sufficient to remember how much less light is given by a gas burner than by a candle whose flame is colder. In the flame of a burner there are present only gases which are transparent, but when a candle burns incandescent particles of carbon glow. They also give light.

This glowing shock wave helped the spaceship to decelerate in the Earth's atmosphere and to land safely.

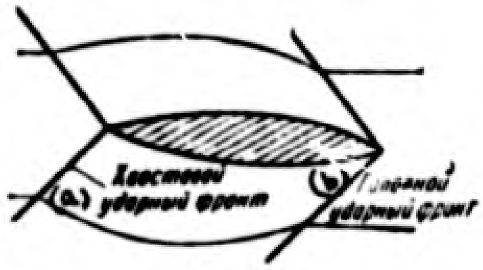

Fig. 18.
KEY: (a) Tail shock front, (b) Head shock front.

In order to decrease resistance of air during takeoff of rocket, or simply during supersonic flight of aircraft, it is advantageous to give the front part a pointed form. Then on the spout will be formed a conical shock wave, which refracts parallel flow lines of incident air. In tail shock wave they are refracted again, and again turn into a parallel flow (Fig. 18).

Both these shock waves are noticeable at a rather large distance from the body. When supersonic planes fly, even at a distance up to 20km and more loud sonic booms are audible, well-known to everyone at the present.

At a close distance the shock waves accompanying supersonic motion can also be destructive.

Such destructive phenomena in grandiose scale were observed when the Tungus meterorite fell (a meterorite is a meteor which has reached the Earth). The place where it landed on Earth was heroically, but unsuccessfully looked for by the great enthusiast L. A. Kulik, and after him many others. At present it is possible to consider it proven that the meteorite in fact consisted of a mass of small particles, moving along a very slanting trajectory. The dense mass of particles caused a total shock wave of enormous force, comparable with the wave of a nuclear explosion of several megatons.

A detailed picture of the action of this wave, and also of the luminous radiation, caused by it still should be restored by falling trees and traces of burn on surviving trees. It is clear that even now it is very difficult to do this - 54 years have passed. Only now in the ground have they begun to find characteristic fused microscopic balls of silicates and of nickel iron. In any case research is being conducted on the basis of a probable scientific hypothesis about the nature of this phenomenon. The most probable is that the Earth collided with a small comet.

Attempts "to prove", that the Tungus meteorite was a spaceship from a strange world, exploding near the Earth itself, wholly pertain to a region of visionaries, which without excessive modesty calls itself scientific.

8. Shock Waves During an Explosion

The striking action of an explosion has to come from shock waves. If the wave is sufficiently great in dimensions, as occurs during nuclear explosions, then with an overpressure of all of 0.35 atmosphere buildings collapse. At several hundredths of an atmosphere window frames fly out. Only waves with a jump of pressure of several thousandths of an atmosphere do not inflict noticeable damages.

The action of a shock wave on a man depends on the conditions in which he is in relation to the wave.

In the introduction we mentioned the pilot who was supported by the shock wave when he fell. Man, flying from a great height, attains, due to resistance of air a terminal velocity near 60 m/sec. Consequently, this had to be the least opposing speed of air in the shock wave. To this corresponds a pressure of less than half an atmosphere, usually not fatal, according to the estimate given just now. A man standing on the ground possibly will be killed not by the actual wave, but by the "kick" it inflicts. The velocity of air in a wave with a pressure of one atmosphere equals 170 m/sec. It is clear that if it will impart to a man a speed of the order of several tens of m/sec, on hitting the ground it is doubtful whether he will survive.

For purposes of protection from shock waves it is very important to know how to calculate their force beforehand.

We will start from very strong waves appearing at close distances from nuclear explosions. Protection from them is possible only by going very deep under the ground. But their properties are very important for further development of explosion and therefore are interesting in themselves, without reference to protection. They will incandesce air, beginning burning thermal radiation. Further we will see that a shock wave influences propagation of gamma rays and neutrons, increasing their striking action. Lastly, from strong waves are generated comparatively weak ones which go out large distances. With respect to destructive action they are by no means weak, as we just now saw. Protection from these "weak" waves is not hopeless.

We will agree to call a wave strong when pressure and density of energy in it are far larger than they were in undisturbed air. Such, for instance, would be a wave with a pressure of one hundred atmospheres in air.

If we analogously defined a strong wave in water, then one hundred atmospheres would be absolutely insufficient. This would be conversely, a weak wave, because at one hundred atmospheres in a shock wave, water is very little compressed and is altogether insignificantly heated. The present strong shock wave in water should have a pressure of several hundred thousand atmospheres. In iron it is still stronger. A wave with a pressure of one hundred atmospheres compresses air almost eight times and spreads with a speed of more than 3 km/sec.

Temperature in it attains 3,5000°. With such temperature an appreciable part of the molecules of oxygen is broken up into atoms. In remaining molecules of oxygen, and also in molecules of nitrogen which disintegrate more difficultly, already occurs intense oscillatory motion of atoms. At room temperature molecules of air do not oscillate at all. They have only forward and rotary motion. To this would correspond, as already was said, sixfold limiting compression. When a molecule also oscillates, the limiting compression is eight fold. Thus, a wave with a pressure of 100 atmosphere in air decidedly can be considered strong.

In studying such wave it is generally valid to disregard initial energy and air pressure. This approximation is put at the basis of the theory of strong explosion.

A strong, and simply speaking, a nuclear explosion is developed from a small volume of bomb. But in the very first stages it captures air not with the help of shock wave. Very hot electromagnetic radiation, issuing from the bomb, has a temperature of around a million degrees. It heats air faster than any motion can appear in it. Therefore temperature of air is increased, and its density remains at first the same as it was prior to the explosion; not being displaced, air obviously cannot be compressed. But higher the temperature is at a constant density, the higher pressure is also.

Nearby the bomb will be formed, thus, a relatively small in volume, but strong compression wave, from which a shock wave subsequently develops.

However it is very significant that dimensions of this compression wave can be subsequently disregarded in comparison with radius of the developed shock wave which spreads far from point of explosion, but is still strong. Not during a nuclear explosion can such a shock wave "from the point" be given in small scale by a strong electric spark. Usual expolsives do not form shock waves of such type.

After a shock wave of nuclear explosion spreads sufficiently far, but still remains strong, all its properties wholly are determined by the initial energy given off by the initial air density, and also by the limiting compression in the shock wave. The latter is an abstract magnitude, i.e., simply a number characterising the wave. Let us examine the value of the first two named magnitudes, those possessing dimension. With their help one can determine law of propagation of wave, i.e., dependence of radius on time.

For that it is necessary at first to remember the units of measurement of energy and density. Energy is measu ed in ergs, the size of which is,

$$1 \text{ erg} = \frac{1 \text{ gram} \times 1 \text{ (centimeter)}^2}{1 \text{ (second)}^2}$$

The measure of density, i.e., mass of unit volume, is

$$\frac{1 \text{ gram}}{1 \text{ (centimeter)}^3}$$

We form now a quotient from division of energy by density; we want to express length, or radius, by time, and the measure of a gram is not what we desire. The desired quotient is measured, obviously, in these units,

$$\frac{1 \text{ gram} \times 1 \text{ (centimeter)}^2}{1 \text{ (second)}^2} \times \frac{1 \text{ (centimeter)}^3}{1 \text{ gram}} = \frac{1 \text{ (centimeter)}^5}{1 \text{ (second)}^2}$$

We will multiply the obtained magnitude by the square of time elapsing form the moment of explosion, so that we will obtain an expression measured by the fifth power of length. By no other method from energy, density and time it is impossible to form another expression with the same dimension. This may be seen from the preceding reasoning.

What in our problem still has dimension of length? Only radius of shock wave. Consequently, the fifth power of radius should be proportional to energy of the explosion divided by air density and multiplied by the square of time, elapsing from moment of energy release (the initial phase, while the shock wave was still not formed, we, as already was indicated, disregarded). The basic principle of composition of physical equalities is that both sides of equality have to have identical dimension. The named magnitudes cannot equal each other, if they are not not measured in identical units. But in reference to strong shock wave there exist only the two above-mentioned magnitudes, measured by fifth power of length. Consequently, they are obliged to be proportional, while the coefficient can already depend only on properties of gas - in this case from limiting compression.

Thus, being the magnitudes - energy and air density, abstracted from constant meanings for every given explosion, we obtained that the fifth power of radius of the wave is proportional to the square of time of its propagation. This is as long as the wave can be considered strong.

The conclusion of this law presented here is based on dimensional analysis. The reader easily will be convinced that the majority of physical laws may be derived by this method, if one abstracts from numerical coefficients.

From the obtained relationship it follows that all strong explosions are similar. We will compare, for instance, two explosions, differing with respect to energy by 10,000 times, for instance, with equivalent generation of energy of 5 thousand and 50 million tons with respect to trotyl. Then shock waves will have identical radii in different moments of time; for high energy all times corresponding to the same radii will be 100 times less. Actually, under this condition products of energy times the square of time will be identical, and air density is identical anyway. Therefore radii will also turn out to be identical.

The law of similarity for strong explosions was expressed by L.D. Landau. On the basis of similarity L.I. Sedov, and independently but with less completeness, K.P. Stanyukovich (grandson of the well-known writer) formulated the theory of the strong explosion wave. They showed, how to find distribution of all gas-dynamic magnitudes with respect to volume of wave, while L.I. Sedov, wittily using the law of the conservation of energy, brought resolution of the problem to numbers and graphs.

In the book of Ya. I. Perel'man "Entertaining Mechanics" are discussed laws of similarity in reference to Gulliver and his relation to the Liliputians and Brobdingnagians. We will repeat the reasoning of Perel'man in somewhat different form in order to show when it is possible to use similarity and when it is impossible.

Gulliver was 12 times as tall as the Liliputians. Therefore he weighed $12^3 = 1,728$ times more. Lifting his hand, he accomplished $12^3 \cdot 12 = 20,736$ times more work than a Liliputian. If energy of consumed food was expended only on accomplishment of work, Gulliver would have to eat 20,736 times more than a Liliputian. But food, besides work, is needed also to warm the body. Heat is transmitted into surrounding space through the surface of the body, which for Gulliver is only $12^2 = 144$ times more. Consequently, a similarity between Gulliver and the Liliputians is impossible: having a 1,728 times larger stomach he would have had to take in either 20,736 times more food, or only 144 times. That and other physiological things are impossible. We note, incidentially, that between large and small animals there is no geometric similarity (in the sense of proportionality) in structure of body.

But if one were to return to the strong shock wave, then here is necessary a similarity with respect to only one parameter. Therefore full conformity of pictures of development of two explosions always can be obtained, changing only scales of length and time.

Applying analysis of dimension, it is necessary first of all to clarify what physical quantities have to enter in the desired relationship. If between them it is possible to construct only one equality compatible with units of measurement of magnitudes, then it will also be the only possible one. From this equality will follow relationships of similarity.

The similarity for shock waves which are not strong is significantly narrower than for strong waves. Here it is necessary to characterize undisturbed air by not only density, but by one more magnitude, for instance, speed of sound in it. Then two blast waves in air can possess similarity only with equal speed of front, or equal pressure on front. Strong waves are always similar to each other and among themselves. When radius of wave is increased twice, or three times, distribution of all gas-dynamic magnitudes inside wave remains the very same, if one takes corresponding magnitudes on front for units of measurement. Therefore strong spherical blast waves are called self-similar, or, as scientists express it, self-simulating, which means literally the very same.

