EXPERIMENTAL STUDY OF THE DISINTEGRATION OF AN INSTANTANEOUSLY HEATED MEDIUM AND THE RESULTING IMPULSE AT ENERGY CONCENTRATIONS LESS THAN THE HEAT OF EVAPORATION

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An experiment using the radiation from a Q-switched laser was carried out to confirm the phenomenon of detachment of the surface layer of a material when it is rapidly heated at energy concentrations less than the heat of evaporation Q [1]. The disintegration of the material was recorded by high-speed photography. Measurements were made of the impulse I for different energy concentrations, and it was shown that the dependence of I on the supplied energy E was in good agreement with the theoretical calculations reported in [1].

It is shown that by determining the pressure impulse produced during the disintegration of the rapidly heated material it is possible to investigate its thermodynamic properties at densities approaching the normal value.

The detachment of the surface layer of the material under instantaneous heating at energy densities less than the heat of evaporation was described in [1], where an estimate was made of the resulting pressure impulse. The results described in [1] show that when an energy E_r is liberated in the surface layer of thickness x_r or mass m_r in a time $\tau < t_g$, where $t_g = x_r/c$ is the characteristic time for gas-dynamic processes and c is the velocity of sound in the medium, the pressure produced in the layer is $p^\circ = (\gamma - 1)E_r/x_r$. Interaction between rarefaction waves propagating from the boundaries of the heated layer results in the appearance of negative stresses. When these stresses exceed the dynamic strength of the material, detachment of the surface layer may take place. The pressure impulse produced during the surface-layer detachment in the case of a uniformly heated layer is given by

$$I = \frac{(\gamma - 1) E_r}{2 \sqrt{c_0^2 + \gamma(\gamma - 1) E_r / m_r}}, \qquad (0.1)$$

where γ is the adiabatic exponent and E_r/m_r is the amount of energy per unit mass. It is clear from the dependence of I on E_r that the values of I can be used to determine the adiabatic exponent γ or the Grüneisen coefficient $\Gamma = \gamma - 1$ at normal density ρ_0, i.e., it is possible to obtain data on the thermodynamic state of the instantaneously heated material. In this paper we report an experimental study of this detachment effect. We have investigated the general features of the formation of the pressure impulse predicted by I. V. Nemchinov, verified Eq. (0.1) and, finally, showed that the equation of state for the instantaneously heated medium can be determined by the method put forward in [1].

1. CHOICE OF MEDIUM

The medium to be investigated must have certain special properties. First, it is necessary that the amount of energy liberated per unit volume be sufficient to generate pressures leading to the disintegration of the medium and the appearance of the mechanical detachment impulse. The absorption coefficient for the ruby laser beam at the working wavelength ($\lambda = 6940$ Å) must not be too low. Secondly, the heating must be instantaneous, i.e., the heated layer cannot be too thin which, in turn, means that the absorption coefficient cannot be too high. Thirdly, since the output power of the laser which was available at the time of the experiment was relatively low, the medium had to have a low heat of sublimation and a low tensile strength, so that the detachment effect could take place.

A further restriction is introduced by the fact that we wish to confine our attention to the one-dimensional problem so that $d \gg x_0$, where d is the diameter of the beam spot on the surface of the target, and x_0 is the range of radiation. In actual fact, the use of small values of d and x_0 to achieve higher energy concentrations may have violated the conditions of instantaneous heating and one-dimensional formulation, while the use of higher values of d and x_0 at low total energy resulted in the fact that the upper limit of the range of values of E/m_0 was too low. We shall discuss these points in greater detail when we evaluate the experimental results. Ice and paraffin were chosen as the working media satisfying the above requirements.

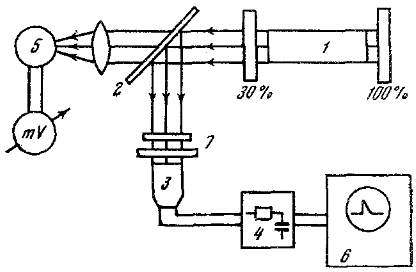

Fig. 1

Other materials with higher heats of sublimation (for example, glass, plexiglas, etc.) can be used with higher intensity laser beams.

