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ARPA Order No. 1622-3

March 17, 1972

This research was supported by the Advanced Research Projects Agency of the Department of Defense and was monitored by the Air Force Office of Scientific Research under Contract No. F44620-72-C-0053. The publication of this report does not constitute approval by any government organization or Informatics Inc. of the inferences, findings, and conclusions contained herein. It is published solely for the exchange and stimulation of ideas.

ARPA Order No. 1622-3
Program Code No: 62701D2F10
Name of Contractor:
Informatics Inc.
Effective Date of Contract:
January 3, 1972
Contract Expiration Date:
December 31, 1972
Amount of Contract: $250,000

Contract No. F44620-72-C-0053
Principal Investigator:
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770-3000
Short Title of Work:
"Soviet Technical Selections"

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INTRODUCTION

This report includes abstracts and bibliographic lists on major contractual subjects that were completed in February, 1972. The major topics are: laser technology, effects of strong explosions, geosciences, and particle beams. A list of selections under material sciences has been included as a fifth optional subject. The abstracted material includes some selections from late 1971 that have not otherwise been reported.

To avoid duplication in reporting, only laser entries concerning high-power effects have been included, since all current laser material will appear routinely in the quarterly bibliographies.

An index identifying source abbreviations is appended.

UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Informatics Inc. 6000 Executive Blvd. Rockville, Md. 20852	2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED 2b. GROUP

3. REPORT TITLE

Selected Material from Soviet Technical Literature, February 1972

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Scientific . . . Interim

5. AUTHOR(S) (First name, middle initial, last name)

Stuart G. Hibben

6. REPORT DATE March 17, 1972	7a. TOTAL NO. OF PAGES 141	7b. NO. OF REFS ---
8a. CONTRACT OR GRANT NO. F44620-72-C-0053 b. PROJECT NO. AO 1622-3 c. 62701D d.	9a. ORIGINATOR'S REPORT NUMBER(S) 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) AFOSR - TR - 72 - 1965	

10. DISTRIBUTION STATEMENT

Approved for public release; distribution unlimited.

11. SUPPLEMENTARY NOTES Tech, Other	12. SPONSORING MILITARY ACTIVITY Air Force Office of Scientific Research 1400 Wilson Boulevard (NPG) Arlington, Virginia 22209

13. ABSTRACT

This report includes abstracts and bibliographic lists on major contractual subjects that were completed in February, 1972. The major topics are: laser technology, effects of strong explosions, geosciences, and particle beams. A list of selections under material sciences has been included as a fifth optional subject. The abstracted material includes some selections from late 1971 that have not otherwise been reported.

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I. Laser Technology

1. Abstracts

Assovskiy, I. G., and A. G. Istratov. Combustion of powders under optical radiation. ZhPMTF, no. 5, 1971, 70-77.

It is noted that the bulk of the literature on optical ignition of powder does not consider the further effect of optical flux on combustion characteristics following ignition. An analysis is accordingly made to correlate combustion rate of a powder with intensity of optical excitation, using both a stationary combustion regime and one in which optical flux varies in some harmonic manner. It is assumed that incident flux is absorbed in the condensed phase according to the exponential Bouguer-Lambert law, at a constant transparency index. In stationary combustion of the powder the optical radiation is shown to be equivalent to raising the initial powder temperature, which permits analysis without consideration of radiation parameters. In the nonstationary case with periodically varying optical flux the model of Novozhilov (PMTF, no. 4, 1965) is used to define combustion behavior. A correction factor to average burn rate, proportional to the square of the optical flux amplitude, is introduced; in the case of an exponential ratio of combustion rate to initial temperature, this correction is a negative one. The authors also discuss the effect of radiation on the stability of combustion in the stationary mode.

Basov, N. G., O. N. Krokhin, N. V. Morachevskiy, and G. V. Sklizkov. Internal and surface effect of laser radiation on optical glass. ZhPMTF, no. 6, 1971, 44-49.

The authors describe an experiment with laser irradiation of glass at energy levels both below and above damage threshold. It is noted that transparent dielectrics generally are an interesting subject for laser effects since they display a wide range of damage characteristics depending on material quality and incident energy parameters. The test was done by a high-speed interferometry method, using a free-running neodymium laser as the active beam and a ruby laser in the giant pulse mode for illumination of the impact region; the method was similar to one reported earlier by Basov et al (Effects of High Power Lasers, Dec. 1971, 80). At an Nd laser level of 100 j and 1 millisecond pulses, a series of interferograms were made of the glass, showing growth of inhomogeneities in the target region at intervals up to 800 μ sec following pulse termination. The results show no time correlation of inhomogeneity development with laser pulse parameters, hence the alteration is concluded to be an integral effect. The most probable mechanism for this is concluded to be the accumulation of thermoelastic stresses from continuous absorption of the laser energy. Basov includes theoretical and experimental data to support this hypothesis. Tests were also made with beam energy increased by 10 to 15%, which exceeded the damage threshold of the glass; interferograms of the resulting flare are presented.

Boyko, Yu. I., Ya. Ye. Geguzin, and A. K. Yemets. Character of deformation in the region of pulsed laser beam action on a CsI single crystal. FTT, no. 10, 1971, 3096-3097.

A brief description is given on alteration and damage effects in CsI single crystals exposed to a neodymium laser. The beam was focused within plane-parallel specimens 3 mm thick to a spot size of 200 microns; energy was 2--3j at a 500μsec pulse width, which is above the damage threshold. Depending on plane orientation to the beam, surface disfigurations of generally square or rhombic form were observed in all cases, at some distance from the destruction center. Two photos of the described figures are included. The authors suggest the effect is due to the crowdion mechanism proposed by Indenbom (ZhETF P, v. 12, 1970, 526), or at least the results would permit the crowdion mechanism, whether or not that would be a sufficient explanation. Analogous disfigurations are noted to have been recently reported in CsI under fast-acting point loading, as described for example by Rozhanskiy et al (FTT, 1971, 411).

Fekeshgazi, I. V. Structure of the flare formed at the input surface of alkali-halide crystals by a laser beam. IN: Kvantovaya elektronika. Kiyev, Izd-vo naukova dumka. No. 5, 1971, 256-259.

A beam-target study is described using a Q-switched ruby on specimens of NaCl, KCl, KBr, and LiF. The laser was run in a spike mode with spikes controlled from one to six or more. Spikes were of approximately equal amplitude, 30--40 nsec wide and separated by 100-150μsec; power was from 2 to 8 Mw. The main effect of interest was the appearance of luminous centers in the specimen each of which corresponded to a single spike in the laser pulse. Sample photos are given showing the effect of a six-spike pulse, which generates a train of six centers starting at the surface. The mechanism appears to be that of a vapor cloud generated by the first spike, which diffuses into the crystal and is illuminated by succeeding spikes; luminosity decays monotonically with rise in number of spikes. Cloud diffusion rate appeared to be essentially constant within a 3--6 x 10^3 cm/sec range. A spectrographic study confirmed that the luminosity was from the metal line of the particular specimen.

Lisitsa, M. P., and I. V. Fekeshgazi. Study of the dynamics of flare development, formed by laser radiation on the surface of transparent dielectrics. IN: Kvantovaya elektronika. Kiyev, Izd-vo naukova dumka, no. 5, 1971, 251-256.

In a companion article to the foregoing by Fekeshgazi, the authors describe the methods used to record flare development in the interaction of a laser beam with type LK-5 glass and NaCl. The main effort was in registering flare brightness and in relating flare development time and pulse shape to the incoming laser pulse; this was done with a photomultiplier and a fast sweep scope giving a flare front velocity resolution of 2.5 nsec. A dual optical grid system was used in the flare development region for velocity measurements; at a grid separation of 3 mm, this permitted velocity measurements up to 10^8 cm/sec. Data on velocity characteristic and density of evaporated material in the flare are given, primarily for glass specimens, for flare generation at both entrance and exit faces.

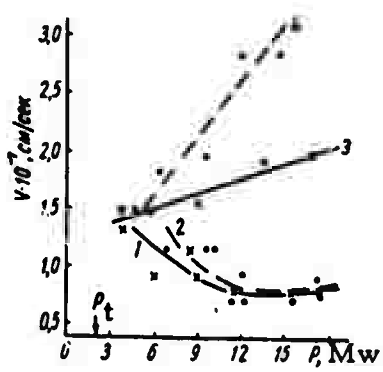

Fig. 1. Flare velocity in beam direction (3, 4) and density of flare atoms (1, 2) vs. laser power. 1, 3 - NaCl; 2, 4 - glass, P_t = damage threshold.

Fig. 1 is an example of flare dynamics at the target face, using a Q-switched ruby with 30 nsec, 18 Mw pulses. Analogous data for flares at the exit face show a secondary peak in luminosity, indicating development of a shock wave during flare lifetime.

Sultanov, M. A. Study of the destruction of polymer films by a laser beam, as a function of type and structure of the material. Mekhanika polimerov, no. 6, 1971, 1092-1093.

A photographic analysis is given of a variety of laser damage types to polymer films, using both focused or nonfocused beams. Test materials cited were oriented and nonoriented thin films of polyethylene, dacron, polypropylene, an α-methyl styrene-plus-styrene copolymer, teflon, and kapron. Film thickness varied from 85 to 350μ; irradiation was by an Nd laser at 3-5j, 1-5 millisecond pulses developing a power density of 3 x 10^9 w/cm^2. For focused beam damage tests f = 35 mm. Results are presented as microphotos of surface (270X) and internal (600X) damage; one example given compares effects on Soviet and Hungarian brands of polyethylene. Characteristic crater formation and ejecta patterns for each polymer type are discussed. In the case of teflon the usual pattern was absent; instead a surface fusion was observed at depths of 3--5 microns, with beam effects detectible down to 20 microns. It is noteworthy that up to 60% of incident laser energy was reflected or scattered by the teflon surface, whereas reflection from all other materials was negligible. The test results prove that the nature of damage in polymers is strongly governed by the physicochemical properties of the material. However, a generalization can be made on damage mechanism according to irradiation type, i.e. for a nonfocused beam, photolysis is called the major destructive factor, whereas a focused beam generates a hydrodynamic explosion with plasma and shock wave formation.

Nevskiy, A. P. Electron temperature at the surface of metals subjected to powerful thermal fluxes. TVT, no. 4, 1970, 898-899.

A theoretical treatment is given to conditions for generation of hot electrons in a metal subsurface layer by external thermal flux, to achieve conditions analogous to exploding wires. A formula was derived for temperature Θ of the electronic subsurface layer in metals, as follows:

$$\theta = T + (l_\epsilon Q / \lambda) \qquad (1)$$

where T $\sim 10^3$ deg K is the temperature of the crystal lattice, Q is thermal flux density on the metal surface, and l_ϵ and λ are thermophysical characteristics of the metal. Formula (1) gives the Q necessary to establish a given (e.g. an order of magnitude) differential between Θ and T, which occurs because of a significant difference in time τ_e of establishment of a Fermi distribution in electron gas and relaxation time τ_ϵ of electrons interacting with the crystal lattice ($\tau_\epsilon \geq \tau_e$). An example shows that $Q \approx 10^5 - 10^7$ w/cm^2 are required to achieve an order of magnitude differential between Θ and T in metals. These densities are presently obtainable in interactions of concentrated laser and electron beams with the surface of solids, of powerful heat fluxes in arc discharges at the cathode, etc. In the case of an arc discharge, this effect of "hot" surface electrons must be accounted for in the analysis of electron emission.

Nemchinov, I. V., and S. P. Popov. Shielding of a surface evaporating under the action of a laser, for the case of temperature and ionization nonequilibrium. ZhPMTF, no. 5, 1971, 35-45.

This paper is an extended treatment of a theoretical analysis published earlier by the authors on the dynamics of shielding by vapor products of a target surface under laser irradiation (Effects of High Power Lasers, Dec. 1971, 34). From an extensive theoretical analysis and numerous citations from other current work on this subject, the authors establish that the critical flux density q_* at which shielding is defined as beginning occurs at a substantially lower value than that predicted by equilibrium ion and electron temperatures ($T_e = T_i$). It is therefore postulated that $T_e \neq T_i$ at shielding onset and appearance of the flare phenomenon. A description of thephysical processes is developed on this theory, under certain simplifications concerning heat transfer, for flare propagation both in a vacuum and in a gas medium. Some calculations are given based on typical experimental parameters, assuming a ruby laser source and an aluminum target; graphical solutions for these are included. The authors note in addition the analogous finding of Popov on the shielding developed in front of a shock wave in gas (ZhETF P, v. 9, no. 3, 1969, 176-179), which also commences earlier than predictable by the equilibrium temperature theory. Another related work by Popov et al has been reported previously (Effects of Strong Explosions, no. 2, 1971, 105), on this subject.

Putrenko, O. I., and A. A. Yankovskiy. Study of optical erosion of metals during a pulse of laser radiation. ZhPS, v. 15, no. 4, 1971, 596-604.

This is a continuation of an earlier study by the authors on characteristics of condensed ejecta from laser impact with metals (Effects of Strong Explosions, no. 2, 1971, 38). The same laser parameters were used, i.e. a free-running type

GSI-1 generating 1 μ sec, 7 j pulses, and using a focal distance of 200 mm. In the present tests a transparent rotating disk was interposed between the beam source and target face, so that a time pattern of condensate products was obtained.

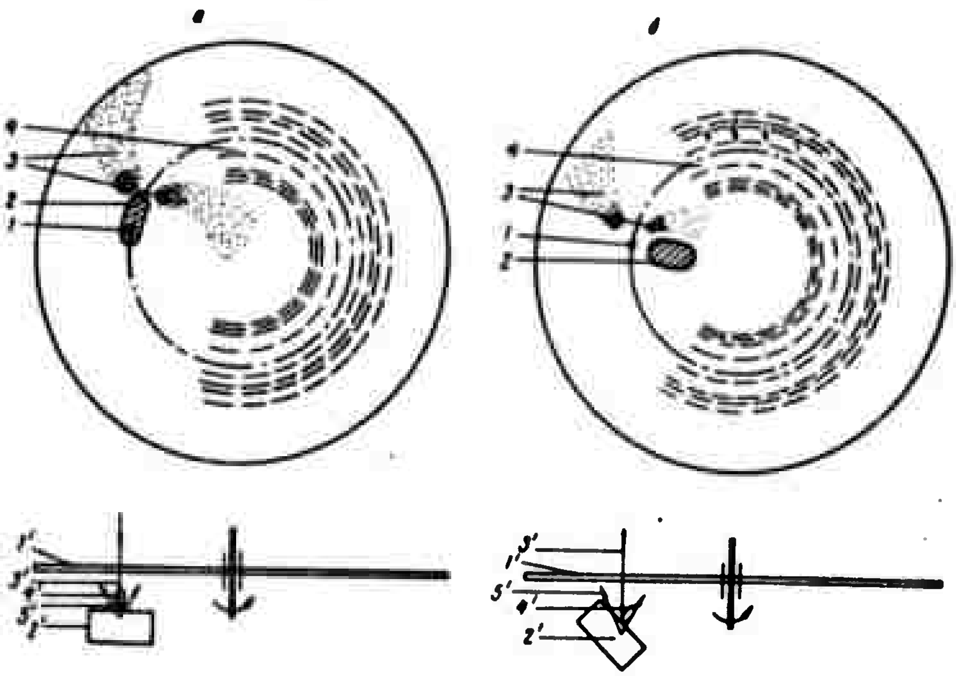

Fig. 1. Condensate distribution, lead target a - normal, b - 45° beam angle. 1 - beam impact point; 2 - condensed vapor; 3 - particle rays; 4 - large particle bands. Disk speed = 3,000 rpm; distance between target and disk = 12 mm.

Fig. 1 shows two examples of condensate distribution for normal and inclined beam angle, using a lead target. Three discrete types of condensed forms can be distinguished with preferential positioning, depending on beam angle. Flare photos are also given for an iron target (Fig. 2), which show that the flare axis will deflect during flare development to line up with incident beam direction, for the case of an inclined beam. Data show that the limit velocity of ejecta was about 100 m/sec. The technique is useful in identifying type and pattern of ejected material during the course of a laser pulse. The results indicate that pulse width need not exceed 200 μ sec, since most of the vaporization occurs well before this time.

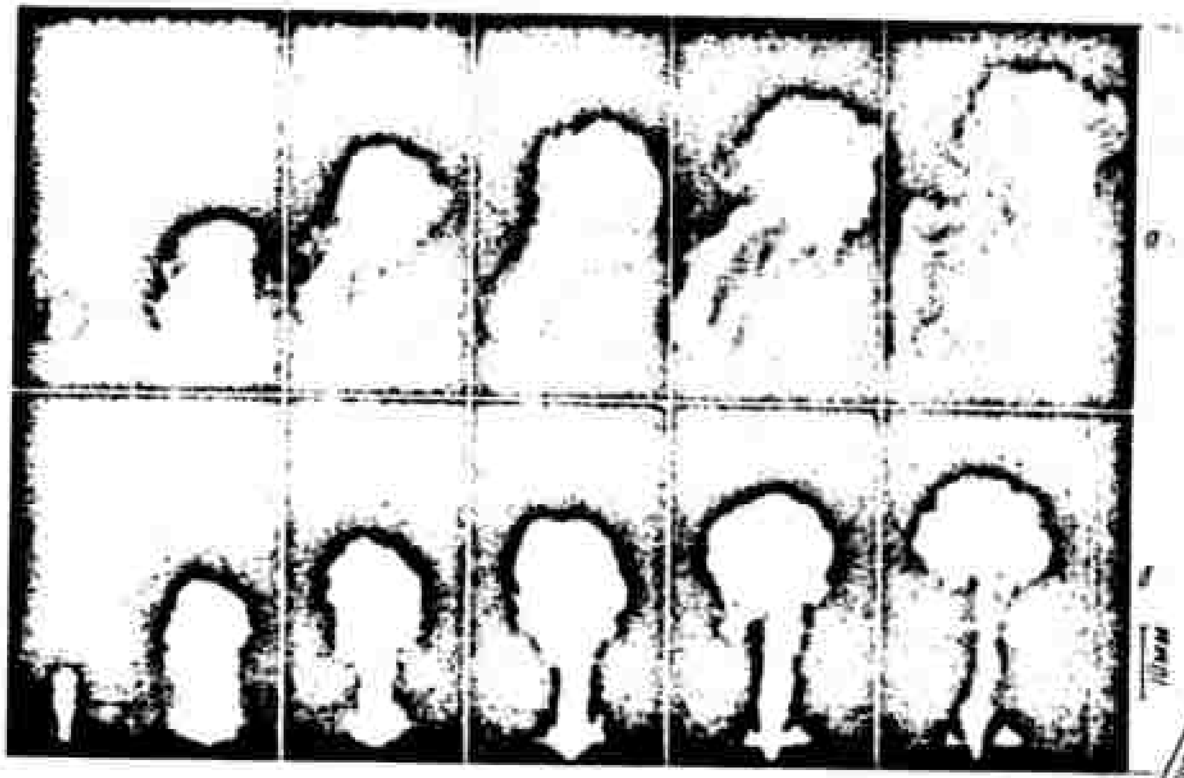

Fig. 2. Flare development, iron target. a - 45° beam angle; b - normal. 64 μsec between frames.

Kasatochkin, V. I., M. Ye. Kazakov, V. V. Savranskiy, A. I. Nabotnikov, and N. P. Radimov. Synthesis of a new allotropic form of carbon from graphite. DAN SSSR, v. 201, no. 5, 1971, 1104-1105.

Applying a free-running neodymium laser beam to a pyrographite target, the authors obtained vaporized deposits which proved to be a new allotropic form of carbon. In one test a pyrographite substrate opposite the target face was used, with a center aperture for the laser beam (Fig. 1); one millisecond pulses were used, at energies of 250 and 500 j. In another variant the target specimen was

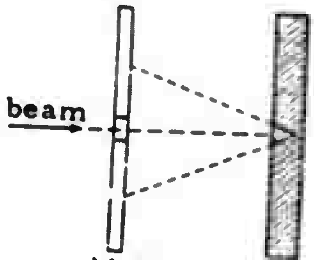

Fig. 1. Irradiation of graphite.

placed in an evacuated glass ampoule, with the vapor products depositing on the inner surface. The deposits typically were silver-white, surrounded by a black border. X-ray studies of the silvery deposit showed a polycrystalline structure having a mean crystallite dimension of 10^{-5} cm; images of the black deposits were characteristic of a highly dispersed substance with diffused diffraction bands. A complete identity was established between electron diffraction patterns from single crystals of both silvery and black deposits, indicating the structural identity of the two products. The black form is identified as carbyne, which has previously been obtained by oxidative dehydropolycondensation of acetylene. The difference in color was attributed to the high degree of dispersion in carbyne as well as the presence of amorphous carbon impurities. It is noted that this allotropic form has been discovered earlier in natural graphite and in meteoric material, and later was produced by electric discharge in pyrographite under vacuum and high temperature (Whittaker et al, Science, v. 165, 1969, 589). The authors intend further publication on the atomic structure and properties of the new allotropic form.

Pogodayev, V. A., V. I. Bukatyy, S. S. Khmelevtsov, and L. K. Chistyakova. Dynamics of the explosive vaporization of water drops in an optical field. IN: Kvantovaya elektronika. Moskva, Izd-vo Sovetskoye radio. No. 4, 1971, 128-130.

Results are described for the droplet dispersion patterns obtained from laser explosion of a water drop. As reported earlier, the critical point at which explosion occurs depends on the product ϵK_p, where ϵ is incident energy density and K_p is a dimensionless factor indicating absorptive effectiveness; the present tests were done above the critical point. The test configuration (Fig. 1) used a

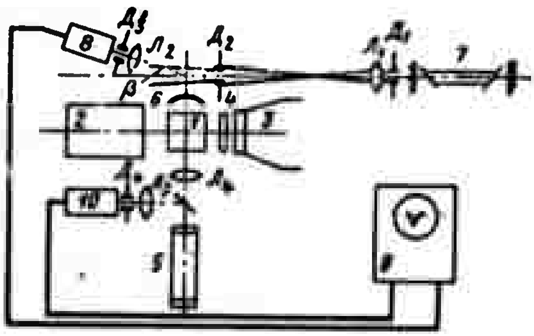

Fig. 1. Water drop explosion experiment.
1 - water drop on movable plate; 2 - camera; 3, 4 - illumination; 5 - ruby laser; 6 - coated screen; 7 - LG-55 laser; 8, 10 - photomultiplier; 9 - scope.

free-running ruby laser to evaporate water drops on a glass plate; the ejected droplets were collected on a coated screen and their distribution patterns were recorded. In addition, droplet velocity was recorded by a second transverse laser beam in the ejecta path, where intersection of droplets was registered as noise in the beam detector system; synchronization with the activating beam gave droplet time of flight. Data presented include directional patterns and velocity characteristics; droplet sizes varied in the range of 5 to 80 microns, depending on the size of the initial target drop. The tests verify the non-central explosion point in the drop, and resultant anisotropic patterns of energy propagation and ejecta motion.

Borisov, V. V. Stable regime in the case of incidence of an e-m signal of finite duration on an ionization front moving at light velocity. IVUZ Radiofizika, no. 12, 1971, 1923-1924.

A brief extension is given to an earlier paper by the author on the same subject (Borisov, IVUZ Radiofizika, no. 1, 1971, 54). A rectangular electromagnetic pulse is assumed to intersect an ionization front moving at light velocity; electron velocity in the intersect region is taken to be well below light velocity, and ion motion is neglected. Using this model the author derives general expressions for the transverse electric and magnetic field vectors in the impact region. Graphical results are included which compare the field characteristics at short pulse widths ($\omega_0 T = 1$) to those at extended widths ($\omega_0 T = 40$). It is shown that at sufficiently great pulse widths the E vector at intersection tends to zero, and practically all energy in the incident pulse converts to a static magnetic field which is confined to a region determined by the pulse width.

Bud'ko, N. I., V. I. Karpman, and D. R. Shklyar. Stability of a plasma in the field of an axial monochromatic wave. ZhETF, v. 61, no. 4, 1971, 1463-1476.

An extended analysis is given of the development of plasma excitation from interaction of an axial monochromatic wave. The discussion is based on the phenomenon reported by Wharton et al (Phys. Fl., 11, 1968, 1761), that for a sufficiently intense wave, satellites are generated in the plasma whose frequencies differ from the beam fundamental by a predictable amount. The present authors interpret the satellite phenomenon as a result of instability, caused by a nonlinear variation in the distribution function of the excitation wave in the plasma. The amplitude characteristics of satellites near the instability point is accordingly investigated; it is shown that for the experimental conditions of Wharton et al, excitation of the satellites is caused by a non-parametric type of instability. The results are compared with those of several other authors on the same phenomenon.

Generalov, N. A., V. P. Zimakov, G. I. Kozlov, V. A. Masyukov, and Yu. P. Rayzer. Experimental investigation of a continuous hot optical discharge. ZhETF, v. 61, no. 4, 1971, 1434-1446.

Rayzer, Yu. P. Continuous sustaining of a plasma by laser radiation, and the optical plasmatron. VAN, no. 10, 1971, 28-32.

Rayzer, Y., G. Kozlov, and N. Generalov. Nonlinear absorption of intensive radiation in plasma. Soviet Science Review, v. 1, no. 1, 1970, 42-46.

These papers generally review and extend the experimental data already reported on the optical plasmatron (Rayzer, Generalov et al, Effects of High-Power Lasers, Dec. 1971, 17-21). The experiment uses a Q-switched CO_2 laser to ignite and sustain a suspended plasma in argon and xenon, over a variety of pressure and laser power levels. The general purpose here has been to define the limits to the critical parameters for plasma maintenance, and to observe the dynamics of plasma development. It is shown for example that there is a limited gas pressure range within which the plasma will subsist, for a given laser power; this is seen in Fig. 1 for Ar and Xe. It is evident from the curves

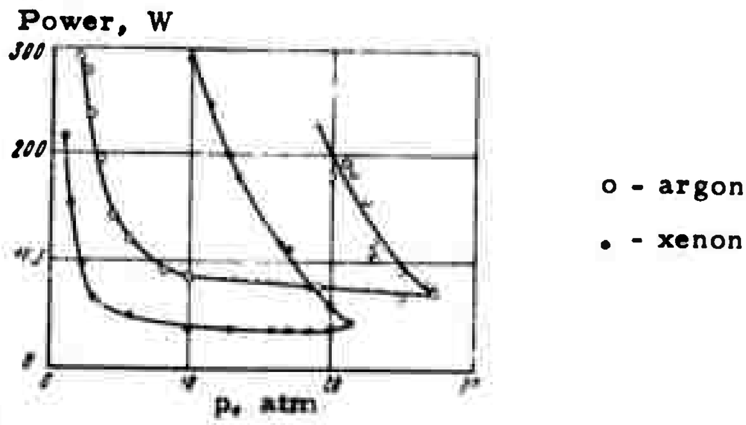

Fig. 1. Limits for optical plasmatron generation.

that over a range of some 10 to 25 atm, threshold power is practically independent of pressure. Other data given include beam transmissibility through the plasma and propagation behavior of the plasma; typical results show an initial velocity of 10 m/sec, decaying to zero at the stable configuration in the order of several hundred microseconds.

