The maximal leanness of the initial mixture and the steady flame propagation rate within 20-30 cm/sec limits will be preferable for any initial pressures in the chamber since at elevated pressures the process of depleting the initial mixture is degraded. This is illustrated well by curve 2 in Fig. 1a where a moderate increase in the pressure in the chamber (on the order of $0.25 \cdot 10^4$ Pa) results in a delay in depletion, and the velocity still had not succeeded in taking on the stationary value on the final segment of the path. At still larger pressures (initial or because of expansion of the reaction products), the depletion is retarded still more while the velocity deviates from the stationary value. The results of investigations at low initial pressures when expansion of the reaction products is compensated by a loss in the number of moles during the chemical reaction and all the processes in the chamber occur at constant pressure, are a good illustration of depletion of the initial mixture and emergence of the quantity v at the stationary regime.

The phenomenon of depletion of the initial mixture was verified experimentally. An electromagnetic valve was mounted at a distance of 2.4 m from the igniting electrodes at the end of the chamber in an apparatus to sample the initial mixture for chromatographic analysis. Opening and closing the valve were determined by a loop oscilloscope, where it was ~0.25 sec in the open state. The initial mixture was sampled at a given time. The investigation was performed for an initial chamber pressure of $0.64 \cdot 10^4$ sec with mixtures containing 10% hydrogen and the flame being propagated from bottom to top. The chromatograph readings in a series of ten tests were: 9.6% hydrogen content in the initial mixture until the beginning of the combustion process in the chamber and 7.9% when the flame front is at the end of the chamber at a distance of approximately 0.23 m ahead of the opening valve.

The experimental investigations confirm the presence of the phenomenon of depletion of the initial mixture ahead of the flame front being propagated over a chamber of finite size.

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LASER PULSE IGNITION OF CONDENSED SYSTEMS

CONTAINING ALUMINUM

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The use of pulsed laser radiation as a tool opens up new possibilities of investigating high-speed processes in explosives. Virtually none of the traditional methods (impact, friction, shock waves, etc.) permits the energy to be regulated over such a wide range for constant energy input time and target spot dimensions, which considerably simplifies the analysis of the experimental results.

Particular interest attaches to the investigation of the factors determining the threshold of sensitivity of explosives to laser radiation, and the establishment of quantitative relations between the parameters of the source and the properties of the target system. The theoretical solution of this problem, associated with the description of nonstationary processes, is still difficult and the available experimental material is extremely heterogeneous and not amenble to precise quantitative interpretation since most investigators do not take into account the scale effect — the diameters of the target spot d_t and of the specimens d_s.

To a considerable extent, the shape and length of the laser pulse also determines the possibility of a correct approach to the analysis of the experimental results. For example,

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in the free-running mode, when the laser generates a random train of several tens of pulses, initiation is usually the result of the most intense of these [1], the total duration of the laser action τ_l considerably exceeding the ignition lag τ_{ig}. Accordingly, the result obtained with a single pulse, when $\tau_l \ll \tau_{ig}$, are the most accurate and convenient for analysis.

In the experiments, therefore, we used a neodymium glass laser ($\lambda = 1.06$ μm) in the Q-switched mode with a half-power pulse length $\tau_l \simeq 15$ nsec. In each experiment we determined the pulse energy E and the diameter of the irradiated spot on the specimen surface d_t, whence we calculated the energy density in the spot and established the dependence of its critical value q, usually taken as the ignition criterion, on the quantity d_t for specimens of different diameters. The length of the specimen was $l \geqslant 10d_s$. The irradiated surface was shielded with optical glass 1 mm thick, to suppress gasdynamic unloading of the high-pressure zone.