A special dye was introduced into the working media to ensure molecular absorption of radiation and, therefore, heating without highly excited internal degrees of freedom, and the dissociation of these molecules did not lead to a change in the absorption coefficient. The most important parameters of the selected media are listed below.

Ice. Heat of sublimation 670 cal/g [2], velocity of sound $c_0 = 3.2 \cdot 10^5$ cm/sec [3] (for water $c_0 = 1.2 \cdot 10^5$ cm/sec [3]), density $\rho_0 = 0.95$ g/cm^3, tensile strength 15 kg/cm^2 [4], and $\rho_0 c_0 = 1.5 \cdot 10^4$ kg/cm . The use of methyl blue as the dye enabled us to obtain the required absorption thickness (range of radiation) which, in our experiments, was 0.1 or 0.2 mm. This corresponded to the characteristic gasdynamic time $t_g = 4\tau$ or $t_g = 8\tau$, respectively. The absorption coefficient of ice, $\varkappa$, was measured by exposing a layer of ice of known thickness to the laser beam and measuring the incident and transmitted energy with the aid of the FEK-09 and FEK-14 photocells.

Paraffin. High-molecular compound of the type C_nH_{2n+2} formed by molecules with different n. The heat of sublimation reported in [5] is 150—250 cal/g (this appears to depend on the degree of dissociation of the molecules). The velocity of sound in paraffin is $c_0 = 2.1 \cdot 10^5$ cm/sec, the density is $\rho_0 = 0.9$ g/cm^3 [3], and the tensile strength is unknown. The use of an anthraquinone dye enabled us to achieve absorption thicknesses of 0.15 or 0.30 mm, the corresponding gasdynamic times being $t_g = 3.5\tau$ or $t_g = 7\tau$, respectively. The absorption coefficient of paraffin was measured by two methods: 1) as in the case of ice, and 2) by placing the material between thin glass plates and attaching a thermocouple to this three-layer sandwich, which measured the change in temperature when the laser beam was passed through the system (the experiment was performed in vacuum). This method of measuring the range of radiation enabled us to determine directly the energy absorbed in the layer, and in the case of scattering media such as paraffin, it was found to be better than the other method. The absorption coefficient of ice and paraffin was measured at liberated-energy densities in the medium of between 10 and 80 cal/g. The accuracy of the measurements was about 20%.

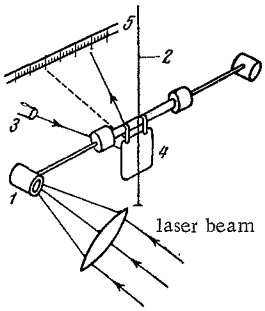

Fig. 2

2. APPARATUS

The experimental arrangement is illustrated in Fig. 1. The source of the radiation used for instantaneous heating was a ruby laser (1) operated under giant-pulse conditions. The pulse length at half-power points was $\tau = 2.0 \times 10^{-8}$ sec. The total energy and shape of the light pulse were determined by a type FEK-09 photocell (3) placed after the filters (7). The measurements were carried out with an SO-1 or OK-17 oscilloscope (6) which was preceeded by an integrating circuit (4). The monitoring system was calibrated by a black-body receiver (5) in the form of a hollow sphere with an attached thermocouple. A special torsional balance, illustrated schematically in Fig. 2, was constructed to determine the pressure impulse.

The target (1) was in the form of a metal cylinder with the working material inserted into it. The cylinder was placed on the torsional balance, the balance wire being a tungsten thread (2) having a diameter of 0.11 or 0.20 mm and fixed at the ends. The pressure impulse was measured by a system consisting of a lamp (3), reflecting mirror (4), and scale (5). In addition to the instantaneous impulse, measurements were also made of the rate of material loss. This was done with an SFR high-speed camera operating as a time magnifier (maximum rate of exposure 5×10^5 frames/sec. The emitted material was photographed by illuminating it with an external pulsed source of light. The detachment effect and the pressure impulse were photographed in a vacuum of about 1–2 torr. The experiments had to be carried out in vacuum because, at atmospheric pressures, even low-intensity laser beams ($2 \cdot 10^8$–$5 \cdot 10^8$ joules/cm$^2 \cdot$ sec) gave rise to air breakdown (flash) at the surface of the obstacle (medium under investigation), which was similar to the phenomenon observed under sharp focusing of the giant pulse without any obstacle [6–12] at intensities of 10^{10} joules/cm$^2 \cdot$ sec or more.

