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Celebrating the 65th anniversary of the Russian Federal Nuclear Center — All-Russian Research Institute of Experimental Physics

(Scientific session of the Physical Sciences Division of the Russian Academy of Sciences, 6 October 2010)

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A scientific session of the Physical Sciences Division of the Russian Academy of Sciences (RAS) took place on 6 October 2010 in the Conference Hall of the Lebedev Physical Institute, RAS (FIAN) on the occasion of the 65th anniversary of founding of the Russian Federal Nuclear Center — All-Russia Research Institute of Experimental Physics (RFNC – VNIIEF).

The agenda of the session announced on the website www.gpad.ac.ru of the RAS Physical Sciences Division listed the following reports:

(1) **Ilkaev R I** (RFNC–VNIIEF, Sarov, Nizhny Novgorod region). Opening remarks "On the fundamental physics research programs at RFNC–VNIIEF";

(2) **Mikhailov A L** (RFNC–VNIIEF, Sarov, Nizhny Novgorod region) "Hydrodynamic instabilities in various media";

(3) **Trunin R F** (RFNC–VNIIEF, Sarov, Nizhny Novgorod region) "Study of extreme states of metals using shock waves";

(4) **Ivanovskii A V** (RFNC–VNIIEF, Sarov, Nizhny Novgorod region) "Explosive magnetic energy generators and their application in research";

(5) **Podurets A M** (RFNC–VNIIEF, Sarov, Nizhny Novgorod region) "X-ray studies of the structure of matter in shock waves";

(6) **Garanin S G** (RFNC–VNIIEF, Sarov, Nizhny Novgorod region) "High-power lasers in studies of the physics of hot, dense plasma and thermonuclear fusion";

(7) **Selemir V D** (RFNC–VNIIEF, Sarov, Nizhny Novgorod region) "Physics research in ultrahigh magnetic fields";

(8) **Mkhitar'yan L S** (RFNC–VNIIEF, Sarov, Nizhny Novgorod region) "Gasdynamic thermonuclear fusion."

Articles based on reports 1–7 are published below. An extended version of report 3 written as a review paper will be published in a later issue of *Physics–Uspekhi*.

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Fundamental physics research at the All-Russian Research Institute of Experimental Physics

R I Ilkaev

1. Introduction

The present article opens a series of publications devoted to the work on the physics of high energy densities at the Russian Federal Nuclear Center — All-Russian Research Institute of Experimental Physics (RFNC–VNIIEF). Historically, the progress in many areas of this science was closely connected with the research aimed at developing nuclear and thermonuclear weapons.

RFNC–VNIIEF was founded on 9 April 1946. The main tasks of the institute were to develop the first Soviet atomic bomb, then the first thermonuclear weapons, and later to design prototypes of nuclear and thermonuclear charges of various types and for various purposes. A number of fundamental physical results were obtained in the course of our activities within this program.

RFNC–VNIIEF is Russia's largest research institute for complex tasks of importance for defense, science, and the economy. The institute has made a decisive contribution to solving problems of the creation of nuclear and thermonuclear weapons in this country and to ending the atomic monopoly of the USA. The activities of the institute allowed achieving nuclear balance during the Cold War and contributed to the balance of powers in the world, thus saving humanity from global military conflicts.

Among those who worked at VNIIEF were eminent scientists I V Kurchatov, Yu B Khariton, Ya B Zel'dovich, A D Sakharov, N N Bogoliubov, M A Lavrent'ev, I E Tamm, G N Flerov, E A Negin, S G Kocharyants, A I Pavlovskii, Yu A Babaev, S B Kormer, and others, who created at the

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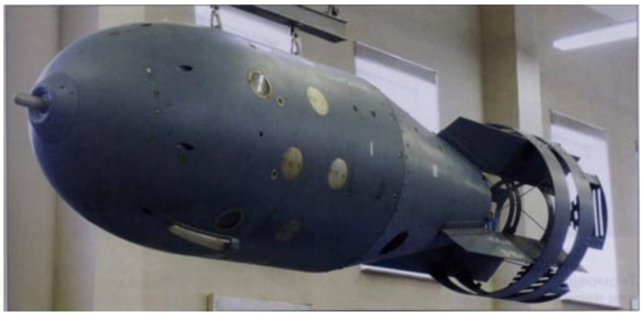
The first Soviet atomic bomb. The nuclear warhead was tested on 29 August 1949 at the Semipalatinsk test site. The charge power is 22 kilotons of TNT equivalent.

