INVESTIGATION OF THE INFLUENCE EXERTED ON A SOLID BY LUMINOUS RADIATION FROM A SOURCE OF THE EXPLOSIVE TYPE

I. F. Zharikov, I. V. Nemchinov, and M. A. Tsikulin

Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, Vol. 8, No. 1, pp. 31–44, 1967

This article presents a qualitative description and analysis of various hydrodynamic and physical phenomena taking place when a solid surface is exposed to a long-term action of a sufficiently intense light flux.

The necessity of experimental studies of these phenomena is demonstrated by showing the complexity of the processes of heating and motion of a vaporized substance and the difficulty of producing an accurate description of the phenomena in question in the absence of certain essential data.

It is postulated that more powerful explosive sources, producing fluxes of 10^6 joules/cm^2 sec should be used as luminous radiation sources. Data is reported which were obtained by experiments using a source of this kind; the source generated a radiation pulse of 30 μsec whose spectrum corresponded to a temperature of $3 \cdot 10^{4\circ}$ K. These experiments proved the feasibility of using explosive sources in studies of the volatilization and heating of vapors under "quiet" conditions. High-speed motion pictures were taken of the luminescent zone produced at an irradiated surface, and the speed at which the boundary of this zone moves (200–500 m/sec) was measured. The luminescent zone was shown to be formed by vapors of the irradiated material. When luminescence was observed, an increase in pressure (up to several kg/cm^2) at the irradiated surface was recorded; this effect was attributed to the recoil action of vapors moving away from a boiling or subliming material surface. A time lag in the onset of volatilization was observed and attributed to the influence of the heat conduction in the material and to the reflection of a part of the incident radiation.

§ 1. Qualitative description and analysis of processes taking place during irradiation of solids. Many investigations are at present concerned with the effect of luminous radiation on solid surfaces and with the resulting hydrodynamic and physical phenomena.

Incident rays penetrate an irradiated solid to a depth which is commensurate with the mean free radiation path l_0 in the material characterized by its normal density ρ_0 and an initial temperature T_0. If the radiation flux is sufficiently intense, the energy generated in the material surface layers raises their temperature to very high levels, right up to their boiling points at atmospheric pressure.

This rapid temperature rise is due to the fact that l_0 of many materials is very small. And so, in the case of luminous radiation acting on metals at, or not very much above, room temperature, l_0 is of the order of the wave length of light, i.e., 10^{-4}–10^{-5} cm [1]. Even in the hard ultraviolet or soft X-ray range, l_0 does not exceed 10^{-3}–10^{-4} cm.

Consequently, the mass of the heated surface layers is small and so is the energy required to generate a quantity of heat equivalent to the heat of volatilization Q of the given material. For instance, the energy flux required to increase the heat content of a mass of 10^{-4} g/cm^2 by $e \approx Q = 10^{11}$ erg/g is $E \gtrsim 1$ joule/cm^2. In the case of long heating, however, the depth of heated surface layers may be substantially increased due to heat conduction.

The thickness of a heated layer is of the order of $\sqrt{at}$, where a is the coefficient of thermal diffusivity of the material in question. It is evident that heat conduction plays a significant part if $\sqrt{a\tau} > l$, where τ is the irradiation time. In the case of good heat conductors a is of the order of 1 cm^2/sec, and the effects of heat conduction are manifested at $\tau \simeq 10^{-8}$ sec if $l \leqslant 10^{-4}$ cm. However, even at $\tau = 10^{-4}$ sec the thickness of a layer heated by heat conduction cannot exceed 10^{-2} cm.

The speed of sound in a solid (normal density ρ_0) heated to $e \approx Q$ is of the same order of magnitude as that at room temperature, i.e., about $3 \cdot 10^5$ cm/sec. It is evident that a layer 10^{-4}–10^{-5} cm thick will start expanding at times as short as 10^{-10} sec, but a layer 10^{-2} cm thick will also expand if $t > 10^{-7}$ sec.

This article is concerned with long heating times τ when the heated layers expand to a considerable extent and when the material passes into the gaseous state. Rapid expansion of the heated layers leads to an increase in the volume in which energy is generated, and, consequently, to a substantial reduction in pressure p as compared with cases in which no expansion takes place ("instantaneous" heating).

When τ is very large, the pressures produced are relatively low and lower than the critical pressure $p_* \approx {}^1/_{30}\, \rho_0 c_0^2$. If the material did not expand, heating it to $e \approx Q$ would produce pressures of the order of the bulk compression modulus $\rho_0 c_0^2$, i.e., pressures of tens or even hundreds of thousands of atmospheres (whereas the critical pressures are of the order of hundreds or several thousands atmospheres).

If one considers the problem of expansion of a continuously heated material at $\rho \approx \rho_0$ (thermoelastic strains) in which energy exponentially decreasing with the distance from the surface is generated, the maximum pressure p_{max} in the resulting compression wave spreading from the heated zone will be $\Gamma q/c_0$, where Γ is the Grüneisen constant and q the energy flux. It is interesting that p_{max} does not depend on the thickness of the heated surface layer. At $q = 10^6$ joules/cm^2 sec, $\Gamma \approx 1$ and $c_0 \approx 3 \cdot 10^5$ cm/sec, we obtain $p_{max} = 30$ kg/cm^2. And so, the pressure is in fact quite low if the energy flux is not too large.

If the heating and expansion of a substance are sufficiently "slow" and if the superheat of the liquid is small, which takes place when the heated layer thickness is "large" (the heated layer thickness l is larger than the free path of radiation due to heat conduction), continuous supply of energy after the substance has reached its boiling point T_k (at the given pressure) will produce further expansion and gradual (quasi-equilibrium) conversion of a part of the substance to vapor, this being accompanied by a rapid decrease in its density; when the internally generated energy e is larger than the heat of volatilization Q, the entire heated layer will volatilize. The vapor temperature under these conditions is near the boiling point at atmospheric pressure, since the variation in the boiling point at pressures considerably below the critical level is small.

