Scientific session of the Physical Sciences Division of the Russian Academy of Sciences (19 December 2005)

A scientific session of the Physical Sciences Division of the Russian Academy of Sciences (RAS) was held in the Conference Hall of the P N Lebedev Physics Institute, RAS, on December 19, 2005. The following reports were presented at the session:

(1) **Krokhin O N** (P N Lebedev Physics Institute, RAS, Moscow) "Electric power transmission using laser radiation";

(2) **Zabrodskii** A G (A F Ioffe Physical-Technical Institute, RAS, St.-Petersburg) "Portable fuel cells: their physics and micro- and nanotechnologies";

(3) Avrorin E N, Simonenko V A, Shibarshov L I (Russian Federal Nuclear Center 'E N Zababakhin All-Russia Scientific Research Institute of Technical Physics', Snezhinsk, Chelyabinsk region) "Physics research during nuclear explosions";

(4) **Preobrazhenskii V L** (Wave Research Center of the A M Prokhorov General Physics Institute, RAS, Joint European Laboratory of Nonlinear Magnetoacoustics of Condensed Media (LEMAC)) "Nonlinear acoustics of front-conjugate ultrasonic waves".

An abridge version of the first three reports is given below. V L Preobrazhenskii's report is close in contents to his communication at the session of the Physical Sciences Division of the Russian Academy of Sciences held on 28 September 2005, whose brief presentation was published in the No. 1 (2006) issue of *Physics-Uspekhi* under the Conferences and Symposia heading.

> PACS numbers: 42.60. – v, 42.79.Gn, **72.40.** + w DOI: 10.1070/PU2006v049n04ABEH005956

Electric power transmission using laser radiation

O N Krokhin

This report is concerned with the feasibility of developing an electric power transmission line through the conversion of energy to laser radiation, which is subsequently converted again to electric current employing a semiconductor structure similar to that of a semiconductor laser. The energy is transferred through an optical fiber.

A special feature of the scheme under consideration is the monochromaticity of the radiation converted to electric

Uspekhi Fizicheskikh Nauk **176** (4) 441–454 (2006) Translated by E.N. Pagazin, E.Vankovsky, and E.G.Sta

Translated by E N Ragozin, E Yankovsky, and E G Strel'chenko; edited by A Radzig

current and, which is of fundamental importance, the spatial coherence of this radiation. The electric energy loss in such a transmission line can be quite appreciable. However, even today there are grounds to expect a value of no greater than 50% for short distances if use is made of semiconductor structures as the element-converters.

N G Basov and the author of this report drew attention to the possibility of the occurrence of an electromotive force (emf) in the bulk of a semiconductor (similar to gallium arsenide utilized for the production of laser diodes) with a band structure that allows a direct optical transition under high-power monochromatic irradiation [1]. The radiation photon energy should be close to the absorption edge $(\hbar \omega \ge \Delta, \text{ where } \Delta \text{ is the band gap})$ where the absorption coefficient is not too high; otherwise, the semiconductor will be damaged by the thermal shock caused by the high radiation flux applied. The electromotive force arises because the absorption of the light flux increases the electron and hole concentrations to produce a strongly nonequilibrium state which may be described by introducing the concept of quasi-Fermi levels μ_c for the electrons in the conduction band, and μ_v in the valence band, and the magnitude of the emf is defined by the expression $(\mu_{\rm c} - \mu_{\rm v})/e$ (where *e* is the electron charge).

In the limit of extremely high incoming radiation flux densities, the difference in the quasi-Fermi levels will tend to the photon energy $\hbar\omega$. This state is referred to as the absorption saturation effect and is familiar in quantum electronics.

Apart from monochromaticity, the incident radiation should possess a high spatial coherence, otherwise it will be impossible to concentrate the radiation on the small input window of the semiconductor structure; in other words, this radiation should originate from a laser. This radiation is delivered using an optical waveguide — an optical fiber which is integrated with the laser source and the structure converting the light energy to electricity. The laser, the converter, and the optical fiber make up a single optical system — a composite resonator.

As is well known, the saturation effect occurs when the optical transition probabilities (the absorption and stimulated emission probabilities) are far greater than the relaxation probability in the quantum system being investigated (two groups of the lower and upper quantum levels). In this case, the absorbed power density asymptotically tends to the energy flux carried to the relaxation channel from a unit volume per unit time. For a semiconductor placed in a strong monochromatic field, the saturation effect reduces, as discussed above, to the asymptotic approach of the energy difference between quasi-Fermi levels of electrons in the conduction and valence bands to the photon energy value. As this takes place, the absorption coefficient, naturally,

tends to zero. Of course, this all applies to the optical transitions near the absorption edge, i.e., for $\hbar \omega \ge \Delta$, because for $\hbar \omega$ appreciably greater than Δ there is no way of approaching the saturation due to a sharp increase in density of electronic states and, therefore, sharp rise in the power density going away through the relaxation channel. Herein, in particular, lies the distinction between the energy conversion scheme under discussion and photoelectric converters (solar batteries) which convert low power densities of light energy. That which we consider in the present report is in essence a scheme akin to a semiconductor laser operating in the inverse order: from light to electric current.

Another significant feature of the scheme being considered is the employment of an optical fiber as the power transmission line, which retains in the ideal case the property of spatial coherence of the electromagnetic wave being transmitted. To put it differently, if a semiconductor laser generates radiation at one end of the fiber-optic line, it has the same brightness at the other end and can be injected into a semiconductor structure with similar geometric parameters, which converts the light energy to electric energy - a converter (Fig. 1). Therefore, the system as a whole comprises a long resonator in which certain light modes are realized. In this case, to lengthen the effective radiation absorption path in the converter, the rear surface of the semiconductor structure can be made totally reflecting. For this purpose, advantage can also be taken of several electrically decoupled sections placed in series to ensure complete absorption of the radiation arriving at the structure or of a multipass scheme.

Let us consider the principle of operation of the monochromatic radiation-to-electric current converter. The device is schematically shown in Fig. 2. The radiation from an optical fiber is fed to a narrow region of the sample with an intrinsic conductivity (i type), which is located between the layers with electron and hole conduction. The optical transition is assumed to be direct, i.e., takes place virtually without a change in electron momentum in the valence band and the conduction band. Figure 3 shows the energy level diagram and the optical transition in the converter. It is



Figure 1. Schematic of the power transmission line.



Figure 2. Conceptual sketch of the light-to-current converter.



Figure 3. Schematic diagram of electronic levels in a semiconductor. Indicated are direct optical electron transitions between the conduction band and the valence band, as well as the positions of the quasi-Fermi levels in these bands.

assumed that the converter should make use of semiconductor materials, and that in the fabrication of the converter advantage can be taken of techniques similar to those employed in the manufacture of semiconductor lasers.