The first hydrogen bomb. The nuclear warhead was tested on 12 August 1953 at the Semipalatinsk test site. The charge power is 400 kilotons of TNT equivalent.



The first serial tactical atomic bomb. Tested in 1953 at the Semipalatinsk test site. The charge power is 30 kilotons of TNT equivalent.

The building of the Institute of Theoretical and Mathematical Physics of RFNC–VNIIEF.

institute much of what constitutes the pride of our science. Large schools of physicists, mathematicians, designers, engineers, and chemists grew up and continue to thrive at the institute.

The main task of the nuclear center today is to ensure and maintain the safety and security of Russia's nuclear weapons.

RFNC–VNIIEF has powerful computational, experimental, testing, technological, and industrial bases, permitting us to rapidly find high-quality solutions to assigned tasks.

RFNC–VNIIEF incorporates several institutes: Theoretical and Mathematical Physics, Experimental Gas Dynamics and the Physics of Explosions, Nuclear and Radiation Physics, Laser Physics Research, and the Center for High Energy Densities, as well as design bureaus and purpose centers under a joint scientific and administrative management.

The high scientific and technological potential allowed RFNC–VNIIEF to broaden the span of research and development, to rapidly join new hi-tech areas, to obtain and successfully develop world-class scientific results, and to carry out unique fundamental and applied research projects. The path to the future of our institute is therefore closely tied to its transformation into the National Security Center of the Russian Federation.

2. Gas dynamics

In the field of applications, the gasdynamic research at RFNC–VNIIEF has always been and continues to be motivated by searching for solutions to various problems of the implosion of fissile materials driven by the explosive energy of chemical high explosives (HEs).

Among the fundamental results in this area, we first of all mention

• determination of the levels of cumulation of explosive energy of HEs under spherically symmetric, axisymmetric, and three-dimensional loading of metals, and conclusions on the sustainability of cumulation;

• implementation of the precision of a shock wave convergence at the center of spherical and axisymmetric systems at the level of $\leqslant 3 \times 10^{-3}$ of the system size;

• achievement of metal compression levels in implosive compression systems by a factor greater than 7 relative to their initial density.

Gasdynamic research is associated with a series of studies aimed at formulating the equations of state for many substances in the range of shock-wave loading, including the pressure range up to ~ 10 TPa.

I must highlight the conclusions about the peculiarities of energy cumulation in highly asymmetric conditions of dynamic flows that underlie the solutions to the problems of nuclear explosion safety of nuclear weapons.

RFNC–VNIIEF scientists have studied a number of aspects of the physics of detonation processes in detail, including the initiation of detonation, the stability of its propagation, and the transfer of detonation through inert shields. In this area, they formulated a system of process stability criteria and/or criteria of process transformation.

Although the program of gasdynamic research is based first and foremost on physical experiments (the experimental settings and diagnostic tools were also designed in our institute), the scientists at RFNC–VNIIEF have developed precision techniques for physical and mathematical modeling of gas dynamics, including three-dimensional simulation. It can be said that theory and experiment complement and enrich each other in this field.

We are traditionally among the world leaders in gasdynamic studies in this area and feel obliged to maintain this leadership; this requires active support of the science schools created in VNIIEF and systematic upgrade of the experimental facilities.

What fundamental problem still remains unsolved in this area? I would single out gasdynamic fusion.