A flash was observed not only when the laser beam interacted with absorbing obstacles (in our case ice and paraffin), but also at the surfaces of transparent media such as plexiglas. The development of this phenomenon was photographed with the SFR-R camera at a rate of $50 \cdot 10^6$ frames/sec.

Experiments showed (Fig. 3) that the velocity v of the front of the flash reached up to 20 km/sec at the surface of the target, and then rapidly fell with increasing distance from it. The flash formation is unrelated to the disintegration process for a number of reasons. First, when the medium is heated at energies of the order of the heat of evaporation, one can hardly expect it to become highly luminous. Secondly, the rate of disintegration, i.e., the mass velocity of the emitted medium, was estimated at the given absorbed-energy densities to be a few hundred m/sec.

The spectrum of the flash was recorded and was found to consist of lines corresponding to singly and doubly ionized atmospheric components (nitrogen and oxygen). There was also a relatively strong continuum, indicating that the temperature in the region of the flash was quite high. In our experiments the flash was an undesirable effect since it consumed about 30% of the laser energy even at low energy densities. The flash also had an additional and very marked effect on the target. Without going into the details of this effect which will have to be examined separately, let us merely note that by placing the obstacle in a vacuum we were able to avoid the flash effect completely for all the media.

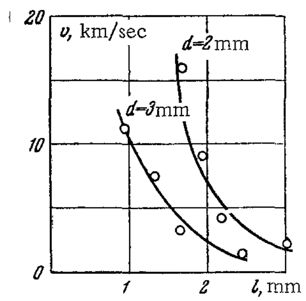

Fig. 3

3. DETACHMENT EFFECT AND MECHANICAL IMPULSE AT ENERGY CONCENTRATIONS LOWER THAN THE HEAT OF EVAPORATION

The detachment impulse was measured as described above. The specific impulse I per unit area of the laser beam at the surface of the target is shown in Fig. 4 as a function of the maximum absorbed-energy density in paraffin, where 1 is the experimental curve, 2 and 3 are theoretical curves for $\gamma \neq$ const, and 4 and 5 are theoretical curves for $\gamma = 3.7$. Curves 3 and 4 correspond to energy concentrations $f(m_W) = 20$ cal/g, while curves 2 and 5 correspond to 10 cal/g. It follows from this figure that the impulse appears at absorbed-energy densities much less than the heat of evaporation—right up to 20 cal/g. It is clear that the absorbed energy (20 cal/g) corresponds to negative stresses which are equal to or less than the absolute magnitude of the dynamic tensile strength σ of paraffin. For $\gamma = 2$ this value ($E/m_0 = 20$ cal/g) corresponds to $\sigma = 400$ kg/cm^2 [1]. The spread in the values of the impulse in this region appears to depend on random factors (differences in the tensile strength and nonuniform distribution of beam energy). These experiments confirm the existence of the detachment effect at energy concentrations $f(m) < Q$, which is accompanied by a mechanical impulse. High-speed photography also confirms that the impulse is produced by the emission of surface material.

Figure 5 shows successive frames of the disintegration of paraffin for different energy concentrations. Figure 5a corresponds to $E/m_0 = 100$ cal/g and shows that there is an initial formation of the gaseous phase propagating with a velocity up to 300 m/sec and corresponding to the hotter surface layers. This is followed by solid material traveling with a velocity of 50–100 m/sec. Small and large pieces of the fragmented material are clearly seen. For smaller values of E/m_0 (in particular $E/m_0 = 15$ cal/g; see Fig. 5b) there is no gaseous phase. It is clear from Fig. 5b that ejection of surface material occurs for a mean energy concentration in the surface layer of 10–20 cal/g. The accuracy of the torsion-balance measurements suggests that the impulse in this region does not exceed 5–10% of the impulse for energy concentrations of 20 cal/g (the impulse falls rapidly from 40 to 2 dynes · sec/cm^2; for $E/m_0 < 20$ cal/g there is no measurable deflection along the scale.