Distribution of magnitudes of pressure and density in a self-simulating wave can be constructed, so to say, once and for all. On the abscissa it is necessary to plot relation of distance of given point from center to the total radius of the wave, and on the ordinate—relation of given magnitude to its value on the front. Then both abscissa and ordinate will be included between zero and unity, and the form of the curves, in general, will remain constant.

These distributions are depicted in Fig. 19a, b. Form depends only on magnitude of limiting compression.

It is remarkable that pressure in center does not turn into zero, but constitutes the final part from pressure on front. Density, conversely, equals zero almost all over volume of wave. Only near the front is all mass concentrated in the form of a thin shell, being initially evenly distributed with respect to volume. The wave involves it in motion and pulls it itself.

The ratio of pressure to density is proportional to the absolute temperature. Therefore in center of wave temperature is extraordinarily high (formally-it is infinite) and toward the edges, that is to the front, it is less.

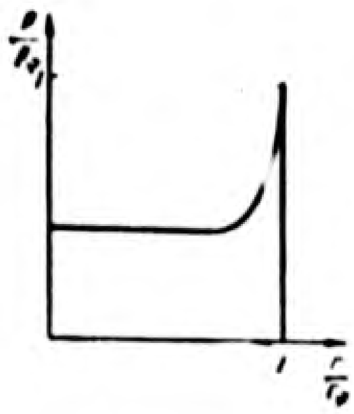

Fig. 19a.

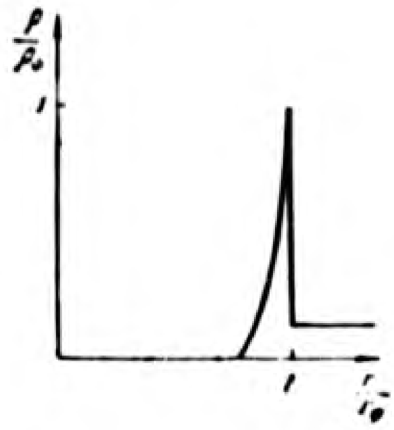

Fig. 19b.

Before we consider the question about glow of shock wave and incandescent air remaining after it, we will mention one essential effect connected with lowered air density inside the wave. During a nuclear explosion penetrating radiation - gamma rays and neutrons - shows a very strong striking action. It turns out that rarefied air surrounding the place of explosion essentially facilitates their passage. O.I. Lepyunskiy* turned his attention to this.

Transparency of air with respect to gamma rays and neutrons practically does not depend on its temperature: the only determinant is density. With respect to visible radiation, temperature renders more essential an influence than density. This is explained in the following manner. Motion of an electron in an atom is characterised by certain definite frequencies which are close to frequencies of optical, visible radiation, or close ultraviolet radiation. When such radiation falls on an atom, there sets in something like resonance: the electron, as it were, is rocked and broken loose by the radiation. At room temperature there is no "rocking" of electrons with such low frequency in the atom. They appear only around 10,000°.

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*O.I. Leypunskiy, Gamma radiation of atomic explosion, Atomizdat, 1959; see also, P.A. Yampol'skiy. Neutrons of atomic explosion, Atomizdat, 1961.

Therefore at room temperature air is transparent for visibel radiation: our eyes, which can see distant objects, were adjusted to this circumstance in the process of evolution. The whole thickness of terrestrial atmosphere weakens visible light of the sun less than twice (in a clear sky).

At very high temperatures, around 10,000°, the bond of electrons with atoms is weakened. Part of them is completely detached, part, as is customarily said, "is excited". Such electrons can be easily pulled from atoms by visible radiation. As a result it turns out that heated gas becomes opaque: it strongly absorbs radiation which develops when electrons break away from atoms.

But we already said that an opague substance in turn strongly radiates. Therefore air which is incandescent by a shock wave gleams like a heated solid body. From a unit of surface at identical temperature they radiate equal energy per unit of time. A shock wave of a nuclear explosion is also called a fiery sphere.

What sort temperature can a fiery sphere have? It is found that during a very bright glow it ceases to be conspicuous. Radiation proceeding from front of shock wave heats air ahead of it so strongly that it in turn becomes opaque and shields hotter radiation proceeding from within. For that the actual wave should heat air approximately to 70,000°. The necessity of such self-shielding was indicated by Yu. P. Rayzer.

But the shock wave itself, no matter how hot it is does not cease to be a shock wave and spreads by shock machanism, and not due to heat conduction. This was proved by Ya. B. Zel'dovich, who analyzed the contribution of radiant transfer of energy in the total balance of energy of shock wave.

Actually air in the shock wave is opaque even during temperatures much lower than 10,000°. This is explained by the fact that high temperatures nitric oxide is easily formed. Its electrons are rocked much easier than for nitrogen and oxygen which are not combined with each other.

The following curious phenomenon is observed: the shock wave gleams approximately up to 2500°, then it ceases to gleam and moves on, and the fiery body remaining after it flames anew and attains 7,000 - 8,000°. Here it no longer has clear-cut lines. This glow lasts a second and longer, whereas a shock wave gleams for hundredth fractions of a second and less.

This origin of minimum of glow is explained by Yu. P. Rayzer. The nitric oxide formed in the shock wave continues to be oxidized further to a dioxide. The latter if opaque even at room temperature, and then it is a brown color. Many have seen it above pipes of chemical factories ("fox tails"). Therefore in the incandescent state nitrogen peroxide should gleam and all the more so when not the oxide but the clear air gleams.

Oxidation of nitrogen to oxide in shock wave no longer can occur when wave has a temperature near 2,200 - 2,500°. With lowering of temperature this reaction is very delayed. When nitric oxide was formed, it very rapidly oxidised to dioxide - speed of this reaction depends n less on temperature. Therefore shock wave gleams as long as oxidation of nitrogen occurs in it (this lasts around 0.01 sec). Here the hot opaque nitrogen peroxide shields the still hotter air which is inside the wave.

After nitrogen ceases to be oxidized, the shock wave does not gleam more. The layer of formed dioxide, being expanded together with the air which is inside the wave, is as it were dispersed and the whole becomes less dense. Through it the hot air inside it begins to be transclucent. This glow lasts a second and longer. It also is, owing to its own duration, the most terrible. Around 30% of all the energy of the explosion goes with it.

Incandescent rarefied air is lighter than ambient air. It surfaces, is expanded, and is cooled. The mushroom-like cloud, known to all by pictures, will be formed.

The shock wave, detached from the fiery sphere, spreads to the far sides, gradually being weakened. The profile of pressure and speed in a weak shock wave

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obstacle, and the direction of propagation, consequently, perpendicular was to it.

An absolutely hard wall, of course, cannot really exist. But any heavy barrier, in any case, possesses insertia and is not accelerated instantly. Therefore in the first moment air before it must stop before the barrier will come into motion. To this first moment, when the barrier still has not shifted, will pertain the idealized presentation, based on the idea of a non-pliant obstacle. In Fig. 21a is shown a shock wave falling on a barrier. In Fig. 21b the speed of air, incident together with wave, is shown by arrow on the left. This speed undergoes a jump on the front of the reflected shock wave forming before the obstacle, and after the wave equals zero.

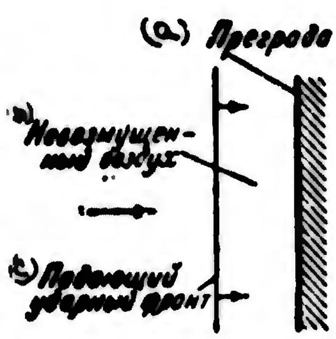

Fig. 21a.
KEY: (a) Barrier
(b) Undisturbed air,
(c) Incident shock front.

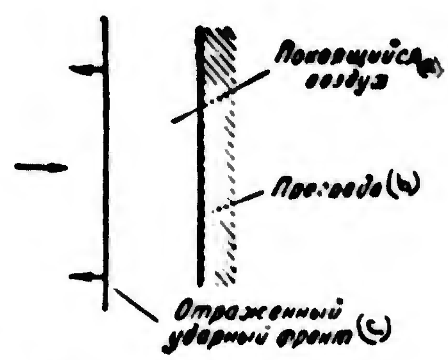

Fig. 21b.
KEY: (a) Stationery air,
(b) Barrier, (c) Reflected shock front.

Before the wave fell on the obstacle, air in its front jumps from a state of rest to a state of motion. In front of reflected wave air again remains. It is compressed both times.

We already said that work of compression in a shock wave in great part is expended on irreversible heating of air. If from the obstacle is reflected a strong shock wave, then in it the same kinetic energy must again irreversibly be turned into internal energy. But since the gas before this was already heated by the first, incident shock wave, the reflected wave must be a few times stronger than the wave in order to absorb the same kinetic energy. If amplitude of reflected wave was only twice as large as the incident wave, as occurs during reflection of sound, irreversible transition of energy would be very weak: we saw in Section 5 that the is completely unlike that of a strong wave. Pressure is distributed approximately as is shown in Fig. 20. On section ba it is somewhat increased, in accordance with magnitude of shock on the front; farther on it drops and becomes less than in undisturbed air, in the very center it is almost the same as it was prior to the explosion. Speed of air in zone of increased pressure is directed from the center; in zone of lowered pressure it is directed - to the center (suction).

The decrease of air density with height influences in a curious way. During any strong explosion the wave in the strong stage goes downwards not more than 16 kilometers. Upwards infinite time it goes extraordinarily high.

This is explained very simply. Speed of shock wave is the reciprocal root to square of density. In upper point of wave air density decreases by the barometric law, so that speed of upper point of shock wave tends to infinity very rapidly with height. With an infinite speed in finite time an infinite path can also be covered. Therefore shock wave escapes upwards so rapidly.

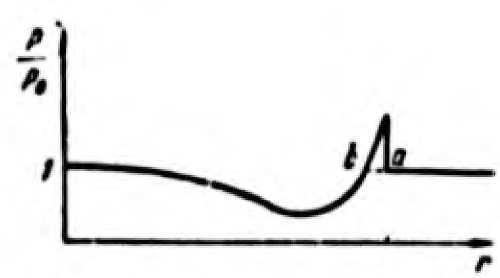

Fig. 20.

The volume of air captured by it tends to infinity. Pressure in strong wave is reciprocal to the volume, so that it becomes zero when the wave goes upwards. But then the lower point of wave remains without support from behind and is very delayed in its own propagation. Thus, the atmosphere is natural protection from strong shock waves.

9. Reflection of Shock Waves

When a shock wave falls on an obstacle, it is reflected. Reflection is the strongest if the obstacle is hard and non-pliable. This case we will also consider. To begin with we will consider that front of wave was parallel to the plane of the shock wave with a relative amplitude of 2, i.e. such, that pressure is increased twice, is nearer in this meaning to a weak than to a strong wave. It turns out that when the incident wave is very strong, pressure in the reflected wave jumps another 8 times. If a shock wave falls, in which excess pressure equals 1 atmosphere, then on the front of the reflected wave the jump of pressure amounts to 1.75 atmosphere. This intensifys the destructive action of shock waves.

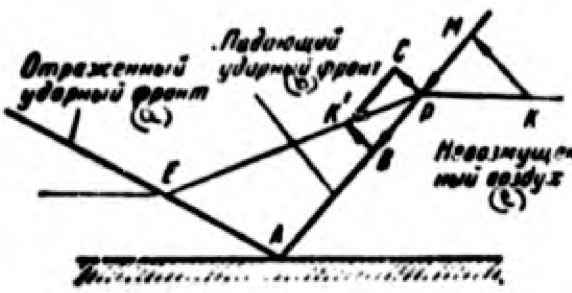

Fig. 22.
KEY: (a) Reflected shock front,
(b) Incident shock front,
(c) Unidsturbed air.