Work on this issue resulted in a major research field in the mid-1950s, because it was very tempting to try to 'ignite' thermonuclear fuel using the cumulation of explosive energy of HEs. More than a hundred large-scale experiments have been conducted since then, but the problem remains unresolved and, apparently, is still far from resolution. Compression levels of the central metal shells have to exceed 50 and the density of the thermonuclear fuel exceed 10^2 g cm^{-3}. Perhaps we are dealing here with the fundamental development of instabilities and it has been beyond our practical capabilities so far to reduce them.

3. Radiation gas dynamics

This line of basic research is primarily associated with the design of thermonuclear charges. The basic principle here is radiative implosion, which assumes that

• a large fraction of the energy released in the explosion of a nuclear charge (primary module) is in the form of X-ray radiation;

• the energy of X-ray radiation is transported to the thermonuclear module;

• the implosion of the thermonuclear module is accomplished by the energy of the 'transported' X-ray radiation.

The implementation of each of the three components of this principle is based on radiation gas dynamics.

The explosion of a nuclear charge with the major part of the energy released in neutron-initiated reactions in the fissile material is accompanied with the transformation of energy into the energy of X-rays and thermal energy of matter, both at equilibrium, and into the kinetic energy of the medium. The process occurring in matter is that of the transfer of X-ray radiation emitted from the surface of fissile material and continuing to propagate through the outer regions of the primary module.

Obviously, this mechanism depends strongly on the fundamental characteristics, i.e., the free path of X-rays over which their interaction with matter occurs. For substances such as uranium, the processes of decisive importance are photoabsorption and discrete–discrete transitions. This stage of the process was investigated under both the approximation of radiant heat conduction and that of the spectral kinetics. A number of mathematical physics models of radiation gas dynamics were developed at RFNC–VNIIEF, adapted to the computing power available at the time. Currently, we use a three-dimensional model in the approximation of radiant heat conduction and two-dimensional models based on the spectral kinetic equation of radiation transfer, used jointly with the equations of gas dynamics.

For a number of years, our Institute commissioned the calculation of the ranges for radiation propagating through various media at the Institute of Applied Mathematics of the Academy of Sciences. We have created precision software using modern computing capabilities for calculating spectral ranges of radiation for various substances and conditions, and developed algorithms for computing the group and average ranges in accordance with the needs of models of radiation gas dynamics. Research on radiation gas dynamics has allowed implementing control of the transfer of X-rays within the primary unit and dramatically improving the quality of the modules as energy sources for radiation implosion; this was extremely important for practical work.

The second part of the principle of radiation implosion is mainly associated with model-based research on radiation gas dynamics in the processes of reflection and transmission of X-rays through multilayer configurations of various materials, which are often multi-element geometric shapes with complex dynamics. The practical result of this research was the determination of the amount of energy available for radiation implosion of thermonuclear modules. The main requirement at the first stage was to maximize the amount of energy of X-rays emerging from the primary module, but at the second stage, it was replaced with the requirement of minimizing energy losses.

The third part of the radiation implosion principle was associated with studying the transformation of X-ray energy in the pressure field compressing the fusion module. This field, which is the result of a complex process of radiation propagation through various materials, is axisymmetrically structured. To obtain acceptable results in the compression of a thermonuclear module, it is necessary to transform the axisymmetric boundary conditions so as to achieve symmetric implosion. The solution to this problem requires the ability to control the radiation flow and the gasdynamic flows of both high-temperature and low-temperature high-density plasmas, which has been achieved by using two-dimensional models of radiation gas dynamics.

The specific features of 'boundary conditions' are such that implosion of a thermonuclear module may be relatively stable, but may happen to be unstable. Important practical applications exist in which the processes are essentially three-dimensional, and we have therefore developed three-dimensional models of radiation gas dynamics. I emphasize that the level of pressure in radiation implosion that determines the compression of fusion modules reaches several hundred TPa, and compression reached during implosion is so high that the density of materials may be greater than the initial density by a factor of several dozen.