Kazakov, A. Ye., I. K. Krasyuk, P. P. Pashinin, and A. M. Prokhorov. Experimental observation of laser radiation amplification from the interaction of opposed laser beams in a plasma. ZhETF P, v. 14, 1971, 416-418.

Experimental data are briefly discussed on the effects of focusing opposed laser beams in an argon plasma. The test configuration (Fig. 1) used

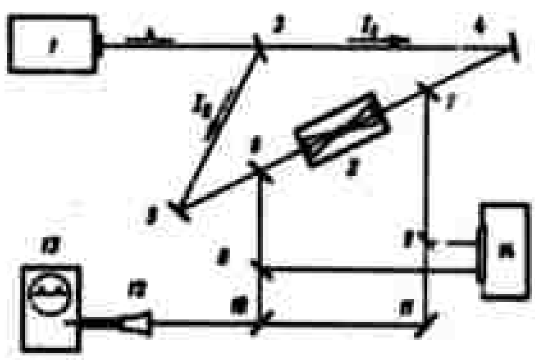

Fig. 1. Colliding beam experiment.
1 - laser; 2 - Ar chamber; 3--11 - splitting deflecting optics; 12 - coax; 13 - scope, 0.2 ns resolution; 14 - spectrograph.

a monopulse laser at 6943Å and 20-100 nsec duration, split and simultaneously focused at f = 2 cm through opposite faces of the argon chamber. The optics were assigned such that $I_2 < I_1$ by varying amounts, but both were above breakdown threshold. Records of exit intensities and spectra of the two pulses showed two distinct effects: the weaker pulse was amplified by the stronger, and also underwent a spectral broadening. These effects were more pronounced with larger initial disparity between I_1 and I_2 intensities. An example given shows I_2 increased by a factor of 1.32, where initially $I_2 = 0.2\ I_1$. Stimulated Compton scattering is suggested as the main mechanism for these results, and calculations on this assumption show a good agreement with actual gain figures for the weaker pulse. The spectral change in I_2 is not explained and must be clarified by additional tests.

Zakharov, S. D., Ye. L. Tyurin, and V. A. Shcheglov. On the propagation of monochromatic radiation through a plasma. ZhETF, v. 61, no. 4, 1971, 1447-1451.

A rigorous analytical solution is obtained to the problem of propagation of pulsed monochromatic radiation in an absorptive plasma. The laser pulse is assumed to have an arbitrary waveform, and a radiation frequency well above plasma frequency; the volumetric change in electron density is also assumed to occur smoothly. With these assumptions reflected radiation may be neglected. It is further assumed that electron collision frequency ν_e meets the condition $\nu_e \tau >> 1$, where τ is the characteristic time to alter the mean electron energy in the plasma; this permits use of the concept of electron temperature. Expressions are then derived for pulse intensity as a function of penetration into the plasma and for absorption coefficient, assuming a bremsstrahlung mechanism.

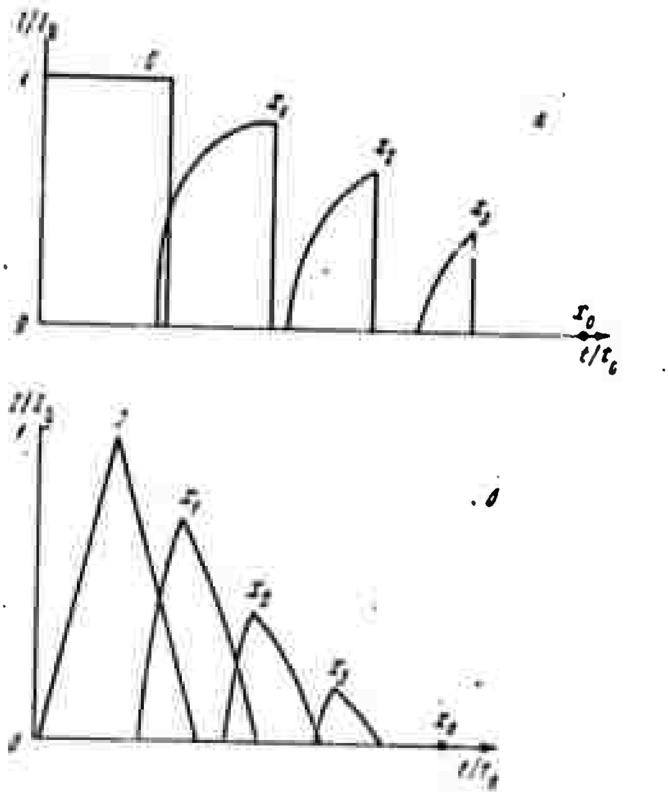

Fig. 1. Variation in pulse waveform vs. penetration into plasma.

Fig. 1 shows theoretical degradation of an initially rectangular and triangular laser pulse vs. penetration depth. Other idealized solutions are presented, based on typical parameters of an Nd glass laser and a hydrogen plasma.

2. Recent Selections

A. Laser Beam-Target Effects

Afanas'yev, A. A., V. S. Burakov, V. V. Zheludok, and S. V. Nechayev. Nonlinear interaction between laser radiation and an alkali metal plasma. DAN BSSR, no. 10, 1971, 889-891.

Anan'in, O. B., Yu. A. Bykovskiy, M. Ya. Minakov, and A. N. Petrovskiy. Self-focusing of ultrashort pulses in transparent media. FTT, no. 11, 1971, 3465-3467.

Arifov, U. A., M. R. Bedilov, and K. Khaydarov. On the nature of ion generation from the effect of laser radiation on solid matter. DAN Uzb, no. 7, 1971, 25-26. (RZhF, 1/72, #1G151)

Askar'yan, G. A., Kh. A. Diyanov, and M. Mukhamadzhanov. New experiments in forming a self-focused filament from focusing a beam at the surface of a medium. ZhETF P, v. 14, no. 8, 1971, 452-455.

Bayratov, B. Kh., B. P. Zakharachenya, and Z. M. Khashkhozhev. Self-focusing of argon laser radiation and light scattering by phonons in bismuth germanium oxide crystals. FTT, no. 11, 1971, 3412-3414.

Brekhovskikh, V. F., Z. I. Mezokh, A. V. Ovodova, A. A. Uglov, A. K. Fannibo, and V. A. Yanushkevich. Dislocation structure of germanium subjected to a laser beam. FiKhOM, no. 6, 1971, 6-10.

Butenin, A. V., and B. Ya. Kogan. The mechanism of optical breakdown in transparent dielectrics. IN: Sbornik. Kvantovaya elektronika. Moskva, Izd-vo Sovetskoye radio, no. 5, 1971, 143-144.

Darznek, S. A., and A. F. Suchkov. Determining the limiting diameter of a self-focusing channel in a medium with cubic nonlinearity. IN: Sbornik. Kvantovaya elektronika. Moskva, Izd-vo Sovetskoye radio, no. 4, 1971, 109-112.

Garber, R. I., Ye. I. Stepina, and A. A. Stepanov. Features of the destruction of calcite crystals by laser radiation. FTT, no. 1, 1972, 243-245.

Gusev, N. V., and A. A. Pyarnpuu. Quantitative study of the ejection of matter from a solid surface by the action of powerful radiation. ZhPMTF, no. 4, 1971, 127-133. (RZhF, 1/72, #1G254)

Kolokolov, A. A., and G. V. Skrotskiy. Kinetics of the self-focusing process for short optical pulses. OiS, v. 31, no. 4, 1971, 650-652.

Kuskova, T. V., Ye. I. Raykhel's, and M. I. Rudenko. Effect of optical flux on the dislocation structure of alkali-halide single crystals. Monokristally i tekhnika, no. 3, 1970, 48-51.

Lisovets, Yu. P., I. A. Poluektov, Yu. M. Popov, and V. S. Roytberg. Passage of a coherent ultrashort optical pulse through a semiconductor. IN: Sbornik. Kvantovaya elektronika. Moskva, Izd-vo Sovetskoye radio, no. 5, 1971, 28-36.

Mirkin, L. I. Analogies between mechanisms of destruction of transparent and opaque materials by a laser beam. DAN SSSR, v. 201, no. 6, 1971, 1335-1337.

Orekhov, M. V., and B. S. Slavin. On the nature of material ejection from the action of laser radiation on materials with varying thermophysical properties. ZhPS, v. 16, no. 1, Jan. 1972, 153-155.

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II. Effects of Strong Explosions

1. Abstracts

Alinovskiy, N. I., V. G. Yeselevich, N. A. Koshilev, and R. Kh. Kurtmullayev. Investigation of the energy spectrum of ions in a plasma heated by a shock wave. ZhETF, v. 57, no. 3, 1969, 706-715.

Using a passive corpuscular diagnostic technique, the authors investigated the energy spectra of ions in a plasma heated by a shock wave. It was observed that for large Mach numbers ($M \gtrsim 3$-4), the one-velocity movement of ions in a plasma was violated up to the moment of wave cumulation at the system axis. Under the given conditions, this phenomenon is explained by the "overturning" of the shock wave front which increases the random behavior of the ions. One of the basic objectives of the experiment was to determine the locus for the start of registering particles inside a plasma and the moment of this start relative to the beginning of the wave process. This task was resolved using a space-time pattern of the wave process and the motion of registering particles. The paper gives a comprehensive analysis of this space-time pattern. At low Mach numbers ($M < M_c$), the start of registering particles and their random velocities were observed to occur after wave cumulation at the system axis. The measured relative width of the energy spectrum of particles emitted in longitudinal and transverse directions indicates a strong collisionless dissipation of energy. This relative width of the energy spectrum at peak energy, exceeding by an order of magnitude the directional energy of the ions in the wave, satisfactorily indicates effective randomness for ion velocities. The temperature determined from the energy spectrum of particles agrees satisfactorily with the progressive energy of ions in a wave. The apparatus used in the study of the energy spectrum and the diagnostic technique used are explained in great detail.

Galeyev, A. A. and R. Z. Sagdeyev. Shock wave model in the solar wind plasma. ZhETF, v. 57, no. 3, 1969, 1047-1053.

A kinetic model of a collisionless shock wave in the solar wind plasma is developed, on assumptions of turbulence created by hose instability and $T_e \leq T_i$, when the effect of resonance ions is the most important. The existence of a hose instability implies plasma compression and an increase in longitudinal pressure $p_{//}$ in the plasma in a weak magnetic field. To simplify the problem of model development, only weak shock waves were considered within the framework of quasilinear theory. The solution of the quasilinear equation of hose instability at a Mach number $M \cong 1$ gave the following expression of anisotropy of plasma pressure p as a function of the level of magnetic field fluctuations:

$$(p_{\parallel} - p_{\perp}) / p_0 = 0{,}92(M-1)h^{1/2} - 0{,}5h^{1/2} - O(0{,}04h). \qquad (1)$$

where h is the energy characteristic of magnetic field fluctuations. The anisotropy $(p_{\parallel} - p_{\perp})$ increases to a maximum with increase in energy fluctuations, then becomes zero again at

$$h_1 \approx 1{,}5(M-1)^{1/2} \ll 1. \qquad (2)$$

which is the upper limit of amplitude of small fluctuations at above-critical shock wave velocity. The quasilinear equation (1) together with a linear equation of energy of rising fluctuations solve the problem of the frontal structure of a weak shock wave. The profiles in Fig. 1 show that decay of h in front of a shock wave (at $S \to -\infty$) follows a power law and instability saturation behind the front obeys an exponential law. The front width is of

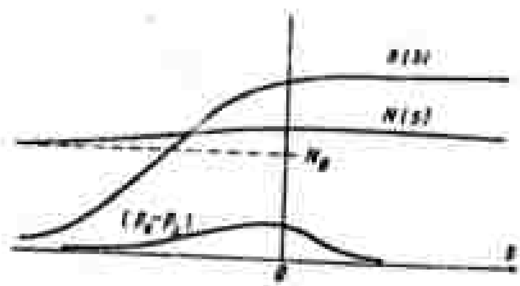

Fig. 1. Profiles of density N, magnetic field h, and pressure anisotropy in the wave front.

the order of the ionic Larmor radius. An analogous calculation for $(p_{\parallel} - p_{\perp})$ within the framework of the quasihydrodynamic equations of Chew-Goldberger-Low indicated that velocity of a weak shock wave is determined by the three-dimensional model of sound velocity (adiabatic exponent = 5/3). This means that hose instability equalizes $p_{\parallel}$ and $p_{\perp}$, as the effective collisons do. Thus, both models indicate that $(p_{\parallel} - p_{\perp})$ increases within the wave front at a sufficiently high propagation velocity.

Zheleznyak, M. B., A. Kh. Mnatsakanyan, and I. T. Yakubov. Study of the nonequilibrium region behind a shock wave in air. IN: Sbornik. 2-y Vsesoyuznyy simpozium po goreniyu i vzryvu, 1969. Avtoreferatnyy doklad. Chernogolovka, 1969, 193-196.

The calculated concentration profiles of N_2, NO, N, O, and their ions and the profiles of translational, vibrational, and electron temperatures are given to describe the kinetics of various processes in air behind the front of a strong shock wave (shock wave velocity v_s = 8 - 12 km/sec). In calculating T_e, allowance was made for energy exchange between electrons and molecular, atomic, and ionic components of plasma. Calculations indicate the existence of an emission peak within the nonequilibrium region of a shock wave. The calculated profiles of emission intensity agree well with the available experimental data in the 0.40 - 0.42 μ range of λ for v_s = 8.6, 10, and 10.9 km/sec and P_1 = 0.1 torr. In the near-peak area, the emission of the first negative nitrogen system is predominant. The contribution of atomic lines increases near the equilibrium point. The concentration of atoms in an excited state was calculated by means of diffusion theory of stepwise processes.

Losev, S. A., and V. A. Polyanskiy. The effect of vibrational relaxation of molecules on characteristics of dissociating air behind the front of a strong shock wave. MZhiG, no. 4, 1969, 84-90.

The effect of vibrational relaxation in gas mixtures, e.g. air, at $T > 5,000^{\circ}K$ upon the rate constant k_i^* of chemical reactions, is discussed in view of the importance of this effect for solving problems of hypersonic aerodynamics. The following types of reaction were considered:

$$O_2 + M \rightleftarrows O + O + M \quad (1)$$

$$N_2 + M \rightleftarrows N + N + M \quad (2)$$

$$NO + M \rightleftarrows N + O + M \quad (3)$$

$$O + N_2 \rightleftarrows NO + N \quad (4)$$

$$N + O_2 \rightleftarrows NO + O \quad (5)$$

$$N_2 + O_2 \rightleftarrows NO + NO \quad (6)$$

where M is Ar, O_2, O, N_2, N, or NO. Using diffusion approximation by the Fokker-Planck equation under certain assumptions the relation between k_i and vibrational state of the molecules is described by

$$\frac{k_i}{k_i^0} = \frac{Z(T)}{Z(\theta)} \exp \frac{Q}{k}\left(\frac{1}{T} - \frac{1}{\theta}\right) \qquad (7)$$

where k_i^0 is the rate constant at statistical equilibrium, $Z(T)$ and $Z(\Theta)$ are the statistical sums of gas and vibrational temperatures, respectively, and Q is the activation energy. Also, the relaxation equation of vibrational energy α per single molecule was derived, where τ is the relaxation lifetime and n is

$$\frac{d\alpha}{dt} = \frac{\alpha^0 - \alpha}{\tau}, \qquad \alpha = \frac{\varepsilon}{n} \qquad (8)$$

the molecular density at time t. The time dependence of concentration γ_i of the reaction components, gas temperature and density, and reaction rates S_j behind the front of shock waves propagating in air at V = 4 and 7 km/sec were calculated with allowance for vibrational excitation of the O_2 and N_2 molecules according to the type (8) equation. Fig. 1 indicates that formation of NO

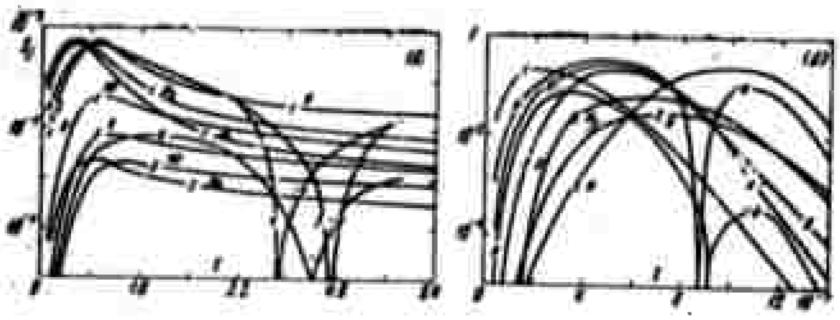

Fig. 1. Reaction rates behind shock wave front at 4 (a) and 7 (b) km/sec. The figures 1 - 6 correspond to the number of reaction and the symbols indicate the colliding partners in dissociation.

proceeds by the (4) and (5) mechanisms, when (6) is delayed. At higher V (8 - 9 km/sec), the decrease in NO and O_2 is controlled chiefly by the reactions (3) and (5), respectively, and dissociation of N_2 by collisions with N prevails over the reaction (4). A satisfactory agreement with the experimental data was obtained for O_2, when the effect of a delayed vibrational excitation is taken into account.

Meshkov, Ye. Ye. Instability of a two-gas interface accelerated by a shock wave. MZhiG, no. 5, 1969, 151-158.

An experimental study is described of the effect of a shock wave propagating in air at the interface between a pair of perfect gases with different densities. Helium, air, CO_2, freon-22, and freon-12 were paired in the measurement section of a cylindrical shock tube (Fig. 1).

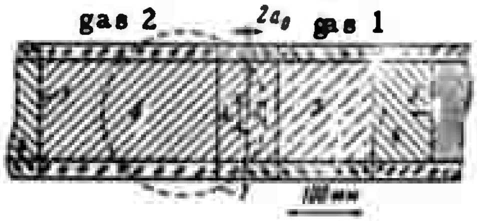

Fig. 1. Measurement section of shock tube: 1, 2 - thin (1μ) films, 3 - shock wave front, 4 - air, 5 - gas #1, 6 - gas #2, 7 - frame area of recording SFR camera.

Gas 1 - gas 2 combinations were tested with ρ_1/ρ_2 ratios in the 1.54 - 21.7 and 1/3 - 1/21.7 ranges. A shock wave in the low-pressure channel was generated by diaphragm breakdown initiated by electrical explosion of a wire. In the case of the initial perturbation amplitude $a_o = 2$ mm, photorecordings reveal that the gas interface is unstable, i.e. perturbation increases with time, regardless of whether the shock wave propagates from the lighter gas to the heavier, or vice versa. The only difference is that the sign of perturbation does not change in the former case, as it does initially in the latter. To a first approximation, the experimental plots of a/a_o versus the interface displacement χ/λ, hence the plots of a/a_o versus time, are linear. The experimental rates $d(a/a_o)/d(\chi/\lambda)$ increase with increase in ρ_2/ρ_1 ratio, in qualitative agreement with theory. The over 10% discrepancy between experiment and theory is tentatively ascribed to several experimental shortcomings, exclusive of the stabilizing effect of the film partition between the gases. In the case of $a_o = 4$ mm, the experimental $d(a/a_o)$ increases stepwise with the time, in agreement with theory. This pattern of increase is interpreted in terms of turbulent oscillations of the transmitted and reflected waves which are visible on photorecordings.

Sinkevich, O. A. <u>Stability of a plane shock wave front at low magnetic Reynolds numbers.</u> TVT, no. 6, 1969, 1126 - 1133.

Propagation of a plane shock wave front in the channel of a MHD device is analyzed assuming that the applied electrical field E(0, E, 0) and magnetic field B(0, 0, B) are interrelated through the parameters of the external circuit and the magnetic Reynolds number $Re_m < 1$. The latter is calculated from $Re_m = \mu\sigma U_{2H} l_e$, where σ is the electrical conductivity and U_{2H} is the velocity of undisturbed flow behind the shock wave front. The shock wave propagates at supersonic velocity in the direction of X<0 in a plane coincident with Y0Z (Fig. 1), hence disturbance in front of it is localized

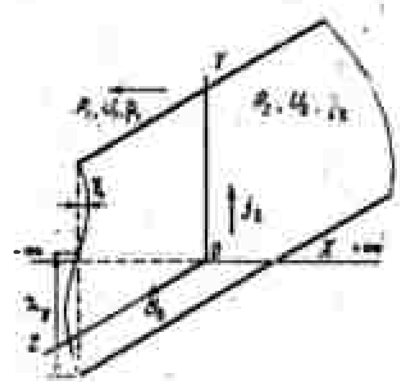

Fig. 1. Disturbance of a plane shock wave front at t = 0: P - pressure; U, ρ - velocity and density of the medium; ξ - shift of shock wave front, B_0 - magnetic field, j - parameter of the medium. Indexes 1 and 2 denote the medium in front of and behind shock wave, respectively.

at the front. The criterion of instability in a shock wave propagating in a magnetic field B was established by solving a set of linearized differential equations which describe small disturbances V', U', P', ρ', and j' of the medium parameters behind the shock wave. The boundary conditions at the shock wave front correlated V', U', P' with the assumed small shift ξ of the shock wave front. Solution of the linearized equations was sought in the form

$$\exp i(K_x x + K_y y - \omega t), \qquad (1)$$

where $K = 2\pi/\lambda$ is the wave vector and ω is the complex frequency of oscillations. Using the VKB method of phase integrals, two variance equations were derived to correlate K and W. In the case of $B_0 \neq 0$, joint solution of the variance equations in the first approximation gave the criterion of instability as $\beta > \beta_{cr}$, where

$$\beta = \partial \ln \sigma_2 / \partial \ln T_2, \qquad (2)$$

Consequently instability can be created only when σ_2 is strongly dependent on temperature T_2. β_{cr} is a function of the Mach numbers M_1 and M_2 of the shock wave and the medium behind the wave, respectively. A magnetic field may generate instability in the plane front in the presence of a small disturbance in a perfect gas. In the case of $B_o = 0$, solution of the variance equations is obtained in the usual form of gas dynamics, i.e. a plane shock wave in a perfect gas is stable against small disturbances.

Podstrigach, T.S. Strong shock waves in partially ionized hydrogen. UFZh, v. 14, no. 8, 1969, 1367-1377.

Theoretical data are given an ionization degree f, electron and ion temperatures T_e and T_i at different distances r from ionic-atomic de-excitation in a shock wave propagating in partially ionized hydrogen at high α values, i.e., at a velocity U_o = 200 - 1,150 km/sec. The parameter $\alpha = mu_o^2 / \chi$, where m is the atomic mass and χ is the ionization potential of the hydrogen atom, determines shock wave intensity. The given data were calculated with allowance for the wave energy losses due to de-excitation, which are described by de-excitation parameter γ. Numerical integration of a set of differential equations, which was developed earlier by the author to describe the shock wave structure, gave the f, T_e, and T_i data for the cited range of U_o and for $\gamma = 10^{-1} - 10^{-3}$. In a first approximation, γ was assumed to be independent of T. A typical calculated plot (Fig. 1) shows the extent of the regions of ionization r_f, T_e and T_i relaxation r_g, and de-excitation r_γ at fixed α and γ (u_o = 360 km/sec). With respect to ionization, three successive steps are distinguished: the initial step extending through the r_f region; the cumulative ionization proceeding from the end of r_f through r_γ up to the point $T_i \cong T_e$; and complete ionization. The r_f region greatly diminishes with increase in U_o, but it is practically independent of γ at $U_o \geq 500$ km/sec, i.e., energy de-excitation has little effect on ionization rate in sufficiently strong shock waves. The cumulative and complete ionization periods vary little with α and γ. At the end of the cumulative ionization period, T_e is maximum, given by

$$T_{e,\max} = \frac{1}{a}\frac{mu_0^2}{k}, \qquad (1)$$

where k is the Boltzmann constant and a is a coefficient dependent on γ.

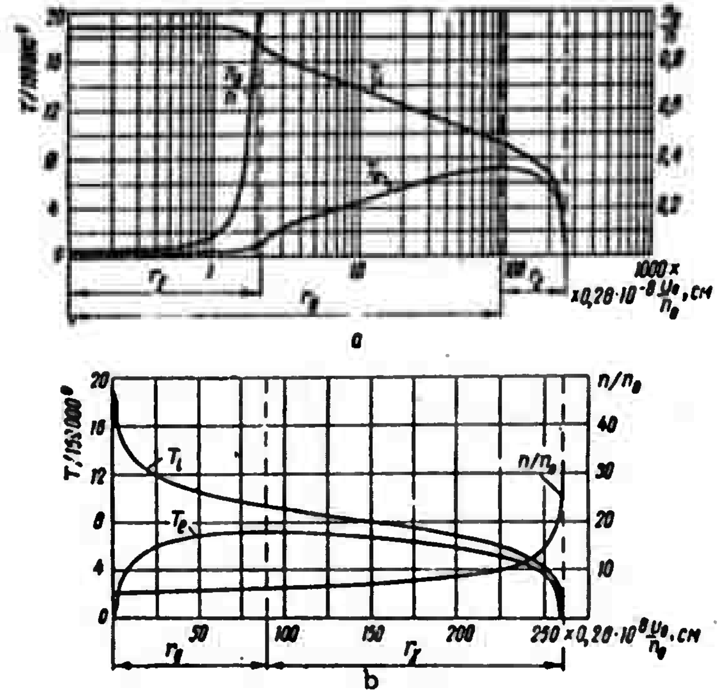

Fig. 1. Ionization degree, ion and electron temperatures, and concentration of gas particles versus distance in the shock wave in the case of $\alpha = 100$, $\gamma = 0.036$ (a - logarithmic, b - linear scale).

The region r_g of nonisothermicity expands with increase in U_o and decrease in γ, and can be approximated by

$$r_g = 28 \cdot 10^7 \frac{u_0}{n_0} \left(\frac{mu_0^2}{30\chi} \right)^6 r_g^{\gamma}, \qquad (2)$$

The most extensive r_γ region shrinks when γ increases at a given U_o. T_i and T_e in this region decrease slowly, however $T_i > T_e$. At the end, the electron gas density N_e sharply increases, T_i and T_e sharply decrease within a short period. Comparison of the cited data with the data calculated by different authors for gases other than hydrogen showed that the described procedure can be also used to calculate some of the parameters of shock waves in air.

Kochmanova, L. V., Ts. G. Breydo, V. L. Goryachev, and G. S. Sukhov. Ionization in argon behind a shock wave front. ZhTF, no. 3, 1970, 600-604.