Analysis of the photographs shows that the area from which the material is ejected is much smaller than the total irradiated area. Measurements were made of the uniformity of the energy distribution over the cross section of the beam by photographing the beam directly.

Figure 6 shows one such photograph (they were found to be reproducible with good accuracy). The energy-density variation along AA and BB was characterized by a plot of the function $J = J(x)$, where J is the energy density and x the distance along the chosen line. It is clear that the energy density varies across the beam by not more than a factor of two. The ejection of material for $E/m_0 < 20$ cal/g is connected with the fact that, in the region of maximum energy concentrations in the plane of the figure, the concentration is still insufficient to produce the detachment effect. No ejection of material was observed for mean energy densities over the area of less than 10 cal/g.

Figure 4 shows the theoretical dependence of the impulse on the energy density E/m_0. Equation (0.1) was obtained for uniform heating. It can be generalized to the case of nonuniform heating by assuming that it is valid for each elementary area. We then have

$$I = \int_0^{m_w} \frac{(\gamma - 1) f(m)}{2\sqrt{c_0^2 + \gamma(\gamma - 1) f(m)}} dm, \qquad (3.1)$$

where $f(m)$ is the energy per unit mass and m_W is the total mass of the detached layer. An analysis of the various associated processes was given in [1] for both uniform and nonuniform heating at low energy densities. The mass m_W of the detached layer can be found from $f(m_W)$ if it is assumed that the liberated-energy distribution is known and use is made of the relation between the initial pressure $p°$ and the dynamic tensile strength σ:

$$p° = \rho_0 f(m_w)(\gamma - 1) = 2\sigma. \qquad (3.2)$$

For a constant absorption coefficient we have the usual energy-liberation function:

$$f(m) = E / m_0 \exp(-m / m_0). \qquad (3.3)$$

It is also possible to use the experimental values of $f(m_W)$ deduced from the minimum E/m_0 for which the impulse due to the detachment effect is still detectable.

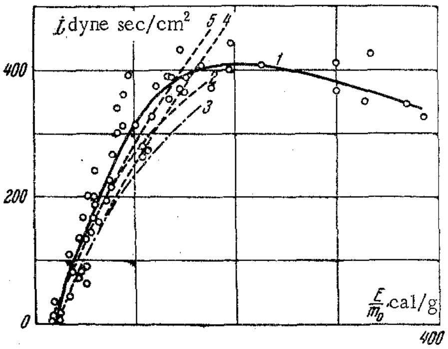

Fig. 4

Substituting Eq. (3.3) into (3.1) and integrating, we have

$$I = m_0\gamma^{-1}\left(\sqrt{c_0^2 + \gamma(\gamma - 1) E/m_0} - \sqrt{c_0^2 + \gamma(\gamma - 1) f(m_w)}\right). \qquad (3.4)$$

In the same way as Eq. (3.1), this formula has a limited range of validity, i.e., it is valid provided that $f(m) \lesssim Q$; moreover, we have assumed that γ was constant. It is expected that γ decreases as the heating takes place.

The values of γ for $\rho = \rho_0$ have so far been obtained only for a small number of materials. It was suggested in [1] that γ could be determined from Eq. (0.1) and measurements of the impulse for uniform heating.

4. DETERMINATION OF γ FROM THE IMPULSE FOR UNIFORM HEATING.

Consider a layer of the material whose thickness is a small fraction, say 1/3 or 1/4 of the range of the radiation, so that the energy distribution in the layer is practically uniform. Thus, if the thickness is 1/3 of the range, the maximum concentration will exceed the minimum concentration by 20%. We have carried out experiments to investigate the impulse produced by heating thin layers of paraffin with different dye concentrations. For dye concentrations of 1% and 0.5% the range of the radiation was found to be 0.15 and 0.30 mm. The thickness of the layer was 0.05 and 0.1 mm. Further reduction in the layer thickness with the aim of producing more uniform energy distribution would lead to noninstantaneous heating.