Methods of physical and mathematical simulation play the major role in solving these problems. This is dictated both by the specifics of information obtained in testing thermonuclear charges and by the lack of testing opportunities at present. The determination of 'stability zones' of radiation implosion in thermonuclear modules, as well as the determination of physical factors that push implosion out of these zones, was among the most important experimental results.

I emphasize that the radiation gas dynamics is an outstanding example of a fundamental field of knowledge underpinning the design of structures in which complex physical processes are intertwined and the available experimental information on key parameters was very sparse. Enormous practical achievements obtained on the basis of radiation gas dynamics has undoubtedly made us leaders in this area; the least I can say is that our research results are on a par with those reported in the US.

What are the issues that I consider to be extremely important in this context?

First and foremost, we need to strengthen the experimental basis for laboratory simulation of the specific features of physical processes that have the same nature as their counterparts in radiation implosion. Such facilities are high-power lasers being developed for laser fusion. Two prototypes of such facilities operate at our institute, but their energy is insufficient for implementing the required simulation. We need a laser with the power output of the order of 1 MJ.

Installations of this class have been implemented in the US and in France and are under construction in the UK and in China. Although we submitted a proposal for building a new high-power laser for experimental research into the fundamental parameters of radiation implosion in the 1990s, the implementation has not started yet. We are very concerned about falling behind, although VNIIEF was among the world leaders in this field up to the mid-1990s. Last year, the president of the Russian Federation made a Decision in principle concerning the creation of a megajoule-level laser facility at VNIIEF.

4. Thermonuclear burning

Our institute designed a device (thermonuclear charge RDS-6c) in which the burning of thermonuclear fuel was realized for the first time on 12 August 1953. This device, developed as a model for the high-power 'hydrogen' bomb, is widely known as Andrei Sakharov's 'sloika' (layer cake). A number of fundamental questions were resolved in this project.

The device was a system of alternating layers of fusion material (lithium deuteride-tritide and lithium deuteride) and uranium with various concentrations of the isotope U-235, providing their gasdynamic implosion. I go into some detail here because this device can be regarded as a physical setup for the implementation of a pulsed thermonuclear reaction.

First, the initial heating of the fusion product was effected by the nuclear explosion of the central core of U-235. To ignite the fusion material, it was important to also subject it to implosion. Second, the developing isothermal regime between the fusion material and the surrounding uranium produced additional compression of the thermonuclear material due to pressure equalization (the process known as 'Sakharization'). Third, the burning of thermonuclear material occurred in the thermodynamic equilibrium regime between radiation and matter. Fourth, the fission of uranium by 'thermonuclear' neutrons provided an additional increase in the temperature of the medium and additional intensification of thermonuclear reactions, followed by further fission of uranium and so forth.

In the USA, Edward Teller considered a 'layered' thermonuclear charge in 1946–1947. But such a charge was never created in the United States. One of the factors that influenced this was the limited scalability of the energy release; another was a fundamental factor, the possible development of instabilities in the implosion of a layered system at the initial stage of nuclear burning.

In our design, we attached great importance to ensuring the precision of the gasdynamic implosion; the experiment confirmed the absence of significant effects of gasdynamic instabilities on thermonuclear burning.

The problem of scaling of energy release was solved by choosing radiation implosion as the method. By the time the potentials of this principle had been recognized (1954), we had in fact already designed a prototype fusion module, which was the central part of the RDS-6c. Under these new conditions of implosion that is many times more powerful, the fusion module significantly increased the energy release (lithium deuteride was used as fusion material). This principle was implemented on 22 November 1955 in testing the RDS-37. It is essential that no effect of hydrodynamic instabilities on the thermonuclear burning was found after this new form of implosion was used.

Cases occurred later during full-scale tests of thermonuclear charges of various types in which thermonuclear burning did not comply with design calculations. With time, as the physical and mathematical models were becoming more sophisticated and computing power was increasing, dramatic growth of large-scale hydrodynamic instabilities was detected in a number of cases, which led to the reduced effectiveness of thermonuclear burning.