Since the mass of the heated layer (at $\rho_0 \approx 1$ g/cm^3) does not exceed 10^{-2} g/cm^2, the energy that must be supplied to the material surface to generate a quantity of heat larger than Q (Q being of the order of 10^{11} ergs/g or 10^4 joules/g) is less than 100 joules/cm^2; it is necessary, of course, to allow for the reflection of a part of incident radiation.

It is therefore certain that if the irradiation time τ is of the order of 10^{-4} sec, the surface layer will be volatilized if the energy flux q of the incident radiation exceeds 10^6 joules/cm^2 sec ($E \geqslant 10^2$ joules/cm^2). The volatilization under these conditions will be "quiescent" as distinguished from "explosive," volatilization taking place when τ is very short.

It should be borne in mind that the expansion of the heated material and its partial volatilization may be accompanied by changes in the absorption coefficient. However, if the radiation spectrum is sufficiently broad (as is the case under experimental conditions described below) and if a large portion of the spectrum belongs to the ultraviolet radiation (with a quantum energy of up to 10 eV), in most cases there are atomic or molecular levels of the volatilized substance whose energy is lower than the maximum energy of quanta present in the spectrum. As a result, the vapors continue to absorb radiation and increase their heat content.

It should be noted that a different situation may arise in the case of a substance exposed to long-wave radiation, when metal vapors may become quite transparent to the incident radiation. However, in the presence of a hard spectrum component which is absorbed by the vapors and when expansion of the vapor takes place, only a part of the radiation will be absorbed by the vapors and raise their heat content; the remaining part will penetrate to the more deeply seated substance layers and produce their volatilization. The mass absorption coefficient during the heating and expansion of vapors may remain constant if the absorption is effected by sufficiently deep atomic or molecular levels, i.e., if the radiation spectrum is not too soft and the heating not too intense.

In the case of a constant mass absorption coefficient, when neither the variation in the state of aggregation of the material nor changes in the vapor temperature and density produce any changes in the mass in which heating takes place, the depth of penetration of the "hard" portion of the spectrum in the vapors (before their ionization) is small. For quanta with an energy $h\nu \leqslant I$, where I is the first ionization potential, the mass absorption coefficient $\varkappa$ is usually of the order 10^5–$3 \cdot 10^5$ cm^2/g. At pressures $p \approx 10$ kg/cm^2 and $T \approx 2 \cdot 10^{3}$ °K, when $\rho \approx 10^{-3}$ g/cm^3, we find that the free path $l \approx 10^{2}$–$3 \cdot 10^{-2}$ cm. At the same pressure, but at $T \approx 2 \cdot 10^4$ °K, when $\rho \approx 3 \cdot 10^{-5}$ g/cm^3, the free path $l \approx 10^{-1}$–$3 \cdot 10^{-1}$ cm (without taking account of ionization).

One of the authors of this article showed [2, 3] that hydrodynamic motion does not strongly hinder the heating of a continuously expanding gas, since its kinetic energy accounts only for about 50% of its total energy.

It is evident, however, that $\varkappa$ cannot remain constant at arbitrarily high levels of heating. When the internal energy of a substance reaches a certain value e_*, levels ensuring the absorption of the hardest portion of the spectrum cease to exist.

If one considers energies of the levels 5–10 eV, i.e., the absorption by the optical electrons of the outer shells, e_* is of the order of 10^5 joules/g [4, 5] ($T_* \approx 1$–2 eV). Let us assume that there is no absorption at $e \geq e_*$ and that the absorption coefficient is constant at $e < e_*$; then the substance cannot be heated above e_*, and a steady-state heating wave is produced.

The temperature T_* corresponding to e_* may be called the transmittance temperature.

When the absorption coefficient decreases rapidly near a certain temperature, this temperature may be taken as the conditional transmittance temperature, and the heating effects above this temperature may be neglected. Naturally, T_* depends substantially on the radiation spectrum, on the composition of the vapors, and on the vapor pressure (and, consequently, on the radiation flux intensity), being weakly dependent on the thickness of the vapor layer (strictly speaking, the motion will not be steady-state in character).

It should be noted that if T_* is lower than the effective temperature T_e of the incident radiation, the quantity of energy re-emitted by the vapor is small. And so, for $T_* = 0.5\, T_e$ the re-emitted radiation flux (even if the vapor behaves as a black body) is by one order of magnitude weaker than the incident radiation flux; at $T_e \approx 3 \cdot 10^4$ °K the re-emission is weak if $T_* \leqslant 1$–$2 \cdot 10^4$ °K. The structure of a quasi-stationary heating wave in a vapor layer whose temperature at the "hot" edge is constant was analyzed in [6].

To estimate the rate of "combustion" we can consider two cases: the case in which there is no movement of the substance behind the wave ($^1/_2\, u^2 \ll e_*$) and the case when the heating wave moves so as to satisfy the Jouguet rule (in this case $^1/_2 u^2 = {}^1/_2 u_*{}^2 = {}^1/_2 \gamma\ (\gamma - 1)\ e_*$). Consequently, in both cases the relationship between the mass burn-up and the incident radiation flux is

$$dm/dt = \dot{m} \approx q/\,(e_* + {}^1/_2\, u^2) \approx q/e_*.$$

If $e_* = 10^5$ joules/g, at $q = 10^6$ joules/cm^2 sec, we obtain $\dot{m} = 10$ g/cm^2 sec. The value m is weakly dependent on the assumptions regarding the motion of the substance. The magnitude of the pulse and pressure is related to the efflux rate: $p \approx u\dot{m}$. The rate of expansion of the substance u does not exceed the value $u_* \approx \sqrt{e_*\,(\gamma - 1)}$, i.e., 5 km/sec; as a result, the average vapor density ρ is higher than 10^{-5} g/cm^2. If the dilation wave moves through the substance in harmony with the propagation of the heating wave, the Jouguet rule is satisfied at its boundary, and this density will be close to the actual. When the vapor escapes not into a vacuum but into any other medium, the maximum velocity of motion may be much lower.