Electrical conductivity σ of an argon plasma in a diaphragm-type shock tube was determined at initial Ar pressures P_1 in the 10 - 1 torr range and corresponding Mach numbers M_s from 8.8 to 11. The bursting pressure of the H_e driver gas was 115 - 120 atm. The σ value in the cited range of argon pressures was calculated from experimental electronic temperature T_e and electron concentration N_e data. The T_e and N_e data were obtained by measuring the intensity of the recombination continuum of Ar behind the shock wave in the spectral regions near λ = 5,700, 5300, and 4800 Å. The estimated relative error of N_e determination was 30 %. Comparison of the experimental T_e and N_e values with the calculated T_e and N_e at equilibrium shows a discrepancy at $P_1 < 5$ torr, which increased with decreasing P_1 to reach more than one order of magnitude at $P_1 = 1$ torr. This discrepancy is explained by the onset of cooling and decomposition of the plasma at $P_1 < 5$ torr before the end of relaxation. This explanation was confirmed by the experimental plots of relaxation time versus P_1. The σ data plotted in Fig. 1 show that the maximum σ = 7.5 mohm/cm corresponds to P_1 = 5 torr.

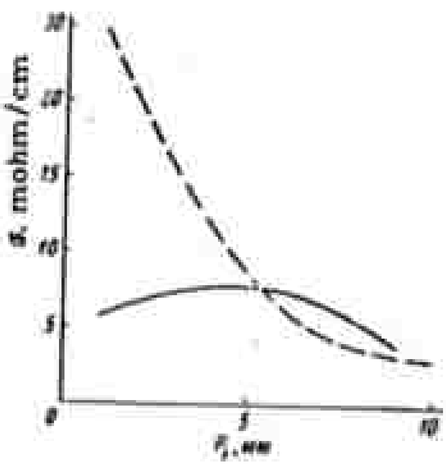

Fig. 1. Calculated and experimental electrical conductivity of plasma behind a shock wave versus the initial pressure P_1.

It was concluded that the increase in shock wave velocity and in T_e behind it, which is achieved by a decrease in P_1 of Ar in the low-pressure channel, is accompanied by an increase in σ of the plasma only up to a certain P_1 value, below which the ionization level decreases. The analysis emphasizes the importance of making allowance for the actual variation of σ within the vapor lock.

Burminskiy, E. P., V. L. Goryachev, and G. S. Sukhov. Application of an electrostatic probe to diagnostics of the boundary layer behind a shock wave front. ZhTF, no. 4, 1970, 884-886.

Preliminary measurements are described of the width δ and structure of a gaseous boundary layer formed along the wall of a shock tube behind a shock wave propagating in argon at Mach number $M_s = 10$. A Π-shaped tungsten wire electrostatic probe was used to measure δ. The measurements were based on a sharp change in the shape of the current-time curve with an increase in height of the probe. The experimental δ versus t dependence was plotted from the oscilloscope traces of signals from the probes of different heights (0.2 - 4 mm). At 1 torr initial pressure, the experimental δ versus t plot was in satisfactory agreement with the theoretical plot calculated for a laminar layer. At $p_1 = 10$ torr, the signal from the probe located near the wall became pulsating. An evaluation of the Reynolds number at $p_1 = 10$ torr indicated that the boundary layer becomes turbulent under these conditions. The use of an electrostatic probe in the study of boundary layer can thus provide valuable information on dynamics and structure of the layer.

Bronin, S. Ya. and A. N. Lagar'kov. Radiation transfer in a nonhomogeneous layer, from spectral lines of a shock profile. TVT, no. 4, 1970, 741-748.

An integration method adapted to digital computer calculations is introduced to calculate energy flux S of single and multiplet spectral lines with a shock profile in a thermally nonhomogeneous gas layer. The method takes into account energy absorption dependence on temperature and pressure at which the contribution of radiation to the energy balance becomes significant. Integration by frequency ν of the expression for S(r) in a point r of a radiant volume led to an approximate formula, accurate to 5%, in the case of a single line with small variations of the shock half-width ν (r) over distances of the order of $1/k_0$ (k_0 is absorption coefficient in the line center) and in the case of a weakly reabsorbed line, regardless of the magnitude of ν (r) variations. In the case of a multiplet, $S_m(r)$ is expressed through a function $G_m(\alpha_1, \ldots, \alpha_m, r, r')$, where variable α_i denotes the characteristic parameters of the i-th component of a multiplet. Simplified interpolation formulas are given for G_2 and G_3 of a doublet and a triplet, respectively. The approximate formulas of the type given for G_2 and G_3 with allowance for absorption by a continuum superposed on a multiplet are shown to be accurate within a few percentage points in the most unfavorable case. In a plane-parallel gas layer whose characteristic depends only on the coordinate x perpendicular to its surface, $S(x)$ transferred on a single line and $S_m(x)$ of a multiplet are expressed by an approximate formula, accurate within 4%, and as a function of G_m, respectively. In the latter case, G_m is expressed through G_1 by using formulas of the G_2 and G_3 types. In an infinite cylindrical configuration, the expression for divergence of radiant flux transferred at a single spectral line in a point r reduces to

$$F(r) = D + Er^2 + Cr^4 + Mr^6. \quad (1)$$

The function (1) can be analytically integrated to give divergence of $S(r)$. The cited formulas can be applied in a slightly modified form to solution of physical kinetics problems, e.g. the Biberman-Holstein equation.

Golovachev, Yu. P. and Yu. P. Lun'kin. Dissociative-vibrational relaxation in the air flow behind a direct shock wave. MZhiG, no. 1, 1970, 48-52.

Profiles of translational and vibrational temperatures of O_2 and N_2, together with relative density and concentrations of the components, were calculated for air flow behind a shock wave front under three different sets of initial relaxation conditions. The three variants of the relaxation process analyzed were: 1 - vibrational equilibrium, 2 - dissociative-vibrational relaxation in the absence of vibrational quanta exchange in the absence of vibrational quanta exchange between O_2, N_2, and NO; and 3 - relaxation with allowance for all possible modes of energy exchange. In the third variant, allowance was made for the effects of vibrational relaxation on the chemical reaction rates and of dissociative relaxation on the vibrational energy of molecular components, and for the exchange of vibrational quanta between different molecules. Calculations were made on the basis of relaxation equations, earlier derived, with explicit expressions introduced for probabilities of molecular dissociation and recombination reactions in collisions with atoms or other molecules; expressions of vibrational relaxation life-time were also related to exchange of vibrational quanta. To simplify calculations, vibrational relaxation in NO was not accounted for, and the molecules from only one vibrational level were assumed to participate in the exchange reaction $O_2 + N_2 \rightleftarrows 2NO$. The calculated data are presented graphically, as an example, for the oncoming flow parameters $M_\infty = 10$, $p_\infty = 0.01$ atm, and $T_\infty = 300°K$. The T, T_{v2}, T_{v4}, and ρ calculated profiles (Fig. 1) show the considerable effects of vibrational relaxation and the vibrational quanta exchange of O_2 and N_2 with NO on the flow parameters. The concentration profiles of NO and N are the most sensitive to relaxation processes.

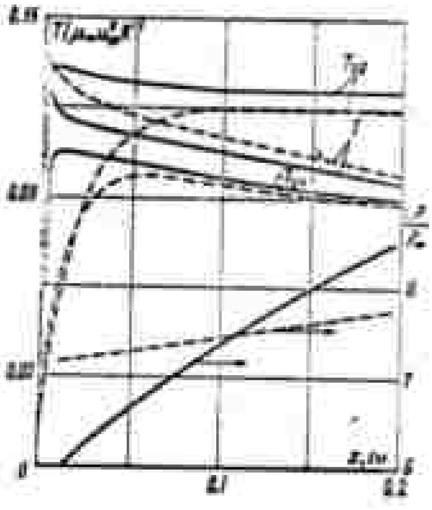

Fig. 1. Profiles of translational T and vibrational temperatures T_{v2} and T_{v4} of O_2 and N_2, respectively, and density profile ρ / ρ_{∞} behind a shock wave front. Solid curves - third variant, dashed curves - second and first variants, for T and ρ, respectively.

Chekalin, E. K., and Yu. I. Tusnov. Electric breakdown of a supersonic gas flow in shock tube. ZhTF, no. 11, 1970, 2354-2360.

The effect of the thermal boundary layer near cold electrode surfaces at the walls of a shock tube was studied experimentally in a supersonic flow of argon or air behind a shock wave generated by an electrical discharge. The initial pressure was 1 and 2 torr in Ar and 1 torr in air; the driving gas (He) pressure was 15.2 - 26.8 atm. Shock wave velocity varied in the 1.65 - 2.12 km/sec range. The oscilloscope traces of discharge current and gas emission from the electrode gap were recorded simultaneously and the current-voltage characteristics were plotted. The series of oscilloscope traces in Ar at both cited pressures revealed sharp differences in shape at different electrode potentials U ($\gtrless$ 310 V at 1 torr and $\gtrless$ 200 V at 2 torr). This difference is reflected in current-voltage characteristics (Fig. 1 and Fig. 2).

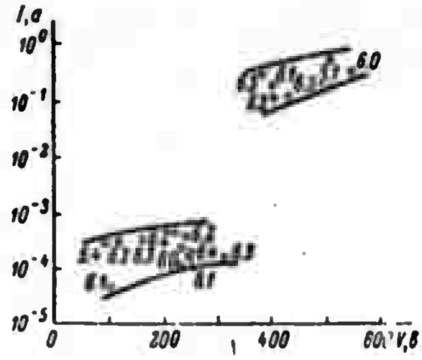

Fig. 1. Current-voltage characteristic in supersonic argon flow: p_1 = 1 torr. The figures next to the points indicate corresponding Mach numbers.

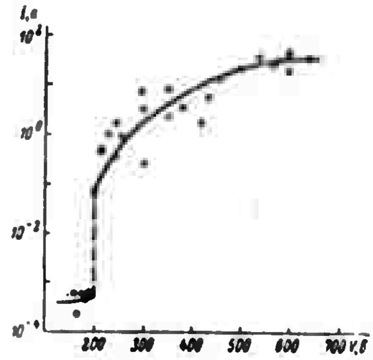

Fig. 2. Current-voltage characteristic in supersonic argon flow. p_1 = 2 torr.

The clearly distinct regions in which current amplitude differs by over three orders of magnitude can be seen in the curves. Also, two series of oscilloscope traces were recorded in air at p_1 = 1 torr. The series at 600 - 900 V potentials show a sharp rise in current immediately behind the shock wave front and an emission in front of the shock wave in the absence of discharge current. The current jump in gasdynamic vapor lock indicates an electric gas breakdown in the gap. A comparative evaluation of the resistance within the gas flow and the total resistance of the gap immediately before the breakdown leads to the conclusion that the applied potential drops in the boundary layer and the observed current jump is caused by the electric breakdown of this layer. Calculations of breakdown voltage based on Paschen's law indicate a good agreement with the experimental data for a laminar boundary layer (Fig. 1) and a 22% higher value for a turbulent boundary layer (Fig. 2). A nonuniform electron energy distribution at the boundary of a charged layer is thought to be the cause of the cited discrepancy. Thus the breakdown potential in a laminar boundary layer in a low-temperature plasma can be reliably calculated from the Paschen curves.

Galaktionov, I. I., T. D. Korovkina, V. D. Mikhalevskiy, and I. V. Podmoshenskiy. Infrared spectral measurements of temperature and CO_2 concentration behind a shock wave. TVT, no. 1, 1969, 85-90.

Dissociation kinetics of CO_2 molecules behind a shock wave is studied by directly measuring gas temperature, its emission and its spectral absorption in the 00^01 - 00^00 infrared absorption band. The unified method of spectrum reversal was applied to temperature measurement using CO_2 emission at λ = 4.45 and 4.3μ, i.e. outside and within the absorption peak of cold CO_2. The experimental setup is described, in which the radiant flux Φ_x from the gas and combined flux ($\Phi_x + \Phi_e$) of the gas and a reference source (graphite rod) less Φ_e are recorded oscilloscopically in separate experiments simultaneously with the shock wave velocity. Then temperature T_x and absorptivity a_λ along the vapor lock of the hot gas were calculated using the formulas derived from the Kirchhoff law and Plank formula. The data show that the measured T_x in the 3,000 - 4,400°K range coincides, within the experimental error, with the theoretical gas dynamic temperature. Measurements at T = 4,400°K, p_o = 1.8 torr, and P = 0.43 atm indicate a significant decrease in T_x and a_λ along the CO_2 vapor lock, independent of λ within the experimental absorption band. Under the same operating conditions, but at λ = 2.7μ, the measured concentration of CO_2 molecules also decreased along the vapor lock. These findings indicated that CO_2 is dissociated at 4,400°K. Thus the agreement between the cited two sets of data offers a direct method of evaluation of the kinetics of CO_2 decomposition behind a shock wave. Also, the conclusion was drawn that asymmetric stretching vibrations of CO_2 molecules are excited at 3600 - 4400°K and Mach 11--12 velocities, before the onset of dissociation. At 3,000°K the excess of ~100°K in measured T_x over vibrational equilibrium level is tentatively attributed to incomplete excitation of the asymmetric stretching vibrations.

Duntsova, Zh. S., I. V. Yershov, V. T. Kireyev, and Ye. I. Ruzavin. Calculating shock wave propagation and flow parameters in a shock tube with non-instantaneous diaphragm opening. MZhiG, no. 2, 1969, 120-128.

A shock wave propagation study is presented which takes account of the finite opening time of the usual diaphragm in a shock tube. This is done by calculating propagation velocity v of a shock wave at different openings of a diaphragm and parameters of the driver and driven gases in the acceleration region of the shock tube, using the flow diagram of Fig. 1, introduced earlier by one of the authors, and the methods of characteristics. Calculations

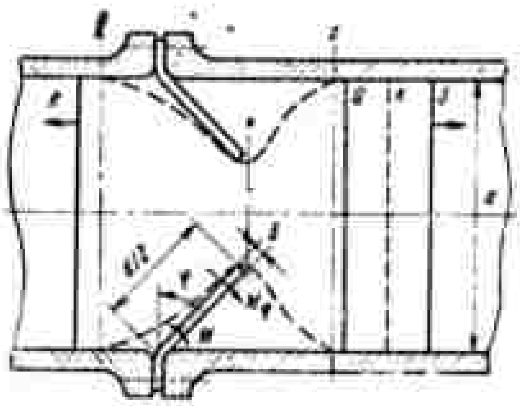

Fig. 1. Flow diagram of a gas in shock tube: R - expansion wave, S - shock wave, * - critical section, Q - driver gas turbulence, K - contact surface, M_φ - torque, M - drag torque.

were made on assumptions of a quasistationary flow in the tube section between 1 and z, and either isentropic or nonisentropic flow through the quasistationary section. Assuming an isentropic flow, parameters of supersonic flow at section z can be expressed as a function of time t by solving a set of equations of the parameters of driver gas simultaneously with the function $f_* = f_*(t)$ of the area of the opening cross-section. The flow characteristics network of Fig. 2 was used in conjunction with the dimensionless parameters

$$T = \frac{t}{t^*}, \quad X = \frac{x}{a_\pm t^*},$$
$$P = \frac{p}{p_+}, \quad U = \frac{u}{a_+}, \qquad (1)$$
$$V = \frac{v}{a_+}, \quad A = \frac{a}{a_+}$$

to plot v/v_m versus x/x_m, a/a_m versus $\eta = (x - x_n)/(x_m - x_n)$ for the driven gas, and a/a_k, u/u_k, p/p_k versus x/x_c for the driver gas, under four different regimes defined by different values of the initial parameters.

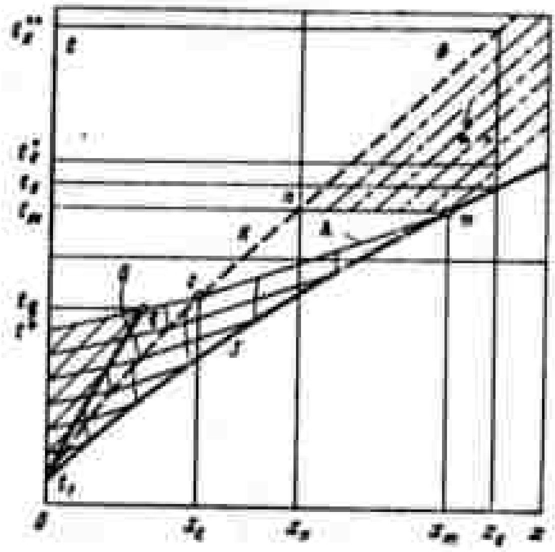

Fig. 2. Characteristics network: L - trajectories of gas particles, λ - characteristics, S, Q, K - same as in Fig. 1, t* - time of complete opening of diaphragm.

The plots show a significant inhomogeneity in the driven gas parameters at the conclusion of the shock wave acceleration, and simultaneous absence of the uniform vapor lock predicted by theory for the driver gas. In the case of a nonisentropic flow between sections * and z , the calculated v/v_m versus x/x_m plot is in good agreement with the experimental plot and with the plot calculated for an isentropic flow. This agreement indicates that the contribution of flow parameter fluctuations to the shock wave acceleration is relatively small at small diaphragm openings. The experimental density profile of the driven gas behind a shock wave is also cited to show the effect of noninstantaneous diaphragm opening.

Suslov, A. A., K. I. Seryakov, and L. V. Gurvich.
<u>Apparatus for producing shock waves in cesium vapors.</u>
TVT, no. 6, 1969, 1168-1177.

A shock tube (Fig. 1) is described, which was designed to produce cesium plasma at pressures up to 10 atm by means of shock waves. The shock waves were generated in a shock tube, heated to 400 - 600°C and filled with cesium vapor at 100 - 200 torr, by rupturing a 0.5-1mm thick copper foil diaphragm under 100 atm pressure of He or Ar. The operating procedure and plasma investigation techniques are described in detail.

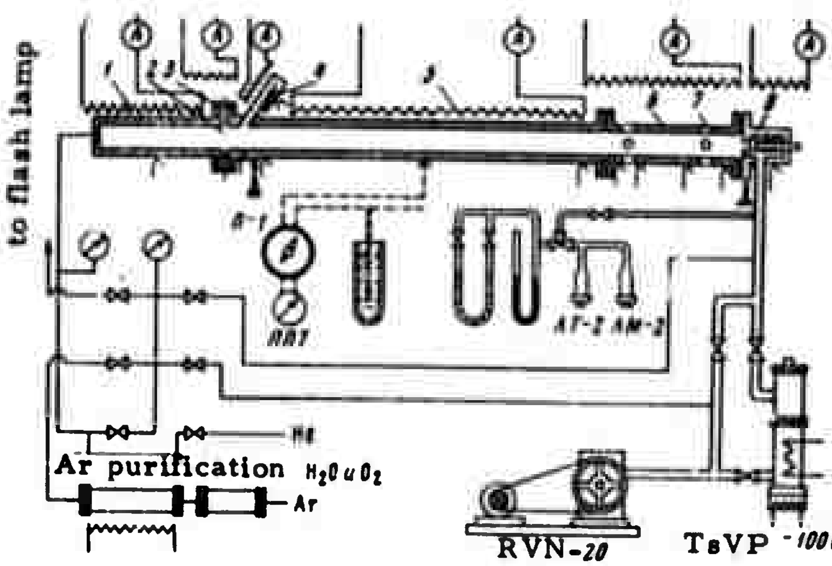

Fig. 1. Diagram of the shock tube:
1 - high-pressure section, 2 - diaphragm,
3 - coupling, 4 - small vaporizer for cesium,
5 - acceleration section, 6 - measurement
section, 7 - fittings, 8 - bellows valve,
A - heating elements; TsVP-100S—diffusion
pump, RVN - 20—forevacuum pump.

In the experiments, recordings were made of the shock wave velocity, time sweep of radiation from the shock wave, and emission and absorption spectra of gas in front of and behind a shock wave. The absorption spectrum of Cs vapor before diaphragm rupture was also recorded. The shock wave experiments were carried out under three different regimes, as shown in Table 1.

Table 1. Experimental parameters of shock waves.

Regime	Driver gas, p = 25 atm	Initial Cs Pressure, torr	Tube T, °C	Wave Velocity, km/sec	Plasma T, °K	Pressure in vapor lock, atm.
I	He	30	450	1,4	4200	1,35
II	Ar	30	450	0,85	2700	0,42
III	Ar	10	600	1,0	3100	0,20

Shock wave propagation under regimes I and II was accompanied by a rapid condensation of Cs vapors behind the shock wave, because Cs pressure exceeded that of its saturated vapor at the initial tube temperature. Under regime III, transmission via the windows in the section 6 was sharply reduced, even though condensation could not occur. The drop in luminosity under regime III can be explained only as the result of a rapid cooling due to energy loss by radiation. Also, the fact that temperature measured in the vapor lock by a spectral method was lower than gas dynamic temperature can be attributed in part to radiant cooling of the plasma. Thus the shock tube experiments confirmed the value of this method of studying thermophysical properties of a dense nonideal plasma, although Cs condensation on the walls and radiant cooling of gas impose a limit on the tolerable increase in pressure and temperature of the plasma. Addition of a noncondensable gas to the Cs vapor is recommended.

Andreyev, V. P. Propagation of a strong shock wave front in a two-dimensional problem with a dynamic boundary. MZhiG, no. 6, 1969, 43-47.

The non self-similar problem of the uniform propagation of a compression shock wave is examined in a medium with a movable boundary. The front initial position x_0, its initial velocity c_0, the mass m_0 of propagating gas, and its energy E_0 are given by Fig. 1. The gas is assumed to propagate in vacuum

Fig. 1. Two-dimensional shock wave model.

with velocity U_0. A set of differential equations is established to describe propagation of the shock wave front by substituting for the equation of energy the initial exponential relation between the dimensionless Euler (x) and Lagrangian (m) coordinates and the energy integral. In a first approximation, the solution is presented for two boundary cases. In the absence of gas escape into vacuum, i.e., $\alpha_3 = U_0/C_0 = 0$, the self-similar solution of a strong explosion problem approximates the solution of the stated problem, for any values of the first two dimensionless parameters $\alpha_1 = m_0/\rho_0 x_0$ and $\alpha_2 = E_0/\rho_0 x_0 C_0$, where ρ_0 is the density of the unperturbed gas. In the case of $\alpha_3 \neq 0$, the solution of the stated problem at dimensionless front radius $R \longrightarrow \infty$ is reduced to that of the problem of a short-duration shock. Then the dimensionless variable $q = c/c_0$ is expressed as

$$q = BR^{\delta} \tag{1}$$

where

$$\delta = \frac{1-\beta}{\beta}, \quad B = \beta A^{1/\beta} \tag{2}$$

β and A in (2) are the self-similarity index and an undetermined dimensionless constant, respectively. The numerical A values for different α_1, α_2, α_3, and γ values provide the link between the self-similar phase of front propagation and the actual origin of the shock wave. Calculations show that A is only weakly dependent on α_1 but varies widely with change in α_2. In the non-self-similar phase of propagation, the velocity of the shock wave front initially increases at high α_2 values.

Pataraya, A. D. Shock wave configuration in binary mixtures. ZhTF, no. 10, 1969, 1770-1773.

A theoretical analysis is given of shock wave structure in binary mixtures in which the atomic weights of the two gases are substantially different. The width L of a shock wave in a binary gas mixture is calculated as

$$L = \frac{n_{22} + n_{12} - (n_{21} + n_{11})}{\left(\frac{dn}{dx}\right)_{max}}, \tag{1}$$

where

$$n = n_1 + n_2 = n_{21}(N_2 + \epsilon N_1). \tag{2}$$

n_{11}, n_{12} are the nonturbulent densities of the first gas, with smaller atomic mass, before and behind the shock wave, respectively; n_{21}, n_{22} are the corresponding densities of the second gas; N_1 and N_2 are the turbulent densities of the first and second gas, respectively, and $\epsilon = n_{11}/n_{21}$. Formula (1) was derived by use of the unified Mott-Smith distribution functions. The functions selected for the first gas were free of limitations imposed by the parameters of the medium. Using the selected model functions, the expression for N_1 was derived in a first approximation of ϵ in the form

$$N_1 = N_1^{(1)} + N_1^{(2)} = N_{20} - A_0(1 - Z')Z'. \qquad (3)$$

where $N_1^{(1)}$, and $N_1^{(2)}$ are the turbulent densities before and behind the shock wave, respectively. Using the Mott-Smith function

$$f_2 = n_{21}(N_2^{(1)}F_{21} + N_2^{(2)}F_{22}), \qquad (4)$$

the analogous expression

$$N_2 \equiv n_{21}(N_2^{(1)} + N_2^{(2)}) = 1 + \frac{(1-\tau_0)}{\tau_0} Z_1', \qquad (5)$$

was derived for the second gas. Also, a formula was obtained for the relative temperature (T_1 - T_2) of the He gases in the first non-zero approximation of ϵ. Using (1) and substituting $Z_1' = Z_1/1 + Z_1$ for Z' in (3), the numerical values of L for an Ar - He mixture were calculated to be 4.6 - 9.1 x 10^{-5}, in agreement with the earlier data published in Western sources.

Gorelov, V. A. Probe measurements behind the front of a strong shock wave in air. ZhTF, no. 1, 1970, 198-205.

A preliminary theoretical evaluation of the method of a double electrostatic probe to measure electron temperature T_e in a shock tube has indicated the possibility of using this method in the case of a probe diameter d greater than the mean free path $\lambda_{i,e}$ of an ion or electron. The applicability of the method was tested in a shock tube experiment by comparison with the method of spectral line reversal. A sinusoidal voltage of 150-200 kHz was applied to the probe placed in the tube channel 200 cm distant from the diaphragmless discharge chamber. The air pressure in the tube was p = 0.5-1.0 torr, Mach number M_s of the shock wave $\cong$20 and initial temperature T_1 = 6000°K. The Ip-Vp characteristics of the probe were plotted for time intervals of 2.5 and 3.3 μ sec at f = 200 and 150 kHz, respectively. The cited frequencies satisfied the criteria of quasistationary response of the probe, hence met the necessary condition for mathematical exploitation of the I_p-V_p characteristics. T_e

calculated by different methods using the I_p-V_p characteristics are given in Table 1.

Table 1. Electron temperature behind a strong shock wave.

Method of T_e determination	T_e, ^oK
From the slope of the curve ln $(\Sigma I_i/I_e - 1) = f(V_p)$	5400
Equivalent resistance method	5500
Interception method	5000
From the half-width of the φ (V_p) curve	5800
Theoretical equilibrium T value	5200 - 5700
Spectral method	5500 $\pm$ 200

In addition, the averaged experimental $T_e = f(t)$ plots at 0.5 and 1.0 torr showed that T_e in the vapor lock increased in the same time as theoretical T. Thus the probe method gave reliable T_e values accurate within 15%, in agreement with theory. The accuracy is sufficient for a qualitative study of T_e versus time dependence. Also, a theoretical analysis of applicability of the method to n_e measurement indicates that the estimated experimental n_e should be of the same order of magnitude as the theoretical n_e value.

Zhikhareva, T. V., and G. K. Tumakayev. Kinetics of initial ionization of a nonatomic gas behind a shock wave front. TVT, no. 1, 1970, 40-45.