Reflection of shock waves from obstacles is very interesting when waves do not fall at a right angle to the surface. In this case the usual law of reflection breaks down: angle of incidence does not equal angle of reflection (Fig. 22). The reflected front will form a smaller angle with the obstacle than does the incident front.

To better grasp Fig. 22 where oblique reflection is shown, it is convenient that we move together with point A, where the incident front crosses obstacle. Then relative to us, air ahead of the wave will move with a speed equal in magnitude and reverse in the direction of speed of point A relative to the ground. "Straddling" point A, we will watch how particles of air will move, passing through both shock fronts - the incident and the reflected one. Relative to us they both are at rest. Trajectories of motion of particles of air we now call flow lines.

The flow line of undisturbed air, obviously, is parallel to the obstacle (which with respect to a point A, of course, moves with the same speed as does the undisturbed air). What happens to this line when it encounters the incident shock front? We decompose the approach stream velocity by the rule of the parallelogram into two components KM and MP. Analogously we will decompose speed PK' for the first shock front into components PB and PC. Parallel to the front, component MP gives no transfer of substance, momentum or energy through the shock front. According to the laws of mechanics it must remain the same also after the front, so that MP = PB. In the front only the perpendicular component of speed undergoes a discontinuity. Behind the front it is as many times shorted, as compared to before the front, as air is denser behind the front. The product of speed times density is, according to the law of conservation of mass, a constant. This pertains to perpendicular components of speed KM and PS, since only they transfer mass through shock front.

But if the perpendicular component of speed is shortened, then, as can be seen from the drawing, the resultant vector of speed after the wave is nearer to front than before wave, that is, angle K'RV is less than KRM. This reasoning is applicable also to the point of intersection of flow line with reflected shock front E, inasmuch as here the gas undergoes repeated compression. But after intersection with reflected shock front flow line has to become again parallel to the obstacle, since it, of course, is not able to intersect it.

Thus, flow line after refraction in front of shock wave both times draws near to it, and as a result becomes parallel to the initial direction. The reflected shock front forms a smaller angle with the obstacle than the incident front. This is proved with help of exact calculations, but unfortunately, as yet it has not been managed to get a simple and graphic proof "at our fingertips" for such a simple fact.

Calculations lead, furthermore, to an unexpected result: in oblique incidence, pressure in the reflected wave can increase even somewhat more than in a straight drop.

In a shock wave with any pressure strength compression cannot excel known limit A; this means that relation PS to KM does not occur as small as desired: it equals the reciprocal of limit compression. Hence directly it follows that the angle of rotation of speed in oblique shock wave is the biggest possible.

We will apply this result to the flow around a wedge shaped body moving with supersonic speed (Fig. 23a) in the direction of bisector of wedge. On tip of body, as we saw, necessarily appears a shock wave. If one were to say that the body rests and air encounters it (practically this is carried out in a wind tunnel), then flow lines ahead of shock waves are parallel to motion of body. In front of wave they are refracted and become parallel to lateral surfaces of wedge. Proceeding from this, it is possible to calculate position of shock front.

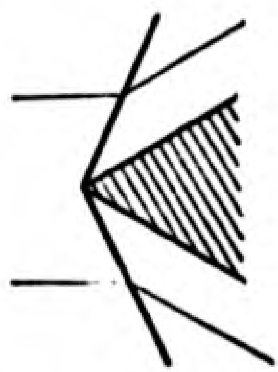

Fig. 23a.

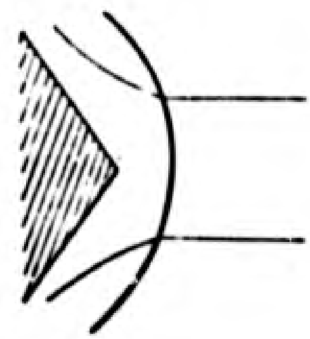

Fig. 23b.

But if wedge is very dull, as in Fig. 23b, then no shock front can turn the line so steeply; as we have seen just now, there exists a maximum possible angle of rotation of flow in shock front. Therefore shock wave cannot start on tip of body. Shock front will be formed a certain distance ahead of the body, as during the flowing around of a blunt-nosed, rounded body. Furthermore, naturally, we obtain a distorted front.

The existence of a critical angle shows also a picture of reflection of shock wave from an obstacle. Let us assume that a very strong wave will form when it hits an angle, which is close to a straight angle, with the plane of the obstacle (Fig. 24a). Then any two discontinuities of the flow line, or both of them, will appear larger than the possible limit angle. Let us note that if waves are weak, then angles larger than the limit angles are possible only in the actual limit when the front will form an angle close to 90° with plane of obstacle. In all other cases the picture during the fall of a weak shock wave is transmitted as Fig. 24b and does not contradict the possibility of the picture of reflection just now described when both fronts start on the obstacle itself.

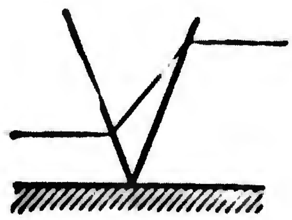

Fig. 24a.

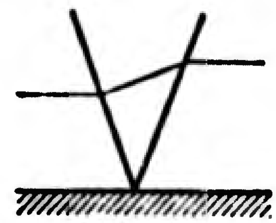

Fig. 24b.

What is obtained in a sufficiently strong wave, if according to the conditions of problem it cannot turn around the flow line so that prior to intersection of incident front and after intersection of reflected front it is parallel to the obstacle? It turns out that the picture of reflection here essentially is changed. It obtains a form, like that in Fig. 25. The point of intersection of incident and reflected front turns out to be above the obstacle. Besides them there exists a third front: from this point up to the obstacle, and the line tangent to it, along which component of speed undergoes a discontinuity (dotted line in Fig. 25). This form of reflection is called irregular or Mach, since it was discovered and described by E. Mach.

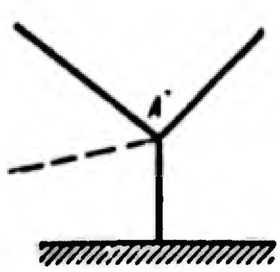

Fig. 25.

In Fig. 26a,b is shown how the Mach reflection develops when the spherical shock wave is incident to the surface of the ground. In the first moment the wave falls perpendicular to the ground, so that it is reflected like a straight line. Later (Fig. 26a) the angle between front of wave and the ground still corresponds to normal, or regular reflection. On the same figure is also shown reflected front. When the angle between front of incident wave and surface of ground attains the limit value allowing regular reflection, a third shock front starts to be formed. It is obtained as if the reflected front rushed to outdistance the incident front. This, of course, it is not able to do, and only runs up over it. On Fig. 26b is shown what happens here. The reflected front is wholly above the ground and nowhere touches it. That section of incident wave through which point of intersection with reflected wave runs up, looks like a "leg" of the Mach wave on the figure. It becomes even higher with spread of wave, so that at great distances from the place of explosion this "leg" travels. It produces destructive action on comparatively remote ground objects, such as walls of buildings.

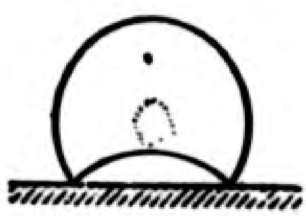

Fig. 26a.

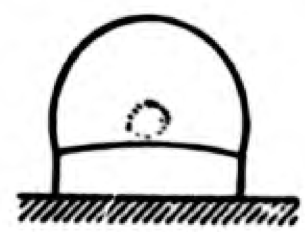

Fig. 26b.

10. Shock Waves in Laboratories and in the Cosmos

Action of shock waves on different objects is sometimes conveniently studied not in natural conditions, that is, not during an explosion in open space, but in a laboratory. The same pertains to the actual process of shock compression, especially, if not air but any other gas is compressed.

During an explosion in open space the wave disperses to all sides and from this rapidly weakens. It is easy to see, for instance that shock wave of a point explosion weakens in reverse proportional to the cube of distance. We will show this with the help of dimensional analysis. The dimensions of pressure is, as is known,

$$\frac{\text{force}}{\text{area}} = \frac{\text{force}}{\text{length}^2},$$

and dimension of energy,

$$\text{force} \times \text{length}.$$

If one were to compose the ratio of energy of explosion to pressure, then force is reduced and there remains only:

$$\frac{\text{energy}}{\text{pressure}} = \text{area} \times \text{length} = \text{length}^3.$$

Eliminating hence pressure, we will obtain,

$$\text{pressure} = \frac{\text{energy}}{\text{length}^3}.$$

But, as we already saw, strong shock wave of a point explosion is characterized by only one magnitude with the dimension of length - its radius; therefore, instead of cube of length, in general in the last formula it is possible to place only cube of radius. It is clear if one were to understand by pressure namely pressure in front of shock wave, then in the relationship it is necessary to place numerical coefficient depending on magnitude of limit compression. But this coefficient is near to unity.

In order to avoid weakening of wave, it is necessary not to allow it to spread to the in sides, but to stop it up in a cylindrical pipe. From the very beginning we considered such shock waves, in order to avoid unnecessary complications.

Actually, it is certainly difficult to insert a plunger in a pipe with such speed, in order to obtain a shock wave of noticeable force. It is possible to detonate a small charge in the pipe, but it is still more convenient to seperate strongly compressed part of gas from the other uncompressed part. Then during rupture of partition for an instant there develops a line between compressed and uncompressed gas.

But one should not think that this line will also spread like a shock wave. We know that in a shock wave besides a jump of pressure there must also be a jump of speed - otherwise conservation laws cannot be fulfilled. Jump of pressure in the absence of a jump of speed would contradict the third law of newton; compressed and uncompressed gas would affect one another with different forces, if directly after contact motion of gas did not appear.

This motion spreads both to initially compressed and to uncompressed gas. Through compressed gas will travel a wave of rarefaction, in uncompressed - a shock wave. In Fig. 27 is shown profile of pressure in a certain moment of time.

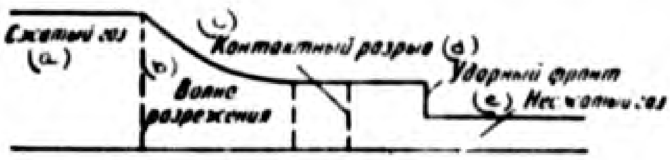

Fig. 27.
KEY: (a) Compressed gas, (b) Wave of rarefaction, (c) Contact break, (d) Shock front, (e) Uncompressed gas.

It is necessary to pay attention to the fact that gas "menorizes", where it passed initial boundary of compression. Pressure on it, certainly, is equalized (third law of newton!) speed - also, according to the law of conservation of mass, but density and temperature undergo a break. The existence of this discontinuity does not contradict the laws of mechanics. Thermal conductivity cannot considerably smoothen this break of temperature, since motion of gas is very fast. Similarly heat transfer practically does not affect compression in sonic wave of rarefaction.

A device in which shock waves are obtained is called a shock tube. In order to obtain in it a relatively large pressure drop, uncompressed gas is taken with a very small initial pressure, of the order of 10 mm Hg and compressed - with a pressure of 10 and more atmospheres. Then very strong shock waves appear. Absolute value of pressure in them is not too great and does not destroy the tube, but its relative change is very great. Correspondingly very great is speed of propagation and temperature - of the order of 10,000°.