Nearly perfect prototypes were created as part of the program of construction of thermonuclear charges, and they continue to form the foundation of nuclear deterrent. As regards their quality, they are definitely at least as good as their American counterparts.

What is the problem I would like to highlight here? Not all the results of full-scale field tests of thermonuclear charges were given consistent physical explanations. This means that not all the features of thermonuclear burning in such devices are fully understood, and we are working on further improvements in the physical and mathematical models in this area. I stress that this requires further expansion of computing power.

5. Boosting

The implementation of ignition and steady-state combustion in the tritium–deuterium (TD) mixture of nuclear charges known as boosting was a fundamental achievement of the physics of high energy density. From the practical standpoint, this led to considerable progress in the overall size and mass parameters of nuclear charges and increased their safety and operational stability in certain environments.

This is physically a very complex mode because TD ignition of a mixture occurs at relatively low temperatures created at the initial stage of a nuclear explosion, and by that instant the TD mixture itself constitutes a complex heterogeneous structure integrated with the surrounding fissile material. Gasdynamic studies play an exceptional role in finding the solution to this problem and involve radiographic methods. Radiographic experiments have shown that meeting certain criteria helps convert the potentially unstable regime of implosion in the TD mixture and the surrounding fissile material into a stable final state.

The implementation of boosting is closely linked with the methods of physical and mathematical modeling, and we have developed a number of techniques involving precision calculations in a semiphenomenological formulation. I emphasize that we were able to develop a number of methods for controlling the boosting based on gasdynamic studies and methods of physical and mathematical modeling. These control capabilities are of exceptional practical value.

Here, I outline a significant problem. The configuration of the 'critical' region that determines the boosting is essentially three-dimensional. To determine it with sufficient accuracy, we need three-dimensional gasdynamics programs, which include a description of the detonation of HEs, and to take the specific properties of burning in this configuration into account, it is necessary to perform three-dimensional calculations of radiation gas dynamics and the nuclear neutron-initiated interaction. Because of the need to take specific characteristics of the 'critical' region into account, we need significantly more powerful computing capabilities than those currently available to us.

6. Initiation of thermonuclear fusion

The fundamental difficulties involved in realizing inertial confinement fusion are well known. This problem was partly solved at RFNC–VNIIEF. To achieve this, in 1962 we subjected a spherical system containing thermonuclear fuel but not containing fissile materials to radiation implosion. As a result, we managed to achieve the ignition of thermonuclear material with low energy release. Again in 1962, we conducted two other successful experiments in which we achieved fusion initiation of lithium deuteride. The fusion-initiation system (FIS) was used to ignite other layers of the thermonuclear fuel.

It was a very important achievement based on fundamental conclusions concerning the key role of the symmetry of compression of the FIS and the feasibility of its practical realization.

The very idea of the FIS in radiation implosion was formulated in 1954 and a series of experiments on its implementation were soon conducted. All of them have been unsuccessful. An analysis of the ignition of the FIS allowed formulating a hypothesis that the level of symmetry acceptable for the implosion of fissile materials is insufficient for the implosion of thermonuclear ignition initiating systems. Success was achieved by implementing the conclusions drawn from this hypothesis.

A large number of different types of FISs were later developed and have found important practical applications. Here, I only mention their fundamental significance for carrying out nuclear explosions for peaceful purposes.

Tests of fusion-initiating systems and the progress in simulation allowed establishing the precise criteria for their ignition taking specific features of their implosion, the materials used, and other factors into account.

7. Neutron-initiated nuclear processes

Fundamental studies of neutron-initiated nuclear processes began at RFNC – VNIIEF with the work on the critical mass of fissile materials in various configurations. This work began simultaneously with the development of the first atomic bomb RDS-1 and continues to this day. This work is based on both experiments performed on critical mass test benches and modern computational methods of simulation. Although the critical masses of important fissile materials have long been known with very high accuracy, new issues arise time and again when special materials are to be used.