Starting from known values of e_* and ρ_*, we may estimate the vapor pressure p; taking $\gamma = 1.2$, we obtain $p \approx 2$ kg/cm^2. Starting from known values of u and m, we obtain $p \approx 5$ kg/cm^2. And so, when the irradiation time is long, the vapor pressure is low. Increasing the heat flux produces an increase in p:

$$p = e_* \rho_* (\gamma - 1) = e_* m (\gamma - 1) / u \approx q / \sqrt{e_*}.$$

The mass burn-up in a given heat flux may be increased, the efflux velocity reduced, and the vapor density and pressure increased, when e_* is reduced. If the bulk of the radiation energy belongs to quanta which are absorbed only by the condensed substance, T_* may be close to the boiling point (with the disappearance of liquid droplets the vapor no longer screens the solid surface).

It should be borne in mind, however, that in this case a substantial role in the energy balance will be played by the energy expended to volatilize the liquid (usually $Q = 10^3$–10^4 joules/g):

$$\dot{m} \approx q_s / (Q + e_k + {}^1/_2 \; u_k^2) \approx q_s / Q.$$

Here $e_k = c_V T_k$; c_V is the specific heat of the vapor; T_k is the boiling point (usually $e_k \leqslant Q$); q_s is the heat flux toward the surface volatilized under the influence of radiation.

When the Jouguet rule is satisfied,

$$u_k \approx \sqrt{\gamma (\gamma - 1) e_k}, \qquad p \approx q_s \sqrt{\gamma (\gamma - 1) e_k} / Q.$$

In this case the efflux velocity does not vary substantially with the variation in the radiation flux; the pressure is proportional to the radiation flux and the pressure pulse $I = \xi E / \sqrt{Q}$, where $\xi = \sqrt{\gamma(\gamma - 1) e_k / Q}$. In the case of iron and lead vapors, respectively, $u_k = 1.0$ and 0.5 km/sec, $e_k = 10^3$ and 2×10^2 joules/g, and $Q = 7 \times 10^3$ and 10^3 joules/g, i.e., $\xi \approx 0.2$. Consequently, when the heat flux at the subliming iron and lead surfaces is $q_s = 10^6$ W/cm^2, the resulting vapor pressures should be of the order of 5 and 25 kg/cm^2.

The heat flux q_s will be close to the total incident radiation flux and the vapor will not be substantially heated if the ionization potential I of the substance is high and the radiation spectrum sufficiently soft, i.e., if only a very small proportion of the total energy belongs to quanta whose energy $h\nu > I$. When the vapor is highly superheated ($e_* \gg Q$), the coefficient $\xi \ll 1$.

It was postulated above that in the case of a sufficiently "hard" spectrum and relatively low ionization potential the value e_* corresponds to the completion of single ionization. However, besides the photoelectric absorption by optical electrons, absorption from excited ion levels and free absorption by electrons during their collisions with ions may take place. The estimation of the absorption coefficient can be carried out on the basis of the classical theory of retarding absorption [4, 7]. And so for instance, in the case of air plasma at $T = 2 \cdot 10^4$ °K, the mean free path of radiation with $\lambda = 6000$ Å for $\rho \approx 4 \times 10^{-5}$ g/cm^3, i.e., at a pressure of 10 kg/cm^2, is 6 cm, while a vapor layer moving at a speed of about 5 km/sec will also be several cm thick. Since $l \sim f(T) \rho^{-2} \lambda^{-2} \sim \varphi(T) p^{-2} \lambda^{-2}$, the transmittance temperature will depend on the vapor pressure, vapor layer thickness, characteristic wave length of the incident radiation, and the vapor composition. For comparison, the mean free radiation path in C, Fe, and Pb vapors [5] under the same conditions ($T = 2 \cdot 10^4$ °K, $p = 10$ kg/cm^2, $h\nu = 2$ eV) is, respectively, 15, 20, and 8 cm.

It should be pointed out that when the electron concentration becomes sufficiently high, the long-wave radiation will be absorbed at shallower levels than the short-wave radiation, which will increase the heating intensity of the hot edge and reduce the absorption coefficient for all the wavelengths.

And so, heating a substance and its hydrodynamic motion leading to a reduction in its density may produce substantial changes in the optical properties of the surface layer. In these circumstances the outer layers of the substance will no longer be heated [3]. The radiation will begin to be absorbed at deeper layers of the substance which, when heated, also begin to move and become transparent leading to the onset of a self-consistent regime of the propagation of the heating and dilation wave [8]. This is accompanied by a slow variation in the maximum temperature of the substance and in the efflux velocity which increase with increasing vapor layer thickness. Rough estimates of various parameters can be made on the basis of solutions for a quasi-stationary wave described above. The value e_* is found from the condition that the optical thickness of the vapor layer is of the order of one, i.e., $l(e_*)/x \approx$ ≈ 1.

The increase in the transmissivity with increasing heating intensity can be observed also at lower temperatures in the case of molecular absorption. In the case of iodine, for instance, the value e_* corresponding to its dissociation is of the order of 10^{10} ergs/g and, correspondingly, $u_* \approx 0.5 \cdot 10^4$ cm/sec. It should be noted that at temperatures close to but lower than T_*, the increase in temperature accompanied by an increase in the concentration of excited levels capable of absorbing radiation may lead to an increase in the opacity of the vapor layer.