In order to obtain essentially higher speeds and temperature we apply another method. First of all, it is necessary to bring gas to the ionized state, that is, obtain in it a large concentration of free electrons and charged atoms being lost one by one, and more electrons. Such atoms are called positive ions in accordance with the sign of their charge. Gas can be ionized either by a strong shock wave, or by passing through it an electrical current during a great potential difference.

Ionized gas conducts electricity very well. For its farthest acceleration, if it already had initial speed from shock wave, the phenomenon of electromagnetic induction is used. It is placed in middle of coil through which passes a strong current pulse. The growing magnetic field of the coil induces a current of opposite direction in the conducting gas. According to the law of Lentz, the magnetic fields of both currents, in the coil and in the gas, have opposite directions, so that gas is forced from the coil and travels through the tube. Since initial density of gas is small, it accelerates in this way to high speeds. It reached 700 km/sec!

Initially accelerated gas, moving through unaccelerated gas, creates in it a wave of compression, which then changes into a shock wave.

We will not remain in detail on how waves can be propagated in ionised, conducting gas. This is the subject of magnetic gas dynamics. Besides laws of mechanics, determining shock jumps in nonconducting gas, magnetic gas dynamics should consider also laws of electro magnetism. Owing to this new types of discontinuities appear.

The obtaining of shock waves in ionised substance can turn out to be very important for resolution of problem of controlled thermonuclear reactions. As is known, this is a basic problem of power engineering of the future.

Thermo, that is, thermonuclear reactions are so-called because nuclei react in them owing to high temperature, or, which is the same, the great speed of thermal motion. These magnitudes directly depend on each other. Intensity of flow of a thermonuclear reaction is very rapidly increased with temperature. Thus, nuclei of heavy hydrogen, deuterium, basics, apparently, of thermonuclear fuel, react at a temperature of two million degrees 3,600 times faster than at one million degrees. And after all, temperature is increased in this example by "all" of two times.

Shock waves give one of the possible ways of compression and heating of deuterium. As yet it is impossible to talk about decisive successes, but it is necessary to conduct the most intense search in all directions. We will talk again in Section 15 about uncontrolled thermonuclear reactions, taking place in so-called hydrogen bombs.

Uses of magnetic gas dynamics as yet are little developed. It is necessary to remember, however that a large part of the matter in the Universe is in the ionized, that is the conducting state: the interior of the Earth, heated matter of stars, rarefied interstellar gas - conduct electricity well. Therefore their motion belongs to the region of magnetic, and not the usual gas dynamics. It is basic to think that only on the basis of magnetic gas dynamics will it be managed to explain the origin of the planetary system of the Sun—surmounting those difficulties which all former theories met.

Let us consider now one phenomenon which it is possible to explain by propagation of shock wave in conducting interstellar gas. From time to time the magnetic field of Earth experiences strong perturbations, so-called magnetic storms. The original cause of the storms are explosions on the surface of the Sun, which are accompanied by ejection of a cloud of ionized particles. It moves through interstellar gas, which has a very small density, from 100 to 1,000 particles per cubic centimeter. These particles also are ionized. Such density is ten million billion times less than the density of the terrestrial atmosphere.

Is it possible to talk about shock waves in so rarefied a substance? We will make certain estimations. We know that the least width of the front of a shock wave is of the order of one free path of molecule. During normal density of the atmosphere a path constitutes around one hundredth of a centimeter. It is inversely proportional to density. Consequently, in interstellar gas it has an order of ten million kilometers. This 25 times more than the distance from Earth to Moon, but nevertheless 15 times less than the distance from Earth to Sun. Consequently, between Earth and Sun it is possible to "place" a shock wave. It will form a cloud of particles, thrown-out by the Sun, driving ahead of itself interstellar (more correct, interplanetary) gas.

For the Sun continuous observations are conducted; they also are called the weather bureau of the Sun. From the moment when on the Sun an explosion is recorded and up to the beginning of a magnetic storm on Earth around twenty-four hours passes. Therefore speed of spread of the process is around 1,500 km/sec. In what sort form does the perturbation reach the Earth?

At a distance of several terrestrial radii the motion of conducting gas encounters on its path the terrestrial magnetic field. But if a conductor moves in a magnetic field, according to the law of Lentz a magnetic field of the opposite direction is induced in it. As a result the field as it were is forced from the moving gas and becomes a stronger on Earth. But it is surprising, then, that it is noticeably increased after one minute. After all, if one were to consider that the width of the shock wave front is of the order of one run, that is, ten million kilometers, then the wave passes the distance from base to peak of front at a speed of 1,500 km/sec for more than two hours. But this estimate pertains to the usual, and not to magneto-gas dynamic shock waves.

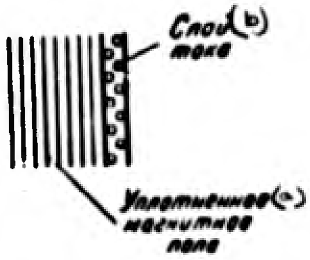

Fig. 28.
KEY: (a) Layer of current, (b) Compressed magnetic field.

Width of front of magnetic shock wave compressing ahead of itself the force lines of the magnetic field, is estimated differently. Along front of such wave flows an electric current whose magnetic field strengthens the field ahead of the front and weakens that behind it (Fig. 28). The width of current layer can be estimated. It approximately corresponds to that value which is compatible with a very small time of growth of magnetic field in the beginning of the magnetic storm.

Action of cosmic shock waves, apparently, also influences tails of certain comets. Usually tails are ejected from comets by pressure of sunlight (light pressure was predicted by Maxwell around 1870, observed by P. N. Lebedev in 1900). However, from certain comets tails are ejected with a speed ten times larger than can be obtained from light pressure. Very possibly these comets encounter on their path shock waves proceeding from the Sun in interstellar gas.

Beyond the orbit of Jupiter moves the very weak Schwassmann-Wachmann I comet, which sometimes flares and becomes 100 times brighter than usual. Thanks to this it was discovered. It would have been possible to think that these flares are caused by the action of interplanetary shock waves. But then it is necessary to explain, why they are lacking for the huge majority of all other comets.

11. Shock Waves in Solid and Friable bodies

Shock waves can compress not only gases. Recently they were used for compression of solid bodies. At very large pressures the specific properties of solid bodies, such as the ability to preserve their own form, do not appear, so that the basic positions of the theory of shock waves at sufficiently large pressures hold true also for solid media. Essentially different than for gas turns out to be only the dependence of internal energy on pressure and density. Therefore the Hugoniot adiabat for solid media is similar to the Hugoniot adiabat for gases only in broad terms.

The biggest pressure which can create an explosion of any substance, of the trotyl type, in direct contact with a solid body is of the order of three hundred thousand atmospheres. If it is necessary to obtain large pressures the body is given a spherical form and a shock wave is started simultaneously from all sides, detonating, for instance, a charge of trotyl around the body.

In body appears a shock wave convergent to the center. If all it converged in one moment of time exactly to the center, then theoretically pressure had to grow ad infinitum. In other words, near the center the wave is very powerful. If, for instance, it went through the gas, then it would compress it up to the maximum attainable compression of density during shock.

The problem about convergence of a shock wave to the center in gas was resolved by L. D. Landau and K. P. Stanyukovich, and also Guderly.

It is very interesting that in the following moment after the wave converged to the center, so to say, it was reflected from itself. With the law of limit compression, which takes place in air (6 times), pressure during reflection of a wave in the center increases still 26 times as compared to what it was directly before the reflection. Let us remember that during flat reflection of a strong shock wave, which is equivalent to a collision "in the forehead" of two shock waves of equal force, pressure is increased eight times.

Therefore a convergent shock wave makes it possible to obtain record-breaking compressions of a substance. Whereas static pressures by incredible efforts of the experimenters cannot be brought to more than several hundred thousand atmospheres, in convergent shock waves a pressure of several million atmospheres can be obtained.

But, of course, shock compression cannot completely replace static compression for the needs of scientific research: after all it strongly heats the substance, so that two parameters characterizing the condition change-pressure and temperature. During static compression, if it is done sufficiently slowly, only pressure changes.

Unfortunately, compression by a convergent wave is different, by far not a scientific use*.

We talk about the harm of atomic bombs. As is known, nuclei of a light isotope of uranium with an atomic weight of 235 or nuclei of plutonium are able to divide when neutrons fall on them.

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* R. Lepp. Atoms and People, IL, 1959.

Energy, is given off which 100-200 and more times exceeds the energy of a falling neutron. During division into two large parts, from the nucleus in the form "of small drops" depart two - three new neutrons, but again able to produce division. In an unbounded medium from divisible material will go a nuclear chain reaction, growing like an avalanche.

In a very little piece of uranium 235 or plutonium, a chain reaction cannot develop because the majority of neutrons will escape outwards, not producing division. It is obvious that there is a certain definite size starting from which the chain reaction will take place. This size is called critical.

But if a reaction is caused in a body of exactly critical sizes, then it will fly apart earlier than a noticeable part of its mass can react. Consequently, it is necessary to detonate only supercritical masses. However, such a mass is impossible to store until the explosion: any neutrons accidentally getting in it from cosmic or from spontaneous fission, not caused by neutrons (discovered by G. N. Flerov and K. A. Petrzak) will start a chain reaction. It is necessary to create a supercritical mass at the actual moment of explosion.

The story of the discovery of chain avalanche-like reactions is interesting. Initially they were discovered in 1926 in chemistry by N. N. Semenov and independently by K. Hinshelwood. Semenov and his pupils, Yu. B. Khariton, V. N. Kondrate'v, A. A. Koval'skiy, and others discovered that certain reactions of ignition of gas mixtures with the same composition proceed in vessels of one dimension but do not in smaller ones. The assumption was expressed that atoms or molecules with unsaturated valences, especially easily reacting lead to a reaction. They were called active centers. On walls of vessel the centers recombine and they do not continue furhter to reaction. Therefore, dimensions of vessel are essential, and also method treatment of walls. If the active center does not "perish" on wall, it reacts in volume and creates as a result of the reaction several active centers. In vessel of supercritical dimensions a chain reaction is obtained.

In chemistry at first the chain reaction was discovered, it was inferred the necessity of existence of active centers. In nuclear physics at first the elementary division reaction of nuclei by neutrons was discovered, and then the possibility of a chain progress was predicted. The actual division was discovered by Gan and Shtrassman in 1938. A clear explanation of the mechanism of division immediately after them was expressed by Frish and L. Meytner. They conducted an analogy between nuclear fission and the breaking apart of a liquid drop, charged by electricity. A quantitative theory of this phenomenon was proposed by Ya. I. Frenkel', and in a more complete form by N. Bohr jointly with Wheeler. As from the neck of a bursting drop will be formed one more or several small drops, during division, by the assumption of Frish and Meytner, from the nucleus neutrons can escape. This was confirmed during experiment by F. Joliot.

Soon after that began the Second World War, and already in secrecy were conducted searches for a method of obtaining large quantities of divisible materials and reduction of them into supercritical masses. In the case of chemical reactions, supercritical mass can be stored, if only in it active centers do not develop spontaneously. But in nuclear active material, it is impossible to protect it from active centers, that is neutrons. Creation of supercritical mass immediately leads to explosion.

It is profitable to create as large an initial supercriticality as possible, during a small supercriticality instead of an explosion a clap will be obtained (a "pshik"-like sound). A strongly supercritical mass, simply due to its own inertia will not be able to fly apart earlier than a significant part of it will react.

We think supercriticality can be achieved by firing two subcritical pieces of uranium or plutonium into each other. They will collide earlier than a chain reaction can develop. However, a large coefficient of "useful" action will not be obtained.