Another research avenue is related to the kinetics of chain reaction in various types of systems and under different neutron exposure conditions, which is in turn one of the foundations for solving problems of nuclear explosion safety. The basis for these studies were experiments on fission cross sections, the cross sections of elastic and inelastic scattering, the numbers of secondary neutrons, and the spectra of fission neutrons; these experiments were conducted on a wide scale at our institute in the first half of the 1950s. Special programs in this field were performed for the creation of the first thermonuclear charge RDS-6c. Later, the accuracy of these 'fundamental constants' was regularly improved in new experiments.

The interaction of fusion neutrons with fissile materials under boosting conditions has become a fundamental issue. These same issues are also important for the burning regimes of thermonuclear modules.

The burning of boosted and thermonuclear charges is a very important stage and requires integrated analysis of the processes of radiation gas dynamics, charge burning, and thermonuclear neutron kinetics in multicomponent media. At the current stage, we are using a number of two-dimensional simulation programs for this purpose.

We have developed a number of methods for calculating the neutron transport in complex heterogeneous configurations and compiled high-precision systems of spectral constants and neutron group constants for all isotopes that we encounter in our work.

8. Nonequilibrium processes

Our work is directly related to studying a number of nonequilibrium processes. I cite a few examples.

One of the modes that may be encountered is where the thermodynamic equilibrium does not have enough time to set in, on the one hand, between electrons and ions, and on the other hand, between electrons and radiation. This mode was produced on numerous occasions and recorded in experiments, and we have developed special physical and mathematical models for its description.

There is a certain probability under the conditions of thermonuclear burning that even if the thermodynamic equilibrium sets in, fast particles produced in thermonuclear fusion reactions enter into new thermonuclear reactions before being thermalized. To investigate this process, we conducted a number of dedicated studies, whose results are incorporated into the models and are used in practical work.

A typical situation is that the energy flux density of X-ray radiation is much higher than the equilibrium flux density corresponding to the ambient temperature, while the spectrum of the X-ray flux is essentially non-Planckian. These factors are also included in the programs of radiation gas dynamics.

9. Conclusion

Here, I am unable to provide the most vivid examples of the work mentioned above. At the same time, these studies were accompanied by scientific searches and generated perfectly nonclassified results. Some of them relate directly to solving our main weapon-related problems, but some are only partly related. In the articles published in this issue of *Physics–Uspekhi*, our leading specialists present the results of such nonclassified research. I hope that these articles give a fairly complete picture of a number of the specific characteristics of our work.

Over the span of 65 years, a large number of outstanding specialists and great scientists in our country have taken part in creating and developing new research fields related to the work at RFNC – VNIIEF. I do not list the names because no sampling would be sufficiently representative. It can be said that we are discussing the science of RFNC – VNIIEF in broad terms.

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Hydrodynamic instabilities

A L Mikhailov, N V Nevmerzhitskii, V A Raevskii

1. Introduction

This article presents results of experimental research on exploring hydrodynamic instabilities and turbulent mixing in liquid, gaseous, and strength media. In particular, it is shown that (1) the development of perturbations and turbulent mixing in gases is sensitive to the Mach number of the shock wave; (2) the speed of propagation of a gas front in liquids does not change as the Reynolds number increases from 5×10^5 to 10^7; (3) the stable and unstable regimes in media with strength depend on the wavelength and amplitude of initial perturbations; (4) hydrodynamic instability may serve as an instrument to explore the strength properties of materials.

One of the most ambitious and important scientific and practical problems is that of controlled nuclear fusion (CNF). The realization of the CNF idea turned out to be principally dependent, among other things, on one 'trifle' — the Rayleigh–Taylor [1], Richtmyer–Meshkov [2, 3], and Kelvin–Helmholtz [4] hydrodynamic instabilities. Arbitrarily small initial perturbations at the interface between different media begin to grow, which, with time, leads to a turbulent mixing of substances. As a result, energy losses occur, leading to limitations on the energy density required for ignition that can be accumulated in targets.