As the experimental results showed, with increase in d_t the critical laser energy density q decreases, approaching its asymptotic value. As the spot diameter increases above $2d_{cr}$ for individual systems and above $3.5d_{cr}$ for composite systems the effect of d_t on q becomes negligible small.* A similar pattern is observed is connection with the effect of d_s on q, which can also be neglected at $d_s \gtrsim 3d_{cr}$ for individual systems and $d_s \gtrsim 6d_{cr}$ for composite systems. By analogy with the ideal detonation velocity, we will call the asymptotic values of the critical laser energy density (free of the effect of the spot and specimen diameters) the ideal critical ignition energy density and denote it by q_0.

Below we present the results of a comparative analysis of the experimentally obtained values of q_0 for various explosive systems.

Let us consider a possible scheme of excitation of a high-speed chemical reaction in an explosive by laser radiation. Since the explosive proper is transparent to radiation, it is usual to assume that the pulse energy is absorbed locally at microinhomogeneities whose characteristic dimension, according to [2], is $r_0 \simeq 10^{-5}$ cm. The possibility of the formation of an ignition center and its initial parameters (temperature and pressure) are chiefly determined by the intensity of the pulse, i.e., by the quantity q_0. However, this center may burn out without igniting the surrounding chemically active medium. Obviously to excite a high-speed reaction in the explosive it is necessary not only to create a system of ignition centers but also to ensure combustion propagation conditions such that in the target zone the rate of energy release exceeds the rate of heat removal. Starting from these considerations, we will attempt to construct a laser ignitability criterion Φ and relate it to the experimentally established critical parameters q_0.

It may be assumed that the ignitability of the explosives is influenced by the physicochemical properties and initial-state characteristics of the explosive single crystal (Φ_1) and by the physical (Φ_2) and optical (Φ_3) properties of the irradiated polycrystalline medium:

$$\Phi = \Phi_1 \cdot \Phi_2 \cdot \Phi_3.$$

We also assume that the concentration of the microinhomogeneities, which constitute the centers of radiation energy absorption, is similar for different explosives and that its influence can be neglected.

As the parameter Φ_1 we can use the expression proposed in [3] for estimating the ignitability of an explosive and characterizing the reserve of heat (per unit surface) in the heated zone of the combustion wave, taking into account the dependence on the initial temperature T_0 and pressure p (without allowance for the heat supplied by chemical reactions):

$$\Phi_1 = \frac{\lambda}{u_l}(T_s - T_0) \simeq \frac{\rho\lambda}{Bp}(T_b - T_0),$$

where λ, ρ, u_m, and u are the thermal conductivity, density, and mass and linear burning rates of the explosive crystal; $u_l = u_m/\rho \simeq Bp/\rho$; B is the constant coefficient in the combustion law taken in the simple form $u_m \simeq Bp$; p is pressure; T_s is the surface temperature of the condensed phase which (for volatile explosives, like most secondaries) at short ignition lags is usually taken equal to the boiling point T_b; T_0 is the initial temperature (henceforth taken equal to 293°K). The parameter Φ_2, characterizing the effect of the crystal size and the porosity of the medium, was obtained from an analysis of the experimental data in the form

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*d_{cr} is the critical detonation diameter.

$$\Phi_2 = \frac{A}{m}\left(\frac{r_c}{r_0}\right)^{2/3},$$

A is a proportionality factor; m is the porosity; and r_c is the crystal size.

The expression for the parameter determining the optical properties of the medium can be written in the form

$$\Phi_3 = 1/(1-K),$$

where K is the reflection coefficient of the irradiated medium.

Thus, we can write the laser ignitability criterion in the final form

$$\Phi = A\frac{\rho\lambda(T_b - T_0)}{B\rho m(1-K)}\left(\frac{r_c}{r_0}\right)^{2/3}.$$

In calculating Φ we made the following assumptions:

1) T_b does not depend on pressure;

2) since the diffuse reflection coefficients for the individual explosives analyzed are similar (K $\simeq$ 0.85), their effect need not be taken into account;

3) in the first approximation the quantity p can be related to the stress required to fracture the explosive crystal within which the ignition center is located. Assuming that these stresses are similar for the crystals of the different explosives, the effect of p can also be neglected. In calculating Φ the values of the thermal conductivity and boiling point were taken from [4-6], those of the coefficient B from [3]; for lead azide and mercury fulminate instead of T_b we used the values of the flash point from [7].