During the irradiation of a semiconductor by a monochromatic light, there occur optical transitions from the valence band to the conduction band with the absorption of a photon, and transitions in the opposite direction with its stimulated emission. When the incident radiation intensity is low, the relaxation (spontaneous radiative and nonradiative transitions) maintains thermal equilibrium and absorption prevails over stimulated emission, and the valence band will therefore be filled almost completely (if the doping with donor and acceptor impurities is not too high). With an increase in radiation intensity, the population of the levels in the conduction band [equal to the distribution function $f_{\rm c}(E_{\rm c})$, where $E_{\rm c}$ is the energy level in the conduction band] will rise, and the level populations in the valence band [described by $f_v(E_v)$, where E_v is the energy level in the valence band] will decrease. Therefore, for the absorption coefficient $k(\omega_0)$ we can write the expression

$$k(\omega_0) = \alpha(\omega_0) \left[f_{\rm v}(E_{\rm v}) - f_{\rm c}(E_{\rm c}) \right],\tag{1}$$

where ω_0 is the incident radiation frequency, $E_c - E_v = \hbar \omega_0 \ge \Delta$, and $\alpha(\omega_0)$ is the absorption coefficient for low intensities and low temperature, when the equilibrium carrier concentration is not high and is independent of the radiation intensity, i.e., $f_c \sim 0$, $f_v \sim 1$.

For direct transitions, one has

$$\alpha \sim \left(h\omega_0 - \varDelta\right)^{1/2}.\tag{2}$$

For highly doped semiconductors, the following estimate is true:

$$\alpha \sim \exp\left[\gamma(\hbar\omega_0 - \Delta)\right],\tag{3}$$

where γ is the parameter, i.e., $\alpha(\omega_0)$ near the absorption edge, where $\hbar\omega_0 \ge \Delta$, is proportional to the density of electronic states.

With an increase in radiation intensity, the quasi-Fermi levels of the band electrons begin to shift into the corresponding bands, which manifests itself in the occurrence of nonequilibrium electrons in the conduction band, and vacancies (holes) in the valence band. At very high intensities, when the relaxation rates are relatively low, the energy difference between the quasi-Fermi levels in the conduction band, μ_c , and in the valence band, μ_v , asymptotically tends to $\hbar\omega_0$:

$$\mu_{\rm c} - \mu_{\rm v} \to \hbar \omega_0$$



Figure 4. Energy structure of a semiconductor converter: (a, b) 'idle' mode, and (c) operation under a load R_e ; V is the electric voltage; pin structure: p region, undoped i region, and n region arranged in series.

Upon substituting into formula (1) the expression for the Fermi distribution function

$$f(E) = \frac{1}{\exp\left[(E - \mu)/T\right] + 1},$$
 (4)

expression (1) can be rewritten as (see Fig. 4)

$$k(\omega_0) = \alpha(\omega_0) \frac{1}{\exp\left[(E_v - \mu_v)/T\right]} \times \left\{ 1 - \frac{1}{\exp\left[(\hbar\omega_0 - \mu_c + \mu_v)/T\right]} \right\},$$
(5)

whence it follows that $k(\omega_0) \to 0$, when $\mu_c - \mu_v \to \hbar \omega_0$.

The number of ingoing radiation quanta absorbed in a unit volume in a unit time is determined by the equation

$$-\frac{\mathrm{d}I}{\mathrm{d}x} = k(\omega_0) I$$

where *I* is the photon flux per unit surface area (the intensity). One can see from relationship (5) that the absorption saturation effect becomes appreciable when $\hbar\omega_0 - \mu_c + \mu_v \leq T$. This circumstance permits expansion of the expression on the right-hand side of formula (5) in terms of the small quantity $(\hbar\omega_0 - \mu_c + \mu_v)/T$ to obtain as a crude approximation the expression

$$k(\omega_0) = \alpha(\omega_0) \,\frac{\hbar\omega_0 - \mu_c + \mu_v}{T} \frac{1}{\exp\left[(E_v - \mu_v)/T\right]},\qquad(6)$$

where the last term on the right-hand side appears because the effective electron masses in the conduction and valence bands (the effective masses of electrons and holes) are not equal.

The quantity $f_v(E_v) - f_c(E_c)$ can be determined in the stationary case from the equality condition for the absorption rate |k|I and the electron-hole recombination rate R(n,p), i.e., the relaxation rate, per unit volume:

$$|k|I = R. (7)$$

For high levels of the nonequilibrium concentrations of electrons, n, and holes, p, the recombination rate is proportional to their product. If advantage is taken of the simplified

expression (6) for the absorption coefficient, formula (7) can be rewritten as

$$\hbar\omega_0 - \mu_{\rm c} + \mu_{\rm v} \approx \frac{TR}{\alpha(\omega_0)I} \exp\left(\frac{E_{\rm v} - \mu_{\rm v}}{T}\right),\tag{8}$$

whence it follows that the difference $\mu_{\rm c} - \mu_{\rm v}$ approaches $\hbar\omega_0$ for high intensities.

Therefore, an electromotive force arises in the absorption region. To realize it in the form of electric current requires that the electrons and holes should move in the opposite directions. This can be achieved by attaching the highly doped semiconductors with n- and p-type conduction to either side of the absorption volume. Upon connection of a load, the electrons will then drift to the n region, and the holes to the p region under the action of the field in the active region (see Fig. 4).

To reduce the losses due to the drift of electrons to the n region, and of holes to the p region, use can be made of a heterostructure which sets up additional barriers for respective electrons and holes. In this case, the resultant electric current 'loads' the volume in which the production of electron – hole pairs occurs, and formula (7) can be rewritten in the form

$$kI = R + \frac{J}{de} \,, \tag{9}$$

where J is the electric current density, and d is the thickness of the layer in which the electron – hole pair production takes place.

The parameters of such an electric power transmission line can be estimated by drawing an analogy to the recently developed devices and elements - semiconductor lasers and optical fibers. A single semiconductor laser can provide an output power up to 10 W with a very high efficiency of about 70% [2]. The emitting window of this laser measures $1\times100~\mu m,$ i.e., the power density amounts to 10 MW cm $^{-2}.$ This is a very high value. A light power density below 1 W cm^{-2} is converted in solar batteries. Since the converter of light energy to electric current is close in design and manufacturing method to semiconductor lasers and constitutes actually a laser operating in inverse order, one might figure on equally high conversion coefficients in the future. Modern optical fibers are capable of transmitting substantial light fluxes of over 100 W and possess very small attenuation coefficients on the order of 0.1 dB m^{-1} [3].

Therefore, the proposed scheme enables transmission of the electric power for a short distance with a transfer coefficient of 50%. It is pertinent to note that the case in point is a low-voltage transmission line with a voltage around that of the semiconductor band gap. The distinction between the converter under consideration and the widely used photoelectric cell (which offers a very high efficiency) consists in the fact that advantage is taken of the spatial coherence of laser-generated radiation. This makes it possible to realize a high power density at the converter input, so that the converter dimensions turn out to be small in comparison with the dimensions of ordinary photoelectric cells.