Instead of increasing mass of divisible material, it is possible to increase its density. From a compressed piece of substance it is more difficult for a neutron to fly out, not producing division. In a denser piece it more accurately encounters a nucleus on its path, in spite of the fact that the path itself is shortened when the piece is compressed.

Let us assume that, for instance, the magnitude of a piece decreases by two times. Then density is increased eight times ($2^3 = 8$). The run of a neutron with respect to division decreases also eight times. Therefore, although the path of a neutron will also decrease twice, the probability of it encountering any nucleus on its path will be increased four times for it. Consequently, initially subcritical mass can remain supercritical during compression and explode by nuclear method. And since together with compression inertia is increased with respect to scattering, use of active material turns out to be very large.

For maximum compression a convergent shock wave is applied. In order to create it, a sphere from the active material is surrounded by a layer of common explosive, which is blasted along all the external surface immediately. There appears a convergent detonation wave (see ch. 3). Reaching the nuclear active sphere, it creates a convergent shock wave. This method of blasting obtained in the United States the conditional designation "fatso", perhaps, in connection with the round form of the compressible body.

It is doubtful whether the possibility of scientific research, opened thanks to convergent shock waves, in some any degree compensate the deadly danger of nuclear weapons. This cursed question in significant measure as yet pertains to all gas dynamics.

Shock waves can be obtained also in friable bodies, for instance in sand. Grains of sand loosely adjoin one another - between them there is always a vacuum. While sand is not under pressure, sand grains are held in equilibrium by frictional force. But if one were to apply pressure, particles can be displaced from their positions of equilibrium and be disposed more densely. For that even a small pressure is sufficient. Conversely, after they lay tight, a significant pressure is necessary for compression of the actual material of sand grains.

Therefore any process of compression of friable sand or other similar material can be presented as a transition from loose to dense stacking of grains. Thus, one should then understand shock compression, occurring during explosion of a charge placed in sand.

If explosion is carried out at a sufficient depth, then no ejection outside will occur. In this case explosion is called camouflet. Gases in blast wave are under high pressure. Acting on walls, they separate it. From this the radius of compressed layer of sand or other friable ground is increased. Ground moves with great speed in whole volume of compressed layer. Moving sand, resting on front of shock wave of compression in still uncompressed friable ground, packs it in turn.

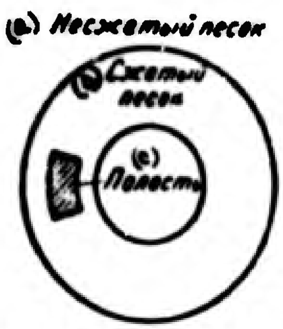

Fig. 29a.
KEY: (a) Uncompressed sand,
(b) Compressed sand, (c) Cavity.

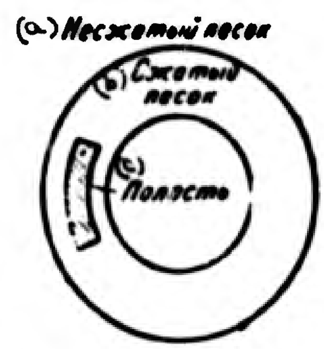

Fig. 29b.
KEY: (a) Uncompressed sand,
(b) Compressed sand, (c) Cavity.

A steep wave front is obtained thanks to the shown property of a friable medium to sharply change its density under load.

Compressed sand continues to move under the pressure of gases in explosive chamber, volume of which grows. In Fig. 29a, . is shown by shading a certain volume of compressed sand at two moments of time. During expansion of explosive chamber ("cavity") thickness of this volume in radial measurement decreases, the wall of a rubber bubble becomes thinner when it's blown up. But if one were to release air from bubble, it again will be compressed and return a significant part of the work expended on blowing it up. Compressed by wave, the sand after being relieved does not return to its initial form; any work against the forces of friction is expended irreversibly. The shaded area also will remain flattened, deformed, and the work of its deformation wholly will change into heat.

The packing during compression of sand on front of shock wave is also irreversible. Balance of energy shows that on shock compression approximately one third of energy of explosion is expended, and on deformation - almost all the remaining energy.

This picture of explosion in friable sand was confirmed in experiments of A. N. Romashov, in the Institute of Chemical Physics of the Academy of Sciences of the USSR.

We already indicated that in gas, shock waves can spread only with supersonic speed. Otherwise a steep front of compression would be impossible; it would be broken up due to running of sonic waves forward. In sand a steep front will be formed owing to a peculiarity of the process of compression. He therefore spread and with subsonic speed. It is clear, such a front will become a source of sonic, elastic wave, which can spread also through a friable substance, if it is so weak that it does not change the mutual location of grains. In other words, forces caused by compression in elastic wave, have to be less than forces of friction between sand grains. In conformity with this, an elastic wave, traveling from front of shock wave in sand, has minute amplitude and removes small part of energy of explosion. According to appraisal of E. E. Lovetskiy not more than one percent of energy of explosion is carried away.

This estimate is essential, if it is necessary to determine action of explosion at a large distance; this is called seismic action. It can help also during registration of the effect of a camouflet explosion.

CHAPTER 3

DETONATION

12. Detonation Waves

Studying nature, man in some sense creates it anew, adjusting to the requirements of practice and problems of scientific research. It is possible to say that civilization began when people learned to reproduce burning artificially, that is to obtain fire. In the transitional epoch from feudalism to the new history, gunpowder was invented and obtained wide use. In this chapter we will speak about yet one more phenomemon of nature, which is connected with burning and explosion — detonation. Now it is still premature to relate it to any stage of development of society.

It is known that a mixture of hydrogen or methane with oxygen can burn fast. Usual speed of propagation of flame in such mixtures is 10 - 20 meters per second.

In order to measure it, the mixture is let into glass tube and ignited from one end by an electrical spark. While the spark is weak, burning spreads in gas with the indicated speed. But strong spark, or explosion of a small charge causes quite another phenomenon; flame propagates in gas with speed around 2,000 meters per second. With this the tube flies to pieces, the explosion is accompanied by strong sound effect. This is also called detonation.

Usual flame is transmitted from one section of gas to the neighboring one by means of processes of heat conduction and diffusion. Heat liberated in the zone of burning heats the adjacent layer of gas, while in it reaction does not start - the speed of such a reaction very strongly depends on the temperature. A mixture which at room temperature will not react even after a million years, at 1,000 - 1,500°C will ignite and will burn for small fractions of second.

Important role is played simultaneously not only by heat transfer, but also by transfer of active centers of reaction, that is of atoms and molecules with unsaturated valences. We already mentioned them, speaking of chain reactions. Such active centers start and support the reaction, where in an inert substance it does not proceed.

Leaving the zone of burning, heat and active centers ignite the neighboring, still not burning sections of gas, and flame propagates. Quantitative theory of this process belongs to Ya. B. Zel'dovich and D. A. Frank-Kamenetskiy. They found the relationship between speed of flame propagation, heat of reaction and coefficient of heat conduction.

Molecular processes of heat transfer and active centers comparatively are slow. Therefore, burning rate is much less than the speed of sound. (Thanks to its own smal heat conduction air is used for thermal insulation, for instance, between window frames). Natural scale of speed in gas dynamics is the speed of sound. Burning rate, (determined by processes of transfer) of the order of 10 - 20 m/sec in this scale is very small.

Detonation velocity, conversely, is several times greater than the speed of sound, and one hundred and more times exceeds the burning rate.

It is impossible to explain detonation by any processes of transfer, although such attempts formerly were made. It is possible to read about them in old literature on physical chemistry.

In fact detonation is a gas dynamics phenomenon and is explained very naturally by propagation of shock waves. Actually, in a wave running at speed of 2,000 m/sec pressure is increased 40 times. Absolute temperature of gas increases 6 - 7 times, and reaches 1,800 - 2,000°. At such a temperature the reaction occurs very fast. Liberated heat of reaction compensates for the irreversible loss of energy occurring during shock compression of gas which still has not entered into reaction.

By this the detonation wave maintains itself. With given calorific value of mixture a strictly determined detonation velocity is obtained; it is proportional to square root from heat of reaction, referred to mass unit of mixture, and almost does not depend on initial pressure of gas. Shock wave in gas can have the most diverse speed, and of course, dies out if external source of energy does not maintain it.

Thus, for detonation the existence of regime is characteristic, that is of fully determined velocity under given conditions of propagation.

Problem of theory of detonation consists of showing just what regime is accomplished in detonation wave, and to explain, why detonation velocity is connected in the first place with heat of reaction.

First of all, it is necessary to clarify under what conditions the existence of regime is possible, that is with constant velocity of propagation of detonation wave all along the length of tube.

For that it is necessary first of all that products of detonation expanding after combustion did not affect the zone of burning. Burning gas can flow outside through open end of tube, or still more rapidly be mixed with air, immediately scattering to the sides if the tube bursts. But all this in no way influences the velocity of propagation of detonation wave through unburned gas. Consequently, the velocity of wave relative to products of detonation can in no way be subsonic.

We will explain this affirmation. Thickness of front of strong shock wave is of the order of one free path of gas molecule. On this path gas is compressed and is heated. But also after heating a chemical reaction occurs far from with each collision of molecules. So that molecule reacted chemically, it should collide with other molecules from ten to one hundred thousand times. Consequently, the reaction proceeds not in the actual front of the shock wave, but in some layer behind it. Thickness of this layer, according to what has been said, is ten - one hundred thousand times greater than free path and can, therefore, reach a millimeter. Region where reaction proceeds, we will call subsequently the reaction zone.

So that constant regime is accomplished, conditions in the reaction zone does not have to be changed with propagation of detonation wave through gas.

But after zone of reaction gas is expanded, that is in it motion occurs with respect to type of rarefaction wave. Rarefaction wave, as we saw in Section 2, can never be stationary. It is continuously stretched in length. Consequently, during propagation of detonation wave the reaction zone, which should be stationary, touches the region of nonstationary rarefaction wave.

This is possible only if sonic perturbations from region of nonstationary motion do not overtake the reaction zone. Otherwise they would bring into reaction zone lowered pressure and temperature and thus delay the course of reaction, so that stationary conditions would not be accomplished. Thus, front of detonation wave should move relative to products of detonation with supersonic, or in extreme case, with sonic speed.

Already in beginning of our century Chapman, and independently of him, Jouguet showed that expression of detonation velocity by heat of reaction will agree with experiment only if just this extreme case is accomplished. If detonation velocity relative to products of detonation is equal to the speed of sound in them, then relative to the unburned gas it is still more. According to the law of addition of speeds it is equal to sum of speed of flow of products of detonation at the point where reaction was completed, and speed of sound in them at this instant, that is up to the beginning of expansion. This is called Chapman-Jouguet condition.

But for several decades it was not proven that it should be thus, proceeding from gas dynamics and general conditions of course of chemical reactions in the zone of burning. It happened thus probably because specialists on gas dynamics were far from problems of physical chemistry, and chemists studying detonation knew gas dynamics insufficiently. Incorrect explanation of detonation, based on phenomena of transfer, predominated.

Only in 1939 Ya. B. Zel'dovich managed theoretically to substantiate the impossibility of supersonic conditions during propagation of detonation wave and thereby developed completely Chapman-Jouguet condition. We cannot trace this proof in detail, but we will outline only the general method.