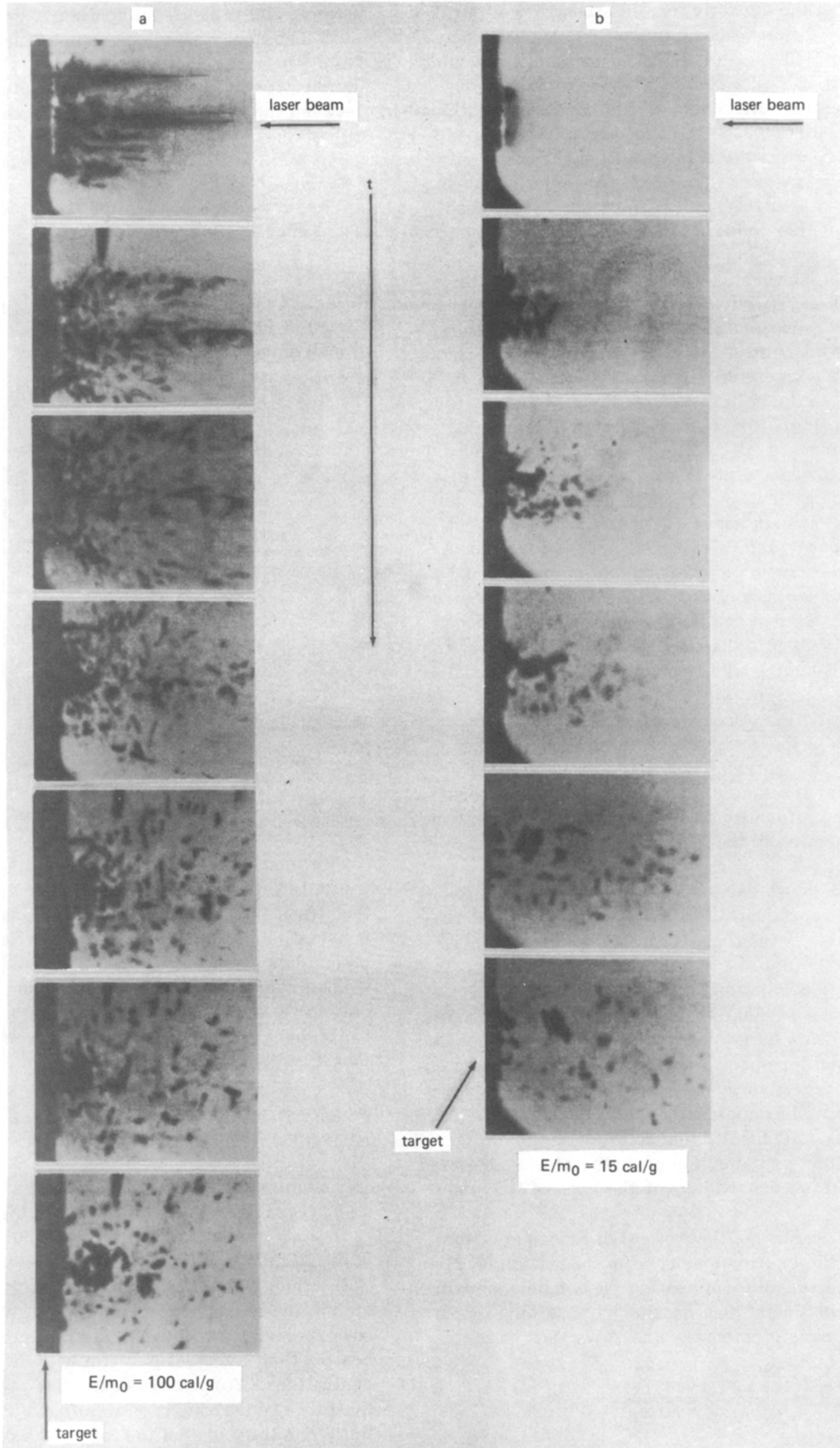
a
b
laser beam
laser beam
t
target
target
E/m0 = 100 cal/g
E/m0 = 15 cal/g

Fig. 5

In these experiments the paraffin was deposited on transparent optical glass so that the gasdynamic situation was somewhat different from that discussed in [1]. In the present case we have vacuum on one side of the medium and a rigid underlying surface on the other. This means that pressure relief is produced only by the rarefaction wave propagating from the free surface. To find the adiabatic exponent γ from the measured impulse we can then use Eq. (0.1), but we must introduce a factor of 2 to take into account the increase in time during which the pressure is present (in reality, a small correction was introduced for the effect of the paraffin-glass boundary).