In Fig. 1 in relative units we have plotted the correlation between the ideal critical energy density of the single laser pulse q_0 and the ignitability criterion Φ. Clearly, the values of q_0 and Φ are in satisfactory agreement, which tends to confirm the assumption concerning the decisive role of the combustion processes in the excitation of high-speed chemical reactions in explosives and also the possibility of using the criterion obtained for an a priori estimate of the ignitability of explosives by laser radiation.

In analyzing the ignitability criterion Φ it should be noted that the influence of such parameters as ρ, λ, and T_b is unimportant, since their values differ only slightly from one explosive to another. The strongest influence is that of the coefficient B characterizing the variation of the mass burning rate with pressure. Thus, for initiating explosives its value is two or more orders higher than for typical secondaries. These parameters are conditioned by the chemical nature of the single crystal and, like the size of the ignition center, are fixed for a specific explosive; accordingly, the ignitability can be controlled by regulating the porosity, the crystal size, and the initial temperature of the explosive in the irradiated zone. At the same time, it is known that a very effective method of increasing the laser ignitability of explosives is to introduce small amounts of certain finely dispersed additives that strongly absorb the radiation, e.g., aluminum [8]. Clearly, this is associated with an increase in the concentration and size of the ignition centers. However, the increase in the size of the ignition center will be limited by the effective size of the additive particle, which is determined by the extent to which it is heated and vaporized during the period of action of the pulse.

In this case a distinctive feature of the energy input mechanism is the formation of a gas phase of the additive material, whose interaction with the explosive leads to ignition.

It should be noted that the process of decomposition of the explosive may be intensified by the additional supply of energy from the chemical reaction between the explosive decomposition products and the gas phase of the additives, which have a high heat of oxidation. This is confirmed by an analysis of the photographic record of the process of ignition of PETN at near-critical pulse energy densities. It follows from Fig. 2 that in the initial stage the process takes place at much higher rates in a mixture with aluminum (1% by weight) than in PETN not containing additives. Introducing this amount of aluminum has practically no effect on the length of the transition interval or the value of the steady-state detonation velocity.
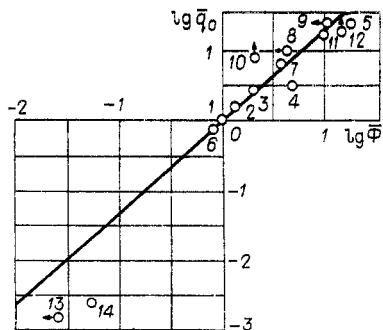
Fig. 1. Comparison of experimental values of the ideal critical laser energy density $\bar{q}_0$ and the explosive ignitability criterion $\bar{\Phi}$. PETN: 1) $m = 0.435$, $r_c = 2.2$ m, 2) $m = 0.322$, $r_c \simeq$ 2 μm [9], 3) $m = 0.209$, $r_c \simeq 2$ μm [9], 4) $m = 0.096$, $r_c \simeq 2$ μm [9], 5) $m = 0.028$, $r_c \simeq 2$ μm [9]; RDX: 6) $m = 0.450$, $r_c = 1.8$ μm, 7) $m = 0.450$, $r_c = 23.2$ μm, 8) $m = 0.350$, $r_c \simeq 40$ μm [10], 9) $m = 0.163$, $r_c < 40$ μm [10]; 10) HMX: $m = 0.465$, $r_c = 12.3$ μm; 11) tetryl: $m = 0.422$, $r_c \simeq 30$ μm; 12) TNT: $m = 0.400$, $r_c \simeq 30$ μm; 13) lead azide: $m = 0.235$, $r_c \simeq 5$ μm [11]; 14) mercury fulminate: $m = 0.2$, $r_c \simeq 5$ μm [11].
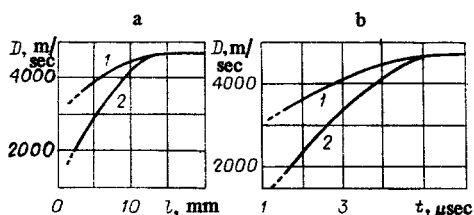