It is likely that there is good reason to fabricate the converter in the form of a layer structure in which the radiation sequentially passes through several layers to experience gradual absorption, the layers being electrically connected in series. Such a converter will then yield a higher voltage at its output. To summarize, the method of electric energy transfer considered in the present report may turn out to be beneficial in low-voltage transmission lines or in other cases where there exists unwanted extraneous electrical noise in transmission lines or circuit commutation devices. Furthermore, it can be employed when there is no way of applying metal conductors (for instance, in high-voltage devices) or when decreasing the weight characteristics of supply lines becomes a paramount requirement.

References

- 1. Basov N G, Krokhin O N Fiz. Tverd. Tela 5 2384 (1963)
- Bugge F et al. Appl. Phys. Lett. 79 1965 (2001); Pikhtin N A et al. Electron. Lett. 40 1413 (2004)
- 3. Broderick N G R et al. Opt. Fiber Technol. 5 185 (1999)

PACS numbers: 82.45. - h, 82.45. Yz, 82.47. - a DOI: 10.1070/PU2006v049n04ABEH005957

Portable fuel cells: their physics and micro- and nanotechnologies

A G Zabrodskii

1. Introduction

This report presents a brief review of the results of investigations carried out at the A F Ioffe Physical-Technical Institute (PTI) and at a number of other institutes of RAS in one of the branches of hydrogen power engineering, dealing with the development of portable fuel cells.

Actually, research in the field of energetics is a traditional topic for the Petersburg Physical-Technical Institute. It was here that Ioffe created the national scientific school of thermoelectricity and began the practical implementation of this effect for cooling. In the 1930s, nuclear studies were launched in a laboratory headed by I V Kurchatov with Ioffe's support. There the young scientists G N Flerov and K A Petrzhak discovered spontaneous uranium fission. At the beginning of the Great Patriotic War (1941–1945), Flerov was studying at a school for aircraft technicians, where he wrote his well-known letter to I V Stalin, in which he stressed the immediate need to begin work on the atomic bomb. This event marked the beginning of the Soviet Atomic Project and the birth of the nuclear power industry, to which the researchers at PTI contributed greatly. It was at PTI that V N Tuchkevich as a scientific leader and his colleagues developed a new area of research — high-current semiconductor electronics. Studies in highly effective solar power engineering based on the use of semiconductor heterostructures may be highlighted as an outgrowth of the backbone area of research in physics, engineering, and technology developed at PTI by Zh I Alferov and the scientific school he created in the field of semiconductor heterostructures. For more than half a century, the PTI staff has participated in physics research programs, in developing technologies associated with controlled fusion based on tokamaks, and in the diagnostics of hot plasma. Several years ago, an entirely new spherical tokamak 'Globus-M' became operational at PTI and physical investigations began on it.

Relatively recently, PTI became actively involved in hydrogen power research within the program that incorporated RAS and the Norilsk Nickel Mining and Smelting Co.



Figure 1. An electrochemical cell operating in the electrolysis mode (a), and in the fuel-cell mode (b).

(later the program gave birth to the National Innovation 'New Energy Projects' Company). Here I will speak only of works dealing with the development of new types of portable fuel cells. The material I will present illustrates the typical approach to research at PTI: from scientific investigations to basic technologies and later to the development of new facilities. The basic technologies in this field are those involving the deposition of monodispersed nanocatalysts (Section 3) and also silicon micro- and nanotechnologies (Section 4) utilized to develop portable fuel cells (Section 5). I will also discuss possible ways of raising the efficiency and specific power of fuel cells (Section 5). Minimum information about hydrogen energetics and fuel cells is given below in Section 2.

2. Hydrogen power engineering and fuel cells

The interest in generating power through the use of hydrogen is stimulated by the gradual depletion of fossil fuel reserves¹ and by ecological problems, as well as by the need to raise the efficiency of energy conversion.

What makes hydrogen so attractive as an energy carrier is, on the one hand, the great variety of sources for its production, among which are coal, natural gas, biomass, solar energetics, thermal energetics, photoelectric power engineering, hydroelectric power engineering, wind energy, nuclear electrical power engineering (the last four via electrolysis), and nuclear thermal power engineering. On the other hand, the merits of hydrogen manifest themselves most vividly when it is used as an energy carrier in key devices of hydrogen power engineering, namely, fuel cells of various types, which encompass a broad spectrum of power outputs: from several dozen milliwatts to several megawatts.

The first fuel cell was developed by William R Grove of Great Britain in 1839 already. His device produced electric current from hydrogen and oxygen reacting at platinum electrodes (Fig. 1 [1]). When an external source of electricity

¹ Note that our ideas about the depletion of oil reserves are basically formed by the rising prices for crude oil and petrol. These prices strongly depend on inflation of world currency and political stability in the main regions of oil production. A sharp increase in oil prices usually accompanies political upheavals and wars in such regions. The absolute record in oil prices with inflation taken into account was not reached in recent years but on the verge of 1970s and 1980s when the Iranian Revolution took place. Nevertheless, the very fact of substantial depletion of reserves of natural fuel, primarily crude oil, is indeed true and is certainly a troubling problem for the oil (and gas)-importing countries.



Figure 2. Schematic diagram showing the operation of a fuel cell.

was attached to this electrochemical cell, the cell could operate in the electrolysis mode. When the external circuit was closed, it experienced a current flow and the electrochemical cell operated in the fuel-cell mode.

Grove was also the first to find that the efficiency of the fuel cell is determined by a 'bottleneck' — the boundary of three phases (gaseous fuel, electrolyte, and electrode), to carefully examine new ways of raising the efficiency of electrolytes and electrodes, and to appraise the importance of hydrogen as an alternative to wood and coal.

Figure 2 schematically shows the operation of a planar fuel cell together with the main electrochemical reactions in the anode and cathode parts. It was found that the reaction rate increases with temperature and the effective surface area of the electrodes, and also increases if a catalyst is utilized (not shown in Fig. 2, but usually located at the electrode – electrolyte boundary; see Fig. 6). Note that at present solid electrolytes are being widely used in fuel cells, namely, fuel cells with a solid-polymer membrane, and solid-oxide fuel cells. The main requirement that such electrolytes must meet is a high proton or ion conductivity but low electron conductivity.

The main merits of fuel cells are as follows:

(a) a potentially high efficiency η , since at room temperature

$$\eta_{\text{max}} = \frac{\Delta G}{\Delta H} = 91\%, \quad \text{H}_2 + \frac{1}{2} \text{ O}_2 \rightarrow \text{H}_2\text{ O},$$
$$\Delta H = -242 \text{ kJ mol}^{-1}$$

(combustion process: formation enthalpy U + pV),

 $\Delta G = -220 \text{ kJ mol}^{-1}$

(generated electric energy: Gibbs energy U - TS);

(b) the possibility of utilizing fuels with high energy content (hydrogen and hydrocarbons with a specific energy capacity several dozen times greater than that of Li-ion batteries);

(c) an ecologically clean sources of energy, and

(d) the absence of moving parts and noiselessness (for portable fuel cells).