Research on the hydrodynamic instability and turbulent mixing has been carried out at the Russian Federal Nuclear Center — All-Russian Research Institute of Experimental Physics (RFNC–VNIIEF) beginning practically from its foundation date. In particular, the main results found by Taylor (1950) (for the so-called gravitational instability) were independently obtained by S Z Belen'kii and E S Fradkin from the Lebedev Physical Institute (FIAN); they took part in work on the atomic problem at that time, and their results were collected in a series of unpublished VNIIEF reports in the late 1940s and early 1950s. This research also proposed the first semi-empiric model for the evolution of the mixing zone [5]. In 1951, through the initiative of A D Sakharov, Yu F Alekseev, I G Proskurin, and N F Zelentsova carried out the first experimental studies on turbulent mixing on an interface between two liquids, the results of which have not been published even to date.

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In the middle of the 1960s, in experiments on a shock tube, E E Meshkov discovered that the interface between two gases is unstable not only when the shock wave (SW) travels from a 'light' gas into a 'heavy' one (according to Richtmyer's results) but also when the SW moves in the opposite direction [3]. Since then, the instability of the interface induced through a SW is referred to as the Richtmyer–Meshkov instability. In the early 1970s, in VNIIEF, V V Nikiforov started developing the first semi-empiric models of turbulence, and the first numerical simulations of turbulent flows saw their implementation at that time (V A Andronov, S M Bakhrakh, A V Pevnitskii, and others).

The first research in the USSR on the Rayleigh–Taylor instability in solids began at VNIIEF in the late 1950s and was associated with the names of A D Sakharov, R M Zaidel', A G Oleinik, and others. The overwhelming majority of their results were not published in the open press, except the series of studies [6].

Over the last decade, hydrodynamic instabilities in different media remained the subject of thorough research, both theoretical, assisted with physical and numerical modeling, and experimental. Experiments, being a source of basic data for verification of physical and numerical models, also serve as the source of information on fundamental laws of process development and properties of substances — their strength, rheology, and phase transitions.

In Sections 2–4, we sketch some directions and results obtained over recent years in classical shock-wave experiments in shock tubes and in explosion gasdynamic systems.

2. Development of turbulent mixing and perturbations at a contact interface between gases

Numerical simulation of flows affected by turbulent mixing requires experimental data to verify and test the models. The information currently available for this purpose (see, e.g., Ref. [7]) is insufficient for the emerging new tasks. To substantiate computational algorithms, in particular, we have carried out a set of experiments in air shock tubes on the evolution of turbulent mixing in three-layer gas systems: air – SF_6 – air, air – He – SF_6, and air – He – air [8]. The contact gas interfaces were arranged perpendicular or at an angle to the direction of the SW, or had breaks. Such location of interfaces resulted in a two-dimensional flow. The gases were initially separated by a thin polymer film (1 μm thick). The Mach number of the SW reached $M \approx 1.3$. The Kelvin–Helmholtz instability, in addition to the Meshkov–Richtmyer instability, was observed at contact interfaces (Fig. 1). A fairly complex flow was formed as a result of the interaction of rarefaction and shock waves with the interfaces, offering ample material to calibrate computational techniques.

When a contact interface between gases is accelerated by a strong shock wave (with the Mach number $M > 5$) or a series of waves passing in sequence through the gases, the gases can be compressed by a factor of several dozen. As a consequence, the contact interface between gases may approach the SW front [9]. In this case, the mixing zone or perturbations appearing at the interface may rest against the front of the SW, which affects the flow character.

To explore such a situation, a laboratory technique enabling research in gases at the SW Mach numbers $M \approx 10$ was proposed in 2002. Obtaining Mach numbers that high in a shock tube was made possible by detonating a gaseous