It follows from the above considerations that it is necessary to know the optical properties of vapors in a wide range of pressures (approaching the density of the solid) and temperatures (ranging from the boiling point, i.e., 1–2 · 10^4 ° K, to temperatures at which the dissociation and ionization of the substance take place, i.e., temperatures of up to 2 · 10^4 ° K), and that the hydrodynamic motion has a substantial effect on the process of heating dispersing vapors. Conversely, studies of the process of dispersion of matter should produce valuable data on those properties of various substances which do not lend themselves easily to theoretical investigations. Naturally, the analysis of the process in question is substantially simplified in the case of a simple motion geometry.

The problem of accurate computation of the heating and motion of vapors is complicated by the fact that the motion may become two-dimensional. In fact, with the speed of sound being about $3 \cdot 10^5$ cm/sec, the acoustic excitations from the edges of an irradiated "spot" will cover a distance of at least 3 cm. during a time of the order of 10^{-5} sec. The two-dimensional character of the dispersion leads to a more rapid reduction in the density and optical thickness of the vapor layer expanding in two dimensions along the radiation path.

Increasing the transmissivity leads to a deeper penetration of radiation and to an increase in the rate of "burn-up" of the substance. The value e_* (and T_*) will be related in this case to the lateral dimension R of the "spot." In fact, even at $\varkappa$ = const, when the mean free radiation path $l = \varkappa/\rho \sim 1/\rho$, the optical thickness of the two-dimensional part of the vapor jet or, as it is often called, "flame," decreases: $\tau = x/l \sim \sim x \cdot \rho \sim 1/x$. A steady-state mode of heating and motion is developed.

And so, the over-all picture of the heating and motion of a substance in the case considered is complex. Since certain essential data (the magnitude of the absorption coefficient, equations of state in the range of phase transformations (especially at high radiation flux intensities when pressures approaching the critical levels are produced), volatilization and condensation rates, dissociation and ionization rates, etc.) are not available, accurate theoretical description of the phenomena in question is difficult which necessitates the use of experimental methods.

Laboratory investigations of the heating and motion of vapors require sufficiently powerful sources of luminous radiation. One of the present authors (I. V. Nemchinov) proposed to use as such sources the radiation emitted by the front of a shock wave moving in an inert gas, the shock wave being generated by detonating a charge of an ordinary explosive. Sources of this kind (flash bulbs), although widely used for illuminating various objects in high-speed photography, have not yet been employed for the purpose under consideration. The problem of construction of radiation sources of this kind is beyond the scope of this article. The results described below were obtained with one of many possible types of such sources; it should be stated here that sources with better characteristics are probably available.

One of the advantages of explosive radiation sources is their large over-all energy and high radiation energy. At T = 30 000° K with 1 cm^2 of a shock wave, surface emits (under blackbody conditions) 4 joules per μsec which is equivalent to a flux of $4 \cdot 10^6$ watts. This makes it possible to irradiate quite large areas (several cm^2 or more) which facilitates producing conditions that are conducive to unidimensional motion of the vapors.

§ 2. Explosive high-temperature source of light. The experiments whose results are described below were carried out with an explosive light source in the form of an explosive tube (with an additional cumulative charge) filled with an inert gas (Fig. 1).* The front of the shock wave inside the source of this type is almost flat except at the starting part. The thickness of the luminescent gas layer (heated by the shock wave) at various times corresponds approximately to a tenfold compression of the gas column involved in the motion. Pure argon (containing not more than 0.01% nitrogen, 0.003% oxygen, and 0.03 g/m^3 moisture) was used as the working gas. The source length was 300 mm and the flash duration 32 μsec. To increase the light flux, the inner tube surface was lined with aluminum

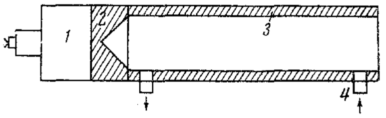

Fig. 1. Schematic representation of an explosive source of luminous radiation: 1) explosive lens; 2) supplementary cumulative charge; 3) explosive tube; 4) argon purging.

The magnitude of the light flux emitted by the source was calculated from the results of measurements of the temperature of the luminescent front of the shock wave in the blue-red spectrum range and of the source geometry and from the measured value of the reflection coefficient of the foil in the visible light under the assumption that the spectrum has a Planckian form and that the reflection coefficient remains constant right up to the ultraviolet region.

The effective temperature of the shock wave front surface was determined by the method of photographic photometry in narrow spectrum regions: red ($\lambda =$ = 6500 Å) and blue (λ = 4400 Å with a half-width $\Delta\lambda =$ = 380 Å). The luminescent shock wave front behind a red light filter was photographed with an SFR camera (in the time loop variant) through a reducing neutral light filter with a density 3.15. As a standard source in the red region we used an SI-6-100 ribbon-filament incandescent lamp whose filament temperature (2600–2700° K) was measured with a pyrometer.

Photographing with a blue light filter was done with a type SFR camera in the photoregister variant. As a standard in the blue region of the spectrum we used a type EV-39 instrument producing an electrical discharge which emits light (as a black body) in the wave length range 4000–6000 Å, effective temperature of this radiation being 39 000° K ± 2000° K [9–11]. The accuracy of the temperature measurements in the red and blue regions is not lower than 10%.

The results of the temperature measurements in the blue and red regions of the spectrum at various times counted from the onset of radiation are given below.

The measurements in the blue region of the spectrum are more accurate because the temperature in the red region is slightly overestimated.

$t, \mu\text{sec} =$	0	4	8	12	16	20	26	32	
$10^{-3}\ T°\text{K} =$	33.7	30.5	28.5	28.6	29.0	29.5	30.0	31.8	at $\lambda = 4400$ Å
$10^{-3} T\ °\text{K} =$	37.8	33.5	31.9	32.0	—	—	—	—	at $\lambda = 6500$ Å

The measured temperatures are in agreement with those calculated (from the measured velocity of the shock wave front) with the aid of the explosive adiabatic curve of argon [12] in whose computation the ionization was taken into account.