It is important to keep in mind that fuel cells can use, in addition to hydrogen, other gaseous (biogas, natural gas, etc.) or liquid (methanol, ethanol, etc.) fuels. Fuel cells are usually divided into three large groups according to the areas of application: stationary, for use in vehicles, and for home appliances and electronic devices.

Table 1 gives a rough idea of the characteristic parameters of fuel cells entering the third group, what is known as portable fuel cells, which are used in power sources for

Table	1
I able	1.

Areas of application	Mobile phones	Laptops	
Dimensions, cm	2-5	5 - 20	
Power output, W	~ 0.1	10 - 20	
Power capacity, W h	1-5	40 - 150	
Main types	Methanol, air-hydrogen	Methanol, air-hydrogen	

mobile phones and notebooks. The market interest in portable fuel cells is, understandably, caused by the growing sales of portable electronic devices. In this report I will touch on the topic of most compact and miniature portable fuel cells. Usually, the electrolyte in such fuel cells is a solidpolymer membrane. Porous carbon or silicon materials are employed as a base for the development of electrodes. Actually, this constituted the entire input data at the beginning of our research. Our approach consisted in using the existing technologies of microelectronics and microelectromechanics for producing porous silicon electrode structures, as well as in applying a technology, developed at PTI for producing monodispersed nanomaterials by laser electrodispersion, to the deposition of catalytic coatings. Parallel to these developments, the problems of fabricating a siliconbased hydrogen-separating membrane and 'extending' the reaction zone by using a currently developed material with mixed electron-proton conductivity were also investigated.

3. The technology of depositing monodispersed nanocatalysts

As is known, the large consumption of platinum in the catalysts of modern fuel cells (at a level of approximately 1 g kW⁻¹) will sooner or later limit the development of hydrogen power engineering. It has therefore become extremely important to formulate and solve the problem of developing a highly effective catalyst with fairly small platinum consumption.

To this end, we used an original laser nanodispersion technique [2], which is a laser ablation, accompanied by the process of self-organizing division of droplets of a target (Fig. 3 gives an idea of the method by which a monodispersed nanocatalyst is formed).

The parameters of the laser beam (1.06 μ m, 1 GW cm⁻², 25 ns) were selected so as to initiate a cascade division of



Figure 3. Fabricating a monodispersed catalyst.



Figure 4. (a) Division of charged droplets in plasma. (b) Daughter droplets on a substrate located near the target (L = 0.5 cm). (c) Distribution of nanoparticles over the surface of the substrate located far from the target (L = 5 cm). (d) Nanoparticle-size distribution.

submicrometer-sized droplets spattered from the target. A nonuniform electric field ($\sim 1 \text{ kV cm}^{-1}$) collected the nanoparticles onto the substrate and separated them.

The physical basis of the method resides in the Rayleigh instability of charged droplets in plasma, which leads to their cascade division. The related problem was examined, for instance, in Ref. [3]. An initially stable spherical droplet of radius R becomes unstable in relation to fission if the charge

Q it acquires in the plasma exceeds a critical value Q_{cr} specified by the relationship

$$Q > Q_{\rm cr} = 8\pi (\varepsilon_0 \alpha R^3)^{1/2}, \qquad (1)$$

where α is the surface tension coefficient of the liquid.

Experiments carried out at PTI showed that the intuitive idea that a droplet divides into two roughly equal parts is unrealistic: one of the daughter droplets proves to be much smaller than the other, which accelerates the disintegration process. This type of droplet division is shown in Fig. 4a. The process was verified through experiments in which droplets were deposited on a substrate located near the target. The geometry of this experiment corresponds to Fig. 4b, where the seeds of small daughter droplets are clearly visible on some of the mother droplets.

If the electron temperature of the plasma in the laser torch exceeds 30 eV, droplets of all sizes prove to be unstable in relation to division. Figure 4a illustrates this fact.

Nevertheless, cascade division finally stops because of a rapid increase in the emission of electrons from the droplets and the rapid discharging of droplets as the size d of the daughter droplets decreases to a certain minimum value. As shown in Ref. [4], this parameter equals

$$d_{\min} \approx 8 \times 10^{-7} \, \varepsilon \alpha^{-3} \,, \tag{2}$$

where ε is the work function.

In particular, d_{\min} for platinum amounts to about 2 nm (Fig. 4c) at a minimum dispersion of the particle diameter (Fig. 4d). It is important that precisely this size proved to be optimal for the effective operation of catalytic coatings.

For instance, most of the platinum nanoparticles produced by this method have the same size d = 1.8 nm. In view of the high cooling rate $dT/dt > 10^7$ K s⁻¹, the particles are amorphous and do not coagulate. This technology allows depositing on the fuel-cell units carefully metered layers (and parts of layers) of monodispersed particles of highly active catalysts (not only platinum) with sizes ranging from 2 to 3 nm, and thus appreciably reduces the consumption of materials of the platinum group to approximately 0.1 g kW⁻¹.

4. Fabricating electrode structures from macroporous silicon. Formation of electrodes

with a 10-nm membrane for purifying hydrogen

The employment of technologies for fabricating porous silicon² solves the problem of moving to micro- and nanotechnologies needed for the miniaturization of the components of portable fuel cells. The microstructurization of silicon opens the possibility of fabricating

• channels for supplying fuel and oxidizer and removing the reaction products;

• porous electrodes (anodes and cathodes) with a welldeveloped active surface which can be utilized for depositing catalysts, and

• radiators for heat removal.

The use of technologies worked out in modern silicon electronics and microelectromechanics helped in developing ways of fabricating multifunction electrode structures from porous silicon. Electrodes fabricated from such structures

² Initially, the development of these technologies at PTI was related to other problems (in particular, problems related to the use of what is known as photon crystals).



Figure 5. (a) Regular channel electrode structure of macroporous silicon. (b) Cross section of the anode part of a fuel cell. (c) Micrograph of the cross section of a 10-nm silicon membrane, taken with the help of a transmission electron microscope. Channels with a diameter of about 20 nm are located above and below the membrane.

with pore sizes ranging from 1 to $100 \ \mu m^3$ substantially reduce the size of fuel elements and guarantee the required specific efficiency.

As an illustration, Fig. 5a presents a micrograph of a regular channel structure of an electrode fabricated from macroporous silicon by photoelectrochemical etching [5]. By



Figure 6. The design of a portable fuel cell that is being developed.

using a simplified version of this technology it is possible to fabricate irregular channel structures with a random distribution of the channels on the basis of the self-organizing effect without employing masks.

Figure 5b depicts the cross section of a multifunction monolithic anode of a methanol fuel cell fabricated from macroporous silicon at the Institute for Microelectronics Technology, RAS in Chernogolovka [6].

To solve the problems associated with the formation of porous electrodes and the purification of hydrogen, a new method has been developed to fabricate electrodes with a 10-nm hydrogen-separating silicon membrane, which effectively operate at room temperature (Fig. 5c). The method is based on a technology elaborated at PTI for fabricating mesoporous silicon (the pore diameter amounts to 20 nm) by two-sided anodic etching.