The specific impulse I (dynes·sec/cm^2) is shown in Fig. 7 as a function of the energy density E/m (cal/g) for a paraffin layer of thickness x = 0.10 mm.

The detachment impulse appears for $E/m_0 = 15$ cal/g (compare this with the value $E/m_0 = 20$ cal/g). This appears to suggest that the cohesive strength between paraffin and glass is close to the detachment strength of paraffin.

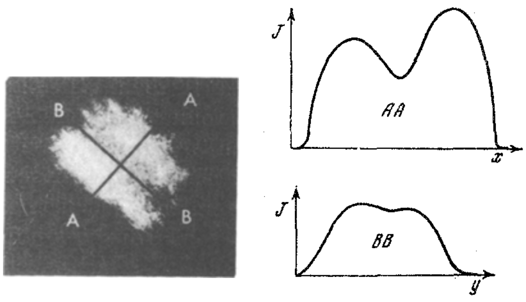

Fig. 6

Visual inspection of the thin layer of paraffin showed that the detachment effect does not occur for energy concentrations less than 15 cal/g (the paraffin remains on the glass; for large energy concentrations the entire layer leaves the surface completely on the irradiated area). However, for concentrations of 5–10 cal/g there are local detachment areas where the paraffin leaves the glass. We note that paraffin is a material with a relatively inhomogeneous structure.

We have used the data of Fig. 7 and Eq. (0.1) to calculate γ for different $f(m) = E/m_0$. The results of these calculations are shown in Fig. 8. The adiabatic exponent was found to remain constant up to $E/m_0 \approx$ ≈ 60–70 cal/g and then began to fall. If we assume that Eq. (0.1) is valid for E/m_0 close to the heat of evaporation, the reduction in γ occurs as a result of heating, and its minimum value is 2.06. Since no measurements of the absorption coefficients were carried out for $f(m) > 80$ cal/g, this part of the $\gamma(f)$ curve is shown dashed.

The function $\gamma(f)$ of Fig. 8 was used to calculate the impulse from Eq. (3.1), and the results are shown in Fig. 4. The dashed and dot-dash curves 2 and 3 show the minimum energy concentrations $f(m_W)$ equal to 20 and 10 cal/g, respectively. The dashed curves correspond to a constant $\gamma = 3.7$. It is interesting that the various curves corresponding to both constant and variable γ are not very different. For an exponential form of $f(m)$ [Eq. (3.3)] we can transform (3.1) so that

$$I = m_0 \int_{f(m_w)}^{E/m_0} \frac{(\gamma-1)\,df}{\sqrt{c_0^2+\gamma(\gamma-1)f}}. \qquad (4.1)$$

It is clear that the impulse corresponds to an average of $\gamma(f)$. Moreover, for $f \approx c_0^2$ the impulse I increases with increasing γ more slowly than for small f.

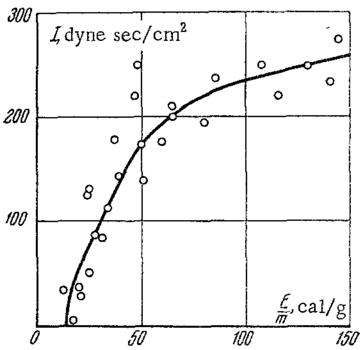

Fig. 7

For low energy densities the calculated and experimental curves are in good agreement, but for higher energy densities there is a discrepancy (there is even a fall in I with increasing E/m_0 which does not follow from [1].

The space of the experimental curves at energy densities close to or greater than the heat of evaporation (Figs. 4 and 7) can be explained by the following factors.

1) The effect of focusing conditions which are reflected in the fact that, to obtain high-energy densities, the value of d had to be considerably reduced (down to about 1 mm), which meant that the conditions $d \gg x_0$ and $d \gg x_W$ were not satisfied. The result was that there was an appreciable retention of material by the cold edges of the hot spot. This led to the formation of a conical depression (instead of the cylindrical depression for $d \gg x_0$ and $d \gg x_W$) and an appreciable reduction in the ejected mass and the impulse.

2) At high energy densities there may be an increase in the energy spent in breaking the intermolecular bonds in paraffin through the dissociation of complex molecules into simpler ones.