The effects of radiation from the equilibrium region and of atom-atom collisions during initial ionization of Ar, Xe, and Hg atoms behind a shock wave front are examined, to resolve the controversy about the relative importance of these two ionization mechanisms. Using a general expression $(dne/dt)_{rad}$ for the rate of electron formation owing to radiation in a given continuum, the authors calculate the rates B_1, B_2, and B_1' of electron formation by absorption of resonance radiation at $\lambda = 2537$ and $1850 Å$ from the equilibrium region and at $\lambda = 2537$ Å from the relaxation region in front of the shock wave, respectively. The analysis of the summary B variations over the relaxation region lead to the conclusion that $B_1' < B_1 + B_2$, hence B_1' can be disregarded in a comparative evaluation of the theoretical and earlier experimental n_e values for Mach numbers M = 8-14. The evaluation showed that the radiation mechanism cannot explain the experimental n_e values for Ar and Hg over the entire range of M, nor that of Xe at small M. In addition, the experimental activation energy of the reactions

$$A + h\nu_0 \xrightarrow{k_\nu} A^*, \quad (1)$$

$$A^* + I \xrightarrow{k_\nu^+} A^+ + e + I, \quad (2)$$

was twice the theoretical value for all three gases in the range of T_2 = 9,000 - 18,000°K behind the shock wave and at an initial 3 torr pressure. Hence the role of radiation in the initial ionization is evidently limited. In contrast, theoretical values of activation energy of the reactions

$$A + A \underset{k_*'}{\overset{k_*}{\rightleftharpoons}} A^* + A, \quad (3)$$

$$A^* + A \xrightarrow{k_+} A^+ + e + A, \quad (4)$$

involving atom-atom collisions were in good agreement with the corresponding experimental values for a concentration N_a of normal atoms 10^{17} cm^{-3}. This fact confirmed the predominance of the (3) - (4) mechanism of initial ionization of the studied gases. The excitation and ionization cross-sections of the Hg atoms excited by atom-atom collisions were also calculated from the experimental electron, normal, and excited Hg atom concentration distribution over the relaxation zone.

Vasil'yeva, R. V., K. V. Donskoy, B. M. Dobrynin, V. Kh. Manerov, G. K. Tumakayev, and V. A. Shingarkina. Ionization of inert gases behind a shock wave front. ZhTF, no. 3, 1970, 605-611.

Ionization of Ar, Kr, and Xe was studied in a shock tube at Mach numbers M = 6 - 10 and an initial pressure p_0 in a low-pressure chamber in the 10 - 200 torr range. The methods of electrical conductivity σ and intensity J_ν of emission continuum were applied. Conductivity σ of the plasma was measured by an induction technique using two resonant circuits simultaneously, each composed of a solenoid and a capacitance. The accuracy of σ measurements was 20%. The emission spectra of gases behind a strong or a weak shock wave were obtained by means of a STE-1 grating spectrograph and an ISP-51 prism spectrograph, respectively. Absolute J_v of emission was measured simultaneously in three spectral regions from photographic recordings of a spectrum. Oscilloscope traces of emission pulses and circuit voltage variations were recorded by a C1 - 33 five-beam oscilloscope. The experimental σ data for Ar, Kr, and Xe were found to be in good agreement with the theoretical σ at high M, i.e. at a high atomic temperature T and ionization degree $\alpha > 10^{-3}$. However the experimental σ data at low M, e.g., at $T < 5,000^{\circ}K$ and $p_o = 50$ torr for Ar, at $T < 6,000^{\circ}K$ and $p_o = 10 - 200$ torr for Xe, were significantly higher than σ calculated on the basis of ionization theory of mono-atomic gases. The discrepancy between the experimental and theoretical σ of Xe increased with decrease in T and increase in p_o, reaching one order of magnitude at $T = 4,000^{\circ}K$ and $p_o = 50$ torr. The experimental σ of Xe at low T was independent of p_o, in contradiction with theory. Also, the J_v of Xe at $T < 7,000^{\circ}K$ was significantly higher than J_v predicted by the Unsoeld-Kramer theory. The observed discrepancies in σ and J_v data at low M cannot be the effect of ionizable impurities, because the measured concentrations Ne of charged Ar and Xe particles exceeded the measured Ne of the impurities. Possible the high σ of Xe at low M could be explained by associative ionization; the measured ionization energy of Xe in the 4,000 - 5,000°K range was 10.5 ± 1 ev.

Gorelov, V. A., and Yu. K. Frolov. Temperature measurements behind the front of a strong shock wave in a shock tube with electrical discharge. ZhTF, no. 4, 1970, 825-832.

The air temperature T behind a shock wave propagating at a rate $V_s = 4-9$ km/sec in a diaphragmless shock tube with electrical discharge (EDST) was measured by the unified method of spectral line reversal. At the cited V_s and initial air pressure $p_o = 0.3 - 1.0$ torr, experimental evidence was obtained of formation of a hot vapor lock behind the wave front simultaneously with separation of the shock front from the gas discharge plasma. The described method of T measurement was modified by introducing an additional thermometric admixture ($BaCl_2$) in the gas discharge channel to improve the accuracy in the case of a short-lived (2 - 15 μ sec) vapor lock and a low ($\sim 10^{-5}$ g/cm^3) gas density at T = 4,000 - 10,000°K. A time resolution of about 2μsec was thus achieved. The vaporization products (mainly H) of paraffin from the walls of the EDST served as a driver gas. The experimental apparatus included a DKSSh-1,000 Xe flash lamp as a reference source; a lens system; a DFS-33 autocollimating spectrometer, and DESO-1 and OK-17M recording oscilloscopes. At $v_s > 7$ km/sec pulsed current was applied to the flash lamp in addition to dc. The BaII 4554Å line was used for T measurements. Shock wave velocity was measured with 2.5 - 3% accuracy. The T measurement data are shown in Fig. 1 where the curves represent theoretical $T = f(V_s, p)$. The accuracy

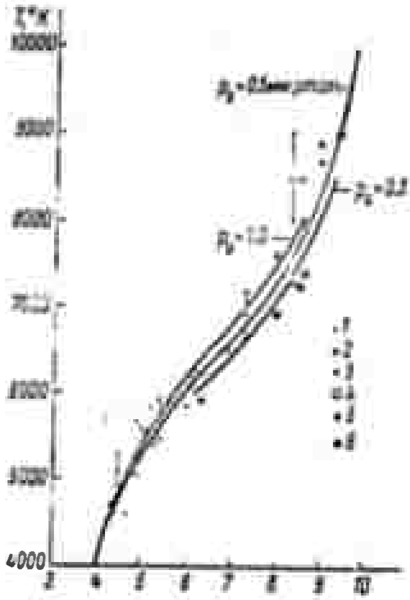

Fig. 1. T versus V_s plot. The points denote experimental T values obtained with dc excitation of DKSSh-1000 (1,2 - p_o = 1; 3,4 - p_o = 0.5 mm Hg; 2,4 - average values of several experiments) or with pulsed excitation (5 - p_o = 0.5, 6 - p_o = 0.3 mm Hg).

of T measurements was 3 - 4% for $T \leq 7,000°K$ and 6 - 10% with pulsed excitation of the flash lamp. The oscilloscope traces of $T = f(t)$ at p_o = 0.5 and 1.0 torr, V_s = 6 - 7 and 5 - 5.5 km/sec show that T remains constant during ~ 30% and less of the vapor lock life time, then increases by 10% toward the end of the lock. Thus T values measured in the area adjacent to the wave front agree well with the theoretical values over the studied range of V_s and p_o, but T is not uniform along the vapor lock. This latter finding must be accounted for in gasdynamic experiments using the full length of the lock.

Zagorodnikov, S. P., G. Ye. Smolkin, Ye. A. Striganova, and G. V. Sholin. Study of collisionless shock waves in magnetized plasma. ZhTF, no. 4, 1970, 717-727.

Experiments are described with magnetized hydrogen and helium plasmas in which collisionless shock waves were generated by trapezoidal magnetic pulses with a rise time $T_o = (3 - 5) \times 10^{-8}$ sec, lifetime $T = (2.5 - 5) \times 10^{-7}$ sec, and amplitude $|\tilde{H}| = (1 - 1.5) \times 10^3$ oe. The pulse train was generated by an impulsing coil in the center of the UV-2 discharge chamber. In all experiments designed to study the mechanism of turbulent heating of plasma, magnetic field $\tilde{H}$ of the first pulse was parallel to the constant magnetic field H_1 in which a plasma was generated by an electric discharge. The magnetic field profile in a shock wave was recorded and magnetoacoustic perturbations were observed at different Alfven-Mach numbers $M_A = U/U_A$ by means of miniature probes introduced into the discharge chamber. Typical profiles in hydrogen plasma (Fig. 1) exhibit two shock waves of nearly equal amplitude

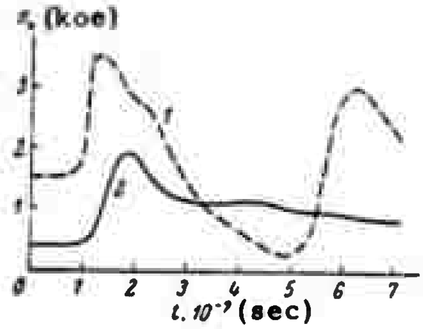

Fig. 1. Magnetic field profiles in a shock wave near the axis of the plasma column. 1 - M_A = 1.5, 2 - 4.

in the first and third half-periods of the magnetic "piston" at a relatively low M_A, and only one shock wave at high M_A. In addition, at high M_A a specific irreversible process is observed in both H and He plasmas in the second half period of the "piston" action at $|\tilde{H}| \geq 2 |H_1|$. Electron temperatures Te_1 and Te_2 in front of and behind the shock wave were determined by measuring line intensity of the plasma recombination spectrum and from the intensity ratio of HeII 4686Å to HeI 5016Å spectral lines, or by a calorimetric method. The temperature jump $\Delta T_e = T_{e2} - T_{e1}$ in the shock wave front increased with increase in M_A, because of the increase in T_{e2} to a value $\geq$100 ev. A spectral analysis of the magnetically confined plasma in the field with mirror geometry excluded the effect of impurity ions and atoms on the shock wave profile and ΔT_e. The observed irreversible process and ΔT_e increase at increased $M_A > M_A^*$ critical = 2 can thus result only from the turbulent collisionless dissipative processes caused by the increase in $|\tilde{H}|$ of the alternating magnetic field.

Kurtmullayev, R. Kh., V. I. Pil'skiy, and V. N. Semenov. Study of electron heating in the plasma behind a shock wave front by a probe method. ZhTF, no. 5, 1970, 1044-1047.

Respective merits and limitations of the openloop and tube-enclosed probes used in measurement of rapidly varying magnetic fields are discussed in the light of cited earlier experiments. These preliminary experiments with collisionless shock waves revealed that the open loop probe is more suitable than the probe enclosed in a tube, because the signals from the latter are delayed and their amplitude is greater in comparison to the signals from the open loop probe. In addition, the cited experiments indicated the possibility of utilizing the difference between signals recorded from the two probes to evaluate electron temperature nT_e behind the shock wave front. In the described experiments, nT_e was measured in H, Ar, and Xe plasmas of initial density $n_0 \cong 5 \times 10^{10} - 5 \times 10^{14}$ cm^{-3} in a quasistationary magnetic field Ho = 200 - 2,000 oe at relative amplitudes $h \sim 2 - 6$ and Mach numbers $M \sim 2 - 4$. A good agreement was revealed (Fig. 1) between the experimental

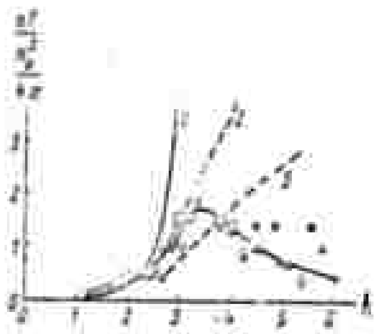

Fig. 1. Electron heating versus amplitude in hydrogen plasma: 1 - Hugoniot adiabat; 2,3 - computer data; 4 - experiment, $\nu = 5/3$.

nt(h) points and the Hugoniot adiabat up to $h \cong 2.7$, as well as between experimental and computed data which take into account the nonstationary state at $h \cong 2.7$. The decay of the experimental curve at $h \geq 3$ coincides with the M > critical M condition. The decrease in electron heating at M > Mcr is tentatively explained as the effect of the shock wave reversal, accompanied by an increase in ion heating behind the front. The data confirmed the applicability of the probe method to recording of electron diamagnetism in a highly inhomogeneous plasma with rapidly varying process parameters in a strong applied field. Limitations of the method are connected with cooling of the plasma along magnetic lines of force perpendicular to the probe cross-section, and with dimensions of the probe. The accuracy and sensitivity of the method can be increased by the use of a compensation scheme which would sum the measured differences between two signals.

Smekhov, G. D., and Yu. S. Lobastov. <u>On the initial stage of argon ionization behind a shock wave front.</u> ZhTF, no. 8, 1970, 1660-1663.

A "cut-off" variant of the microwave diagnostic technique is described in experiments with recording of electrons in an electromagnetic wave (λ = 8.5 mm) reflected from ionized Ar in a shock wave. In the described shock tube experiments, the electron concentration in the plasma was assumed to be n_H = 0.9 n_{cr} = 1.5 x 10^{13} cm^{-3}; time resolution of the apparatus was measured to be 1 μ sec. In contrast to some earlier measurements, the experimental time in which n_H concentration is attained was judged to be reliable, because of its low sensitivity to the ν/ω parameter, where ν is the effective frequency of electron-atom collisions and ω is the angular frequency of the incident electromagnetic wave. The experimental rise time t_H versus

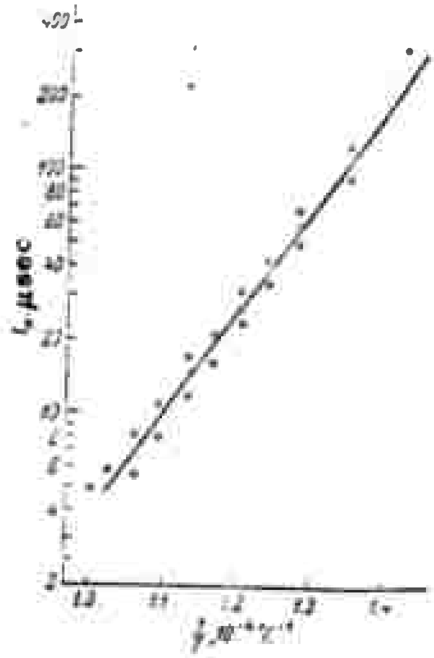

Fig. 1. Rise time of electron concentration to n_H = 1.5 x 10^{13} cm^{-3} behind a shock wave front versus temperature. Time (in a coordinate system coupled with moving particles) is based on an initial pressure p_o in the shock wave = 5 torr.

T^{-1} plot is shown in Fig. 1. Assuming a two-step mechanism in ionization of argon atoms, i.e.

$$Ar + Ar \xrightarrow{k_1} \text{[illegible]} \qquad (1)$$

$$Ar + Ar^* \xrightarrow{k_2} Ar^+ + Ar + e. \qquad (2)$$

the theoretical electron concentration $[e]$ was found to vary linearly with time, if $(k_2[Ar])^{-1} < t_H$; the t_H (T) dependence corresponded to an excitation energy $E^* = 11.5$ ev. In the case of $(k_2[Ar])^{-1} > t_H$, $[e]$ varies as t^2 and the t_H (T) dependence corresponds to $E^* = 7.9$ ev. The slope of the experimental plot (Fig. 1) is 8.2 ev. Thus the experimental data indicate, in contrast to a cited earlier study, a two-step initial ionization by an atom-atom collision mechanism, and a temporal rise in electron concentration behind the shock wave front to a level of 1.5×10^{13} cm^{-3}, following a square-law.

Karpov, V. P. Determination of acceleration of combustion when a shock wave interacts with a flame. FGiV, no. 4, 1970, 504-509.

Experiments were performed in cylindrical combustion chambers using mixtures of oxygen plus methane, propane, hydrogen and acetylene. The shock wave introduced in the chamber deforms the flame front immediately upon contact, converting the laminar flow to turbulent flow, and thus increases the combustion rate, forming a second shock wave. Formulas are presented for determination of the increase in combustion rate in the flame front as a result of interaction with the shock wave.

Mozzhilkin, V. V., Fal'kovich, S. V. Propagation of shock waves in channels of variable transverse cross section. IN: Sbornik. Transzvukovyye techeniya gaza. Saratov, Saratov University. No. 3, 1971, 3-11. (RZh-Mekhanika, 8/71, #8B183)

Self-similar modeling of polytropic gas flows with shock waves in channels where the cross section varies according to a power and exponential law is discussed. It is shown that there exist self-similar flows with discontinuities of constant intensity. A sequential approximation method is proposed which has a fairly good accuracy even in the first approximation.

Yakushev, V. V., O. K. Rozanov, and A. N. Dremin.
<u>Measuring polarization relaxation time in a shock wave.</u>
ZhPMTF, v. 54, no. 2, 1968, 396-400.

This paper gives a description of some refinements in measuring shock-induced polarization changes in dielectrics, a phenomenon first reported by Eichelberger and Hauver (Les Ondes de Detonation, Paris, 1962). In particular a method was devised of interposing a foil sensor element between plane dielectric elements to detect polarization relaxation characteristics, following passage of the shock wave through the dielectric. Relaxation was clearly observed for explosion-generated shocks in plexiglass and vinyl plastic dielectrics. In plexiglass the mean relaxation time over a compression range of 100 - 170 kbar was about 1.1 μ sec, compared to 0.15 μ sec for the vinyl.

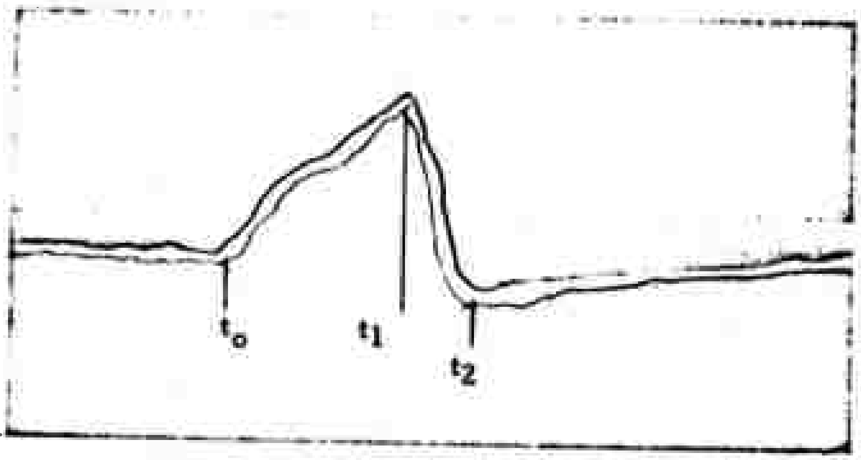

Fig. 1. Shock polarization rise and decay in plexiglass. t_o - shock wave enters first dielectric wafer; t_1 - wave exits first wafer at foil pickoff; t_2 - wave enters second dielectric wafer. Scale = 0.25 μ sec/main division.

Figure 1 shows a typical polarization and relaxation pulse for a 2 mm thick plexiglass specimen. This technique could be extended to dielectrics of a wide range of relaxation times.

Dremin, A. N., K. K. Shvedov, and O. S. Avdonin. Compressibility and temperatures from shock loading of various porous explosives. FGiV, no. 4, 1970, 520-529.

Tabulated results are given for shock adiabats and other explosion characteristics of porous specimens of hexagene (1 g/cm^3), tetryl (0.86 g/cm^3), TEN (0.82 g/cm^3), and ammonium nitrate (0.86 g/cm^3). The measurement method proposed by Veretennikov et al (FGiV, no. 3, 1969) was used as being the least subject to experimental error in rapid explosions of this type. The method yields shock compressibility from simultaneous measurement of mass velocity at the shock wave front and wave front velocity, using an electromagnetic sensing element, and assumes a rectangular shock wave profile. Mass velocities ranged from 0.44 - 3.5 km/sec and wave front velocities from 1.4 - 6.5 km/sec for the tested explosives.

Stepanov, G. V. Influence of barrier temperature on the depth of the crater formed by the impact of fast-moving particles. ZhTF, no. 3, 1970, 612-614.

The calculation method used and the results obtained are presented for an experimental investigation of the influence of barrier temperature on the depth of a crater formed by the impact of spherical particles. Graphs are given for experimental points which correspond to conditions whereby incandescent steel balls and balls made of other materials were impacted into a target consisting of a lead mass at temperature ranges of 20 - 200°C. Analysis of the graphed results indicates that the change in crater depth as a function of barrier temperature is determined by changes in the dynamic hardness of the impacted material as well as by the compressibility characteristics of the impacting bodies.

Adadurov, G. A., A. N. Dremin, and G. I. Kanel'. Split-up of shock waves in porous KBr. FGiV, no. 4, 1970, 529-532.

The authors describe experiments on shock wave propagation through porous potassium bromide. The tests were concentrated in the KBr density range over which phase change occurs during wave propagation, resulting in a split of the shock wave into two components. Shock wave velocity and profile were measured for KBr in the range of 2 to 2.7 g/cm^3; the sensor was a moving e-m pickoff in an external magnetic field. Explosive pressure on the specimen was regulated from 30 - 40 kbar by altering the density of the explosive charge (TNT - talc, 50/50). Limit conditions on the split-wave mode are discussed; for example, below a specimen density of 2 g/cm^3, it was impossible to distinguish two discrete shock waves. A comparison of the results with shock adiabats for dense media is also given.

Dremin, A. N., and O. N. Breusov. Physico-chemical processes caused by shock compression. VAN, no. 9, 1971, 56-59.

A general qualitative review is given of the phenomena occurring on passage of a shock wave through various solid media. At the present state-of-the-art, studies on these effects may be broadly divided into two categories: investigation into physical effects during the course of shock propagation, and physico-chemical studies of macroscopic changes in the host material after passage of the wave. The authors consider mainly the second category, and discuss the effects of temperature, shock pressure and microstructure of the material on the changes which may be induced. The possibilities of extrapolating present techniques such as explosion-hardening of metals and shock polymerization are considered; examples of shock polymerization are cited as illustrations and some anomalies in the results are discussed. Shock-generated reactions are also cited as a simple way of generating very high local temperatures. From the abundance of defects often arising in these cases, the effects may be considered analogous to those from hard radiation.

Yampol'skiy, P. A. Propagation of shock waves in organic monomers and polymers. (Seminars of the Institute of Mechanical Problems.) MTT, no. 4, 1971, 199.

The author notes that the effect of a shock wave in organic solids, particularly those in which chemical reactions are difficult to obtain, can produce very effective reactions. In such cases a significant volume of material may be made to react in the order of a few microseconds; an example cited is the shock polymerization of acrilamide. In such a case temperature may be assumed to play no part in the reaction; the major dynamic effect would appear to be shear of material particles within the shock wave. A combination of static and shock wave pressures may thus be used to achieve a desired type and level of polymerization.

Mardukhayev, I. R. Determining the location of an inflection point in a $T(\epsilon)$ diagram for the case of a transverse shock. IN: Volny v neuprugikh sredakh, 1970, 153-157.

The author analyzes the special case of the stress T vs. deformation ϵ relationship for which the $T(\epsilon)$ curve will have one or more inflections, as is the typical case for polymers and some plastics. The presence of an inflection point in the curve is taken as the criterion for shock wave generation in the material. Depending on the material, the shock wave may or may not be preceded by a Riemann wave. It is shown that if the $T(\epsilon)$ characteristic is known up to an inflection point, it may be extrapolated further. Numerical examples illustrating the method are given for transversely-stressed polyvinyl, rubber and kapron.

Mar'yamov, A. N. Self-similar convergent shock wave in metal. IN: Volny v neuprugikh sredakh, 1970, 157-161

It is shown that the solution of the problem of a converging shock wave in an ideal gas can be adapted to the analogous case of shock wave propagation in a metal. From the equation of state for a metal and an expression for differential entropy using the limiting value of the Gruneisen parameter ($\Gamma = 2/3$), the author establishes that the cited equation of state is an analog of the case of a converging shock wave in an ideal monatomic gas for shock adiabat $\gamma = 5/3$. It follows that the distribution of flow parameters behind the shock wave in metal is analogous to that in the ideal gas, with the exception of temperature effect; this contribution may be calculated from a separate expression. With the introduction of an assumed self-similar parameter, it is then possible to obtain expressions relating wave front velocity to pressure and density at the wave front. Numerical examples are given for some typical conditions.

Boronin, A. P., Yu. A. Medvedev, and B. M. Stepanov. Short-wave r-f emission from an explosion shock wave. DAN, v. 192, no. 1, 1970, 67-70.

A technique is described for recording and analyzing shf emission from the region behind an explosive detonation wave. The main object of this method is to enable determination of ion and electron density behind the shock wave as a function of time after detonation. The explosive used was spherical charges of TG 50/50, in amounts from 50 to 600 g; the receiving antenna was a rod type placed 1.5 m from the explosive charge. Emission was recorded in the 1 to 100 MHz range; below 1 MHz the local radio noise level was too high for explosive signal detection. A characteristic feature here was the lag in signal appearance (t_0) following detonation. This is attributed to the shielding effect of explosion products and plasma behind the wave front, which is more pronounced for the higher frequencies. Lag characteristics as a function of explosive charge size are seen in Fig. 1 for three detected frequencies. The curves generally

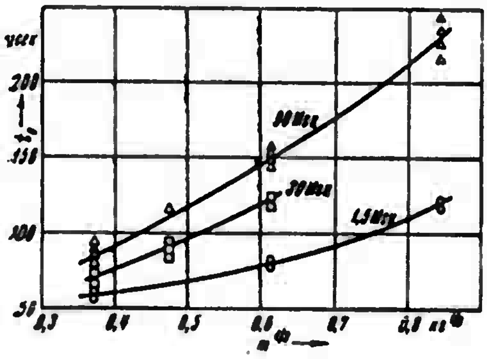

Fig. 1. Lag characteristics of explosive emission.

satisfy the relation

$$t_0 = t_0^0(f)\, m_{кг}^{1/3}, \qquad (1)$$

where f is frequency and m is charge mass. The paper is concerned only with analysis of the radiated signals and does not consider their generation mechanism.

Bogomolova, L. A., V. A. Gridneva, and I. Ye. Khorev. High velocity impact between solid bodies having identical physical parameters. ZhPMTF, no. 3, 1971, 94-98.