Fig. 2

Fig. 3

Fig. 2. Variation of the rate of development of the ignition process D along the length of the specimen (a) and with time (b) in PETN (2) and a PETN—aluminum mixture (1) at $m = 0.435$.
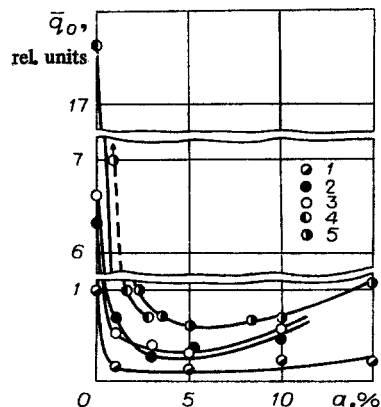
Fig. 3. Ideal critical laser energy density $\bar{q}_0$ as a function of the aluminum content a by weight for bulk-density model mixtures of aluminum and PETN (1), RDX (2), HMX (3), tetryl (4), and ammonium nitrate (5).

On the basis of these considerations we can explain the results of experiments to investigate the effect of the finely divided aluminum (mean particle size 2.2 μm) content on the laser ignitability of various individual explosives and ammonium nitrate (Fig. 3). The nature of the $q_0(a)$ dependence is completely identical for the different systems. The introduction of 1-3% aluminum is followed by a sharp fall in q_0. Further increase in the aluminum content (on the interval investigated) has practically no effect on the ignitability. It may be assumed that this behavior of the $q_0(a)$ dependence is associated with the analogous variation of the parameter Φ_3 which in integral form characterizes the optical absorptivity of the system, this, in its turn, depending on the concentration, particle size, and optical

properties of the additive material. It is also interesting to note that the less easily the system ignites (without the additive), the greater the relative effect of introducing the additive into its composition. This pronounced decline in the effect of the system's own properties on the ignitability of mixtures containing an aluminum additive is evidently associated with the extremely high efficiency of the gasdynamic and chemical interaction between the gas-phase aluminum and the active medium, the mechanism of which is complex and will require further research to elucidate.

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SPARK IGNITION LIMIT OF TURBULENT FUEL MIXTURES

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The spark ignition of turbulent fuel mixtures is a topical problem with regard to both the development of the theory and practical applications, in particular in the area of explosion-proofing. Theoretically, this is a very difficult problem because of the complexity of the theoretical description of turbulence. Experimental studies of the spark ignition limits of turbulent fuel mixtures have been fairly extensive [1-3]. The experimental data on the spark ignition limits of homogeneous turbulent fuel mixtures obtained in a spherical combustion chamber with turbulence generators [4-6] are examined below with a view to establishing an empirical relation between the properties of the fuel mixtures and the turbulence parameters at the spark ignition limit. By the spark ignition limit of the turbulent fuel mixture we understand the minimum value of the fluctuation velocity at which following spark ignition in a closed combustion chamber the pressure does not rise and the nuclear flame that develops after the spark is smeared out by the turbulent fluctuations over the volume of the chamber and is quenched without appreciable burnup of the fuel mixture [4].

In [4] a method of measuring the turbulent burnup rate using a combustion chamber with turbulence generators is described. The method is based on the assumption that to each instantaneous value of the pressure in the chamber there corresponds a certain volume of products which collect in the center and are separated by a spherical surface (combustion sphere) from the unburnt mixture. As the burnup rate W we took the rate of growth of the radius of the combustion sphere dr_c/dt divided by the adiabatic degree of expansion of the