3. At high-energy densities, where it was difficult to measure the absorption coefficient, the values of this coefficient may be very different from those for E/m_0.

4. The formula given by Eq. (3.1) is itself only approximate.

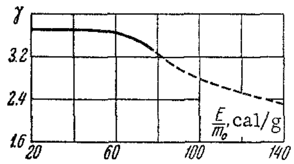

Fig. 8

Detailed studies of the detachment impulse at energies of the order of or greater than the heat of evaporation Q are being carried out at the present time, using a large focusing area and a higher laser-beam energy. This should ensure that the problem is two-dimensional in a broad range of energy densities. More accurate calculations of the disintegration of a heated medium are being carried out. It is also intended to improve the values of the absorption coefficient at high energy densities.

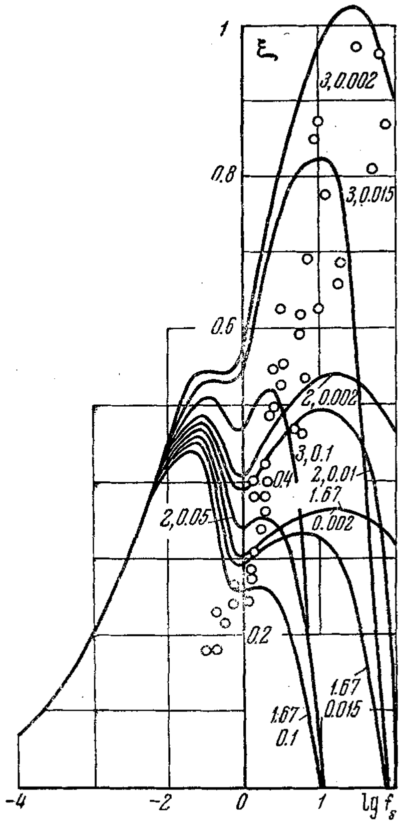
1
ξ
0.8
0.6
3, 0.002
3, 0.015
2, 0.002
3, 0.1
2, 0.01
1.67
0.002
0.4
2, 0.05
0.2
1.67
0.015
1.67
0.1
-4
-2
0
1
lg f_s