Solutions are obtained for the one-dimensional problem of high velocity impact between a projectile and a semi-infinite target area. The analysis assumes the case of identical materials in both elements, and derives expressions for the shock propagation within them for the velocity range of 2 to 6 km/sec. The problem is treated in two stages; the first starts at the moment of impact and assumes plane shock waves of constant intensity propagating through both elements. The second stage begins upon reflection of the shock wave back from the exit surface of the projectile, and extends until the shock processes decay to zero. The problem is solved from equations of state in the form $p = p(\rho, \epsilon)$, in which p is pressure, ρ is density and ϵ is unit internal deformation energy. For the first stage this is done analytically; for the second stage where wave interactions must be accounted for, solutions are obtained by the finite-difference method of Richtmaier using a BESM-4 computer. The authors thus obtained shock adiabats for Al, Pb, Cu and Fe from which propagation velocities were calculated. Fig. 1 shows close agreement of the results with experimental data

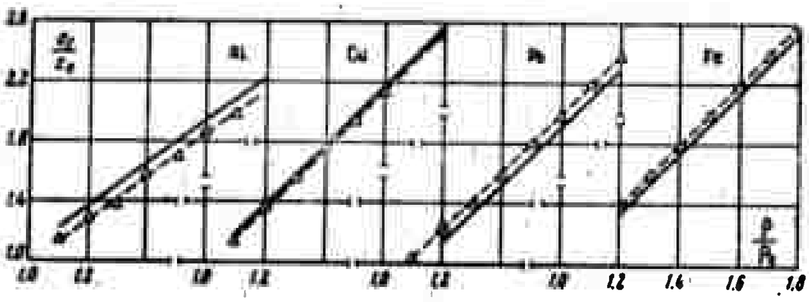

Fig. 1. Relative shock velocity in metal.
——— calculated; ----- experimental

of Al'tshuler et al (ZHETF, v. 58, no. 4, 1960). The method can also be extended to the case of a target of finite width, rather than the unbounded width assumed in the present article.

Krasovskiy, A. Ya. Effect of the viscous drag coefficient in dislocations on attenuation of a plane shock wave. FTT, no. 6, 1970, 1834-1836.

The author considers the attenuation of a shock wave in a solid in terms of the drag coefficient of the crystal lattice through which the wave is propagating. The drag is a viscous type obeying the relation f = Bv, where f is drag per unit dislocation length, v is dislocation rate and B is drag coefficient. Analytical values of B/N are obtained, where N is density of moving dislocations, and compared to shock wave results from other experimental data. Discrepancies between theoretical and experimental values of B are ascribed to some incorrect assumptions concerning dislocation motion behind the shock wave. The data also show that over a range of 100-600°K, temperature has no measurable effect on density of moving dislocations resulting from a shock wave.

Alekseyev, Yu. L., V. P. Ratnikov, and A. P. Rybakov. Shock adiabats of porous metals. ZhPMTF, no. 2, 1971, 101-105.

Physical effects occurring in passage of a shock wave through porous metal are discussed, assuming air in the interstices between metal particles. Shock adiabats in terms of volume, mass velocity and compression are obtained for the case of multiple shock wave occurrence in the medium, and in the general case are given by

$$V^* = V + (k-1)\left(\frac{\gamma-1}{\gamma+1}\right)^2 V_0 \qquad (1)$$

$$\frac{1}{\sigma^*} = \frac{1}{\sigma} + (k-1)\left(\frac{\gamma-1}{\gamma+1}\right)^2 \qquad (2)$$

$$u^* = \left[u^2 + \frac{4\gamma}{(\gamma+1)^2}(k-1)\,pV_0\right]^{1/2} \qquad (3)$$

in which V = unit volume, k - porosity coefficient, σ = relative compression, u = mass velocity, p = pressure, and γ = adiabatic index of air. An asterisk indicates the porous combination; other terms apply to the metal alone. From these expressions the authors calculated the curves of Fig. 1 for Cu, Ni and W, which were in fairly good agreement with experimental results. Additional data

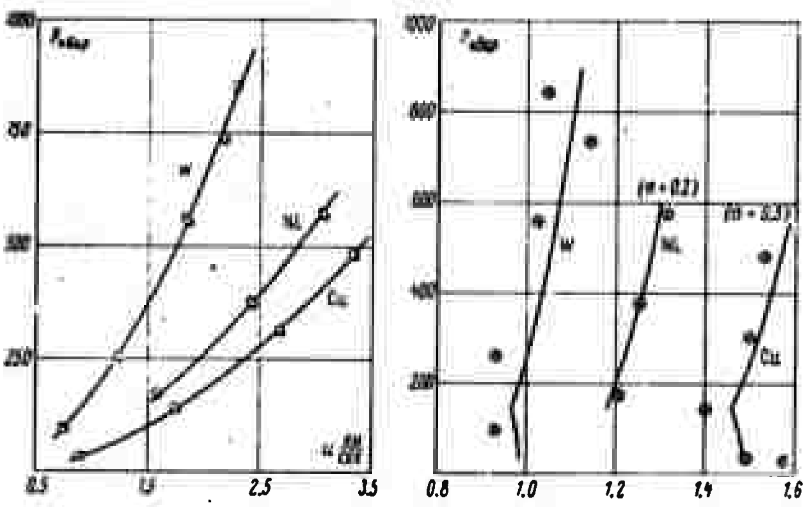

Fig. 1. Shock adiabats of porous W, Ni, and Cu.

are given on the unloading characteristic of porous copper, starting from a shock pressure of 485 kbar. The possible contributions of interstitial air heating or cooling and of surface vaporization from metal particles are also considered.

Zubarev, V. N. Shock compression of piezoceramics. ZhPMTF, no. 2, 1971, 106-110.

Shock adiabats and shock effects on electrical characteristics of a PZT piezoceramic are given and the test techniques described. The piezo element tested was $Pb_{0.95} Sr_{0.53}(Zr_{0.53} Ti_{0.47})$ + 1% Nb_2O_5 by weight. Tests were done by a shock wave reflection method over a dynamic range of 100-470 kbar, with piezocurrent and dielectric constant being recorded over this range. The shock-induced changes in these parameters, particularly in conductivity, can be seen from Table 1. A general increase in density from 7.35 to 7.8 g/cm^3 was observed, although x-ray analysis showed that crystal structure and lattice parameters were unaffected by the shock loading. However, shock compression at this level was found to completely depolarize the test specimens. It is concluded that shock depolarization starts at about 5 kbar and increases as a function of dynamic pressure.

P, kbar	diel. constant, $\epsilon \times 10^{-3}$	$\lambda \times 10^3$/ohm cm
105	4.3 ± 0.4	4.5 ± 0.5
149	4.6 ± 0.4	6.6 ± 0.9
278	9.6 ± 5	22 ± 2.5
332	11	40 ± 15
467	--	100

Table 1

Al'tshuler, L. V., and M. N. Pavlovskiy. Electromagnetic method for determining density behind colliding shock waves. ZhPMTF, no. 2, 1971, 110-114.

An inductive pickoff method is described for determining shock compression from opposed shock waves. The method proposed by Al'tshuler et al has been reported in earlier tests (Al'tshuler, L. V. Uspekhi fiz. nauk, v. 85, no. 2, 1965). The method, shown in Fig. 1, uses a rectangular coil whose plane is normal to the shock wave plane, placed in a transverse magnetic field, so that shock compression is registered by an induced voltage as the coil deforms. With this technique the authors obtained compression characteristics for paraffin, clay and crystalline KCl and NaCl. The p, σ adiabats for these materials are given,

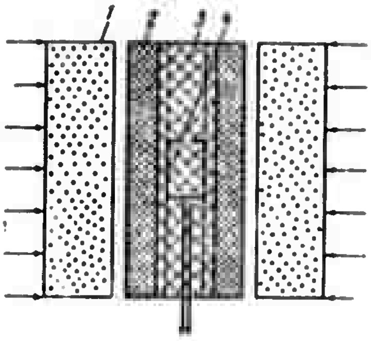

Fig. 1. Shock compression sensor.
1 - explosive; 2 - paraffin shield;
3 - specimen; 4 - coil.

where σ is compression factor, at levels up to 400 kbar. Both synchronized and staggered detonation times were used for the opposed charges, resulting in single or multiple shock wave action.

Stepanov, Yu. S. Interaction of high velocity microparticles with a system of polymer obstacles. ZhPMTF, no. 2, 1971, 115-118.

A statistical study is described of the cratering or perforating action of high-velocity microparticles on a variety of polymer target combinations, as well as on aluminum foil. The impacting particles were glass pellets on the order of 100 microns in diameter; particle velocities up to 21 km/sec are mentioned. An approximately normal distribution of crater dimensions, or hole diameters in the case of the foil, was obtained. Target materials were two variants of polyethylene; tests were done in a vacuum chamber. A definite peaking in pellet penetrating action as a function of velocity is analyzed, and can be ascribed to the increased effects of temperature on the impacting bodies at higher velocities. Thus for glass pellets in the cited tests the critical velocity was approximately 10 km/sec for 95 micron pellets impacting onto polyethylene; at 21 km/sec pellets deteriorated more rapidly on contact and lost much of their penetration capability.

Bagdoyev, A. G. Determining nonlinear equations of motion of a medium in the vicinity of shock wave contact points. DAN ArmSSR, v. 52, no. 4, 1971, 201-208.

The problem is attacked of defining the motion of a compressible medium in the vicinity of conjunction of a weak shock wave and a diffracted or point wave, as indicated in Fig. 1. The treatment applies to reflection of shock waves from an obstacle forming the angle O in the figure, as well as to penetration of shock waves or solid masses into a liquid. The motion is expressed by a

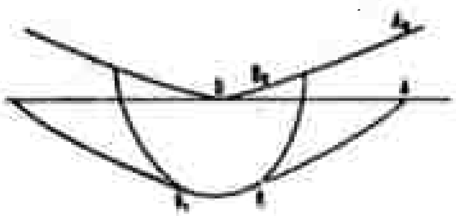

Fig. 1. Wave conjunction model.
AB - shock wave; BB_1 - diffracted wave;
OA - surface of medium.

system of nonlinear hyperbolic equations, for which solutions are obtained by various linear simplifications and substitutions. The analysis is extended to the case in which the medium is a compressible fluid.

Skripov, V. P. and P. A. Pavlov. Explosive boiling of liquids and fluctuating nucleation. TVT, no. 4, 1970, 833-839.

Explosive boiling of water and some twelve organic liquids (ethers, acetone, benzene, aliphatic alcohols and hydrocarbons) was studied experimentally to ascertain the role of fluctuating centers in vapor generation in the near-wall layer of a superheated liquid. A large volume of a liquid was heated at variable high rate by an immersed Pt wire connected in a bridge circuit with a rectangular pulsed current source. Heating pulses and fluctuations in wire resistance as a function of its temperature were recorded by a dual-beam oscilloscope, and microphotographs of the wire were taken at different times from the start of heating. An avalanche-type increase in the number of spontaneous bubbles on the wire surface in water corresponded to an anomaly in the oscillogram recorded at 302°C. At atmospheric pressure some bubbles always appeared in the same spot on the surface at a definite temperature most probably at the available boiling centers. Others appeared at random in suddenly increasing numbers which caused explosive boiling. Each liquid had its characteristic threshold time τ_0 of heating up to explosive boiling temperature. Only at heating times $\tau^* < \tau_0$ was explosive boiling observed, where temperature T* is weakly dependent on heating rate. The experimental T* agreed with T* calculated from the theory of homogeneous fluctuating nucleation for each experimental frequency of spontaneous nucleation. Thus the explosive pattern of boiling was experimentally produced by heat transfer from a solid wall. The fluctuating centers of vapor formation then determine explosive patterns of boiling.

Aleksandrov, A. F., V. V. Zosimov, A. A. Rukhadze, V. I. Savoskin, and I. B. Timofeyev. A possible mechanism of pinched high-current discharge in the atmosphere. KSpF, no. 8, 1970, 72-78.

The experimental time-dependences of temperature T and radius r_d of a rapid discharge in the air at atmospheric pressure are given and compared to a model of high-current discharge introduced by Basov et al [ZhTF, v. 40, 1970, 516]. The discharge at a 15 kv potential was initiated by explosion of 8 cm long silver wires, which produced a 20μ sec periodic current with $F = 5.6 \times 10^{10}$ amp/sec. The $r_d(t)$ plot determined by high-speed photography shows the pattern of discharge channel expansion to have two stages: the first at a $\sim 4 \times 10^5$ cm/sec rate, the second, after 5 μ sec at a practically steady $\sim 5 \times 10^4$ cm/sec rate. A time sweep of the discharge spectrum indicated an oscillating pattern of T (t) dependence in the region of blackbody radiation near the current peaks. According to the proposed interpretation, the first stage of discharge is described by a thermal wave model, and the second stage can be correctly represented by the "high-frequency" pinch model roughly equivalent to vacuum pinch, described by $J(t) = J_{eff}(t)$. Consequently, the radius R of the discharge channel is determined to a first approximation by J_{eff}. Theoretical R (t) and T (t) dependences calculated from Basov's and the authors' formulas agreed with the experimental R (t) and T (t).

Lebedev, S. V. <u>Phenomena associated with electron emission from "exploding wires" in the process of melting.</u> TVT, no. 2, 1970, 252-259.

Two series of experiments were conducted to explore the earlier observed anomalous pulsed current I flowing in a vacuum diode from a tungsten filament to a collector, for the case of high-density filament current. In both series, 0.9 - 5.5 mm long wires were heated by a current density j in the 6.2×10^9 - 2.1×10^{10} a/m^2 range and oscillograms were recorded of the emission current I and photocurrent before and during melting of wire. In the first series of experiments, the collector was kept at a potential $V < V_{cr}$, at which magnetic field H of the filament current i prevents the flow of electrons to the collector. In this case, I was triggered at a time t_s by switching off i prior to melting. Switching on i again at $t_s < t_m$ (t_m = time of initial melting) made I reappear inspite of the presence of H and reach a peak at t_m. Thus the earlier observation was confirmed of I existing in an inhibiting field H before and during melting. Generation of a pulsed I (t_m) in an inhibiting H at $V < V_{cr}$ may be explained as the result of interelectron collisions. In the second series of experiments, at $V > V_{cr}$ and in the absence of discharge at t_m, I (t_s) and I (t_m) spikes and a depression of I before the I (t_m) spike were observed. The depression was explained by the effect of W vapors or liberated gases on diffusion of electrons at increasing density. The effect of ionization of W vapors or gases on the wire surface at $t \simeq t_m$ was shown to be insufficient to generate pulsed I (t_m) in the absence of discharge. The results were interpreted in terms of anomalous emission due to generation of crystal lattice defects. The observed phenomena may be of interest to the study of electric breakdown in vacuum.

Lebedev, S. V., A. I. Savvatimskiy, and Yu. B. Smirnov. Measurement of the heat of fusion of refractory metals. TVT, no. 3, 1971, 635-638.

The heat of fusion E_f of pure Ni, W, Ta, Mo, and Pt; type 20 steel; MV-50 (Mo:W = 50:50), BP-20 (80% W, 20% Re), NIVO-25 (61-63% Ni, 24-26% W, balance Fe), NIMO-25 (66-69% Ni, 25-28% Mo, balance Fe), Kh 20 N 80 (80% Ni, 20% Cr), and NMts 5 (4.6-5.4% Mn, balance Ni) alloys was measured by the method of "electric explosion." Metallic wires approximately 1 cm long and 0.05-0.1 mm dia. were rapidly heated in air at atmospheric pressure by a rectangular pulsed current of densities from (1.5-4) x 10^{10} amp/m^2, and iR and ir drops across the wire and a standard resistance r, respectively, were measured from photographs of the V_R (t) oscillograms. The average random error of E_f measurements varied from 2-6% depending on the metal. In addition, the maximum systematic error due to the equipment used was estimated to be 8%.

Some measured E_f values of the pure metals agreed with the literature data, while others differed considerably, presumably on account of unreliability of the experimental data from cited literature. The measured resistivities at melting point in the solid and liquid states were in agreement with the literature data. It was concluded that the method used gives sufficiently accurate values of E_f and electrical conductivity of metals and alloys, in comparison to data from stationary measurements.

Arkhangel'skiy, N. A. Algorithm for numerical solution of a cylindrical explosion allowing for counter-pressure, by the net-point method. ZhVMMF, no. 1, 1971, 222-236.

Propagation of an intense cylindrical shock wave through a stationary perfect gas is described by a system of nonlinear equations as follows:

$$\frac{\partial u}{\partial \tau}+A\frac{\partial p}{\partial \eta}=0,\qquad \frac{\partial p}{\partial \tau}+B\frac{\partial u}{\partial \eta}+\Pi=0,\qquad A\frac{\partial r}{\partial \eta}=\frac{1}{\rho},\qquad (1)$$

$$\frac{\partial}{\partial \tau}(p\rho^{-\gamma})=0,$$

Here the partial derivatives of dimensionless variables u, τ, p, η, r, and ρ are functions of pressures P_0 and P, densities R_0 and R, and released energies E_0 and E at the times 0 of explosion onset and t, respectively, and Lagrangian coordinates. Gas motion was assumed to be adiabatic, since heat dissipation was not accounted for. Initial conditions at $\tau = \tau_0$ and boundary conditions in the center and for the shock wave were formulated to solve (1) for u, p, r, ρ, and c_{sw} (shock wave velocity) as functions of η and τ at a given Poisson adiabatic exponent γ. System (1), with allowance for counterpressure, was reduced to a system of difference equations which were asymptotically solved by the net-point method. Solution of the difference equations was obtained by iteration using successive calculations at each iteration step; only two iteration steps were required. The described algorithm was applied to numerical computations of the cylindrical wave problem at $\gamma = 1.4$ and $\gamma = 5/3$.

Alenichev, V. S., M. A. Mel'nikov, and T. N. Barchenko. Exploding wires as a source of shock waves in water. Elektronnaya obrabotka materialov, no. 1, 1971, 32-35.

The pressure P at the front of a shock wave generated in water by electrical explosion of copper and constantan wires was measured as a function of different pulsed current generator and wire parameters. A piezoelectric pickup was used to measure P instead of the earlier used measurement of diaphragm deformation used by other cited authors. The generator charge potential was varied from 7 to 20 kv. It was shown that the maximum P, i.e. that realized with optimum wire cross-section for a Cu wire was 1.2 times the Pmax for a constantan wire at equal pulse energy output. The optimum cross-section of Cu wire varied linearly with potential at equal capacitance (20 μ f). The experimentally determined optimal section and length agreed with the corresponding theoretical data within the cited ranges of generator and exploding wire parameters. Graphical data are included showing generated P as functions of wire dimensions. The tests verified that the lower resistivity wire material produced the greatest shock wave pressure.

Ocheretin, V. N. Characteristics of energy released in a channel formed by an exploding wire. Elektronnaya obrabotka materialov, no. 3, 1971, 74-75.

The conditions of obtaining maximum power output P, i.e. maximum hydroacoustic efficiency, in the discharge channel of an exploding wire are formulated. Account is taken of the fact that an exploding wire cannot be simply matched to the current generator impedance, because the wire impedance is nonlinear during the explosion process. The formula for energy density u released in a discharge channel, which was derived from the Poynting equation, indicated that u depends mainly on the magnitude of discharge current I and radius r_0 of the discharge channel. Equation (1) for P was derived on the valid assumption that nonuniformity of energy release along a channel can be disregarded. It is recommended on the basis of (1) that high-voltage, low capacitance capacitors be used in designing electrohydraulic assemblies using the exploding wire principle. Also, steel is preferable to Al or Cu wire, and minimum oscillatory frequency and a significant damping constant are further requirements for an efficient discharge.

$$P = \frac{2\pi l \varepsilon_0 \mu (1 + C^2 \mu \varepsilon) U^2}{\varepsilon \omega^2 L^2} \cdot e^{-2\delta t} \cdot [\omega t \cdot \sin 2\omega t - \sin^2 \omega t \, (2\delta t + 1)], \qquad (1)$$

Karakhanov, S. M. and V. V. Polyudov. Shunting discharge in vacuum heating of wires by pulsed current. ZhTF, no. 7, 1971, 1430-1435.

Experiments are described with Ni and W wires heated in a (2-5) x 10^5 torr vacuum by electric discharge from a capacitor at 3-8 kv initial potential, negative or positive. The vaporization rate of Ni or W was made negligible by selection of appropriate parameters for the discharge circuit. This experimental arrangement enabled evaluation of the maximum energy input to the wires prior to the appearance of a shunting discharge. The experimental plots of potential U and current I versus time T exhibited three distinct phases, both with preliminarily degassed and nondegassed wires. The onset of the second phase at a time t_1, when U drops abruptly and I begins to rise, corresponds to the shunting discharge. In Ni wires, the corresponding energy E_{t1} calculated from the I (t) plot was either lower or slightly higher than the energy of fusion E_f at a negative U, while E_{t1} was significantly higher than E_f at a positive U. In W wires $E_{t1} < E_f$ for any U. Comparison with the effect of discharge in air at atmospheric pressure shows that the energy released from Ni wire in air is much higher than E_{t1}. In addition, a rapid decrease in I before an electric explosion does not occur in vacuum and U decreases instead of increasing, because of onset of shunt discharge. The dependence of E_{t1} on the polarity of U leads to the conclusion that anomalous electron emission from the conductor is the main determining factor of a shunting discharge.

Anik'yev, I. I., M. I. Vorotnikova, and V. O. Kononenko. Some experimental data on the effect of a lateral shock wave in water on a cylindrical shell. Prikladnaya mekhanika, no. 9, 1971, 106-109.

Shock deformation was studied of cylindrical shells, 300 mm long x 120 mm ID, made of a glass-reinforced plastic or stainless steel. The hermetically sealed shells were immersed in water. A shock wave was generated by electrical explosion of a 0.07 mm thick copper wire in a horizontal position parallel to the shell axis, and at a distance equal to two or more diameters from the shell. Shock wave pressure and deformation of shell elements were recorded simultaneously by an OK-17 M dual-beam oscilloscope with inputs from two piezoelectric pickups. The deformation process was also photographically recorded with an SFR high-speed camera through plexiglass windows at both ends of the shell. The steel shell lost its stability by the irreversible formation of 6 to 8 longitudinal plane surfaces by the impact of a shock wave of about 90 atm amplitude. In contrast, the plexiglass shell, initially deformed by shock wave impact at a 110 atm peak pressure, completely reverted to its original cylindrical shape. Oscillograms of the plexiglass shell show that stability loss proceeds simultaneously at several harmonics, predominantly those with the wave numbers 6-8 and 25. Also, the time for evolution of maximum deformation was substantially longer than the time of wave propagation over a distance equal to the shell diameter.

Abramova, K. B., and B. P. Peregud. Emission from electrically exploded metals. ZhTF, no. 10, 1971, 2216-2225.

An experimental study is reported of the emission accompanying a true electric explosion (before breakdown and arc discharge) of copper wire at atmospheric and 10^{-6} torr pressures. The absence of any data in the literature on the emission in the IR and vacuum UV spectral ranges and scarcity of information on emission in the visible range prompted this study. Oscilloscope traces of current and spectroscopic measurements of emission in the 1.35 - 2.2 μ range reveal two intensity peaks at λ = 1.5 and 1.8 μ, the latter disappearing after termination of the current pulse. The measured energy of the 1.5 μ emission peak was about 150 times that of the thermal emission of an absolute black body at 1,900°K, and the power of the emission peak was three orders of magnitude greater than that of the cited thermal emission, since the emission spectrum was considerably narrower than the Planck spectrum. It was thus shown that the observed

IR spectrum could not be of thermal origin. The measured emission spectra in the 2,200-6,000 Å range of an electric explosion with and without discharge revealed the existence of only a long wave "tail" of intensity distribution. The Planck approximation of these spectra suggested the possible existence of an emission peak at ~ 1,000 Å, i.e. in the vacuum UV range. This was confirmed in the present experiment at 10^{-6} torr by measuring de-excitation of a $CaSO_4$-Mn phosphor preliminarily exposed to the emission from an exploding Cu wire. Estimates of energy requirements for the observed emission led to the tentative conclusion that emission from the electrically exploding metal wires in the IR as well as in the short wavelength spectral ranges exhibits characteristics of electroluminescence. The onset of emission coincides in time with the constricted magnetohydrodynamic instability which causes destruction of the conductor. Presumably, electroluminescence of the metal is excited either by a high overvoltage of the electric field generated by MHD instability, or by the extremely rapid destruction of the metal. Oscillographic and spectral data are included.

Dikhter, I. Ya. and S. V. Lebedev. Study of thermophysical properties of tungsten and molybdenum near the melting point, using the method of electrical explosion. TVT, no. 5, 1971, 929-933.

An exploding wire experiment is described in which the data on temperature dependence of heat capacity C of liquid and solid Mo, and on temperature dependence of electrical resistivity ρ of liquid and solid Mo and W are reported and compared to earlier published data. The C data of Mo (Fig. 1) were obtained by graphical treatment of the experimental E (T) plot, where E is the energy input to a wire (d = 80 μ) from an electrical wire explosion induced by a pulsed current at a 5 x 10^{10} a/m^2 density. E and ρ were measured from oscilloscope traces of voltage drop and current. The blue and red data referred to in Fig. 1 pertain to measurements made at the 400 μ and 818 μ wave lengths, respectively. The experimental ρ (T) plots are shown in Figs. 2 and 3. A discrepancy observed in Fig. 1 between the authors' curve 1 and curve 5 near the melting point (2900°K) of Mo is tentatively explained as the result of a difference in the state of the metal described by the respective curves, i.e. a nonstationary state in the case of curve 5, the latter having a higher number of paired interstitial defects (holes and atoms). A discrepancy between the blue and red data indicates a temperature dependence of the spectral emission coefficient ϵ_λ immediately after melting. In spite of the cited discrepancy in C data, it is apparent that the energy consumed by electrical heating of a metal to its melting point is the same whether for slow or rapid (electrical explosion) heating.

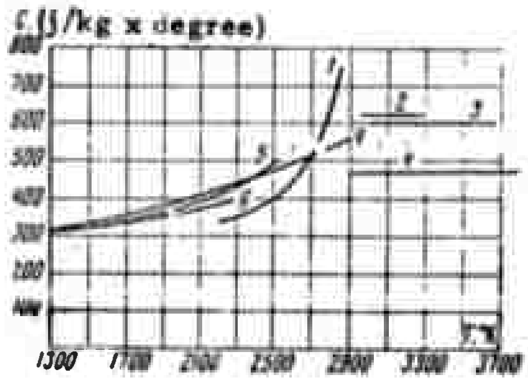

Fig. 1. Heat capacity of Mo versus temperature.
1 - authors' data, solid state; 2 - authors' blue data, liquid state; 3 - authors' red data, liquid state;
4 - calculated literature data; 5, 6 - literature data obtained by the modulation method and by the alternating induction heating and modulation methods, respectively.

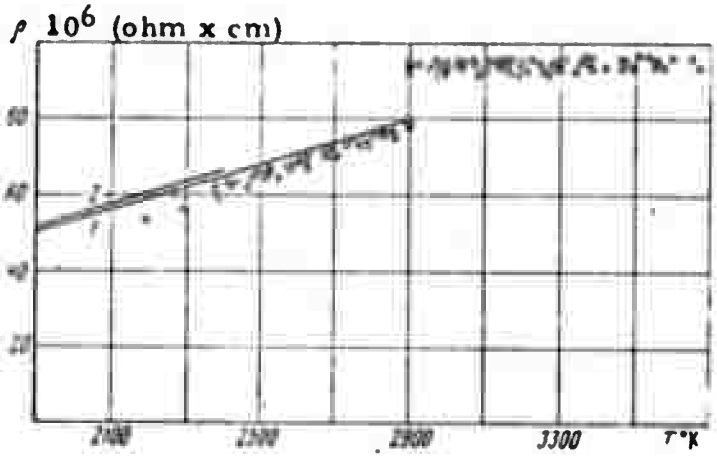

Fig. 2. Electrical resistivity of Mo vs. temperature: the points are the authors' data, 1 and 2 are from literature data.