We sill show in Fig. 30 two Hugoniot adiabats. Solid curve, passing through the initial state, pertains to the actual front of the shock wave, where reaction still had not begun. Such an adiabat would correspond to shock wave running through the same gas as detonation, but without further chemical reaction. Since reaction starts after shock compression of gas, it is clear that this adiabat has a fully determined meaning. Dashed curve is also Hugoniot adiabat; it is constructed by the same equations, but on the assumption that the chemical reaction was completed and completely liberated its own energy. In other words, here in condition of energy conservation the internal chemical energy of unburned substance; is included also for the burned there is still none of it. For that adiabat which corresponds only to shock compression, the chemical part of internal energy is reduced from both sides of equality.

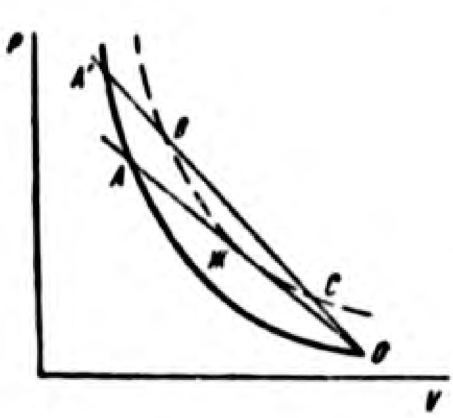

Fig. 30.

Dashed adiabat cannot pass through the initial state in which chemical energy still is not liberated. It should lie above the solid curve. Actually, when heat of chemical reaction is liberated, gas is heated; from this with constant volume its pressure becomes greater. Therefore, dashed curve also is plotted higher.

We indicated that the state during shock compression changes along the chord connecting the initial state with the final: this follows only from laws of conservation of mass and momentum. Since these laws are observed also in the course of chemical reaction, the state with this also can be changed only along the same straight line. It follows from this that chord by all means should have common point with dashed adiabat, because otherwise the state, (being changed in the course of chemical reaction), cannot anywhere correspond to complete liberation of chemical energy. That state in which all that should burn burned, belongs to dashed adiabat on its actual determination, but lies also on chord with respect to laws of conservation of mass and momentum.

Any shock transition up to beginning of reaction is carried out directly from initial state O at point A' of solid curve. After that chemical reaction will start. As was already said, the point illustrating a state will shift on the chord from A' to B, (lying on dashed curve), where reaction is finished.

However, analysis shoes that if the chord crosses the adiabat at point B, then subsonic conditions are obtained, which we excluded earlier by condition of stationariness.

If reaction was completed at another point of intersection of chord with dashed adiabat - C, then by means of such an analysis it could be shown that this would correspond to supersonic conditions. With this the reaction zone would escape from products of reaction with supersonic speed, which does not contradict condition of stationariness.

But between points B and C the state would pass through points corresponding to more than complete liberation of chemical energy. It is obvious that to strike them is in no way impossible; with energy from nowhere. It would have been possible still to assume intermittent transition from B to C, passing all intermediate, inconceivable energy states. But this would be shock wave of rarefaction, which is excluded by second principle of thermodynamics (see Section 3).

Thus, neither subsonic nor supersonic regimes of propagation of detonation wave are impossible. There remains only sonic regime. To it corresponds one definite chord OA, touching dashed adiabat at point J (Jouguet point).

In it the velocity detonation wave relative to products of reaction is equal to the speed of sound in them.

In the discussion given here we silently assumed that the energy release follows the occurrence of the reaction, that is that while the substance reacts, energy only is liberated. We conceive, however, another occurrence of the reaction; in its initial phase energy is liberated and then part of it is absorbed and is expended on further course of the reaction. In this case there is a phase of the reaction in which heat emission is greater than final. Is it possible that supersonic conditions will be fulfilled, for which it is precisely required that the energy released in the course of the reaction is greater than the resultant energy? However, K. I. Shchëlkin showed that here also the Chapman-Jouguet condition preserves its force. It is necessary only so that reaction itself proceeded all the time in one direction.

Thus the only conditions of detonation are selected. According to the Chapman-Jouguet condition the velocity of detonation wave can be calculated, which for gases in accordance with the experiment depends only on heat of reaction. Let us note that all this pertains only to a so-called free wave, not supported from behind by anything.

There is one more assumption, which is essentially much more important. We assumed that flat front of detonation thus also propagates through gas, not being distorted. Experience shows that in fact this is not always so. We will see further that detonation wave can propagate not with any concentration of mixture and not with any diameter of tube. There exist known limits of its propagation, concentration with respect to radius. Near limits the front of detonation wave never is flat. With what this is connected will be shown below.

13. Limits of Detonation

Far from any combustible mixture of gases can detonate. Frequently it happens that it is sufficient somewhat to dilute it with inert gas, not entering into the reaction, and mixture does not detonate any more. Or the same mixture detonates in wide tube and does not detonate in a narrow. In such cases they say that detonation has a limit.

It is curious that at the limit the velocity of detonation drops not quite to zero and remains almost as great as with well-developed detonation. But detonation wave cannot propagate already at this slightly decreased speed.

This is connected in the first place with the fact that the chemical reaction rate in detonation wave very strongly depends on temperature. Mixtures, reacting fast and at low temperature obviously will not "wait" until detonation wave ignites them.

Why does heating so increase the rate of chemical reactions? In order to explain this it will be necessary to make a fairly long digression.

First of all, chemical reaction is a strongly hampered process. Molecules must enter into very close contact and besides stand in definite position one to another (with valence forces), in order to react chemically. But then it is necessary at first to surmount by it large repulsive forces, which, (as we said in Section 6), act between all molecules at close distances. Consequently, in order to enter into the reaction, molecules must first accomplish great work against the repulsive forces. It is clear, if the reaction then occurs, this work will be compensated with excess, but first it is necessary to expend work on the drawing together.

This work the molecules can accomplish only owing to the kinetic energy of their own thermal motion. As is known, the heat capacity of gases is approximately constant, so that for each degree of temperature approximately the same energy is obtained. Therefore the kinetic energy of thermal motion of the gas is proportional to the absolute temperature.

If we divide this energy by the number of molecules, then energy will be obtained, which each of them has "on the circle", (that is on the average). At room temperature the following energy is allotted on the average for a fraction of the progressive motion of each molecule: divide 4 by 10 in the fourteenth power of ergs. This energy is fifty times less that what is necessary to overcome repulsive forces. Consequently, a molecule with average energy can in no way enter into the reaction.

Actually, of course not for all molecules is the energy equal to the average, as not all people have identical height. But as there are no people having height fifty times more than average, so at room temperature there are also no molecules of fuel mixture able to enter into the reaction.

We will not misuse this comparison. At a temperature which is six times higher than room, (around 2,000°), the average energy of molecule is already eight-nine times less than is necessary to enter into the reaction. But with this it turns out that from one ten-thousandth to one hundred-thousandth of all molecules already can enter into the reaction, since they possess sufficient kinetic energy, to overcome repulsive forces. But of course not one man in two billion has height six times more than average. Molecules have, so to speak, not such a distribution with respect to energies, as people with respect to height. This pertains also to low energies; one millionth of all molecules have energy one hundred times less than average, but in general, there are no people 17 millimeters in height.

If one hundred-thousandth of all molecules are able to enter into the reaction, then the reaction zone extends to a hundred-thousand paths. This length is of the order of one centimeter. Let us assume that temperature in the reaction zone dropped from 2000° to 1700°. From this the reaction rate can be lowered, for instance, three times; so the smaller part of molecules will have sufficiently high energy to react.

But the moving gas is braked against walls of the tube, and moreover, returns energy to the surrounding space by means of radiation, or simply heating the tube. All this is pure losses in momentum and in energy. If reaction zone is extended, three times then losses are also increased approximately as many times. It is possible to show that heat emission of reaction will become insufficient for maintaining the wave, and detonation will cease. At the same time lowering of temperature from 2000 to 1700 signifies lowering of velocity of wave by 8%. Therefore, detonation has narrow limits with respect to speed.

To lower the temperature by 300°, that is by 16%, it is sufficient to add to the mixture the same percent of inert gas. Then the heat of reaction will be unproductively expended on heating the gas, not liberating heat in turn. Hence one may see why a small addition of inert gas can make a mixture incapable of detonating. These considerations belong to Ya. B. Zel'dovich.

Studying the role of losses on friction against walls of the tube, K. I. Shchelkin increased roughness of tubes artifically. For instance, the internal wall of tube was covered with a wire spiral. In a surprising manner it turned out that in such tubes mixtures lying outside the concentration limits for smooth walls detonate.

However, Shchelkin managed to explain this in a natural manner. A shock wave, striking the coils of spiral, is reflected from them. In reflected wave, as we know, pressure and temperature are increased a few times. There, where temperature was increased, chemical reaction rate in mixture sharply increases. Reflected sections of shock wave ignite it, and then burning propagates all over section in the gas. That part of it which is compressed by the incident shock wave far from the walls also burns.

Detonation proceeds in an unusual manner also in smooth tubes near the concentration limits. This special form of detonation was discovered in 1926 by Campbell and Woodhen. We will describe it ir the form in which it is now known, and we will tell about experiments, used for proof of the picture accepted now.

It turns out that if a flat shock wave near the limits is incapable of igniting gas, then it changes its own profile in such a way as to preserve a separate section with sufficiently high temperature.

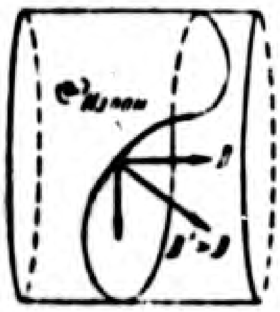

Fig. 31.
KEY: (a) Break.

In Fig. 31 such a detonation wave is depicted approximately in lateral projection; D - is the velocity of propagation of detonation through the tube, D' is the speed of break. On it fold will be formed, or section at an oblique angle to the axis of the tube. On boundaries of oblique section in fact Mach configuration appears, which we did not show in Fig. 31 in order not to encumber it. But every point on front of shock wave can shift through the gas only perpendicular to the surface of front. Consequently, there are component speeds not only along the axis of the tube, but also perpendicular to it. As a result the fold not only moves together with the wave, but also slips along the circumference of tube. Gas does not accomplish rotation with this: the fold goes along the surface of the front, like a wave on water. (That water does not move together with wave Leonardo da Vinci already noted).

Thus, the fold moves both forward, and in rotation. Put together, both these motions give resulting helical displacement, the velocity of which, obviously, is greater than axial speed of wave. Consequently, on fold the front of shock wave runs relative to unburned gas faster than flat shock front would run. Temperature of gas on front of wave is approximately proportional to square of its velocity.

Therefore, the fold much more easily ignites the gas than the flat front would ignite it. Afterwards combustion spreads over the entire gap of the tube (on several radii, plotted its length). But since igniting occurs at increased temperature, the entire reaction zone turns out to be shorter than it would be with a flat front. From this losses decrease, and wave becomes able to maintain itself.

If one were to make the tube of durable material and cover its internal surface with some substance, on which there remain traces, for instance, of soot, then on the path of fold there indeed remains a helical furrow.

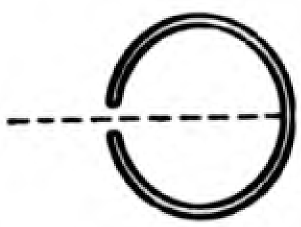

Fig. 32a.

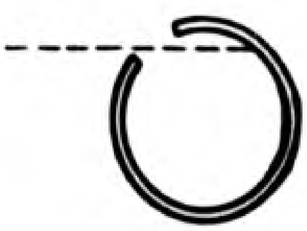

Fig. 32b.