5. The use of mature technologies in manufacturing portable fuel cells. A way of increasing the efficiency and specific power output of fuel cells

The technologies I have described above have been applied to developing portable fuel cells of various designs [7]. Figure 6 gives an idea of the design of such a cell with a protonconducting polymer membrane, in which a monodispersed nanocatalyst was deposited on an electrode structure fabricated from mesoporous silicon with a hydrogen-separating 10-nm Si membrane.

In order to increase the reaction zone of fuel cells, interfacial composite layers based on polymers and carbon nanotubes have been developed at PTI and the Institute of High-Molecular Compounds of RAS [8]. The structure of such layers which possess mixed electron – proton conductivity is shown in Fig. 7. Their utilization in electrode structures suggests that the reaction zone will get 'extended', which will raise the efficiency of fuel cells.

6. Conclusion

In this report I have not mentioned the problems associated with the development of portable fuel cells that lie outside the scope of my topic, i.e., fuel cells that are not grounded on micro- or nanotechnologies, but nevertheless were subjects of our investigations. Among them is the problem of optimizing

³ Such materials are known as 'macroporous'.



Figure 7. Original carbon nanotubes (a); nanotubes covered with polyaniline (b and c) with 70 and 90 wt.% of polyaniline, respectively.

the fuel for these cells. Due to its high energy content, the most widely used fuel for portable solid-polymer fuel cells — methanol — has many essential drawbacks, which forces researchers to look for substitutes [9].

Among the most important difficulties in developing new fuel cells is the problem of matching their elements that are fabricated in different technological processes, say, matching the solid-polymer membrane with electrodes fabricated from a porous inorganic material.

Nevertheless, all research, including the development of our basic micro- and nanotechnologies described in this report, some of which are already among the best in the world,⁴ suggests that the problem of developing efficient portable fuel cells on the whole will be solved.

References

- 1. Larminie J, Dicks A *Fuel Cell Systems Explained* 2nd ed. (Chichester, WS: J. Wiley, 2003)
- Kozhevin V M et al. Dokl. Ross. Akad. Nauk 387 785 (2002) [Dokl. Phys. Chem. 387 324 (2002)]
- Landau L D, Lifshitz E M *Elektrodinamika Sploshnykh Sred* (Electrodynamics of Continuous Media) (Moscow: Gostekhizdat, 1957) [Translated into English (Oxford: Pergamon Press, 1960)]
- 4. Kozhevin V M et al. J. Vac. Sci. Technol. B 18 1402 (2000)
- 5. Astrova E V et al. J. Micromech. Microeng. 14 1022 (2004)
- 6. Vyatkin A et al. J. Electrochem. Soc. 149 G70 (2002)
- Astrova E V et al., in *Mezhdunar. Forum "Vodorodnye Tekhnologii* dlya Proizvodstva Energii", Moskva, 2005 (Intern. Forum "Hydrogen Technologies in Energy Production", Moscow, 2005) Abstracts (Moscow, 2006) p. 188
- Kompan M E, Sapurina I Yu, Stejskal J, in *I Rossiiskaya Konf. po Fizicheskim Problemam Vodorodnoi Energetiki, Sankt-Peterburg,* 2004 (1st Russian Conf. on Physical Problems in Hydrogen Power Engineering, St.-Petersburg, 2004) Abstracts (St.-Petersburg, 2004) p. 23
- Goryachev D N, Malyshkin V G, Zabrodskii A G, in Mezhdunar. Forum "Vodorodnye Tekhnologii dlya Proizvodstva Energii", Moskva, 2005 (Intern. Forum "Hydrogen Technologies in Energy Production", Moscow, 2005) Abstracts (Moscow, 2006) p. 147

PACS numbers: **28.70.** + **y**, **47.40.** - **x**, **62.50.** + **p** DOI: 10.1070/PU2006v049n04ABEH005958

Physics research during nuclear explosions

E N Avrorin, V A Simonenko, L I Shibarshov

1. Introduction

Possibly no other engineering or technical endeavors of humankind have involved as much science as nuclear explosives have. The development of atomic and hydrogen bombs has required integrating knowledge from a wide circle of scientific fields and demanded huge technical and material resources — while, on the other hand, stimulating research into physical processes occurring under conditions beyond the reach of laboratory experiments.

Nuclear explosions produce pressures of up to several billion atmospheres and temperatures of up to hundreds of millions of degrees; they emit intense radiation — electromagnetic waves ranging from radio waves to hard gamma rays, and neutron fluxes in the energy range from fractions of an electron-volt to dozens of megaelectron-volts, and they involve a variety of physical processes, including shock and detonation waves, cumulation, turbulence, phase transformations, radiative energy transfer, dissociation and ionization, as well as fission and fusion nuclear reactions.

Given all this, nuclear explosions offer a unique set of fundamental and applied research opportunities — some of which unfortunately have been left unaddressed.

Listed below are research areas where much effort has been spent and good progress made.

(1) Thermodynamic properties of substances, equations of state, and phase transformations.

⁴ For instance, the results achieved in research on monodispersed catalysts seem to be unique.

(3) Thermonuclear burning and detonation processes.

(4) Electromagnetic radiation accompanying nuclear explosions.

(5) Radiation damage effects in materials and technological elements.

(6) Production of far transuranium elements.

(7) Neutron cross section measurements.

(8) Development of high-power optical and X-ray lasers. Both in the USSR and in the USA, these studies were conducted in specially designed experiments using nuclear explosions, but also in passing with tests of explosive devices or with peaceful applications of nuclear explosions.

In the USSR, two nuclear research centers currently known as the Russian Federal Nuclear Center 'All-Russia Research Institute of Experimental Physics' (VNIIEF) in Sarov, and the RFYaTs 'E I Zababakhin All-Russia Research Institute of Technical Physics' (VNIITF) in Snezhinsk dominated most of the field. Along with these, some other institutes, both industrial and academic, contributed significantly to a number of research projects, and mention should also be made of the numerous organizations and bodies — not least the test site services — that helped in preparing and carrying out the explosions.

2. Radiation length measurements: the first physics-oriented experiment (1957)

At certain stages of a nuclear explosion, the predominant mechanism of energy transfer is a radiative heat conductivity. The importance of this radiative transfer mechanism first became clear with respect to stars, and the meaningful theoretical insights into this process were obtained in the 1930s. The vast majority of stellar objects are predominantly composed of elements with low atomic numbers. The main interaction mechanisms between radiation quanta and matter are bremsstrahlung interactions and Compton scattering.

Nuclear explosions give rise to energy densities comparable to those characteristic of stellar objects. What complicates things, however, is that nuclear explosives contain elements with high atomic numbers, which have highly complicated energy spectra and are multiply ionized at high temperatures — a situation in which radiative transitions between excited states and ionization processes start to significantly affect the way radiation and matter interact. Besides, the set — and state — of particle energy levels are significantly influenced by the thermodynamic conditions. Obtaining data on all these aspects is a daunting task even today — and in times past, in addition, it was not even known whether or how much the particular processes involved really matter. As things stood, however, there was indirect evidence from tests on even the first radiation implosion systems which cast doubts on the radiation transport data of the time.