Fig. 9

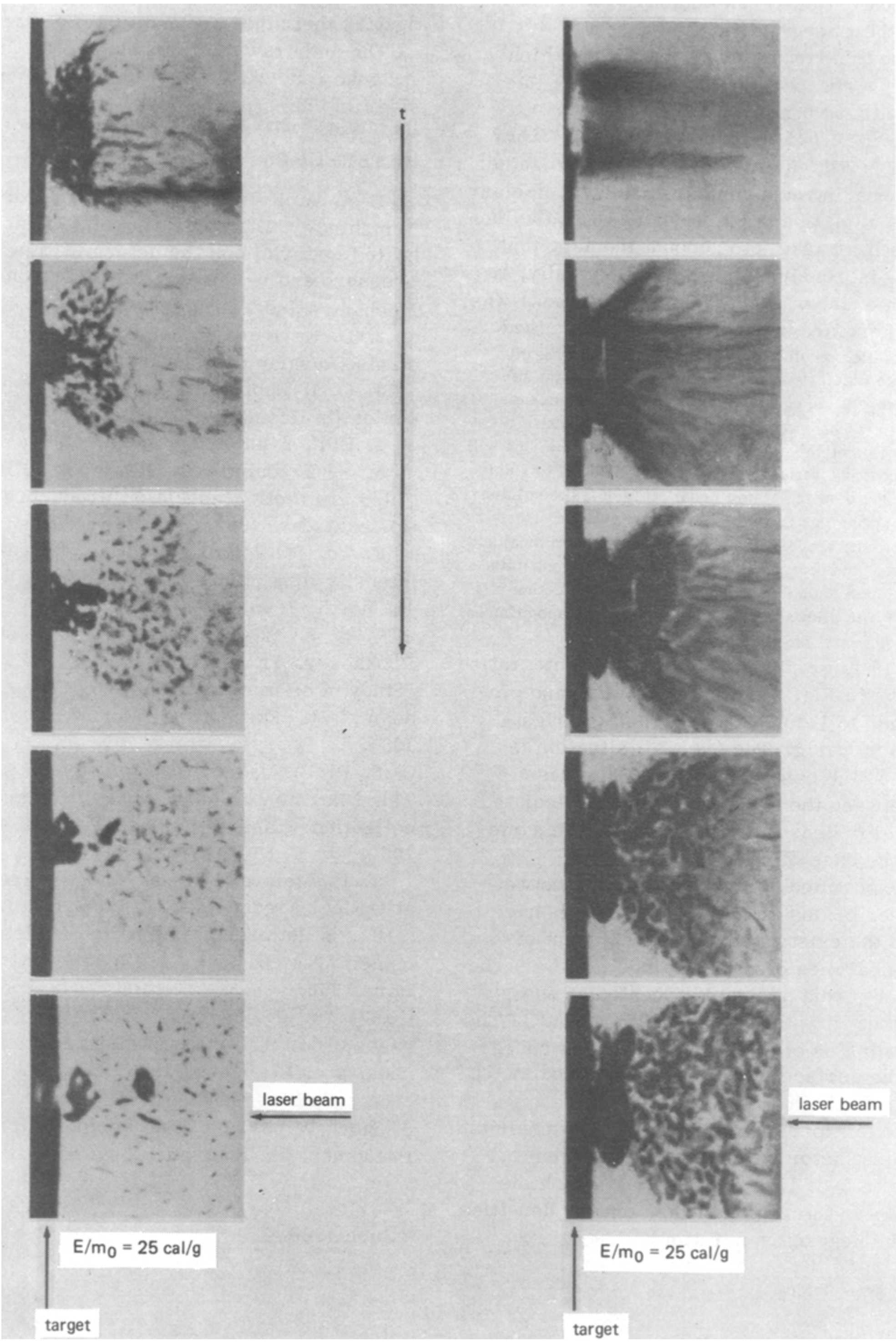

Fig. 10

Analogous properties were also investigated in the case of ice. Equation (0.1) can be used to find the relation between the energy utilization factor $\xi = I\sqrt{Q}/E$ and the parameter $f_S = Qm_0/E$, which represents the degree of heating. Functions of this kind were given in [1] for $\gamma = 3,\ 2,\ 1.67$ and $w = f(m_W)/Q = 0.002,\ 0.015,\ 0.010,\ 0.05,\ 0.10$). They are reproduced in Fig. 9 for $\lambda = c_0^2/Q = 0.75$ together with the corresponding experimental points. It is clear that the experimental points can be made to fit the theoretical curves if we take into account the fact that γ decreases with increasing temperature. Finally, the tensile strength of ice was not known [since $f(m_W)$ was too low] and, therefore, w could not be determined.

The tabulated tensile strength σ given in the literature may be different from the value which we have used here because of the different methods of preparation of ice and because these values were obtained under static conditions. We shall not, therefore, carry out a quantitative comparison of calculated and experimental data, but will merely note the fact that a variation of the energy supplied to a unit area by a factor of 200 shows an almost linear relation between I and E, as predicted in [1] (the coefficient ξ changes by a factor of only 3 to 4). It follows from the above relations that the maximum measured ξ lies in the range of low energy densities, and its order of magnitude is close to the maximum (calculated) value of ξ for the ejection of a gaseous medium [1] with allowance for energy losses in evaporation as expected from the estimates in [1].

High-speed photographs of the surface disintegration of ice are shown in Fig. 10, where the left-hand picture corresponds to $E/m_0 = 25$ cal/g and the right-hand picture to 50 cal/g. The over-all situation is similar to that in the case of paraffin. There is a discrepancy between the experimental and calculated data at high energy densities (probably for the same reasons as in the case of paraffin).

The above experiments on the interaction between Q-switched laser beams and certain materials have thus confirmed the existence of the detachment effect and the appearance of a recoil impulse I when the surfaces of such media are rapidly heated at energy densities not exceeding the heat of evaporation Q. The quantitative estimates of the impulse at given energy E supplied to the surface, which were reported in [1], have been confirmed.

Moreover, our experiments show that the maximum energy utilization factor lies in the region of energy densities close to Q or less, and may approach the maximum values in the region of high energy densities (in excess of the heat of evaporation).

We note that studies of the mechanical parameters of disintegrating materials reveal new ways of investigating their thermodynamic properties.

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