It was shown in [12] that at a velocity of 17 km/sec the brightness temperature of argon is very much low-

---

*Thanks are due to E. G. Popov who took an active part in the preparation of explosive light sources.

er than its real temperature, this difference being attributed to intense screening of the luminescence of the wave front by the heated zone [4, 13–15]. Evidently, there is no screening at velocities of 8–12 km/sec obtaining in our experiments.

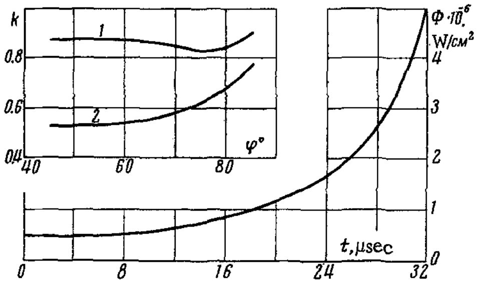

Fig. 2. Top: Dependence of the reflection coefficient k on the reflection angle plotted for the visible light: 1) aluminum mirror on glass; 2) polished aluminum foil. Bottom: Time dependence of the light flux at the tube outlet taking into account the energy absorption in cold argon ($\lambda < 1070$ Å).

Our results are in good agreement with those obtained in [16] where the temperature in the blue-red region of the spectrum (with the wave front moving at a velocity of 8.5 km/sec) was 29 000° K.

To estimate the emissivity of the radiation, one can calculate the mean free path of quanta from the more accurate Unsöld-Kramer formula [4, 17, 18]. For quanta with an energy $h\nu = 1.7$ eV the mean free path in argon at 30 000° K is $0.5 \cdot 10^{-1}$ cm. The mean free path can be also estimated [16] from the rise time of the record of the photomultiplier measuring the light flux when a shock wave is emitted by the explosive into argon. This estimation gives the mean free path (at 29 000° K and quantum energy $h\nu = 3$ eV) equal to $1.2 \cdot 10^{-1}$ cm.

Since the heated layer in the source used in this investigation is several cm, the radiating surface of the shock wave may be regarded as an absolutely black body with a Planckian radiation spectrum. However, it is necessary to take into account the continuous absorption of the hard part of radiation in cold argon due to the photoeffect (the ionization potential = 15.7 eV), and also the possibility of energy losses for excitation at quantum energies starting from about 11 eV. The validity of the assumption of the Planckian character of the spectrum is proved also by the fact that, within the limits of experimental error, the measured temperatures of the shock wave front in the red and blue regions of the spectrum are practically the same.

It should be borne in mind that the temperature measurements were carried out in the visible region of the spectrum ($\lambda = 4400$ and 6500 Å), while the bulk of the energy is radiated in the ultraviolet range ($\lambda = 1300$ Å). When a luminescent surface consists of zones characterized by different luminance and temperature (which occurs in the initial stages of the process as a result of collisions between shock waves in the radiation source), the spectrum in the long wave range may be close to Planckian with a certain average (over the wave front surface) temperature, differing from the Planckian spectrum in the short wave range.

Moreover, the spectrum of the radiation reflected from the foil may change if the absorption coefficients of different parts of the spectrum are not the same. However, the largest quantity of energy is transferred to the specimen at moments close to the moment at which the shock wave is emitted from the tube. And yet it is precisely at this moment that the luminescence appears to be uniform across the tube cross section, and the bulk of the energy transmitted to the specimen comes directly from the shock wave front (without being reflected from the foil). Consequently, the above cited factors which could distort the Planckian character of the spectrum, do not play a significant part during this period. In view of these considerations, and because of the known difficulties of measurements in the ultraviolet range of the spectrum, henceforth we shall assume the Planckian character of the spectrum.

The calculated structure of the radiation emitted by the source employed is given below (for T = 32 000° K) in terms of the percentages of various wavelengths relative to the over-all flux.

λÅ from		1000	1500	2000	2500	3000	3500	4000	>4500
to	<1000	1500	2000	2500	3000	3500	4000	4500	
%	34	27	16	9	5	3	2	1	3

For comparison the following data is cited on the wave lengths λ_I corresponding to the first ionization potential I of atoms of certain substances used in our experiments:

Al	S	Fe	Cu	Zn	Sn	J	Pb
2070	1200	1570	1610	1320	1690	1190	1670

Let us calculate the light flux per unit surface area placed at the outlet of the radiation source tube and normal to its axis. The light flux dΦ emitted from a luminescent surface dS on to a surface ds at a distance R is

$$d\Phi = J \cos \vartheta_1 \, dS \, (d\Omega / ds) =$$

$$= (J \cos \vartheta_1 \cos \vartheta_2 / R^2) \, dS.$$

where J is the radiation intensity in the direction normal to the luminescent surface, ϑ_1 is the angle between the beam and the normal to the luminescent surface, and ϑ_2 the angle between the beam and the normal to the irradiated surface.