Accordingly, obtaining experimental information on the radiation lengths in high-Z media became a top agenda issue in the 1950s. To this end, a physical experiment, known by its Russian abbreviation as FO-1 and involving a full-scale nuclear explosion, was prepared and carried out in 1956 on the initiative of the VNIIEF scientific leaders Ya B Zel'dovich, A D Sakharov, and Yu B Khariton. However, because of a methodical shortcoming — an inadequate accounting for radiation effects on the instrumentation — no useful information was obtained. In 1957, a team of young researchers at VNIITF, the USSR's second nuclear research center, set out



Figure 1. Schematics of the FO-3 setup, showing the explosive device (1), the radiation withdrawal pipes (2), the water tank (3), and the light channels (4).

to conduct a similar experiment (FO-3). Figure 1 depicts the schematic setup of the VNIITF experiment (the height of the apparatus was about 5 m, and the lateral dimension was about 2 m).

Key FO-3 participants were:

Idea: Zel'dovich, Sakharov.

Initiative for the experiment: K I Shchelkin, E I Zababakhin, Yu A Romanov, V S Imshennik.

Scientific leadership: Yu A Romanov.

Physical design of the experiment, theory and calculations, result processing: E N Avrorin.

Engineering: V F Grechishnikov, V D Kiryushkin, A S Krasavin.

Physical measurements: A D Zakharenkov, V K Orlov, A S Dubovik, P V Kevlishvili.

Test site experiment supervision: V Yu Gavrilov.

The idea behind the FO-3 experiment was that the energy flux attenuation along a pipe depends on the heat conductivity in the pipe walls: the higher it is, the faster the energy flux attenuates. The energy absorption in various sections of the pipe wall was determined with the help of the shock wave velocity measurements in the experimental elements mounted there, by means of a light flash registering at the moment of the wave exit to the element's outer surface. Based on lessons from FO-1 experiment, the reliability of measurements was given a high priority. The process of choosing a reliable configuration of the experiment greatly benefited from the help of Zel'dovich. The optical radiation detection system was located at a distance of 2 to 5 km and involved high-speed moving-image cameras developed at the Institute of Chemical Physics, AS USSR. Examples of the photochronograms obtained are given in Fig. 2.

The large body of FO-3 experimental evidence, together with test data from a number of thermonuclear explosions as



Figure 2. Examples of FO-3 photochronograms. Scale ~ 40 ns to the millimeter of the film.

processed by M P Shumaev, landed support to the view that the effect of the bound-bound transitions must indeed be taken into account.

The experimental results stimulated rapid development of quantum-mechanical models for calculating the opacity of materials. The major contributors to the theoretical development of the field were Zel'dovich and Yu N Babaev. The task of practically realizing theoretical models and computational algorithms and that of accumulating calculation data were given to A F Nikiforov and V B Uvarov's team at the Institute of Applied Mathematics, AS USSR [1].

3. Equations of state and phase transformations in dynamically loaded materials

The study of the properties of matter in dynamic processes under record-high pressures (up to 3.6 Gbar) was included in the program of a large number of specialized physical experiments and nuclear explosion tests [2, 3]. The property which proved the simplest to study, viz. shock compressibility, was measured using the reflection method, which had been developed by L V Al'tshuler, K K Krupnikov, et al. [4, 5] for experiments with chemical explosives and which assumes the knowledge of the equation of state for a reference material (usually Fe or Al).

The first large-scale on-site experiment involving such measurements was conducted by the VNIITF team in March 1966 under guidelines developed by V A Simonenko, K K Krupnikov, and L P Volkov.

An example of the experimental arrangement is shown in Fig. 3. An explosive device was placed in the box constructed in a rock and encircled by a by-pass with recesses for placing measuring assemblies. Specifically, the assemblies were attached to a smooth polished surfaces made in the rock, each surface being oriented perpendicular to the direction toward the explosion center. The arrival times of a shock wave at the chosen points were registered by electrocontact sensors.

Even the first experiment enabled an extended, sixassembly program to be carried out. One of the assemblies was used to measure the shock compressibility of granite relative to that of iron, producing, for the shock adiabat of granite, a point at twice the pressure achieved in laboratory





Figure 3. (a) Schematics of an experiment to study the relative compressibility of various materials: *1*, rock massif; *2*, main adit; *3*, ring drifting. (b) Schematic arrangement and location of the measuring assembly: *1*, rock; *2*, contact sensors; *3*, reference material; *4*, sample under study; *5*, protective housing; *6*, protective pipe with cables.

experiments at the time. Subsequent measurements yielded improved shock compressibility values for water and aluminium and also revealed the effect of the melting process on shock front evolution in quartzite. All in all, VNIITF specialists have used more than sixty measuring assemblies in their measurements using underground test explosions. In particular, the same experimental arrangement was employed in the Institute's last nuclear explosion studies in 1988, in which useful data on the shock compressibility of quartzite, wave bifurcation in quartzite caused by near quartz – stishovit phase transition [6], and the shock compression of porous aluminium were obtained.

A similar arrangement was also used by VNIIEF researchers, first under the direction of Al'tshuler and later under R F Trunin (see Ref. [5] for reviews).

The body of data reveals the existence of two phase transitions in quartzite: from the normal to the high-density phase in the pressure range from 230 to 350 kbar, and melting at about 1.15 Mbar [7]. Figure 4 illustrates the shock adiabat for the region of the transition.

Originally, in constructing wide-range equations of state people used data from the variously modified forms of the Thomas–Fermi model [8-11] with due account of regular quantum corrections in various modifications. These models, however, are flawed in that they ignored the irregular influence of the atomic electron shells, and a number of





studies were conducted in parallel with underground nuclear explosions to see to what extent this irregularity plays a role in shock-compressed high-density media. Specifically, the shock compressibilities of Al, Pb, water, and quartz relative to that of iron were measured at record high pressures using the reflection method [12, 13]. The experimental data on the shock adiabats of Al and Pb are given in Table 1 [14].

Table 1. Shock adiabats.

	Aluminium			Lead	
D, km s ⁻¹	P, Mbar	$\delta=\rho/\rho_0$	D, km s ⁻¹	P, Mbar	$\delta=\rho/\rho_0$
43.57 49.45 50.53 65.22 75.03 80.11 85.98 107.10	36.3 48.5 50.6 87.3 115.9 132.5 152.5 237.9	$\begin{array}{r} 3.73 \\ 4.00 \\ 4.05 \\ 4.55 \\ 4.61 \\ 4.66 \\ 4.64 \\ 4.73 \end{array}$	30.42 35.0 35.44 46.6 53.43 56.98 61.33 76.7	79.6 107.2 111.6 197.3 262.4 300.2 346.5 543.8	4.13 4.37 4.60 5.00 5.26 5.40 5.31 5.39
<i>Notes</i> : <i>D</i> , shock wave speed; <i>P</i> , frontal pressure; ρ_0 , initial density of the material, and ρ , density behind the shock front.					