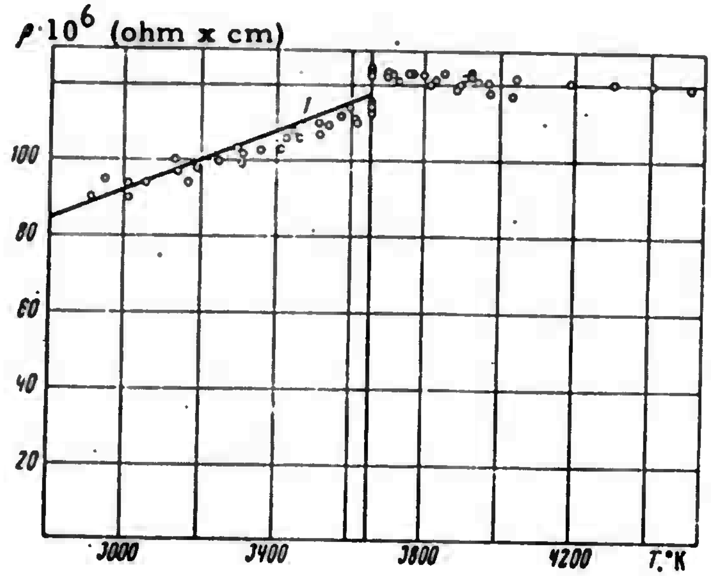

Fig. 3. Electrical resistivity of W vs. temperature: the points are the authors' data, 1 is taken from the literature.

Basov, N. G., B. L. Borovich, V. S. Zuyev, V.B. Rozanov, and Yu. Yu. Stoylov. High-intensity discharge in gases. I. Experimental study of optical and energy characteristics of a powerful discharge in air. ZhTF, no. 3, 1970, 516-522.

Basov, N. G., B. L. Borovich, V. S. Zuyev, V. B. Rozanov, and Yu. Yu. Stoylov. High-intensity discharge in gases. II. Description of dynamics of a powerful gas discharge with the help of self-similar solution of gas dynamic equations in the case of nonlinear heat conductivity. ZhTF, v. 40, no. 4, 1970, 805-813.

A high-intensity (~400 ka) electric discharge at atmospheric pressure was produced by electric explosion of thin (0.03-1 mm diameter) Cu or W wires, 8 to 46 cm long. Photographs taken with a high-speed photochronograph show that the plasma column formed by the explosion expands at a rate of 2 - 2.5 km/sec during the first 10 - 15 μ sec. The radiation temperature of the plasma was measured to $\pm$ 10 - 15% accuracy by oscillographic recording of radiation intensity of the wire compared to that of a standard source. The emission spectra of the discharge column at λ = 2400, 3340, and 5000 Å were almost identical, hence the emission was analogous to that of an absolute blackbody with temperature varying from 5 to 2 ev during the first 20μsec. A small pinch effect was noted after 12 μ sec on the plots of T(t) and d(t), where d is the diameter of the plasma column. The effects of wire geometry and discharge parameters on both T(t) and d(t) were found to be insignificant. Measurements of the current I and voltage U characteristics of the discharge indicated that up to 25 kj electrical energy was released into the discharge column during 20 μsec. Calculations show that the energy in a 20 cm long column amounts to 60% of the energy accumulated in the discharge capacitors, but only 20% of the total released energy is converted into radiation in the atmospheric transmission band. Such high-intensity discharges can be used for pumping lasers which emit short high-power pulses. The power density of radiation from such a discharge exceeds that of conventional gas-discharge lamps by a factor of approximately 15:1.

In the second paper by Basov et al, a theory based on approximate self-similar solution of gas dynamic equations is developed to explain the characteristics of gas discharge which were described by the authors in the foregoing article. The solution of the equation of continuity, Euler, and energy equations is presented in the general form

$$\left.\begin{aligned} \rho &= M(t)\,g(\xi), \\ v &= V(t)\,u(\xi), \\ T &= \Pi(t)\,\tau(\xi), \\ \xi &= \frac{r}{R(t)}. \end{aligned}\right\} \qquad (1)$$

where ρ, v, T and R are, respectively, density, velocity, temperature, and radius of the thermal wave front. The time functions in (1) are exponential in the form:

$$R = Bt^{k_1}, \quad \Pi = Ct^{k_2}, \quad M = Dt^{k_3}. \qquad (2)$$

Equations (1) and (2) describe a uniform propagation of a shock wave in front of a thermal wave of the second order (HW-2). An approximation in (1) consisted in disregarding the contribution of photon diffusion to v, i.e. in assuming that R = V, hence v is equal to the velocity of gas dynamic propagation. This is precisely the condition of self-similarity of (1). The characteristics of a gas discharge in a channel through which a flow of direct current I is sustained by a constant field E were calculated by substituting for the coefficients B, C, D and the exponents k_1, k_2, and k_3 in (2) the expressions derived from (1). A satisfactory agreement was shown between the calculated T, 2R, released energy E, and ohmic resistance r of the discharge column, and the corresponding experimental parameters. The theory also confirmed that the discharge is not affected by the geometry of the exploding wire, provided the mass of the wire is smaller than the mass of air in the region of the thermal wave.

Voskoboynikov, I. M. and V. M. Bogomolov. Comparative study of the equations of state for detonation products of organic liquids. TVT, no. 1, 1970, 81-87.

The applicability of equations of state for molecular crystals to the determination of gas properties at high temperatures and pressures is investigated. It is shown that the equation of state for molecular crystals

$$p = p_x (V) + c_{v1} \Gamma T/V \qquad (1)$$

where c_{v1} is the translational component of heat capacity, $\Gamma = -\partial \log \Theta_D / \partial \log V$, and Θ_D is the characteristic temperature of intermolecular interaction, describes most adequately the thermodynamics of liquefied gases which are the potential components of detonation products, and detonation products of common explosives such as RDX, TEN, and TNT. The unknown functions $p_x(V)$ and $\Gamma(V)$ in (1) were calculated for liquefied gases using the $\Gamma(V)$ dependence introduced by Slater and the experimental shock adiabats p (u), where u is the flow velocity behind the shock wave. It was shown that p (u) for liquefied gases and detonation products can be derived from a common expression with sufficient accuracy for the solution of many gas dynamic problems. Hence, the calculated 2000 - 5000°K p (V) isotherms of the components of detonation products can be used to plot the p (V) isotherms of detonation products of the cited explosives. The calculated polytropic exponents n of the model compositions of detonation products at the most probable detonation temperature agreed with the experimental n and showed negligible variation in the 150-350 kbar range. The cited analysis confirms the applicability of the equation of state of organic liquids to describe the thermodynamics of detonation products of powerful explosives.

Fortov, V. Ye. and Yu. G. Krasnikov. Development of a thermodynamically complete equation of state for a nonideal plasma on the basis of dynamic experiments. ZhETF, v. 59, no. 5, 1970, 1645-1656.

A method of development is outlined for the equation of state of a highly imperfect plasma, which includes temperature T in addition to the usual thermodynamic parameters. The method is based on determination of T from the second law of thermodynamics and the experimental E = E (P, V) function, solving the system of equations

$$\frac{dP}{dV} = -\frac{P + (\partial E/\partial V)_P}{(\partial E/\partial P)_V} = f_1(P, V), \qquad (1)$$

$$\frac{dT}{dV} = -\frac{T}{(\partial E/\partial P)_V} = f_2(P, V). \qquad (2)$$

A thermodynamically complete equation of state is thus obtained using the experimental shock wave velocity D and specific volume V data. The energy surface E is computed in the form

$$E(P, V) = \sum_{k+l \leq q} \sum c_{kl} V^k P^l. \qquad (3)$$

by applying the method of least squares to a system of normal equations, assuming that N random experimental points are given in the P-V plane. The applicability of the outlined method to a dense cesium plasma in a heated shock tube is illustrated by plotting the P-V isentropes within the experimental limits and comparing the results to the isentropic characteristics calculated independently from Debye theory in a large canonical ensemble. Statistical tests by the Monte Carlo method have shown that the method of approximation of (3) is accurate within ~2%. The universality of the method is stressed in application to any given medium.

Plotnikov, M. A., R. A. Chernyavskaya, and A. F. Shmeleva. Determination of thermodynamic properties of a gas at pressures above 10-15 kbar. FGiV, no. 3, 1970, 263-267.

In connection with calculations of gas explosion and compression processes, certain problems of hypersonic aerodynamics etc., the specific volume V, enthalpy I, entropy S, sound velocity a, and specific heats C_p and C_v of gases were calculated at pressures in the 16-20 kbar range and temperatures in the 700 - 3,000°K range. The calculations were based on the assumption that V, I, and S of a gas under the cited pressures are accurately described by the equation of state for liquids at a high pressure. Based on this assumption, the tabulated V, I, and S data were computed using the formulas derived by Antanovich et al [PMTF, 1969, 3], and the empirical parameters σ_V (p), σ_S (p), and σ_I were determined from the cited equation of state for liquids. The c_p, c_v, and a data were calculated less accurately for nitrogen, using an average value of σ = 3,540 Å. The tabulated data show a continued rise of the I-S isotherms with increase in pressure, similar to the rise noted in the above cited study for pressures up to 15 kbar. This study is an extension of a previously reported paper by Plotnikov et al (Effects of Strong Explosions, no. 2, 80-81).

Rodionov, K. P. The problem of the equation of state for a solid. FMiM, no. 6, 1970, 1169-1176.

An analysis is given of parameters entering into the equation of state for solids. The parameters n and π in the empirical equation of solid state are defined respectively as the baric coefficient of the true compression modulus K_t, or $n = dK_t/dP$, and as a negative pressure $\pi = -P^*$ which characterizes the interatomic cohesive force:

$$P = \pi\left\{\left(\frac{V_0}{V}\right)^n - 1\right\} \qquad (1)$$

The numerical value of n and π for 35 elements was then calculated, over a range of P up to 100,000 kg/cm^2, calculated from the approximate formulas

$$n = \frac{2b}{a^2} - 1; \qquad (2)$$

$$\pi = \frac{1}{a\left(\frac{2b}{a^2} - 1\right)}, \qquad (3)$$

where a and b are the coefficients in the Bridgman equation of state. The most reliable a and b data from the literature were used in these calculations. The calculated n values were in agreement with Slater criterion and π values were also reasonably close. The discrepancy between some of the calculated n and π values and the corresponding data of Coock [J. Appl. Phys, 1963, 34, 2330] were tentatively attributed to the Thomas-Fermi approximation of the solid state model used by Coock. Equation (1) was also used to derive simple formulas for the relative baric and thermal coefficients of compressibility and baric coefficients of thermal expansion and specific heats as functions of pressure. Generally, the calculated coefficients of the elements in question agreed with the literature data. A significant discrepancy was noted in a number of cases between the thermal coefficient of compressibility data calculated by the author and the corresponding calculated data in the literature. The derived formulas will yield initial compressibility at any given temperature. The importance of the derived formulas of $C_p(P)$ and $C_v(P)$ was stressed for elements such as Pb and Cu with low coefficients $C_p(O) - C_p(P)/C_p(D)$ and $C_v(O) - C_v(P)/C_v(O)$, which cannot be measured.

Malyshev, V. V. An experimental study of the equation of state of uranium hexafluoride. DAN SSSR, v. 197, no. 1, 1971, 73-74.

An experiment is described which was designed to yield the equation of state for UF_6. The P versus t isochores of pure UF_6 were plotted in the range of t = 99 -320°C and for densities up to 2.1 g/cm^3 using a constant volume piezometer. The P of UF_6 and t of the piezometer were measured by a compensation method with a 0.01 bar sensitivity and by a platinum resistance thermometer with 0.1 - 0.2°C accuracy. The error of density measurement was less than 0.3%. The discrepancy between the experimental and earlier calculated P values increased with increased density and decreased t, reaching 4% at 227° and 2.0 - 2.1 g/cm^3 densities. A formula was obtained for saturated vapor pressure P_s versus T which was in good agreement with the literature data. The calculated heat of vaporization for liquid UF_6 in the 129 - 215°C range differed by less than 4 - 6% from the literature data. Thus, the state of UF_6 in the 229 - 320° range and for densities above 0.8 g/cm^3 can be described by the equation

$$Z = Pv/R_\mu T = 1 + a\rho + b\rho^2 + c\rho^3, \qquad (1)$$

where the error in determination of a, b, and c increases with T to reach respectively, 0.1, 0.3, and 3% at 593.5°K. The critical parameters of UF_6 calculated from (1) are given.

Zamyshlyayev, B. V. and M. G. Menzhulin. Interpolated equation of state of water and steam. ZhPMTF, no. 3, 1971, 113-118.

Expressions are derived for thermodynamic functions of water with allowance for vaporization, dissociation, and asymptotic behavior at ultra-high pressures. In the equation of state

$$p = p_x(V) + \frac{R}{\mu}\frac{T}{V}\left(\frac{5\gamma + z_1}{1 + z_1} + 2\frac{z_2}{1 + z_2}\right) + p_e \qquad (1)$$

$p_x(V)$ and p_e are, respectively, the elastic and thermal components of p; γ is the Gruneisen constant, z_1 and z_2 are corrective terms for vaporization and dissociation, respectively and μ is molecular weight. The p_e in (1) can be approximately evaluated by solving the Thomas-Fermi equation. The γ (V) function was evaluated from experimental data on static and dynamic compression of water and the asymptotic value $\gamma = 2/3$ at $V \to \infty$ and $V \to 0$. An interpolation function was introduced in the γ (V) formulas for $V > 1$ and $V < 0.59$ cm^3/g, which adequately describe earlier experimental data. The tabulated p/p_x data from static experiments show a good agreement between p_x at different p in the 22 - 26,600 atm range. The formulas for $p_x(V)$ were also derived as an approximation of the data from dynamic experiments on shock compression of water in the front velocity-particle velocity coordinates. The cited formulas were used for interpolation of the shock adiabat of water over an intermediate range of p. The error of p evaluation from (1) is less than a few percent over the pressure range of the static experiments but is unknown in the range of ultra-high pressures. Presumably in the latter range the accuracy of evaluation of the shock adiabat is sufficient for practical purposes.

Roytburd, A. L. The equilibrium of crystals formed in the solid phase. DAN SSSR, v. 197, no. 5, 1971, 1051-1054.

The evolution of a two-phase structure in the process of phase transformation in the solid state is analyzed, for the cases of equal and different elastic modulus λ_{iklm} of the phases. Variation of the Gibbs function in the process of expansion of phase 2 was considered as the work of thermodynamic force F which was formulated as

$$F = [(\mu^2 - \mu^1) + 1/2(\sigma^1_{ik} + \sigma^2_{ik})\varepsilon^0_{ik}]\,n, \tag{1}$$

or as

$$F = \{(\mu^2 - \mu^1) + \sigma_{ik}\varepsilon^0_{ik} + 1/2\sigma_{ik}\dot{\varepsilon}_{ik}\}\,n. \tag{2}$$

respectively, in the cases of identical or different λ_{iklm}. In (1) and (2), μ^1 and μ^2 are the "chemical" energy densities of the phases 1 and 2, respectively, σ^1_{ik} and σ^2_{ik} are strains at the interface on the sides of the phases 1 and 2, respectively, σ_{ik} is the total strain, ϵ^0_{ik} is deformation of phase 2, $\epsilon^*_{ik} = \tilde{\epsilon}^0_{ik} - \epsilon^0_{ik}$, where $\tilde{\epsilon}^0_{ik}$ is the deformation of a uniform medium with the modulus $\tilde{\lambda}_{iklm}$, and n is the normal to the interface. The following expressions are derived:

$$(\mu^2 - \mu^1) + 1/2(\sigma^1_{ik} + \sigma^2_{ik})\varepsilon^0_{ik} = 0, \quad e = 1/2(\sigma^1_{ik} - \sigma^2_{ik})\varepsilon^0_{ik}. \tag{3}$$

and

$$\sigma_{ik}(\mathbf{r}_s) \equiv \frac{\sigma_{ik}^{1} + \sigma_{ik}^{2}}{2} = \sigma_{ik}^{eh} + \sigma_{ik}^{c} = \sigma_{ik}^{\text{вн}} + \lambda_{iklm} \int_s G_{lp,m}(\mathbf{r}_s - \mathbf{r}) \lambda_{pnrs} \varepsilon_{rs}^{0} n_n \, ds(\mathbf{r}), \qquad (4)$$

where e is the energy of formation of the phase 2 crystal within phase 1, σ_{ik}^{el} and σ_{ik}^{c} are the strains produced by an external load and the crystal surface, respectively, and G_{lp} $(r_s - r)$ is the Green function. Together these represent an integral equation of equilibrium at the interface. Expression (3) is the condition at F = 0 in (1); the expression (4) is the condition at F =0 in (2), which is the equation of crystal equilibrium in an elastic matrix.

Vasserman, A. A., Ye. A. Golovskiy, and V. A. Tsymarnyy. The equation of state and thermodynamic characteristics of carbon dioxide at pressures up to 2,500 bar. I-FZh, v. 20, no. 4, 1971, 734 (annotation).

A reference grid was constructed using new experimental density data obtained by the authors for liquid CO_2. The grid is described with high accuracy by the equation of state

$$P = A(T)\rho + B(T)\rho^{3} + C(T)\rho^{6} + D(T)\rho^{7}. \qquad (1)$$

where

$$\begin{aligned} A(T) &= 2387{,}3 + 3{,}1525T - 16169 \cdot 10^{3} T^{-1} + 20186 \cdot 10^{4} T^{-2}, \\ B(T) &= 2316 - 10{,}02T + 4032 \cdot 10^{2} T^{-1} - 8885 \cdot 10^{4} T^{-2}, \\ C(T) &= -4640 + 15{,}6T, \quad D(T) = 1860 - 4{,}5T. \end{aligned} \qquad (2)$$

The functions of (2) were derived by rectification of isotherms. The rms and maximum deviations of ρ values calculated from reference were, respectively, 0.02 - 0.06% and 0.05 - 0.13%. Generally, discrepancies with the experimental ρ were within $\pm$ 0.05%. Equation (1) describes fairly well the ρ of liquid state within the ranges from triple point to 10°C and to -40°C, respectively, in the saturation and solidification processes. Thermodynamic characteristics of CO_2 were tabulated by using (1) for pressures up to 2,500 bar in the 220 - 320°K range. The calculated isobaric heat capacity differed from the experimental values by less than 2%. A satisfactory agreement was also noted with the data from the adiabatic differential Joule-Thomson effect. An earlier paper on this subject by Vasserman et al was included in Effects of Strong Explosions, no. 1, p. 84.

2. Recent Selections

A. Shock Wave Effects

Afanasenkov, A. N., I. M. Voskoboynikov, and A. Ya. Apin. Transmission of detonation through an air gap. IN: Detonatsiya vzryvchatykh veshchestv i bezopasnost' vzryvnykh rabot (Detonation of explosives and blasting operation safety). Moskva, Izd-vo nedra, 1967, 101-110.

Akhiezer, A. I., and R. V. Polovin. Oscillation profile of a shock wave in plasma. UFZh, no. 9, 1971, 1467-1472. (RZhMekh, 1/72, #1B104)

Akimov, A. I., Yu. G. Lisin, V. V. Shugayev, and Yu. F. Makovskiy. Flow pattern at impact of a shock wave with a body in a hypersonic flow. DAN SSSR, v. 200, no. 1, 1971, 56-57. (RZhMekh, 1/72, #1B195)

Aslanov, S. K., and I. P. Kopeyka. Generalization of triply-detached configurations. IN: Sbornik. Matematika i mekhanika. Tezisy dokladov 4-y Kazakhstanskoy mezhvuzovoy nauchnoy konferentsii po matematike i mekhanike. Ch. 2. Alma-Ata, 1971, 171-173. (RZhMekh, 1/72, #1B215)

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IV. Particle Beams

1. Abstracts

Fursey, G. N. and G. K. Kartsev. Transition from field emission to vacuum arc. ZhTF, no. 10, 1969, 1917-1919.

An experimental set-up is described in which a rectangular pulse from a high-voltage generator was applied to a tungsten needle cathode in a 10^{-8} - 10^{-9} torr vacuum, and the pre-breakdown field emission current was recorded by an oscilloscope in a driven sweep. Temporal characteristics of transition were studied experimentally under conditions of a slow or accelerated approach to the critical state of breakdown, where $I_{cr} \approx 5 \times 10^{-3}$ a. In the slow approach mode, the pulse amplitude was increased from 1 to 2 kV by 25-50 v increments. A 100-150 nsec period of very insignificant fluctuations was recorded after an initial 15-30 nsec period of sharp increase in I. A second or high-intensity period followed the period of stability. The rate of I increase was 10^8 a/sec during the initial period, rising to 10^9 a/sec in the high-intensity period. In the accelerated approach, the pulse amplitude was increased to a value 10-50% higher than the amplitude at which I becomes critical. In this case, the stability period was significantly shorter and pulsations were observed on the oscilloscopic trace. A schematic and typical pulse waveforms are given.

Fursey, G. N. and P. G. Shlyakhtenko. Kinetics of field emission from p - Ge. FTT, no. 2, 1970, 645-647.

A preliminary experimental study is reported on the kinetics of transition to steady state of field emission from a p - Ge point cathode in a 10^{-9} torr vacuum device. High-voltage (0.5 - 10 kv) rectangular current pulses of negative polarity were supplied to the cathode. The volt-ampere characteristic of the emitter (Fig. 1) displays deviations from the Fowler-Nordheim theory in the II and III regions. The emission current decrease in region II is believed to be the consequence of electron depletion in the subsurface layer of the emitter. Presumably, the initial current rise in region III is due to multiplication of carriers in a strong internal crystal field. At a high current density, the increase in emission current at the end of region III led to self-heating and usually to destruction of the emitter. Irreversible disappearance of nonlinearity of the volt-ampere characteristic and of all kinetic effects resulted from such heating. The observed phenomena underscored the correlation of the kinetic effects and volt-ampere characteristic with the rate of electron movement toward the emitter surface.

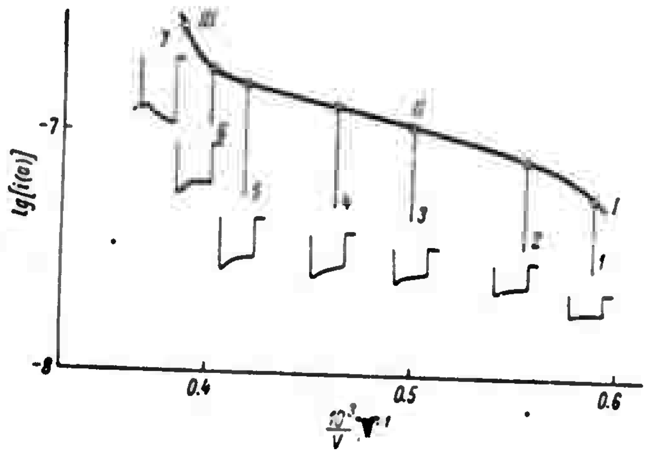

Fig. 1. V-a characteristic of a p-Ge emitter of 40 ohm x cm resistivity, and corresponding oscilloscopic traces of current versus time dependence. T = 273°K, T_i = 5 msec.

Ventova, I. D., A. S. Nasibov, G. N. Fursey, Ye. G. Shirokov, and V. N. Shrednik. Some peculiarities of formation of a high-current electron beam. Vestnik Leningradskogo Universiteta, no. 10, Fizika i khimiya, no. 2, 1971, 79-82.

High-current field emission from three types of multineedle cold cathodes has been studied experimentally in a 10^{-7} torr vacuum by applying negative voltage pulses at 30 nsec duration and 40 - 400 kV amplitudes. The results were presented in May 1970 at the 14th All-Union Conference on Emission Electronics in Tashkent. In the experiments described the collector current was recorded on a nanosecond-resolution oscilloscope; an electron microscopic study of the emitting elements was also made. The linear volt-ampere characteristics of the cathodes (Fig. 1) indicate an emission mechanism common to all three cathode types. The current pulses peaked at 700, 450, and 780 A for types I, II, and III, respectively. Reproducibility of current measurements of up to 10^5 pulses was within 15%, although marked changes in geometry of the eroded microtips and microprotrusions were observed after 3 x 10^4 pulses. Oscilloscope traces show pulsations with ~ 3 nsec periods at a 0.1 mm distance between tips. Application of repeated pulses typically produces a second current pulse whose amplitude exceeds that of the first. Analysis of the experimental data indicates that the observed high electron currents cannot be explained by a pure field emission mechanism. The formation of electron beams in this case is suggested to have the following sequence: explosive field emission ⟶ formation of a rough tip with microprotrusions ⟶ microprotrusions explosion ⟶ formation and surface propagation of plasma ⟶ field emission from the surface of a microtip in a space-charge-strengthened external field.

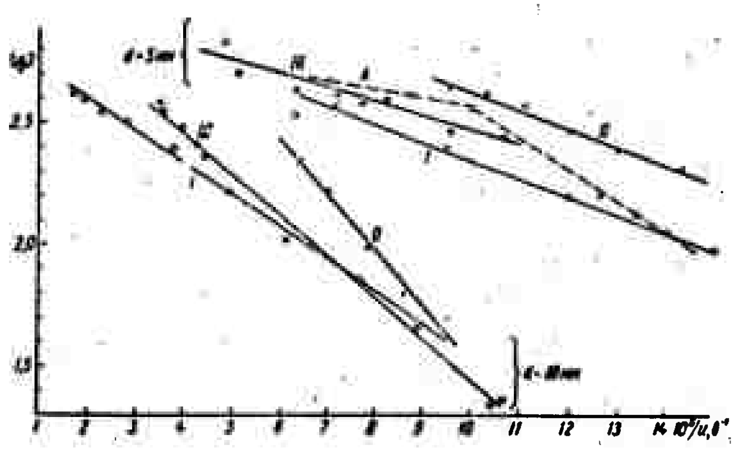

Fig. 1. V-a characteristics of multineedle cathodes.

Fursey, G. N., A. A. Antonov, and B. F. Gulin. Tungsten field emission induced by nanosecond pulses. Vestnik Leningradskogo Universiteta, no. 10, Fizika i khimiya, no. 2, 1971, 71-74.