It is possible to note rotation also by another method. For this it is necessary to make on the tube a transparent window of strong material. If we photograph the tube in such a manner that line of sight struck the window directly on diameter (Fig. 32a), then bend or fold, (which shines brighter than remaining part of the wave), passes by the window in identical intervals of time. It is seen also when it directly touches the window, and when it is diametrically opposite the point. If however we photograph as is shown in Fig. 32b, then the fold will be seen through window not on diameter, but on chord. After one turn two flashes also will be seen, but separated by unequal intervals of time, respectively with short and long arcs of circumference.

Frequency of rotation reaches up to 70,000 rps.

Such a detonation is called spin, from the English word signifying rotation. It has nothing in common with spin of electron besides the root of the word.

Spin detonation is obtained only at the limit itself. Taking concentrations of mixtures farther from the limit, more complicated pictures of propagation of detonation wave can be obtained. K. I. Shchelkin, Ya. K. Troshin and Yu. N. Denisov studied them. They observed that trace of wave on surface of soot further from limits does not have spiral-like, screw form, but looks quite different. The entire surface of soot is as if divided into cells and becomes like leather sofa. The named authors interpreted the origin of cells thus. On surface of the front two or more transverse sections run toward each other. These sections meet, are reflected from one another and run in the opposite direction, then are reflected from the walls and meet again. Cells on surface of soot are obtained because they are traced by opposite slanting waves. Of course such waves have greater temperature on front than a direct shock wave; after all their velocity relative to the unburned gas is correspondingly greater. Where waves collide, the temperature is increased still more strongly, here are main focuses of igniting gas.

This picture no longer is strictly stationary, like straight wave or helically running spin wave. But this process is periodic, in conformity with frequency of collisions between slanting waves. The nearer the detonation to the normal, the further it is from the limit, the greater the frequency of oscillations, and the smaller the waves. They are turned into a ripple, and then the front of shock wave becomes absolutely smooth.

This, of course, does not disturb the correctness of the general theory of detonation presented in the preceding paragraph. It is true for any mechanism of igniting, if, of course, the mixture is ignited by the detonation wave itself, and not, for instance, by a sequence of electrical sparks along axis of tube. But picture of detonation near limits turns out to be essentially nonplanar, so that theory of limits of detonation should be definitized in corresponding direction.

14. Detonation of Condensed Substances

Detonation of solid and liquid explosives produces much greater destructive action than detonation of gases. This is explained by the fact that chemical energy in liquid and solid body is collected in much smaller volume. Roughly speaking, per unit of volume in condensed explosive is collected a thousand times more energy than in gas.

Detonation of condensed explosives, or, as military abbreviate them. VV, is studied less than detonation of gases.

For this there are two reasons. First, the mechanism of course of chemical reactions in solid body is much more complicated than in a gas. Here it is impossible to present the interaction between molecules as totality of separate collisions. Molecules of solid or liquid body all the time are in contact among themselves, and here reaction proceeds not owing to specially energetic molecules. But apparently, active centers, that is atoms or their groups with free valences, play an essential role.

After reaction passed and VV was decomposed into components (usually carbon monoxide CO, water vapor H_2O, nitric oxides, etc) they all at first were packed just as densely as up to decomposition. Consequently, the products of explosion initially are compressed to density of solid body, but during expansion change into gases. About gases in so dense a state very little is known. And this is the second reason why detonation of condensed VV is little studied.

Mechanism of course of reaction, of course, is very important and is interesting by itself. But in the first place it is necessary, of course, to know how to apply the general relationships of the theory of detonation, such as the Chapman-Jouguet condition, to detonation of condensed VV. Into this condition there enters, as we saw in Section 12, speed—of sound in products of explosion, which equals the very velocity of detonation relative to products of explosion. As the speed of sound is simply expressed in not-compact gases, so it is complicated to express it theoretically in gases compressed to density of solid body, when molecules touch each other.

The first researchers tried to consider this circumstance, considering molecules as solid balls. This model of moleucles is convenient when their separate collisions with each other are studies, but it very badly reflects the real properties of solid substance.

L. D. Landau and the already mentioned K. P. Stanyukovich found the correct approach to the question. They paid attention to that circumstance, that in very compressed gases pressure can have double nature. Besides that pressure which is produced by thermal motion of molecules and appears in gases of usual density, in dense products of explosion purely elastic pressure should also exist. It appears simply from very close approach of molecules and is connected with the potential energy of their compression, and not with kinetic energy of motion. Strongly compressed gas conducts itself as a clump of linked springs, and low-density gas as a cluster of flies beating against a wall. Pressure is formally defined as force, acting per unit of surface of wall. It is clear that it appears both during compression of springs, and also with disorderly blows, if they occur sufficiently frequently. But, of course, the nature of "thermal" and elastic pressure is absolutely different.

Just as much different in their own nature are thermal and elastic energy of compressed gas. The first is kinetic, and the second potential. The role of this potential energy and pressure corresponding to it were correctly estimated by L. D. Landau and K. P. Stanyukovich.

Picture constructed by them of the state of super-dense gas of course has a semiqualitative character. It would be very difficult to create an exact quantitative theory which would connect pressure, density, temperature and energy of products of detonation in the entire interval of states from the greatest to the least density, and the chief for all explosives. After all, products of explosion of various explosives have different composition. Therefore, it is impossible to indicate a total quantitative regularity; elastic forces between different molecules are not identical. Theory of L. D. Landau and K. P. Stanyukovich, in which general correct approach to the problem is found, in a certain sense can be considered final; a more exact theory of necessity will appear less general.

L. D. Landau and K. P. Stanyukovich correctly estimated the dependence of velocity of detonation on initial density of explosive. In contrast to detonation of gas mixture, velocity of which practically does not depend on initial density, velocity of detonation of condensed explosives is approximately proportional to their initial density, the so-called density of charging. The greatest density of charging of such explosives as trinitrotoluene (trotyl) is a little more than 1.5 g/cm^3, and velocity of detonation is 7 - 8 km./sec.

Theory allows us to calculate pressure in detonation wave and velocity of substance in it. Pressure for explosive of trotyl type turns out to be of the order of 200,000 - 300,000 atmospheres, and velocity of substance near 3/4 of detonation velocity. Huge pressures in flat wave can be still intensive in convergent wave.

Very little is known about chemical processes during detonation of condensed explosives. The assumption was expressed that atoms in molecules of such explosives occupy a little-stable postion of equilibrium, like the equilibrium of a pencil, set with unsharpened end on horizontal table. With strong compression in detonation wave atoms emerge from these postions and then do not return to them. Instead of this they are reconstructed in stabler positions, to which corresponds the composition of superdense mixture of products of explosion. Mainly at the expense of elastic energy of these compressed molecules is the energy of detonation freed.

But if the assumption expressed here about the simple transition of atoms from less stable equilibrium to more stable under the influence of compression was true, then also slow static compression would produce the same effect - explosion. In fact explosion is produced not by static, but by shock compression. This may seem well when transmission of detonation from one explosive to another is studied.

Such a transmission has by no means only academic interest, since in practice always large mass of substance detonating with difficulty (for instance, trotyl) explodes from easily detonating - of the type of mercury fulminate. Until use, they are kept separately (as far as possible).

Lead azide detonates especially easily. In the experiments of A. F. Belyayev, M. A. Sadovskiy and I. I. Tamm at the Institute of Chemical Physics of the Academy of Sciences of the USSR, it was shown that shock wave with amplitude of pressure of 30 atm is sufficient to cause detonation in pressed powder of lead azide. It, detonating, develops pressure of more than 100,000 atmospheres. It is difficult to assume that 30 atmospheres could lead out atoms of crystal substance from positions of equilibrium so much that after this reconstruction should occur.

In fact, during shock compression of powder the air in its pores is heated. Fast load from incident shock wave leads to the fact that air in pores experiences adiabatic compression, that is does not succeed in returning heat to surrounding solid matter. Adiabatic compression up to 30 atmospheres heats air to 1,200°. Then from this decomposition of lead azide starts, which proceeds so violently that detonation wave is developed.

During denser pressing larger amplitude of pressure in incident shock wave is needed also, since with equal pressure compression of air in pores is the further from adiabatic, than the smaller pores. After all the transmission of heat proceeds through boundary of volume, so that it is easier to return heat to small volume than to big; then adiabatic compression requires full thermal insulation. Considerations presented here concerning the role of bubbles are widely spread, but cannot be considered proven.

It is curious that lead azide in general can exist only in the form of powder of small crystals. If a sufficiently large crystal grows, then it detonates by itself; why - is now unknown.

If we take liquid explosive nitroglycerine, then detonation is transferred to it thanks to small bubbles of air included in it. Nitroglycerine is a sufficiently viscous liquid so that small bubbles do not emerge from it. Air in bubbles is compressed and is heated in the same way as in pores of lead azide. Heating leads to explosive decomposition of nitroglycerine.

If bubbles are excessively small, then during the time of compression air succeeds in returning its own heat to surrounding liquid substance and does not reach such a high temperature, which is needed for explosive decomposition. Then detonation does not occur. In quite pure nitroglycerine, free of any bubbles, shock wave with pressure near 100,000 atmospheres is needed, in order to cause detonation. This already is close to pressure caused by the detonation wave itself. Such nitroglycerine will not explode, even if we fire a bullet into it.

Role of heating up is easily seen in the following experiment. Nitroglycerine, absolutely purified from bubbles, is poured into vessel and is plugged, leaving a bubble of air at the top. Then the vessel is shot through. Then if bubble is small, detonation does not occur. If bubble is a little larger, the bullet causes detonation, but if it is still larger, nitroglycerine again does not detonate. Consider that bubble is compressed especially strongly when oscillations of density in the vessel caused by bullet fall in unison with oscillations of bubble. Then compression and heating up of air in it are especially strong*).

Detonation wave in condensed explosive can be caused not with any form of charge. If we give it the form of a thin sausage, then detonation will not

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*) This fact L. G. Bolkhovitinov reported to me.

propagate along its length. Yu. B. Khariton explained this unique limit of detonation by the fact that compressed substance after front of shock wave scatters before it succeeds in reacting.

Sometimes thin sausages also detonate, but with significantly lesser velocity, - of the order of 2 or 2.5 km/sec. Apparently in wave with this full decomposition of explosive does not manage to occur.

15. Nuclear Detonation

In 1919 E. Rutherford for the first time in the world artificially produced a nuclear reaction. Before this only spontaneous transformation of nuclei was known - their radioactive disintegration. One of forms of such disintegration is emission of nuclei of helium, or alpha particles. Bombarding nitrogen with alpha particles, Rutherford accomplished the following reaction; nitrogen + alpha particle = proton + isotope of oxygen, that is oxygen with atomic weight of 17 (in nature oxygen with atomic weight of 16 is much more widespread).

Energy of escaping protons in this reaction is less than for incident alpha particles. Using term, accepted in chemistry, we say that this reaction is endothermic; it requires expenditures of energy of reacting particles.

But there are also exothermic nuclear reactions, which liberate more energy than is brought in. Before writing equations of such reactions, we will explain the accepted symbolic designations. Nucleus is written the same as element to which it belongs, while atomic weight is written above, for instance, H^1 is the nucleus of usual hydrogen, that is proton, H^2 is the nucleus of heavy hydrogen, or deuterium, H^3 is the nucleus of tritium, or super heavy hydrogen. In this symbolism alpha particle is designated as He^4, light isotope of helium He^3, Li^6 and Li^7 are - isotopes of lithium, and n - is a neutron.