Based on this information, the applicability of various theoretical models in this field can be assessed [15-19].

The method with which the above results were obtained is a relative one, thus requiring a knowledge of the equation of state of a reference material.

The absolute measurement of shock compressibility requires that the mass velocity and shock wave velocity be simultaneously measured, but the known laboratory methods for determining mass velocity have physical limitations under high-pressure and high-velocity conditions.

In a scheme proposed by US researchers [20], the mass velocity in the region of high pressures is measured using the fact that interaction resonances between neutrons and the nuclei of a moving material experience a shift from their positions for nuclei at rest (Doppler shift).

The resonances are most pronounced in molybdenum which is precisely the element studied in Ref. [20]. Uranium was compressed to $P \approx 90$ Mbar, and in molybdenum a shock wave velocity D = 18.7 km s⁻¹ and a mass velocity behind the



Figure 5. Schematic diagram of an experiment with gamma-ray benchmarks.

shock front $U = 10.2 \text{ km s}^{-1}$ were measured. The accuracy of $\pm 5\%$ achieved in velocity measurements is not sufficient for the obtained experimental point to be used for gauging the equations of state of molybdenum. The major error sources in the measurements are associated with the uncertain emission duration of the neutron source used and with the difference in the resonance smearing mechanism, but because for many of these factors the contribution to the total error decreases as the mass velocity increases, it is in principle possible to achieve an accuracy of $\Delta U/U \approx 1\%$ at $U \approx 100 \text{ km s}^{-1}$.

As suggested in Ref. [21], the quantities D and U can be measured simultaneously using gamma-active benchmark layers introduced into the material being studied; an intense gamma-ray source can be obtained by neutron irradiation of a material with the radiation capture cross section of nuclei more than ~ 10³ times that of the material being studied. A suitable material for the benchmark layers is europium, for which the (n, γ) -reaction cross section $\sigma = 220 \pm 80$ b at $E_n = 10-100$ eV. As the benchmark layers are dragged by the moving material in the process of gasdynamical motion, the instants of time they pass the control points are registered by a system of collimating slits (Fig. 5).

Practical implementations of the reflection method widely utilize aluminium as a reference material. Because its equation of state is strongly nonunique in the pressure range of 5-150 Mbar, aluminium became a focus of interest in the early applications of the new method. Table 2 summarizes the measurement results obtained using the latest methodical achievements in oscillogram processing and in how nonstationary motions and benchmark layers must be taken into account.

Table 2. Results of absolute measurements in aluminium.

Experi- ment No.	$\rho_0, \mathrm{g}\mathrm{cm}^{-3}$	D, km s ⁻¹	U, km s ⁻¹	P, Mbar	$\delta=\rho/\rho_0$
1 2 3	2.71 2.71 2.71	$\begin{array}{c} 24.2 \pm 0.7 \\ 23.4 \pm 0.6 \\ 40 \pm 5 \end{array}$	$\begin{array}{c} 15.1 \pm 0.4 \\ 14.5 \pm 0.3 \\ 30 \pm 2 \end{array}$	$\begin{array}{c} 9.9 \pm 0.3 \\ 9.3 \pm 0.2 \\ 32 \pm 5 \end{array}$	$\begin{array}{c} 2.65 \pm 0.1 \\ 2.63 \pm 0.07 \\ 3.9 \pm 1.2 \end{array}$

Experience in applying the gamma-ray-benchmark method to the measurement of shock compressibility shows that the method has much room for improvement by using various combinations of the benchmark with the material to be studied.

4. Thermonuclear burning research

In a number of explosion experiments, the conditions of thermonuclear ignition in deuterium and a deuterium – tritium (DT) mixture were investigated.

A theoretical criterion for a thermonuclear ignition was developed by the VNIITF–VNIIEF collaboration [22] and then extended to the case of thermonuclear fuel subject to inhomogeneous compression and heating [23].

Thermonuclear ignition turned out to be a problem of extreme complexity. In 1956-1962, a number of attempts were made by the two Institutes to ignite 'clean' units (the term clean meaning that a design contains only thermonuclear fuel and no fission materials).

The first success came in 1963 (VNIIEF, V B Adamskii, V N Mokhov, Yu A Trutnev).

Very special significance should be placed on an experiment based on the proposal of L P Feoktistov at VNIITF in 1965. The experiment was successful in initiating the ignition of deuterium and DT units and it also started research into the possibility of thermonuclear detonation.

Leader of the experiment: E I Zababakhin.

Engineering: B V Litvinov.

Theory and calculations: L P Feoktistov, E N Avrorin, A K Khlebnikov, L I Shibarshov, E G Gamalii.

Physical measurements: Yu A Zysin, A I Saukov, V G Rukavishnikov.

Based on the results of this physical experiment, the combustion of gaseous deuterium about 100 kt in power was realized in 1966. In 1972, the VNIIEF and VNIITF researchers teamed up to conduct a test of a record-clean (i.e., minimally radioactive) industrial-scale explosive charge with a power of 140 kt (which could be virtually infinitely increased). The research team included Yu S Vakhrameev, V N Mokhov, A V Pevnitskii, E N Avrorin, B V Litvinov, and B P Mordvinov. The year 1967 witnessed an experiment designed to determine the ignition limits of gaseous deuterium by testing a set of thermonuclear units made in various sizes. A very close agreement between the measured and predicted values for the limiting size was obtained.

In several experiments, attempts to model laser fusion targets have failed to produce ignition, presumably due to nonuniform irradiation and lack of precision in producing the models.

In the 1970s, the thermonuclear detonation of pipes filled with a DT mixture (DT cords) attracted much interest for its potential use in obtaining unlimited energy gain in the inertial fusion process.

Along these lines, research into detonation, first theoretical and then experimental, was started at VNIITF on the initiative of L P Feoktistov.

The theoretical studies involved both numerical simulation [24] and analytical calculations and estimations [25].

Thermonuclear detonation turned out to be, in Feoktistov's words, 'much richer in physics' than the detonation of explosives, requiring that a variety of physical phenomena be considered, including the following:

- thermonuclear reactions,
- electron and photon heat conduction,
- hydrodynamical motion,
- alpha-particle transport,
- neutron transport.

Depending on the parameters, one process or another turns out to be leading: either 'hydrodynamic' detonation occurs or a supersonic burning wave originates.



Figure 6. Images of detonating cords.

Feoktistov and his colleagues were able to obtain estimates for the detonation velocity and the limiting size of the detonating cord, i.e., the two major parameters of thermonuclear detonation. Curiously enough, there is orderof-magnitude agreement between the limiting detonation diameter of a DT mixture and the critical diameters of highpower chemical explosives.