Since the shock wave front and the irradiated surface are parallel, we have $\vartheta_1 = \vartheta_2 = \theta$, where θ is the angle between the beam and the tube axis. Substituting in the above expression values dS and R expressed

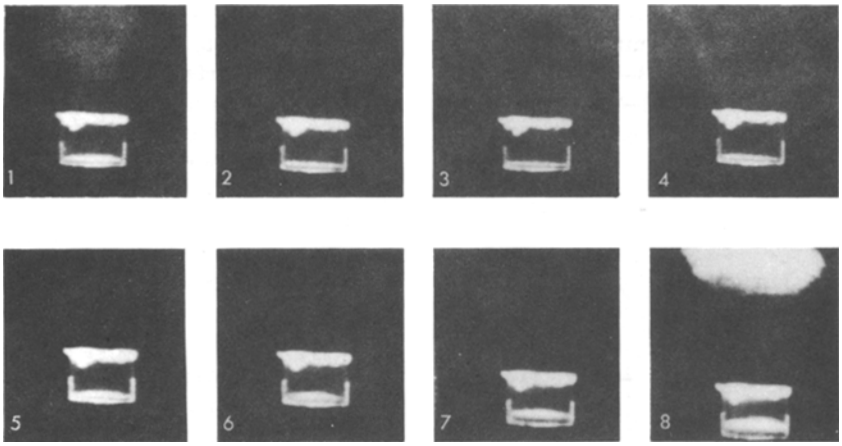

Fig. 3. High-speed photographs of the effect of irradiation on iodine. The frames are spaced at 4 μsec intervals.

through the distance of the shock wave front from the exit aperture of the tube and the angle θ, we obtain

$$d\Phi = 2\pi\, J \sin\theta \cos\theta d\theta .$$

In the presence of reflecting channel walls, an observer placed at the tube outlet will see circular zones of mirror reflection of the shock wave front relative to the channel axis, the zones being bounded by beams at angles θ_0 (without reflection), $\theta_1-\theta_0$ (single reflection), $\theta_2-\theta_1$ (double reflection), etc. Under these conditions the ratio of the light flux at the tube edge to the flux emitted from the luminescent surface will be (for each of these circular zones)

$$\begin{aligned}\Phi_0/\sigma T^4 &= \sin^2\theta_0\\ \Phi_1 / \sigma T^4 &= k\,(\sin^2\theta_1 - \sin^2\theta_0)\\ \Phi_2 / \sigma T^4 &= k^2\,(\sin^2\theta_2 - \sin\theta_1)\\ &\cdots\cdots\cdots\cdots\\ \Phi_n / \sigma\, T^4 &= k^n\,(\sin^2\theta_n - \sin^2\theta_{n-1}) .\end{aligned}$$

Here k is the reflection coefficient of the channel walls. The total light flux will be

$$\Phi = \Sigma\Phi_n .$$

In calculating the light flux we took into account changes in the temperature of the moving shock wave front and the variation taking place in the reflection angle as the wave approaches the tube outlet.

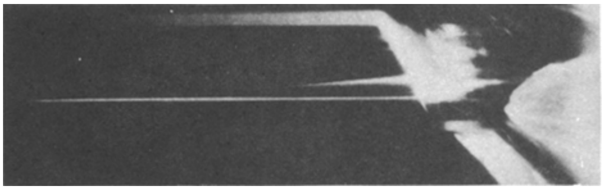

Fig. 4. Phototrace of the effect of radiation on sulfur.

In Fig. 2 (top) the measured values of the reflection coefficient of polished aluminum foil is plotted (for the visible light) against the reflection angle. In the calculations it was taken that k = 0.5. The reflection coefficient may vary with the wavelength. According to data in [19], however, the variation in the case of aluminum mirrors is small (from 0.85 to 0.75) right down to λ = = 2000 Å. It was, therefore, assumed in the calculations that the reflection coefficient is independent of the wavelength.

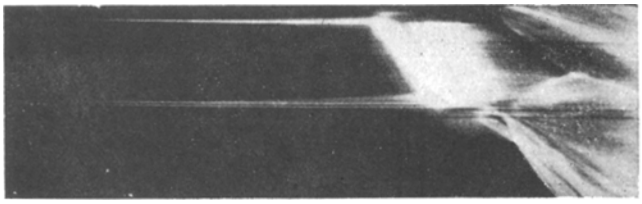

Fig. 5. Phototrace of the effect of radiation on lead.

A curve representing the time dependence of the light flux (in whose computation the absorption of radiations with wavelengths $\lambda < 1070$ Å in cold argon was taken into account), is also shown in Fig. 2 (bottom). Here the total energy transmitted to unit surface area of the irradiated specimen during the entire period of the operation of the radiation source E = 40 joules/cm^2, and the average energy flux during this period is equal to $1.3 \cdot 10^6$ joules/cm^2 sec.

§ 3. Effect of radiation on irradiated substances. The specimens studied (up to 40 mm diam., 1–2 mm thick) were mounted in a glass tube at a distance of 10–20 mm from the tube outlet, and argon was flown through the assembly for the entire duration of each experiment. The interaction between the emitted radiation and the irradiated surface was recorded on a type SFR instrument (time magnifier and photorecorder).

When iodine, sulfur, lead, tin, and iron were irradiated, the broadening of the luminescent zone was observed (Fig. 3). The boundary of this zone moved toward the radiation flux at a velocity of the order of several hundred m/sec which varied from one material to another. It can be shown that the luminescent zone boundary will be flat only in the initial stages, becoming convex in the later stages of the process. When the specimen diameter is close to the tube diameter, the radius of the boundary curvature is quite large (see Fig. 3 relating to a specimen 40 mm diam.). The broadening of the luminescent zone in our experiments did not begin immediately after the onset of irradiation, the time lag varying from one substance to another (Figs. 4–6). Figures 4 and 5 show clearly the rise of the luminescent zone boundary, then its movement toward the shock wave front, and, finally, the reflection of this wave; the luminescence time was 32 μsec, the displacement of the luminescent zone boundary (at the moment of the arrival of the shock wave) being 6 mm in Fig. 4 and 4 mm in Fig. 5. No formation of a luminescent zone was observed during experiments with zinc, nickel, magnesium, copper, and aluminum.

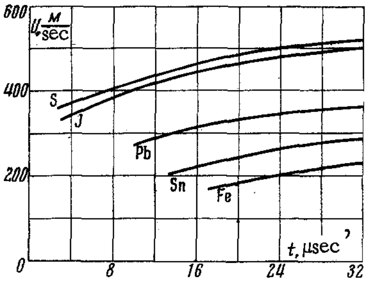

Fig. 6. Time dependence of the velocity of the luminescent zone boundary plotted for various substances.