A field emission experiment under conditions of strict purity control of the emitting surface is described, in a paper presented in 1970 at the 14th All-Union Conference on Emission Electronics in Tashkent. The experimental apparatus used for this purpose consisted of a field-emission microscope-projector in which a nickel disc collector with a fluorescent coating served for observation of emission patterns. Emission from a single-crystal tungsten needle with a tip radius of 3 x 10^{-5} cm was induced in a sealed-off tube at a maximum 10^{-9} torr residual pressure, by applying 5 to 33 nsec pulses at a rise time < 1.5 nsec and amplitudes of 3 - 50 kv. The emitting surface was purified before each pulse application by a brief heating at 2,000 - 2,500°C. The volt-ampere characteristics of emission at 7 and 10 nsec pulse durations exhibit a significant deviation from linearity in the region of large current densities; maximum current density was $\sim 10^9$ a/cm^2. Critical current density increases with the shortened pulse duration, which is ascribed to inversion of the Nottingham effect and cooling of the emitter. The emission patterns were recorded with an electron-optical amplifier and a camera. Peculiarities of emission patterns in the pre-breakdown period, and the increase in the emitter tip radius after its partial destruction, led to the conclusion that destruction proceeds in several stages: destruction of the primary tip followed by erosion of the remaining tip by an increase in electron current during breakdown. Another characteristic of field emission-to-breakdown transition was the observed growth of submicroscopic tips after the first stage of breakdown. This fact suggests that part of the tip becomes liquid at the time of transition.

Fursey, G. N., A. A. Antonov, and V. M. Zhukov. Explosive emission accompanying the transition from field emission to vacuum breakdown. Vestnik Leningradskogo Universiteta, no. 10, Fizika i khimiya, no. 2, 1971, 75-78.

An explosive emission experiment is described which was designed to clarify the mechanism of field emission in the first stage of development of vacuum breakdown between needle electrodes. Tests were made using single-crystal tungsten needles with a tip radius of 2×10^{-5} - 5×10^{-5} cm in a sealed-off tube at a vacuum $< 10^{-9}$ torr. Stepwise voltage pulses with $\sim 30\%$ step decrements were applied to better segregate the various stages of the pre-breakdown process. The apparatus design and the experimental set-up were similar to those described by Fursey et al in the previous paper. Emission current densities in the 4×10^7 - 3×10^9 a/cm^2 range were recorded. Confirmation of the abrupt rise in field emission current at the onset of explosive breakdown was the main result of the experiment as seen in Fig. 1. In good agreement with earlier data [e.g., Fursey and Kartsev, ZhTF, v. 39, no. 10, 1969, 1917], the abrupt current rise rate in region II was on the order of 10^9 a/sec at $j \approx 10^9$ a/cm^2. The occurrence of a tip explosion during decay of the current pulse indicates an energy accumulation in the needle tip. Electron micrographs of the exploded emitter show that the magnitude of tip erosion depends primarily on explosion current density. The observed microprotrusions form on the molten emitter surface in 2 - 3 nsec during the transition to breakdown. This fact proves the presence of a strong electrical field (at least 10^8 v/cm) near the surface of the exploded tip. The explosive emission may thus proceed in the following sequence: explosion of the emitter tip $\rightarrow$ fusion and increase in radius $\rightarrow$ maintenance of electric field on the surface by polarized plasma ⟶ pulling out of microprotrusions from the liquid phase ⟶ explosion of microprotrusions and additional plasma formation near the surface.

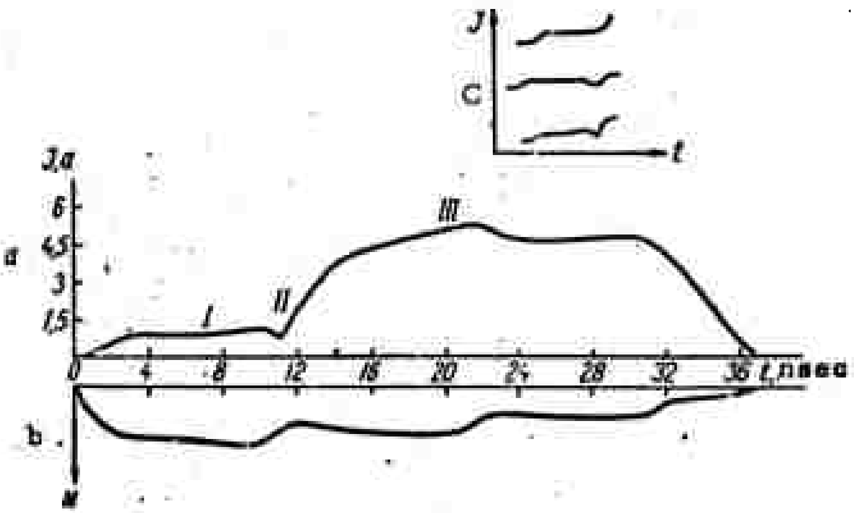

Fig. 1. Oscilloscope traces of emission current (a, c) and voltage pulse (b). Region I corresponds to a pure field - emission current, regions II and III - to the explosive emission current.

Bartashyus, I. Yu., L. I. Pranevichyus, and G. N. Fursey. Explosive electron emission from a liquid gallium cathode. ZhTF, no. 9, 1971, 1943-1948.

An experimental study is described of the surface state of a liquid cathode, and of the electron emission from that cathode in the process of vacuum breakdown. The study, presented in 1970 at the 14th All-Union Conference on Emission Electronics in Tashkent, was designed to establish conditions under which microprotrusions of the type earlier reported in solids may form on a liquid metal, and to explore the possibility of obtaining a stable electron emission in the initial phase of vacuum breakdown. Growth of microprotrusions was studied in a vacuum tube at 10^{-5} torr. Vacuum breakdown was induced in a two-electrode system by voltage pulses with an amplitude in the 20 - 75 kv range and durations from 10^{-8} to 10^{-5} sec. High-purity Ga heated to 50°C or Hg at -20°C were used as cathodes. Changes in geometry of the cathodic surface were recorded by high-speed shadow photography with a 10^{-6} sec resolution. Photographs taken during the breakdown initiation and during the transition to arc discharge confirmed the formation of microprotrusions on a liquid metal in both phases of the breakdown process. In an attempt to optimize the conditions for breakdown, microprotrusions were formed artificially, in agreement with theory, by preliminary excitation of the cathode by means of a quartz piezo-oscillator. As a result, the breakdown voltage decreased significantly and reproducibility of breakdown conditions was increased, as shown by the comparative measurements of the electron charge transferred in the breakdown. With artificial excitation of the cathode, stability of emission was better than 6% versus 10 - 15% without the excitation, and the amplitude of emission current from the liquid Ga cathode reached 2×10^3 a.

Mesyats, G. A., V. V. Kremnev, G. S. Korshunov, and Yu. B. Yankelevich. Current and potential across the spark gap in a breakdown in gas by pulses in the nanosecond range. ZhTF, no. 1, 1969, 75-81.

A theoretical analysis is given correlating pulse and circuit parameters for short breakdowns in gas. The voltage-time relationship u (t) across the spark gap connected to the active resistance R and a source at U_o potential is described by the equation

$$y\ddot{y} + \dot{y}(1-\dot{y}) + b(1-y-\dot{y})\psi(ay) = 0, \qquad (1)$$

where $y = U/U_o$, $\dot{y} = dy/d\tau$, $\ddot{y} = d^2y/d\tau^2$, $\tau = t/\Theta$, $\Theta = RC$, $a = E_o/p$, $b = p^2C_o\,\Theta/E_o$; E and $E_o = \frac{U_o}{\delta}$ are field intensities in the gap δ and at the time of breakdown in the air respectively, and C is the interelectrode capacitance. Equation (1) implies that current i in the gap increases owing to development of electron avalanches. The relative current $x = i/i_o$ is given by $x = 1 - y$. Theoretical $y(\tau)$ plots calculated from (1) for $E_o/p \approx 60$ and 85 v/cm x torr at an initial number of electrons $N_o = 1$ were in satisfactory agreement with the experimental $y(\tau)$ plots, obtained on the basis of earlier data for $N_o > 1$. A simple formula for the maximum gradient $\overset{*}{y}_m$ across the gap was derived from (1) without taking C into account. The theoretical $y(\tau)$ plots calculated from (1) and $\overset{*}{y}_m(E_o/p)$ plots calculated for $C = 0$ were found to be in good agreement with the respective experimental plots obtained from oscillograms of 0.1 - 0.4 mm gaps in which breakdown was initiated by random electrons. This confirmed the assumption of the role of electron avalanches in high-voltage gas breakdown.

Mesyats, G. A., V. P. Rotshteyn, G. N. Fursey, and G. K. Kartsev. Determining velocity of plasma propagation formed by electrical explosion of a microspike from high density field emission current. ZhTF, no. 7, 1970, 1551-1553.

This is an explosive emission experiment which was designed to get an exact picture of plasma propagation following the emission explosion. The test was specifically designed to correlate plasma kinetics with excitation pulse parameters and needle geometry, for the case of an exposed needle electrode in hard vacuum. The authors used an etched single-crystal tungsten needle with a tip radius of 3×10^{-5} cm as a cathode, in a discharge tube held at 5×10^{-9} torr, with a grounded grid interposed 5 mm from the cathode. Collector current through the grid was monitored after explosive emission was induced by applying a large negative pulse to the cathode, at a rise time of 1 nsec, a 4μ sec duration, and amplitudes of 19 - 30 kv. In this case current flows to the collector until the plasma reaches the grid, at which time an arc condition obtains between cathode and grid and collector current is cut off. Thus a synchronized oscilloscope trace of collector current duration gives a precise transit time for the plasma to reach the grid, yielding its mean velocity. Graphical results obtained in this way are shown in Figure 1, giving plasma velocity as a function of voltage rise time at the needle tip. An effect of interest here is that, over an order of magnitude change in pulse rise rate, plasma velocity is effectively unchanged and remains in the 2-2.5 x 10^6 cm sec range, which is consistent with the flare velocities reported by several other authors. This technique also allows adjustment of the explosion time with respect to the applied voltage pulse; thus in Figure 1 the left-most data point corresponds to an explosion occurring at the peak of the voltage pulse, whereas all other data points are for explosions occurring during pulse rise time. In the latter cases the current at the tip reached 50 - 60 a in the order of a nanosecond. Maximum energy of tungsten ions in the moving plasma was put at about one Kev.

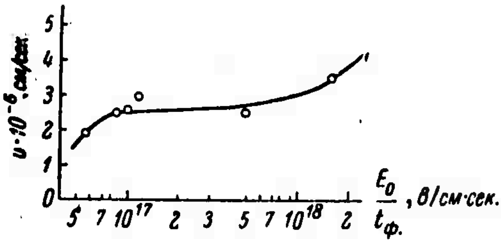

Fig. 1. Plasma velocity vs. voltage rise time.

Mesyats, G. A., S. P. Bugayev, and D. I. Proskurovskiy. Explosive emission of electrons from metallic needles. UFN, v. 104, no. 4, 1971, 673-675.

Recently published Soviet R and D data on high-intensity (up to 10^5A) pulsed electron beam accelerators based on explosive emission are briefly summarized in a paper presented on February 17 - 18, 1970 at the Joint Scientific Session of the General Physics and Astronomy and Nuclear Physics Divisions of the Academy of Sciences. The data presented are the results of studies by the Fursey group, including the present authors and other groups of Soviet researchers. A plot is shown illustrating the dependence of the mass ejected from exploding Mo and Cu needles on the number of applied pulses. A classification is given of all electron beam accelerators using explosive emission. Development of two types of such accelerators is noted: one with a controlled cathode emitting 10 ka beams with up to 500 kev energy, the other with a multiple tip cathode emitting 50 ka beams with up to 1,000 kev energy.

Dmitriyev, M. T. The stability mechanism of ball lightning. ZhTF, no. 2, 1969, 387-394.

A natural occurrence of ball lightning, about 13 cm diameter was observed for about 1.3 minutes over a water surface following a normal lightning stroke. A mass-spectrometric analysis of air samples taken in the vicinity of the lightning revealed that its composition was practically identical to that of ordinary air, except for ozone and nitrogen oxides. The maximum O_3 concentration, determined from tritium concentration, and the maximum NO_2 concentration were, respectively, 52 and 110 times higher than the corresponding usual concentrations in air. The potential difference between the lightning and the ground was estimated to be 300-400 kv by analogy with a slow electric discharge. The maximum discharge energy was calculated from the quantity of NO_2 formed to be 240 j/m^3. Temperature (~ 14,000°K), gas density (25.3 mg/l), initial ionization degree (22%) and a total charge of positive and negative ions (20.7 c) of the ball lightning were determined from experimental data, visual observations and their comparison with plasma phenomena. The excess charge (~ 2.7 x 10^{-6}) was evaluated from equilibrium conditions between the lightning and the ground. The total accumulated energy was estimated to be 530 j, the potential explosive power 0.7 million HP, and the most probable explosive power to be equivalent to 100 g of nitroglycerin. Radiation-oxidation of N_2 by chain reaction is suggeste as the most probable explosion mechanism of ball lightning. Presumably, the observed spontaneous disappearance of the lightning was the result of ion recombination by a pulsating mechanism. Stabilization of the lightning results from a deceleration of recombination with increase in temperature. The most important factor of stabilization is the formation of a cold shell of negative ions, which prevents ion diffusion and heat transfer from the center of the ball to the ambient air. The energy capacity of the ball lightning is concluded to present a potential danger to aircraft and living organisms.

Volosov, V. I., V. N. Lazarev, and V. Ye. Teryayev. Certain characteristics of field emission from cylindrical cathodes. ZhTF, no. 4, 1970, 855-858.

An experimental study was made of field emission in a 10^{-5}- 10^{-8} torr vacuum from tungsten and molybdenum wire cathodes at 2 - 6 kv anode potentials, U_a. The emission current i was several orders of magnitude higher than indicated by the Fowler-Nordheim theory for an ideal metallic cathode. A specific hysteresis effect was observed on current-voltage characteristics at a $3 \cdot 10^6$ v/cm field. At a constant U_a = 4-5.2 kv, i after 20 minutes became stabilized at a constant level of 0.25--0.8 ma within 5% and remained at that level for 40 hr. of continuous emission. The cited effects are explained by an increase in field intensity in certain areas of the wire because of roughness and micro-protrusions on the surface. These microdeformations on the cathodic surface were observed from electron micrographs of the wire surface after 8 hours of anomalous emission. Presumably the emitting protrusions preserve a definite shape over long time, thus determining stability of emission on account of an equilibrium between electrostatic and surface tension forces. A filament-like cathode of this type thus can be effectively used as a stable electron emitter.

Belkin, N. V. and E. A. Avilov. Certain temporal characteristics of breakdown in vacuum by application of a pulsed voltage with a nanosecond rise time. ZhTF, no. 8, 1970, 1723-1724.

Breakdown in vacuum was studied experimentally in X-ray tubes with a flat anode and a hemispherical or disc cathode. High-voltage pulses of 5 nsec duration and 200 kv amplitude were applied across 1-2 mm electrode gaps. Breakdown voltage U_b was expressed as the pulse coefficient $K = U_b/U_1$, where U_1 is the breakdown voltage using microsecond pulses. The experimental plots of voltage decay time t_d versus K (Fig. 1) show that t_d can decrease from 55 to 5 nsec when K increases from 1.5 to 3.2. Also,

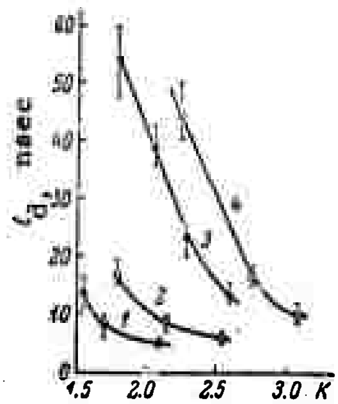

Fig. 1. Voltage decay time versus pulse coefficient K. Hemispherical cathode: 1 - d = 1.3, 3 - 2mm; disc cathode: 2 - d = 1, 4 - 2 mm.

the length of X-ray pulses generated by breakdown decreases from 45 to 8 - 10 nsec with an increase in K. A field emission mechanism of breakdown (arc) excitation is believed to be the most probable under the cited experimental conditions.

Babaritskiy, A. I., B. A. Demidov, and S. D. Fanchenko. The effect of voltage polarity on surface breakdown in a slot-type vacuum discharger. ZhTF, no. 7, 1970, 1507-1509.

The effects of the wall region and polarity of initial voltage U on performance of a slot discharger were studied experimentally, using the apparatus described earlier by the authors [PTE, no. 3, 1969, 167]. Breakdown was triggered by ignition pulses from a TGI-1-400/16 thyratron using plasma guns. The gap between the brass electrodes was 40 mm. The image of the luminescent area at the end of discharger was projected through a 2 mm optical slit onto the photocathode of an electron optical device and recorded by a high-speed camera. Recordings were made of the pre-breakdown discharge phase at U = 0 and of the breakdown itself at $U \neq 0$ with anodic or cathodic ignition. Breakdown is initiated at the discharger wall opposite to the current-carrying bus. The main breakdown is delayed in relation to the onset of luminescence by $\sim 2.5 \times 10^{-7}$ sec and $\sim 10^{-7}$ sec in the case of anodic and cathodic ignition, respectively. Simultaneous oscilloscope traces of current derivative show a strong deformation and a high-frequency modulation of the derivative in the case of cathodic ignition. Thus the characteristics of anodic ignition are significantly better with respect to the initial current amplitude and deformation. The wall effect makes it advisable to use a slit as narrow as feasible to decrease the inductance of the discharger.

Gel'tsel', M. Yu. and A. A. Podminogin. High-power controlled gas discharge tubes with a cold solid cathode for switching of large pulsed currents. ZhTF, no. 8, 1970, 1707-1717.

The problem of energy supply to the magnets of accelerators has prompted this experimental study of parameters of cold cathode grid-controlled gas discharge tubes, which are capable of switching large currents. Tubes of this type have been developed at the Novosibirsk Institute of Nuclear Physics. Tubes with plane electrodes, with or without a vacuum chamber, were tested for dielectric strength, nonstationary processes, discharge propagation velocity, and anode stability. General design conclusions were as follows: The system of a low-pressure ($< 10^{-1}$ torr) arc discharge between symmetrical electrodes with triggering elements in each electrode is the only type of gas discharge device with a single discharge gap which permits bipolar operation. The interelectrode gap should be minimal (5 - 6 mm) to obtain a maximum dielectric strength and minimize nonstationary processes in switching. In agreement with theory, the experimental average velocity of discharge propagation at 1 cm distance from the center was 5×10^4 cm/sec for a 500 μsec pulse and a 30 ka current amplitude. The discharge velocity decreases sharply near the lead-ins to the tube, because the retarding effect of the localized magnetic pressure is much greater than that of gas kinetic pressure which predominates near the center, thus forcing the discharge to expand continuously. The discharge gap should be made variable from 10 mm in the firing area to $\sim$5 - 6 mm, since discharge velocity decreases by a factor of 2.5 when the interelectrode gap is decreased by a factor of 6. Restoration of dielectric strength is faster in a system with vacuum chamber; tube durability is a function of time, current, and rise velocity of inverse voltage. Improvement of the parameters of grid-controlled tubes can be achieved by increasing de-ionization surface, using H_2 or Ar instead of air and a pulsed longitudinal magnetic field for firing. The most advanced design of a tube with plane electrodes and short arc is shown in Fig. 1 which is capable of reliably switching 40 - 50 ka currents pulses on the order of milliseconds at a 4 - 5 kv inverse voltage, or 15 ka currents at 10 kv and $\sim 5 \times 10^{-3}$ torr initial pressure.

Krivoshchekov, G. V. and Ye. G. Shirokov. Pre-arcing phenomena on a tungsten knife-edge. Knife-edge damage resulting from arcing in vacuum. ZhTF, no. 8, 1970, 1669-1674.

Forming of a cathodic emission surface and development of a vacuum arc were studied experimentally in a field-emission microscope with a knife-edge shaped tungsten cathode, electrochemically etched and heat-treated. The emission patterns of the knife-edge surface in a continuous emission mode revealed levelling of the emission by microprotrusion surfaces due to the space charge effect. The emergence of impurities with a low work function (3.5 - 4 ev) to the grain boundaries in tungsten polycrystal was observed during the period of surface forming. These impurities generated arcs at the microprotrusions. In a continuous emission mode a generally heavy damage to the knife-edge surface was observed concurrently with the transition from field-emission to vacuum arc. In a pulsed mode, microprotrusions of different radii and heights were detected on the tip and lateral surface of knife-edge as the result of vacuum arcing. The growth of microprotrusions by the effect of a strong field on molten metal was also found to enhance discharge. The critical current density on the knife-edge of a disk is pointed out and discussed. Arc ⟶ plasma dispersion ⟶ neutralization of a space charge on the next surface area ⟶ subsequent cycle, are suggested as the sequence of events in propagation of the arc over the entire knife-edge surface. The data obtained may explain development of a vacuum arc in the case of a macroscopic cathode surface.

Borovich, B. L. and V. B. Rozanov. Self-similar description of a high-intensity gas discharge with allowance for the Kirchhoff circuit equation. KSpF, no. 12, 1970, 3-7.

Self-similar solutions of the gas dynamic and Kirchhoff equations are used to describe a discharge to which energy is supplied by a battery of capacitors. Discharge energy E is approximated by an exponential function of time E(t), then earlier data obtained by Basov et al are applied [ZhTF, no. 4, 1970, 805]. The energy supplied to the discharge is expressed by

$$E(t) = \int_0^t J^2 r_{sw} dt. \qquad (1)$$

where J is the current and r_{ohm} is the ohmic resistance of the plasma. Calculations indicated that the fraction η of the stored energy supplied to the discharge during time $\pi\sqrt{LC}$ is a universal function η (q) which determines the parameters of a discharge path. The parameter q expresses the relationship between r_{ohm} and wave resistance. The energy η plotted against q is shown in Fig. 1.

Fig. 1. Universal function $\eta = \eta$ (q), characteristic of match between discharge and the capacitor battery.

Different formulas for E and temperature T in the center of the discharge were derived for three successive phases of discharge: 1 - temperature rise ($t < \sqrt{LC}$), 2 - transfer of most of the energy to the discharge ($\sqrt{LC} \leq t \leq \pi\sqrt{LC}$), and 3 - conversion of the plasma thermal energy into gas dynamic propagation energy ($t > \pi\sqrt{LC}$). The energy E in phases 1, 2, and 3 is expressed as a function of an approximation parameter E_o and t, of the battery parameters L and C, η , and t, and of an another approximation parameter α , respectively. The calculated T(t) plots differed from the experimental ones found by Basov et al [ZhTF, no. 3, 1970, 516], particularly in the value of maximum temperature T_m (Fig. 2). The discrepancy between theoretical and experimental T_m is explained as the result of a too high Rosseland mean value used in the calculations. An order of magnitude lower value of the coefficient χ_o of thermal conductivity should be used to calculate T_m in order to obtain agreement with experimental results.

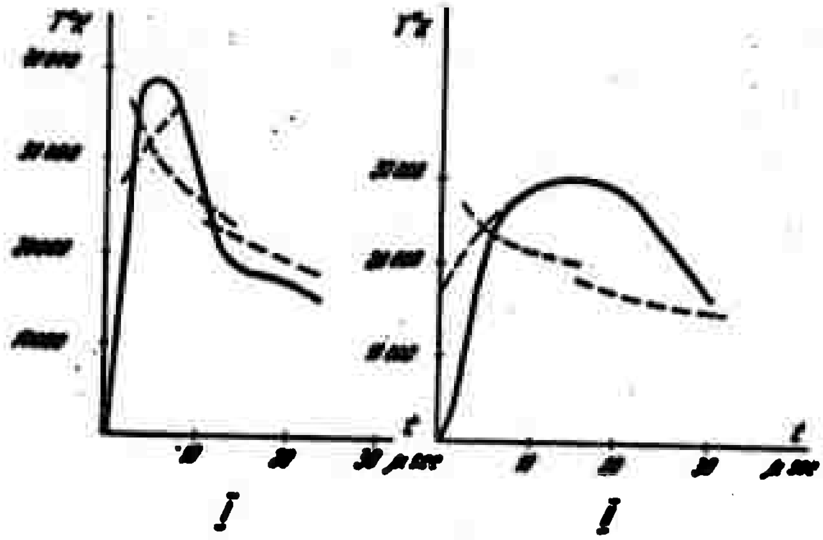

Fig. 2. The experimental and theoretical time functions of discharge temperature. ———— experiment, ---------calculation. I - 1 = 25 cm, $2 \pi \sqrt{LC} = 20.10^{-6}$ sec, $CU_o^2/2$ = 37,5 kj. II - 1 = 50 cm, $2 \pi \sqrt{LC} = 30.10^{-6}$ sec, $CU_o^2/2$ = 36,5 kj.

Andrianov, A. M., V. F. Demichev, G. A. Yeliseyev, P. A. Levit, A. Yu. Sokolov, and A. K. Terent'yev. Generator of powerful current pulses. PTE, no. 1, 1971, 112-114.

A battery of capacitors is described which generates current pulses with up to 3.5 x 10^6 a amplitude and features a relatively low (58 kj) storage capacity. The battery circuit (Fig. 1) is composed of 16 sections connected

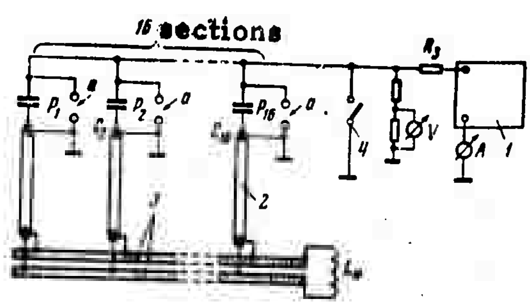

Fig. 1. Pulse generator circuit.
1 - rectifier, 2 - coaxial cables, 3 - collector busses, 4 - ground.

parallel. Each section comprises a KMK-30-8 low-inductance capacitor and a low-inductance vacuum spark gap shown in section in Fig. 2. The spark

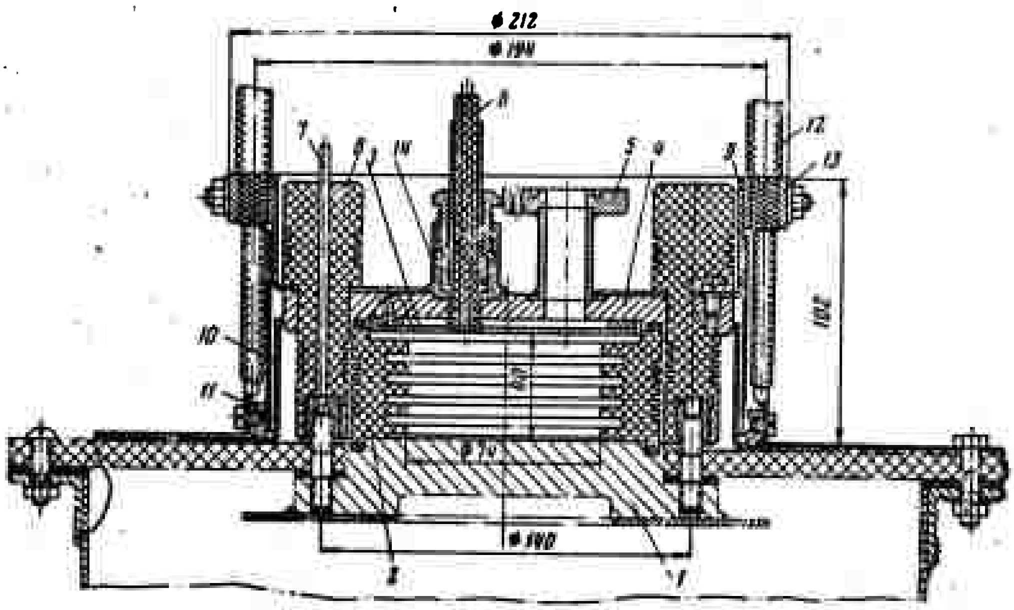

Fig. 2. Vacuum spark gap. 1, 3 - electrodes, 2 - insulator, 4 - flange, 5 - vacuum connecting pipe, 6 - control electrode, 8 - insulated bolts, 9, 11 - busses, 12 - cables, 13 - clamp strips, 14 - bushing.

gap is switched on by the spark generated between the control electrode and the upper electrode by applying a high-voltage pulse. A cable oscillator is used to synchronize switching of all spark gaps. In principle, an arbitrary number of parallel sections can be incorporated to obtain pulses of different amplitude and frequency. With 16 sections, self-inductance of the battery is 5 nh, the measured amplitude of short circuit current is 3.5 ma, and the nominal pulse power is 1.4×10^{11}w. Tests conducted at 20 kv charging voltage, 200 ka current amplitude, and 200 kHz discharge frequency showed that the spark gap is capable of producing 20,000 discharges, if a vacuum of 3×10^{-3} torr or better is maintained. The described battery can be used in plasma physics experiments, for generating strong pulsed magnetic fields, and other applications.