These estimates were confirmed reasonably accurately in a number of experiments using the energy of a nuclear explosion to precompress DT cords and cause ignition. The DT mixture was compressed to ~ 10 g cm⁻³ by nuclear implosion, the diameters of the cords being compressed to 2 to 3 orders of magnitude less than their length. The diameter at which detonation terminated was somewhat greater than predicted, possibly due to the lack of homogeneity in compressing and heating the thermonuclear mixture.

The detonation velocity was measured to range between 5×10^8 and 8×10^8 cm s⁻¹, and the maximum temperatures between 50 and 70 keV, all in accordance with theory. As an example, Fig. 6 demonstrates a photograph of the time-integrated neutron images of several DT cords, taken in one of the experiments.

5. 1983 multitask physics experiment

The 1983 experiment was designed, first, to apply the reflection method to measure the shock compressibility of Al and Pb relative to that of Fe, as well as the compressibility of Fe relative to that of Pb. For this purpose, some of the horizontal channels were used. In other channels, averaged and spectral opacities of Al and Fe were measured (the remaining horizontal channels) and detonation regimes investigated (the top of the apparatus). The experimental apparatus is shown schematically in Fig. 7.

At maximum pressures, the required information was collected by placing the measuring assemblies in the immediate vicinity of the nuclear explosive. Because large radiative



Figure 7. Schematic setup of the 1983 multitask experiment: (a) side view, and (b) top view — I, light channels for shock-wave and integrated optical measurements; 2, channels for spectral optical measurements, and 3, channels for registering thermonuclear detonation.

fluxes prevented the employment of electrocontact sensors, optical detection means were developed.

The experiment provided data on the shock compressibility of Al and Pb relative to the compressibility of Fe, and the compressibility of Fe relative to that of Pb, while also improving results on radiation lengths (both integral and spectral) and measuring the major parameters of thermonuclear detonation.

6. Production of transuranium isotopes

Using intense neutron fluxes accompanying nuclear explosions, American and Soviet scientists were able to discover a number of new isotopes of transuranium elements [26, 27]:

- ²⁴⁴Pu, ²⁴⁵Pu, ²⁴⁶Pu;
- ²⁴⁶Am;
- ²⁴⁶Cm, ²⁴⁷Cm, ²⁴⁸Cm;
- ²⁴⁹Bk;
- ²⁴⁹Cf, ²⁵²Cf, ²⁵³Cf, ²⁵⁴Cf;
- ²⁵³Es, ²⁵⁵Es;
- ²⁵⁵Fm.

In the late 1980s, cooperation began between the Soviet nuclear research centers and American nuclear laboratories, in which connection, in particular, the prospects for internationally collaborative research using nuclear explosions were discussed.

However, the USSR's 1989 nuclear testing moratorium and the Comprehensive Nuclear Test Ban Treaty that followed have put an end to this research.

References

- Nikiforov A F, Novikov V G, Uvarov V B Kvantovo-statisticheskie Modeli Vysokotemperaturnoi Plazmy: Metody Rascheta Rosselandovykh Probegov i Uravnenii Sostoyaniya (Quantum-Statistical Models of High-Temperature Plasma: Methods for Calculating Rosseland Lengths and Equations of State) (Moscow: Fizmatlit, 2000) [Translated into English: Quantum-Statistical Models of Hot Dense Matter: Methods for Computation of Opacity and Equations of State (Basel: Birkhäuser-Verlag, 2005)]
- Avrorin E N, Vodolaga B K, Simonenko V A, Fortov V E Usp. Fiz. Nauk 163 (5) 1 (1993) [Phys. Usp. 36 337 (1993)]
- 3. Trunin R F Usp. Fiz. Nauk 164 1215 (1994) [Phys. Usp. 37 1123 (1994)]
- Al'tshuler L V Usp. Fiz. Nauk 85 197 (1965) [Sov. Phys. Usp. 8 52 (1965)]
- Al'tshuler L V, Zel'dovich Ya B, Styazhkin Yu M Usp. Fiz. Nauk 167 107 (1997) [Phys. Usp. 40 101 (1997)]; Al'tshuler L V et al. Vestn.

Ross. Akad. Nauk 74 1011 (2004) [Herald Russ. Acad. Sci. 74 613 (2004)]

- 6. Vil'danov V G et al. Khim. Fiz. 14 (2-3) 122 (1995)
- 7. Zhugin Yu N et al. Fiz. Zemli 35 (6) 46 (1999)
- 8. Latter R Phys. Rev. 99 1854 (1955)
- Kirzhnits D A Zh. Eksp. Teor. Fiz. 32 115 (1957) [Sov. Phys. JETP 5 64 (1957)]
- Kalitkin N N, Kuz'mina L V, Preprint No. 35 (Moscow: Institute of Applied Mathematics of the USSR Academy of Sciences, 1975)
- Kopyshev V P Chislennye Metody Mekh. Sploshnykh Sred 8 (6) 54 (1977)
- Avrorin E N et al. Pis'ma Zh. Eksp. Teor. Fiz. 31 727 (1980) [JETP Lett. 31 685 (1980)]
- Avrorin E N et al. Zh. Eksp. Teor. Fiz. 93 613 (1987) [Sov. Phys. JETP 66 347 (1987)]
- Avrorin E N et al. Pis'ma Zh. Eksp. Teor. Fiz. 43 241 (1986) [JETP Lett. 43 308 (1986)]
- 15. Troshin O V Izv. Vyssh. Uchebn. Zaved. Fiz. (4) 57 (1968)
- 16. Zink J W Phys. Rev. 176 279 (1968)
- Sin'ko G V Chislennye Metody Mekh. Sploshnykh Sred 10 (3) 124 (1979)
- Nikiforov A F, Novikov V G, Uvarov V B, in Matematicheskoe Modelirovanie: Fiziko-khimicheskie Svoistva Veshchestva (Mathematical Modeling: Physical and Chemical Properties of Matter) (Eds-in-Chief A A Samarskii, N N Kalitkin) (Moscow: Nauka, 1989) p. 162
- 19. More R M et al. Phys. Fluids 31 3059 (1988)
- 20. Ragan III C E, Silbert M G, Diven B C J. Appl. Phys. 48 2860 (1977)
- 21. Simonenko V A et al. *Zh. Eksp. Teor. Fiz.* **88** 1452 (1985) [*Sov. Phys. JETP* **61** 869 (1985)]
- 22. Vakhrameev Yu S, Mokhov V N, Popov N A At. Energ. **49** (2) 91 (1980) [At. Energy **49** 567 (1980)]
- Avrorin E N, Feoktistov L P, Shibarshov L I Fiz. Plazmy 6 965 (1980) [Sov. J. Plasma Phys. 6 527 (1980)]
- 24. Avrorin E N et al. *Fiz. Plazmy* **10** 514 (1984) [*Sov. J. Plasma Phys.* **10** 298 (1984)]
- Feoktistov L P Usp. Fiz. Nauk 168 1247 (1998) [Phys. Usp. 41 1139 (1998)]
- 26. Ingley J S Nucl. Phys. A 124 130 (1969)
- 27. Adamskii V B At. Energ. 81 207 (1996) [At. Energy 81 651 (1996)]