The variation in pressure on irradiated specimens was studied in the following way. A specimen 12 mm in diameter was attached to a piezoprobe (a barium titanate disk in an epoxy resin) and placed in the outlet of the radiation source. The electrical pulse (Fig. 7) was amplified and fed to the input of a type OK-24MA oscillograph.

The probe was calibrated using a shock air wave of a known amplitude.

The results of measurements of the maximum pressure p_{max} (kg/cm^2), pressure pulse J (kg μsec/cm^2), time lag t° (μsec) of the onset of the effect and the maximum velocity u_{max} (m/sec) of the luminescent zone boundary are reproduced in a table. No mechanical pulse was recorded in experiments with zinc, i.e., the substance which produced no optical effects.

It was postulated above that volatilization of irradiated substances can be expected under certain experimental conditions. Taking into account this postulate and the experimentally established fact that the mechanical effect is associated with the velocity of the luminescent zone boundary, it may be postulated that the light flux produces sublimation of the solid surface, after which the vaporized substance expands, being continually heated by the radiation, which explains the luminescence of the vapors.

Of course the above reasoning and the arguments outlined below are only indirect proofs of the volatilization of solids under the influence of radiation. Direct (spectrographic) studies of luminescence are also carried out, however.

The delay in the onset of volatilization can be attributed to the intense heat removal into the subsurface layers of the substance. Volatilization becomes possible at the moment at which the radiation flux absorbed by the substance exceeds the inward heat flux, since otherwise the solid surface cannot reach its boiling point.

The time elapsed from the onset of irradiation to the moment at which these two fluxes become equal corresponds to the delay in the onset of volatilization. Assuming that the temperature of a flat specimen surface remains constant at the boiling point, we obtain the following expression for the maximum inward heat flux:

$$q_1 = T_{\text{к}} \sqrt{k_T \rho c_v} \,/\, \sqrt{\pi t}\,.$$

Here k_T is the thermal conductivity coefficient, ρ is the density, c_v the specific heat, and t time.

Estimates of the delay of the onset of volatilization made with the aid of the above formula for substances, for which the reflection coefficients in the ultraviolet range of the spectrum are known and are in good agreement with experimental data (iron). In the case of copper and aluminum the delay times approached the total radiation time so that the volatilization did not occur. The behavior of zinc is evidently attributable to its high reflection coefficient in the ultraviolet range of the spectrum.

Consequently, with radiation fluxes of the order of 10^{13}–10^{14} ergs/cm^2 sec the onset of volatilization is determined by the thermal conductivity and reflection coefficient of a given substance.

A layer of expanding vaporized substance produces a mechanical pulse on the specimen. Under usual experimental conditions the vaporized substance comes in contact with a gas at atmospheric pressure and loses a part of its energy to accelerate the initially stationary gas and to produce in it a shock wave, which differs from the case when the vaporized substance escapes into a vacuum.

The estimation of the pressure behind a shock wave produced in a gas by a flat piston moving at constant velocity equal to the velocity of the vaporized layer boundary gives a value approaching (within 30%) the measured maximum pressure for all the substances studied except iodine. In reality the motion is not uniform. A solution of the problem of a spherical piston moving at a constant velocity [20] showed that the pressure p_p exerted on the piston is only 50% higher than the pressure p_s at the front of a shock wave (at $p_p \approx$ ≈ 2–6 kg/cm^2). And so, the pressure at the surface of an irradiated specimen corresponds to the pressure behind a shock wave produced in a gas with an expanding vaporized substance, and the pressure in the entire vapor layer is approximately the same.

	$t°$	u_{max}	p_{max}	J	$\xi \cdot 10^{-2}$
J	4–5	480	3.2	64.5	0.8
S	3–4	520	5.7	112	4
Pb	10	360	3.0	49.2	1
Sn	13	280	2.3	35.5	1.5
Fe	17	220	2.1	27.3	1.5

The last column in the table gives values of a dimensionless coefficient $\xi = J\sqrt{Q}/E$, where J is the pressure pulse, Q the heat of volatilization, and E the total energy supplied. This coefficient, which can be conditionally called the coefficient of utilization of energy, is lower for iodine than for other substances. This can be explained either as a result of possible experimental errors (iodine forms a low quality bond when glued to a piezoprobe; calculated pressures determined from the velocity of the vapor layer boundary are 100% higher than the measured values), or by the fact that the characteristic property of iodine is its dissociation energy Q_d rather than its heat of volatilization Q, i.e., a value that is larger by approximately one order of magnitude. In fact, the dissociation "potential" of iodine is 1.6 eV, i.e., a large part of the energy supplied should be used up to heat the vapor before the dissociation of iodine (in contrast to lead, tin, and iron, in the case of which $I = 7.5-8$ eV, i.e., $\lambda_1 \approx 1500$ Å and a large proportion of the energy can pass through the vapors even if they are heated considerably above the melting points of these substances). The magnitude of the pulse produced in the case of metals listed in the above-cited table should be substantially affected by the removal of energy due to inward heat conduction as indicated by long delays in the onset of luminescence and in the build-up of pressure.

The estimation of the energy which, on the one hand, is supplied to the vapor layer boundary and, on the other, expended on volatilizing the substance, used up for accelerating the vapor produced and abstracted into the solid substance is difficult because the pressure measurements were carried out under conditions of substantially two-dimensional motion. In fact, the diameter of piezoprobes to which specimens of the substances studied were attached was 12 mm, while the displacement of the luminescent zone boundary at the end of the process was 5–10 mm. Control experiments showed that the pressure exerted on a 40-mm-diameter sulfur specimen is 1.5 times higher than that recorded for a 12-mm-diameter specimen.