Korshunov, G. S., and G. A. Kiselev. Possibility of using water as working medium in a nanosecond peaking spark gap. Elektronnaya obrabotka materialov, no. 1, 1971, 40-45.

Electrical characteristics of a spark gap in water were studied experimentally, to explore the possibility of shortening rise time of a high-voltage pulse to the order of a few nanoseconds. An Arkad'yev-Marx (GIN) generator was used to produce high-voltage (U_a = 100-300 kv) pulses with a rise time t_f = 0.15-1.5 μ sec. The generator was connected to the spark gap of width δ by a 25 m long coaxial cable. All metallic parts, except the steel electrodes of variable gap δ (Fig. 1) were insulated from the water.

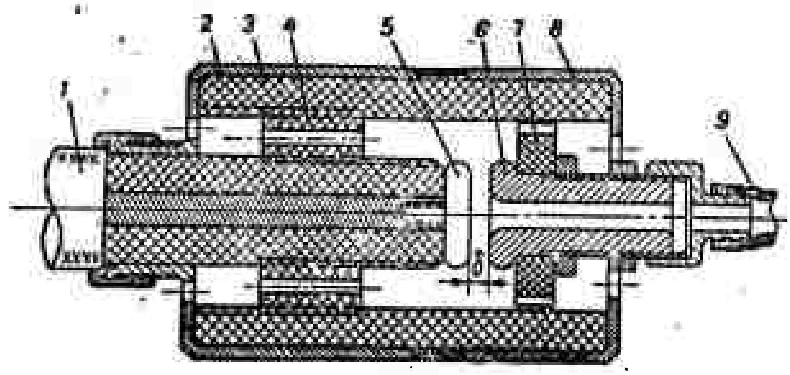

Fig. 1. Spark gap: 1 - KPV-1-300 type cable; 2,8 - frame; 3,7 - bushings; 4 - centering insulator; 5,6 - electrodes; 9 - hose to the pump.

Water was pumped through the discharger at the rate of 60ℓ/min. The oscilloscope traces of pulses produced with δ = 2-12 mm show a significant deformation which increases with the increase in rise time of the applied pulse from 0.2 to 1.3 μ sec. Also, a strong pulse deformation occurred when water resistivity ρ was decreased from 10^4 to 10^3ohm.cm. In contrast, pulse deformation diminished at $\rho > 10^4$ ohm.cm., and also when the electrode active area was decreased from 10 to 3 cm^2. The minimum recorded switching time t_s of peaking pulse was 4-5 nsec. Theoretical analysis of variations in voltage U_δ across the gap before its breakdown indicated (in good agreement with the experiment) that U_δ max for the case of a nanosecond rise of the applied pulse is determined by the ratio K of wave impedance z_w to R_δ. The discrepancy between the experiment and calculations increases with an increase in t_f from 0.2 to 1.3 μ sec because of increase in R_δ. It is concluded that pulses with hundreds of kv in amplitude and rise times of 3 nsec to 1.3 μ sec can be produced in a peaking gap in technical grade water. To optimize pulse parameters, the rise time of the applied pulse and K should not exceed 0.2-0.3 μ sec and 0.1, respectively.

Fal'kovskiy, N. I. Spectroscopic study of a high-intensity pulsed discharge in air. ZhPS, v. 14, no. 3, 1971, 378-382.

Temporal and radial characteristics of the emission from a high-intensity (10-100 ka) discharge circuit (up to 40 kv) at atmospheric pressure were determined in a special apparatus, using a mirror device for a time sweep of the spectrum. The image of the emission is projected across the spectroscope slit so that the emission of the total cross-section of the channel at a given time is recorded photographically. The electrical trigger pulses were quasi-aperiodical, with a 3.5-7.5 μ sec rise time to the maximum amplitude. The device emitted only the spectral lines of single- and double-ionized nitrogen and oxygen atoms. The total intensity of each line measured over 6.5 μsec decreased smoothly from the center to the periphery of the path and exhibited a maximum at 4 μsec from the onset of a 100 ka pulse. The discharge path temperature T, measured by the method of relative intensity of the N II line, continuously decreased in time from ~65,000°K at t = 0.1 μsec to 30,000°K at t = 3/4 of the total pulse length. T corresponding to the maximum of the calculated plot of N III ions relative concentration versus T was found to be ~45,000°K, which agrees with the T value at the same t_{max} = 4 μsec determined from the experimental plots of intensity of the N II line versus time.

Danilychev, V. A., and D. D. Khodkevich. High-intensity pulsed electron gun based on the ELIT-1 accelerator. PTE, no. 3, 1971, 157-158.

An electron gun is proposed which is designed to produce pulsed electron beams up to 1 ka. The simplified diagram (Fig. 1) shows a pulse transformer with spark gap and an electron gun which acts like a diode. High pulsed voltage is supplied by an ELIT-1 system. The cold cathode (d = 8 mm) is made of a 50 μ thick tungsten foil, and is designed to produce an electron current of maximum intensity and highest amplitude stability. The anode is a tungsten grid. The optimum electrode gap is varied from 10 to 15 mm, depending on voltage (0.5-1 Mv). The variable spark gap is formed by brass electrodes, d = 100 mm. The cylindrical insulator (d = 140 mm) supporting both the spark gap and the cathode is made of compressed cardboard impregnated with epoxy resin. A magnetic lens increases the electron current density by a factor of 2-3. Electron beam spread was estimated to be ~30°. The pulse shape is nearly rectangular, with 2 peaks and a 10 nsec duration. The working vacuum was 10^{-4} torr, with a lower limit at 7 x 10^{-3} torr. The described gun is simpler in design and more durable than the ELIT-1 injector, and has sustained

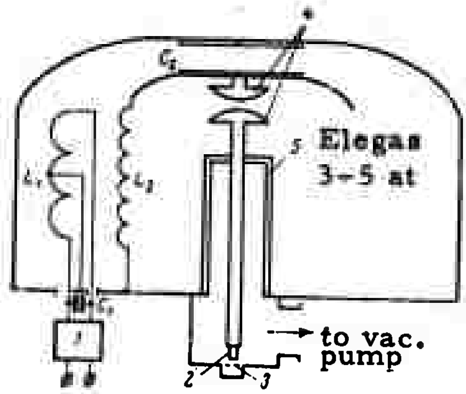

Fig. 1. Diagram of the pulsed electron gun.
1 - device for charging capacitor of the primary circuit, 2 - tubular cathode, 3 - anode, 4 - spark gaps, 5 - insulator, L_1 - inductance in the primary, L_2 - inductance in the secondary, C_1 - capacitance of the primary winding, C_2 - capacitance of the secondary winding.

several million discharges without breakdown. The 1 ka currents were obtained with a maximum 300 a/cm^2 at 1 Mev power, and a 5 Hz pulse frequency. Attainment of a 10 ka current with 1 ka/cm^2 density is foreseen for this type of design.

Komel'kov, V. S. and V. I. Modzolevskiy. Formation of a plasma jet at atmospheric pressure. ZhTF, no. 5, 1971, 963-971.

Experiments of the authors are described with formation of a high-density (10^{19} - 10^{20} cm^{-3}) plasma jet by electric discharge in the air at atmospheric pressure, without resorting to focusing or compression by an external magnetic field. Electric breakdown in the experimental apparatus (Fig. 1) is initiated by a capacitive discharge at an initial charge U_o = 20 or 40 kv. Capacitors 1 were connected through a trigatron discharger 2 to a system of electrodes 3 and 4 forming a nozzle. The breakdown recurred between the tip of 4 and the upper end of the conical port of 3 and was recorded, together with the plasma jet and shock wave, by a SFR-2M high-speed photo camera through a slit in the nozzle. The luminous front moving out of the nozzle after breakdown accelerated continuously to a maximum velocity of 2.3 x 10^6 cm/sec within 2 μ sec from the start of discharge. A second luminous front moving towards

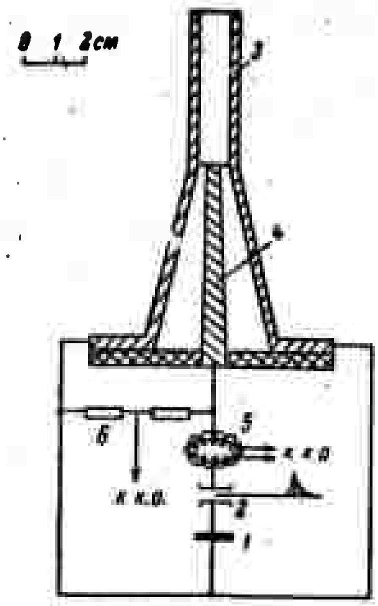

Fig. 1. The electrode system and experimental electrical circuit.

the nozzle base reached a maximum velocity at maximum current, then decreased to zero and reversed direction. At zero current, there is a second breakdown. Thus a multiple acceleration of gas occurs in each half-period, which can be utilized for capture and acceleration of gas in high-frequency and pulsed high-intensity plasma accelerators. The cylindrical section of the nozzle is essential in obtaining a high plasma velocity, as verified in an experiment with the cylindrical part omitted. The experimental graphs of motion of the current gravity center and shock wave front show formation of a continuous plasma piston within the cylindrical section, with a 1.2×10^6 a/cm^2 maximum current. At maximum plasma velocity, pressure in the shock wave front and magnetic field formed 3 mm distant from the nozzle axis reached 6×10^3 atm and 400 koe, respectively. Trajectory of motion and velocity of the luminous front in the first and second half-periods of current were calculated by means of snow-plow and constant mass models, respectively. The calculated plots were in agreement with experimental data, except in the initial acceleration phase.

Bel'kov, Ye. P. Gas cooling and restoration of dielectric strength after a spark discharge. ZhTF, no. 8, 1971, 1678-1681.

Plots of dielectric strength of a 2 - 10 mm spark gap versus time and shadow photographs of the gas volume in the discharge channel after a spark discharge were obtained in experiments designed to determine the cause of gas propagation and its effect on restoration of dielectric strength of the spark gap. A spark was initiated either by short, powerful (I_1 and I_2) or long and small amplitude (I_3) current pulses. The plots of dielectric strength (Fig. 1a) indicate a low initial recovery (300-900 v) followed by a nearly exponential rise in strength to ~90% of the initial strength after passage of long I_3 pulses, and an almost completely exponential recovery in 5-10 msec after short I_1 and I_2 pulses. The recovery of dielectric strength is associated with gas cooling, as shown by the shadow photographs taken 0.25 to 25 msec after the discharge current was cut off. The hot gas expanded in volume instead of shrinking as anticipated, on the assumption that heat is transferred to the electrodes. It was concluded that the energy of the hot gas is dissipated mainly in the adjacent layers of cold gas. This finding was confirmed by a

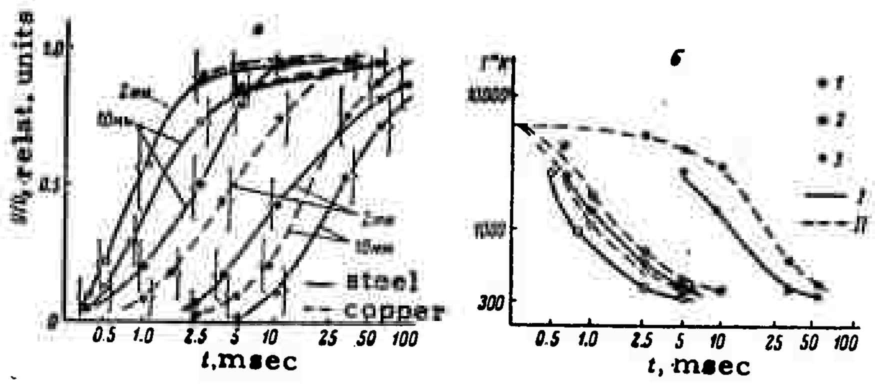

Fig. 1. Plots of regenerated dielectric strength of S = 2mm and S = 10 mm spark gaps (a) and cooling curves of gas in the S = 10 mm spark gap between copper electrodes (b) after passage of current pulses. 1 - I_1 (J_m = 20 ka, t_s = 10 nsec), 2 - I_2 (I_m = 4 ka, t_s = 3 nsec), 3 - I_3 (I_m = 0.65 ka, t_s = 1500 nsec). I - gas temperature determined from the plots of fig. 1a in agreement with Paschen rule, II - gas temperature calculated from the relative increase in volume occupied by hot gas.

fairly good agreement between gas temperature estimated from T-V diagrams based on the theory of gas cooling by energy dissipation in cold gas, and temperature evaluated by applying the Paschen rule to the experimental strength recovery data (Fig. 1b). The shadow photographs indicate that gas propagation towards the center of the cooling volume is laminar in the case of long pulses, but becomes turbulent 150-200 μ sec after current cutoff in the case of short high-current pulses.

Martynov, Ye. P. Initiation of electrical breakdown in vacuum by impact of metallic particles on the electrodes. ZhTF, no. 8, 1971, 1731-1737.

The field intensity E_b of vacuum breakdown initiated by the impact of conductive particles with a diameter $\geq 10\mu$ on the cathode was measured, in the experiments designed to explain the mechanism of initiation of the induced breakdown. The breakdown was produced between plane electrodes in a $1\text{-}2 \times 10^{-5}$ torr vacuum by forcing a certain number of metallic particles through a 0.5 mm orifice in a ground plate into the discharge gap as shown in Fig. 1. The number of particles entering the gap was controlled by the amplitude and length of negative pulses supplied to electrode 3 which contained metal powder. The probability P_b of breakdown with Ni or Al particles of 5 - 150 μ diameter generally increased with increasing E, but a few decreases were also observed on the experimental $P_b(E)$ plots. These decreases were related to the gaps on the plot of particle size distribution n(r) versus 2r.

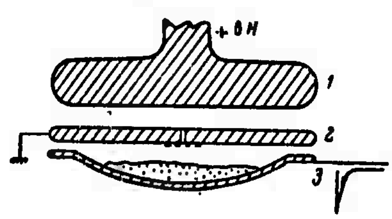

Fig. 1. Diagram of the electrodes system.

This relationship and additional experiments with a 13 x 13 μ grid over the injector orifice led to establishment of the E_b dependence on 2 r. Assuming that a microdischarge of slow particles onto the cathode initiates breakdown, the condition for the onset of breakdown by particles of widely variable size is formulated by the author as

$$E_b + K r^{0.9} E_b^{1.3} = D. \qquad (1)$$

where K and D are constants. The condition of (1) implies a localized increase of cathodic field on account of the volume charge of positive ions, and agrees with the available experimental data within the experimental error. In the case of high velocity ($v \geq 1$ km/sec) very fine particle impact on the electrodes, breakdown at a given E and discharge gap h is described by $rv^3 = C$ or $r^2v^3 = C$ on the cathode or anode, respectively. In the case of particles accelerated by the gap field, the breakdown is described approximately by $U_b \sim h^{\alpha}$, where U_b is the breakdown potential across the gap and α is a constant defined by $0.5 < \alpha < 1$.

Tarasov, V. D., V. A. Balakin, and O. P. Pecherskiy. Dielectric strength of water subjected to 0.5-5 μ sec pulses at a potential in the 0.5-1.7 Mv range. ZhTF, no. 8, 1971, 1749 - 1750.

A brief description is given of an experiment in which the breakdown potential U across a variable electrode gap d was measured in degassed and purified distilled water. The purpose was to test dielectric strength for the possible use of water in high-intensity generators of relativistic electrons. A pulse capacitor circuit was used as a high-voltage source U_o, and 100 mm diameter stainless steel electrodes formed a variable gap of 1-6 cm. The applied sinusoidal voltage wave was varied from 0.5 to 1.7 Mv and pulse width from 0.5 to 5μsec. For a given width, U increased linearly with increase in d, thus the electric field intensity at breakdown is practically constant. The breakdown strength of the gap was 300 kv/cm and 400 kv/cm for 5 μ sec and 0.5 μ sec pulses, respectively. It follows from these results that dielectric strength of water for sufficiently short pulses is not inferior to that of transformer oil.

Baksht, R. B. and V. I. Manylov. Spectroscopic study of cathodic flare generated in the initial phase of a vacuum discharge. IVUZ Fizika, no. 9, 1971, 148-150.

A spectral analysis was made of the plasma of a cathodic flare, generated from electrical explosion of a needle or plane aluminum cathode. The time of interest is the subnanosecond interval just preceding electrical breakdown. The electrode gap was set at 2 and 0.5 mm for the amplitude of applied pulse of 35 and 40 kv, respectively, for the cases of both needle and plane cathodes. Under these conditions, electric field intensity at the microtips was equal for both electrode configurations. The pulse length was 20 nsec with 2 nsec rise time. The plasma spectrum was recorded by photoelectric scanning of the 400-600 mμ region at 0.1 mμ resolution. A 10^{-6} torr vacuum was maintained in the test chamber. The emission and discharge current recording systems are described and the experimental data are tabulated together with the calculated transition probabilities for Al III ions. Analysis of spectral data indicates qualitatively identical spectra obtained with both types of cathode. Plasma temperatures on the order of 40,000-50,000°K were estimated from the presence of Al III ions and the absence of neutral atoms.

Proskurovskiy, D. I., and Ya. Ya. Yurike. Rise of spark current in breakdown of short vacuum gaps at a constant voltage. IVUZ Fizika, no. 9, 1971, 93-97.

A comparative experimental study of the rise of spark current in breakdown at a steady-state vs. a pulsed voltage was undertaken to clarify the controversial mechanism of breakdown at a constant voltage. In the constant voltage experiment, the external discharge circuit included coaxial cables with $\rho = 75$ ohm to obtain a time resolution on the order of a nanosecond. The high-voltage d.c. was supplied to the cathode at a ~ 0.5 kv/sec rate prior to the first breakdown; in the pulsed case the applied pulses were 200 nsec long at a 2 nsec rise time. The discharge chamber was evacuated to 5×10^{-6} torr. Hemispheric copper or molybdenum electrodes with a 10 mm radius were used. In both constant and pulsed voltage breakdowns, the current rise time t_c measured from oscilloscope traces increased linearly with increase in gap length d from 0.1 to 1 mm, and the d/t_c ratio was approximately 2.5×10^6 cm/sec. Also, in both cases an identical x-ray emission during current rise was detected, and material transfer from the anode to the cathode was observed. A transition to an avalanche-like current rise at a 10^8 a/sec rate occurred in 1-3 nsec time. The experimental data were interpreted as a proof of the correlation between the initial current rise at a constant voltage and the appearance on the cathode of efficient electron sources, apparently in the form of cathodic flares, as was also the case in pulsed breakdown. The explosive formation of flares can be related to the breakdown initiation. In both cases studied, the initiation, independent of the rise rate of applied voltage consists of an explosion-like destruction of the emitting microtips. Only the interference of some other processes, such as migration, gas desorption, etc, with the breakdown initiation by a slowly rising voltage was found to effect a difference with the initiation by fast increased (pulsed) voltage. The onset of cathodic flares signals the beginning of irreversible damage of vacuum insulation; the cathodic flares emit a powerful electron beam which causes an x-ray burst and erosion of the anode.

Syutkin, N. N., and N. N. Vyatkin. Autoionization microscopy of tungsten following a vacuum breakdown. ZhTF, no. 9, 1971, 1979-1982.

Models of the microprotrusions which form on a needle electrode surface during vacuum breakdown were obtained and studied in an autoionization microscope. The surface of a tungsten needle with a curvature radius ~500-1,000 Å was observed in the test. The initial autoionization image of the needle tip surface, which was recorded at 28 kv, shows a significant inhomogeneous plastic deformation of the crystal as the result of a cutoff of the needle tip. A subsequent image at 12 kv shows a typical emitting prominence with a perfect crystal structure. The prominence resulted from a vacuum breakdown initiated by the previously generated inhomogeneity. The subsequent micrographs obtained by stepwise vaporization in electric fields at 13-50 kv show the structure of successive subsurface layers of the emitting microtip. The cross-section of a typical structure is presented in Fig. 1, in which the dashed lines correspond to the cited micrographs.

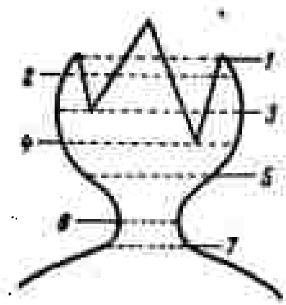

Fig. 1. Schematic structure of cross-section of an emitting prominence.

In summary, it is noted that the needle undergoes a strong plastic deformation after cutoff of the tip by electric field; the plastic deformation disappears in the emitting prominence formed by vacuum breakdown. The structure of the prominence is perfectly crystalline and the observed light and dark rings around such prominences are effects of the microtip shape.

Poshekhonov, P. V. and V. I. Solov'yev. Initiation of vacuum breakdown under a pulsed voltage by a macroparticle breaking away from the electrode surface. RiE, no. 9, 1971, 1705-1711.

Probability and mechanism of breakdown initiation by a particle breaking away from an electrode surface by application of a varying potential were explored in a sectional model of superposed electrodes. The lower, concave-upward electrode contained a metallic particle, 0.05-1 mm in size. A vacuum of better than 5-7 x 10^{-5} torr was maintained. Single pulses were 5·3,000 μsec long, at up to 60 kv in amplitude. Length of the pulse front was controlled within 2 to 3,000 μsec limits. The pulse parameters, breakdown voltage and breakdown delay in relation to the onset of a pulse were recorded by oscillograph. The experimental data show that the breakdown can be initiated during pulse rise by a particle breaking away from the negative electrode, in addition to a delayed breakdown initiated by the particle crossing the gap. The probability of breakdown at the pulse front increases with increase in slope of the front, i.e. with the decrease in its length. The breakdown potential U_b simultaneously decreases. U_b is independent of the particle size above 100 μ. The conclusion was drawn that the probability of a breakdown for a given particle size, depending on the magnitude of current, increases with the increase in slope of the pulse front. The field emission current generated by the external electric field between the particle and the surface charges the particle. In the case of particles larger than 100 μ, breakdown occurs before the charging current is cut off.

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VI. SOURCE ABBREVIATIONS

DAN ArmSSR	-	Akademiya nauk Armyanskoy SSR. Doklady
DAN B	-	Akademiya nauk Belorusskoy SSR. Doklady
DAN SSSR	-	Akademiya nauk SSSR. Doklady
DAN Uzb	-	Akademiya nauk Uzbekskoy SSSR. Doklady
EOM	-	Elektronnaya obrabotka materialov
FGiV	-	Fizika goreniya i vzryva
F-KhMM	-	Fiziko-khimicheskaya mekhanika materialov
FiKhOM	-	Fizika i khimiya obrabotki materialov
FMiM	-	Fizika metallov i metallovedeniye
FTT	-	Fizika tverdogo tela
IAN Az	-	Akademiya nauk Azerbaydzhanskoy SSR. Izvestiya
IAN B	-	Akademiya nauk Belorusskoy SSR. Izvestiya
IAN Energetika i transport	-	Akademiya nauk SSSR. Izvestiya. Energetika i transport
IAN LatSSR	-	Akademiya nauk Latviskoy SSR. Izvestiya
IAN Met	-	Akademiya nauk SSSR. Izvestiya. Metrologiya
I-FZh	-	Inzhenerno-fizicheskiy zhurnal
IVUZ Fiz	-	Izvestiya vysshikh uchebnykh zavedeniy. Fizika

IVUZ Gornyy zhurnal	-	Izvestiya vysshikh uchebnykh zavedeniy. Gornyy zhurnal
IVUZ Radiofiz	-	Izvestiya vysshikh uchebnykh zavedeniy. Radiofizika
KSpF	-	Kratkiye soobshcheniya po fizike
LZhSt	-	Letopis' zhurnal'nykh statey
MiTOM	-	Metallovedeniye i termicheskaya obrabotka metallov
MTT	-	Mekhanika tverdogo tela
MZhiG	-	Akademiya nauk SSSR. Izvestiya. Mekhanika zhidkosti i gaza
NM	-	Akademiya nauk SSSR. Izvestiya. Neorganicheskiye materialy
OiS	-	Optika i spektroskopiya
OMP	-	Optiko-mekhanicheskaya promyshlennost'
Phys ab	-	Physics abstracts
PMM	-	Prikladnaya matematika i mekhanika
PTE	-	Pribory i tekhnika eksperimenta
RiE	-	Radiotekhnika i elektronika
RZhElektr	-	Referativnyy zhurnal. Elektronika i yeye primeneniye
RZhF	-	Referativnyy zhurnal. Fizika
RZhFotokinotekhnika	-	Referativnyy zhurnal. Fotokinotekhnika
RZhMekh	-	Referativnyy zhurnal. Mekhanika
RZhMetrolog	-	Referativnyy zhurnal. Metrologiya i izmeritel'naya tekhnika
RZhRadiot	-	Referativnyy zhurnal. Radiotekhnika

TVT	-	Teplofizika vysokikh temperatur
UFN	-	Uspekhi fizicheskikh nauk
UFZh	-	Ukrainskiy fizicheskiy zhurnal
VAN	-	Akademiya nauk SSSR. Vestnik
VAN KazSSR	-	Akademiya nauk Kazakhskoy SSR. Vestnik
ZhETF	-	Zhurnal eksperimental'noy i teoreticheskoy fiziki
ZhETF P	-	Pis'ma v Zhurnal eksperimental'noy i teoreticheskoy fiziki
ZhPMTF	-	Zhurnal prikladnoy mekhaniki i teoreticheskoy fiziki
ZhPS	-	Zhurnal prikladnoy spektroskopii
ZhTF	-	Zhurnal tekhnicheskoy fiziki
ZhVMMF	-	Zhurnal vychislitel'noy matematiki i matematicheskoy fiziki

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