The following can serve as examples of exothermic reactions.

$$H^2 + H^2 = He^3 + n, \quad (1)$$

$$H^2 + H^2 = H^3 + H^1, \quad (2)$$

$$H^2 + H^3 = He^4 + n, \quad (3)$$

$$Li^6 + n = He^4 + H^3, \quad (4)$$

We will talk about these four reactions in this paragraph. First two of them give approximately identical yield with equal energy of initial nuclei; their energy release if also approximately equal.

In nuclear physics special unit of energy - million electron volt is used. One elementary charge, passing potential difference of million volts, obtains this energy. In abbreviated fashion they say megavolt. In one erg there are around six hundred thousand megavolts. Reactions (1) and (2) liberate around 3.5 megavolts in the form of kinetic energy of products and (3) whole 17 megavolts. This is one of the record-breaking magnitudes for nuclear physics.

Energy of splitting of uranium with a neutron yields 180 megavolts, but with this per unit of mass even somewhat less energy than in reactions (1) and (2) is necessary. In reaction (3) output of energy is 3.5 megavolts per unit of mass. With this the energy of particles entering into the reaction can be 1,000 times less.

Soon after discovery of exothermic reactions there appeared the question about whether they can serve as source of energy. If we talk about laboratory conditions, in which these reactions were carried out for the first time, the answer can be only negative. The fact is that far from every sent particle produces a nuclear reaction. Majority of them uselessly squander their own energy on knocking out of electrons from shells of neutral atoms of the bombarded substance.

Only one hundred-thousandth or even one millionth of all particles succeeds in reacting with the nucleus before it expends its own energy.

After the energy is expended, flying particle cannot closely approach another nucleus any more; after all, all the nuclei have positive electrical charge and are repulsed from each other.

Here, however, there is one important peculiarity which must be noted. So that one deuteron, that is heavy hydrogen H^2, could closely approach another, overcoming electrostatic repulsion, it should possess kinetic energy approximately of one megavolt. In fact it turns out that nuclear reaction gives noticeable output and with energy of deuteron of several tens of kilovolts, and even at ten kilovolts. If we consider the motion of such a deuteron according to the laws of classical mechanics, then it should be repulsed from its own partner long before it approaches it. But in reality, the laws of classical mechanics are not always applicable to motion of nuclei.

According to quantum laws the motion of particles is similar to the propagation of waves, so that repulsion of two charged particles is reminiscent of reflection of waves from barrier. But any wave, even when it is reflected, always (although a little) penetrates the reflecting barrier, if the barrier is not absolutely hard. This small penetration turns out to be sufficient so that the deuterons touch and react.

In distinction from Newtonian laws, which on initial state of system with complete authenticity predict further movement, as in astronomy solar eclipses are predicted, quantum mechanics allows us to predict only the probability of one or another event. Waves which describe the propagation of particles permit to determine the probability of appearance of particle in one or another point of space. For instance, by energy of flying nucleus H^2 it is possible to calculate the probability of the fact that it, in spite of repulsion, will penetrate another nucleus of H^2 and will cause a reaction.

This probability very strongly drops with decrease of energy. Therefore, so that reaction yields good output, it is necessary strongly to accelerate the flying particles. But then the energy, released in the reaction in no way will cover expenditures on acceleration, if we consider that huge majority of accelerated particles in general do not produce a reaction, but only knock out electrons from atoms in their own path. These particles "perish" uselessly.

Another matter is neutrons - they do not have electrical charge and, consequently, are not repulsed from nuclei, but freely penetrate into them. They do not knock out electrons from atoms and, therefore, do not squander uselessly their own energy on the way through substance.

If neutron somehow is obtained, then its effectiveness for another nuclear reaction is almost hundred-percent. On neutrons reaction proceeds (4). Chain uranium or plutonium fission also proceeds on neutrons. Therefore, fission turned out to be the first reaction in which man liberated nuclear energy in large quantities.

After that the question was set anew, is it impossible to obtain also self-supported reactions on charged particles, type or reactions (1), (2), (3). For this it is necessary that nuclei do not yield their own energy to atomic electron. There will not be such an energy transfer, if the atoms remain without electrons—are bared. This is possible only at very high temperature. If a significant part of the energy liberated during a nuclear reaction between charged particles is expended in order to hold the substance at such a high temperature, then the reaction indeed will be able to maintain itself. In order to simply detach electrons from atoms, relatively small energy is needed, but very combustible substance emits much energy into the surrounding space. Liberation of nuclear energy in reaction $H^2 + H^2$ exceeds loss by radiation only at a temperature of several tens of millions of degrees. At lower temperature kinetic energy of nuclei is still so small that reaction proceeds at low rate and does not compensate losses by radiation.

In bowels of stars radiation is locked in huge thickness of substance. There everything is in thermal equilibrium with each other: nuclei, and electrons, and electromagnetic radiation. Colliding with electrons, nuclei on the average yield to it as much energy as they obtain from them - this also is condition of thermal equilibrium. In other words nothing hinders each nucleus able to enter into the reaction from reacting.

Such a nuclear reaction at very high temperature is called thermonuclear (see Section 10). It is a source of solar energy, and, obviously, the original cause of our existence.

But in terrestrial conditions it is impossible to maintain for a long time the same conditions as inside the sun. During atomic explosion, for instance, state of substance close to stellar is less than one millionth of second. These stellar conditions are created in this case not owing to thermonuclear, but owing to chain reaction on neutrons. Is it impossible, at least just as briefly, to cause self-supported thermonuclear reaction, whose energy would heat substance to such a high temperature, at which reaction proceeds?

Here a thought about detonation intrudes. Is it possible, for instance, using the usual atomic bomb as a detonator, to cause detonation wave, running through deuterium (that is heavy hydrogen) similar to that which spreads in explosive substance? Detonation of deuterium would give ten million times more energy per unit of mass than, for instance, detonation of trinitrotoluene.

To calculate such a wave in deuterium according to the usual formulas of the theory of detonation is not any labor. At first glance it can appear that the difference between nuclear and chemical detonation is purely quantitative, if trotyl, let us say, detonates, then why does deuterium not detonate, if we explode it properly?

Let us note that detonator of such a reaction, the usual atomic bomb, cannot liberate energy more than a certain upper limit, which is set by the fact that it is impossible sufficiently rapidly to create an excessively large supercritical mass from subcritical. After all up to explosion isotope of uranium 235 or plutonium should be subcritical, and this means that it cannot be in one piece. If however there exists sustained nuclear detonation, especially in such a cheap substance as deuterium, then force of bomb is not limited above by anything. Hence idea appeared of terrible bomb, which they called "hydrogen" before they were convinced of the possibility of its creation. And the possibilities, if we speak specially about nuclear detonation, turned out to be not quite the same as we assumed at first.

First of all it was proved that detonation of pure deuterium is unrealizable*). This is connected with unique losses peculiar only to nuclear, but not to chemical detonation.

The fact is that with chemical detonation temperatures are not too high, some 2,000°. With this thermal radiation absorbs an insignificantly small fraction of total energy and does not participate at all in the common energy balance.

Energy of substance grows, roughly speaking, proportionally to temperature, but energy of thermal radiation - proportionally to fourth power of temperature. Hence it is clear that at sufficiently high temperature thermal radiation always will absorb a very large part of total energy. But if energy is proportional to fourth power of temperature, then temperature, conversely, is proportional to root of fourth power from energy. Thus, temperature increases much slower than heat emission. If we admit that the substance is in thermal equilibrium with radiation, then temperature of substance also increases correspondingly slowly.

Let us assume now that nuclear detonation wave released all the energy included in deuterium, in such a way however that radiation obtained its own overwhelming fraction. Then temperature of substance will appear so low that nuclear reaction will be able to proceed only very slowly. And this means, that also the width

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*) See R. Lepp. Atoms and people, IL, 1959.

of zone of reaction will appear very great. If we image the detonating charge in the form of a long cylinder, then with any, (not absurd) diameter the substance in the reaction zone will be scattered to the sides before it succeeds in reacting at all noticeably.

It is possible to approach the question of detonation of deuterium in a somewhat different fashion. We will imagine usual atomic bomb, placed inside spherical deuterium charge. Then atomic explosion can cause detonation of deuterium only if it creates in deuterium the same conditions which would be accomplished in self-supported wave in the same volume. Spherical detonation wave itself would go further. But it turns out that atomic explosion is insufficiently strong in order to heat so great a volume of deuterium to thermonuclear temperature.

Radiation, in thermal equilibrium with substance, sets upper limit for temperature of deuterium. Even with full liberation of all nuclear energy, radiation would not allow temperature to be lifted above several tens of millions of degrees. For thermonuclear reaction in terrestrial conditions this is rather little. But cannot detonation proceed in unbalanced conditions, when the substance still does not succeed in coming into thermal equilibrium with radiation? After all, does establishment of equilibrium require known time? Beforehand it is not excluded that at very high temperature a thermonuclear reaction will proceed faster than thermal radiation will be emitted. Then radiation indeed will absorb less energy and will not so influence the temperature.

We said that losses very strongly affect the ability of substance to detonate. It turned out, however, that also with incomplete losses of energy by thermal radiation deuterium is not able to detonate. This gives idea of the difficulties standing in the way of the peaceful use of thermonuclear reactions, where there cannot be atomic detonators.

Reaction (3) of deuterium with tritium is one hundred times more probable than reactions (1) and (2). Therefore a deuterotritium mixture is capable of detonation.

There was an attempt to accomplish such a detonation experimentally during explosion of American nuclear device in 1952. Energy was released 75 times exceeding the energy of explosion of "nominal" atomic bomb with equivalent of 20,000 tons of trotyl. Exploding device weighed 65 tons (it had, besides other things, to maintain mixture up to explosion in liquid state). With respect to energy release it is clear that only 25 kilograms of deuterotritium mixture burned. How much of it was laid, we do not know. It is very probable that here there was obtained not a real detonation wave, but only a strong flash, which could not maintain itself.

It is doubtful whether such a system could be useful as a weapon. Besides tritium is obtained by means of irradiation of lithium with neutrons in nuclear reactors, according to reaction (4). But each neutron expended in this reaction could be instead of this expended on obtaining an atom of plutonium from atom of isotope of uranium 238. Plutonium fission releases 180 megavolts of energy, and reaction (3) - ten times less. Finally, tritium half disintegrates after 12 years and is therefore more difficult to store than stable material. Therefore deuterotritium hydrogen bomb "did not go".

What is then called a "hydrogen bomb"? *) Diagram of it consists of the following. Usual atomic bomb is surrounded by a layer of lithium deuteride, and it, in turn, by a layer of uranium 238 (uranium 235, of which in nature there is 140 times less, or plutonium goes into atomic bomb). During chain reaction in uranium neutrons partially change into lithium deuteride. It is strongly heated, and furthermore, reaction (4) proceeds in it. Tritium appears, which already by

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*) See M. B. Neymani, and K. M. Sadilenko, Thermonuclear weapon, Voyengiz, Moscow, 1958.

thermonuclear method reacts with deuterium - we indicated that this reaction proceeds easily. Reaction (3) creates fast neutrons with energy of 14 megavolt. These neutrons get into shell of usual uranium and cause fission in it.

Now already fission neutrons of uranium shell revert to lithium deuteride and form with it new nuclei of tritium. Furthermore, uranium from intense fission is heated and compresses light substance inside. This strengthens the thermonuclear reaction - in more solid substance nuclei collide and react more frequently. Let us note that this whole phenomenon naturally causes explosion, and not detonation.

Looking at device, in this bomb significant part of energy is released from usual uranium. Such a bomb poisons atmosphere with products of uranium fission. Therefore one should consider that concentrated blow on large territory for some time will contaminate the atmosphere all over the globe up to a very dangerous concentration.

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