The estimation of the velocity of the shock wave front from the velocity of the piston formed by the "vapor" layer shows that the shock wave front is shifted to approximately the same distance from the vapor layer boundary. A rough estimation of the volume of argon heated by the shock wave can be made if it is assumed that this volume and the vapor are in the form of a segment of a sphere (see Fig. 3).

If it is assumed that the pressure and velocity are the same in the entire zone between the shock wave front (moved by the vapors) and the boundary, one can estimate the energy expended on accelerating the vapors. It is found then that this energy is of the same order of magnitude as the total energy supplied. A more accurate calculation of the energy expended on heating and accelerating the vapors would necessitate more detailed measurements and a more careful analysis. It should be pointed out, however, that our estimates of the volatilized mass are in agreement with the measured values of pressure, pressure pulse, and vapor velocity, as well as with qualitative concepts outlined in § 1 and with the estimates of the "quiescent" mode of volatilization and heating of vapors presented in this paragraph and in § 1. More accurate quantitative calculations would require not only more extensive experiments but also a more precise formulation of the theoretical concepts.

The results of the present investigation showed that radiation emitted by light sources of the explosive type can be used in studies of the effects of intense luminescent radiation fluxes.

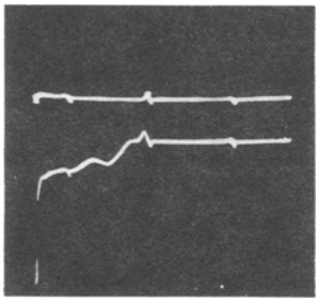

Fig. 7. Oscillogram of pressure exerted on irradiated lead specimen. Time scale runs from left to right and is marked at 25-μsec intervals. The termination of the trace corresponds to the arrival of the shock wave to the specimen.

This paper presents the results of studies of this kind in which one of the possible sources of this type was used. The source produced radiation pulses of 30 μsec (the radiation fluxes at the tube outlet increasing from 10^5 to $5 \cdot 10^6$ W) whose spectral composition corresponded to $T = 3 \cdot 10^4$ °K. High-speed motion pictures showed that the luminescent zone at the irradiated surface is formed by the vapors of the irradiated substance. The fact that no formation of the luminescent zone took place in the case of some of the substances studied was attributed to the effect of good thermal conductivity of those substances and reflection of radiation from their surfaces. When luminescence effects were observed, an increase in pressure (by several kg/cm^2) exerted on the irradiated surface was recorded; this was attributed to the recoil action of effluent vapors.

REFERENCES

1. A. V. Sokolov, Optical Properties of Metals [in Russian], Fizmatgiz, 1961.
2. I. V. Nemchinov, "Dispersion of a flat gas layer during a gradual evolution of energy," PMTF, no. 1, 1961.
3. I. V. Nemchinov, "Dispersion of a heated gaseous mass in a regular regime," PMTF, no. 5, 1964.
4. Ya. B. Zel'dovich and Yu. P. Raizer, Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena [in Russian], Izd-vo Nauka, 2-nd ed., 1966.
5. I. V. Nemchinov and M. A. Tsikulin, "Estimation of the heat transferred by radiation to large meteoroids moving through atmosphere at high speeds," Geomagnetizm i aeronomiya, vol. 3, no. 4, 1963.
6. I. V. Nemchinov, "Some nonstationary problems of heat transfer by radiation," PMTF, no. 1, 1960.
7. N. G. Basov and O. N. Krokhin, "Conditions of plasma heating by radiation from an optical generator," Zh. eksperimen. i teor. fiz., vol. 46, no. 1, 1964.

8. V. V. Afans'ev, V. M. Krol', O. N. Krokhin, and I. V. Nemchinov, "Gasdynamic phenomena during the heating of substances by laser radiation," PMM, vol. 31, no. 6, 1966.

9. S. G. Grenishin, A. A. Solodovnikov, and G. P. Startsev, Transactions of the Pyrometry Committee at the All-Union Scientific Research Institute [in Russian], Standartgiz, collection 1, 1958.

10. N. N. Ogurtsov and I. V. Podmoshenskii, "Investigation of high intensity pulse discharges with a limited channel diameter," Optika i spektroskopiya, vol. 4, no. 4, 1958.

11. N. N. Ogurtsov, I. V. Podmoshenskii, and M. Demidov, "A light pulse source emitting radiation similar to that emitted by an absolutely black body at 40 000° K," Optiko-mekhanicheskaya promyshlennost, no. 1, 1960.

12. I. Sh. Model, "Measurements of high temperatures in strong shock waves," Zh. eksperimen. i teor. fiz., vol. 32, no. 4, 1957.

13. Ya. B. Zel'dovich, "High-amplitude shock waves in air," Sh. eksperimen, i. teor. fiz., vol. 35, no. 5, 1957.

14. Yu. P. Raizer, "Structure of the front of strong shock waves in air," Zh. eksperimen. i teor. fiz., vol. 32, no. 6, 1957.

15. Yu. P. Raizer, "Luminance of strong shock waves in air," Zh. eksperimen. i. teor. fiz., vol. 33, no. 1, 1957.

16. J. Roth, "Measured temperature of strong shock waves in argon," J. Appl. Phys., vol. 35, no. 5, 1964.

17. L. M. Biberman and G. E. Norman, "Calculation of the photoionization absorption," Optika i spektroskopiya, vol. 8, no. 4, 1960.

18. L. M. Biberman, G. E. Norman, and K. N. Ul'yanov, "Calculation of the photoionization absorption in atomic gases," Optika i spektroskopiya, vol. 10, no. 5, 1961.

19. K. U. Allen, Astrophysical Constants [Russian translation], Izd. inostr. lit., 1960.

20. L. I. Sedov, Methods of Similarity and Dimensions in Mechanics [in Russian], Fizmatgiz, 4-th ed., 1957.

17 August 1966 Moscow