Physics – Uspekhi **51** (10) 1047 – 1053 (2008)

FROM THE HISTORY OF PHYSICS

PACS numbers: **01.65.+g**, **28.52.–s**

Thermonuclear fusion in the explosion of a spherical charge (the problem of a gas-dynamic thermonuclear fusion)

N A Popov, V A Shcherbakov, V N Mineev, P M Zaydel', A I Funtikov

DOI: 10.1070/PU2008v051n10ABEH006688

Contents

Abstract. **A review is given of gas-dynamic thermonuclear fusion (GDTF) — a novel line of inertial thermonuclear fusion research based on the cumulative spherical compression of the deuterium – tritium gas using a high explosive charge. Major aspects of the research are examined and the record results achieved by the mid-1980s are discussed.**

1. Introduction

The problem of thermonuclear energy release (TE) under the fast spherically symmetric compression of a gaseous deuterium – tritium (DT) target placed at the center of a cumulative charge of a high explosive (HE) involves various aspects of the physics of high energy density that have both purely academic and practical application value. As a result of implosion in the appropriate cumulative systems, the energy of detonation of an HE is concentrated in the central part of the device.

For a DT mixture to achieve thermonuclear ignition of an explosion as a result of its compression by the shell, the integral ignition criterion [1, 2], which is a generalization of the Lawson criterion, must be satisfied. In a simplified form, it is written as the conditions

$$T \geqslant 2-3\ \text{keV}, \quad \rho r \geqslant 1\,\text{g}\,\text{cm}^{-2}, \tag{1}$$

where T is the maximum temperature [keV], ρ is the maximum density [g cm^{-3}], and r is the minimum radius [cm] of the spherical DT mixture. Hence, for thermonuclear ignition of the central DT mixture, it must not only be heated to a sufficiently high temperature but also be simultaneously compressed to a sufficiently high density.

The following condition must be satisfied to ignite the DT mixture by a focused shockwave (SW) (behind the wavefront of the SW reflected from the center) [3 – 5]:

$$\rho_0 r_0 u_0^{2.2} \geqslant 1, \tag{2}$$

where ρ_0 is the initial density [g cm^{-3}], r_0 is the initial radius of the spherical DT target [cm], and u_0 is the initial velocity of compression of the gas [10^7 cm s^{-1}] ([100 km s^{-1}]). Under GDTF conditions, inequality (2) for the initial radius of the DT gas (with r of the order of 1 mm) can be implemented if the gas is precompressed to a density ρ_0 of the order of several tens of grams per cm^3.

This may ignite the central part of the DT gas, after which fusion spreads to the entire precompressed gas, the so-called fast ignition — the term often used to denote thermonuclear ignition of a compressed gas by an external high-intensity laser beam.

Obviously, ignition conditions (1) require the cumulation of energy in the GDTF system, which depends on the source of the initial energy of the HE charge, that is, on the mass of the HE and the design of its cumulation into the central thermonuclear region, as well as on the achieved maximum density of the DT fuel, which mostly depends on the choice of material of the compressible shell (the degree of compression increases as the initial density of the shell increases, and hence so-called heavy shells are typically used, made of metals such as gold, platinum, tungsten, etc.) and on the time-dependent external pressure, which is determined by the overlying layers of the multilayer cumulation system.

The real conditions for ignition are significantly affected by the symmetry of compression, which determines the maximum achievable density of fuel, and by mixing at the boundaries between layers with unequal densities, which

---

N A Popov, V A Shcherbakov Russian Federation Nuclear Center
'All-Russian Scientific Research Institute of Experimental Physics',
prosp. Mira 37, 607188 Sarov, Nizhegorodsk. region, Russian Federation
Tel. (7-83130) 2 83 86
E-mail: napopov@vniief.ru
V N Mineev, R M Zaydel', A I Funtikov Joint Institute
for High Temperature, Russian Academy of Sciences,
ul. Izhorskaya 13/19, 125412 Moscow, Russian Federation
Tel. (7-495) 484 16 22. Fax (7-495) 485 79 90
E-mail: funtikov@ihed.ras.ru

Received 24 June 2008
Uspekhi Fizicheskikh Nauk **178** (10) 1087 – 1094 (2008)
DOI: 10.3367/UFNr.0178.200810f.1087
Translated by V I Kisin; edited by A M Semikhatov

determines the degree of cumulation and the maximum temperature at the center of the thermonuclear fuel [6].

The work on GDTF seems to have been pioneered in Germany during the Second World War in connection with the German nuclear bomb project [7, 8]. The idea of implementing thermonuclear fusion in the focal point of a spherical charge with an inserted shell [9] extended the principle of cumulative projectiles with shell plating, also first suggested in Germany as part of the Faustpatrone weapon development. This work was stimulated by the extension of Guderley's theory of implosion of a shockwave [10].

Nothing about this was known at the time in the USSR. Only in 1945 did Landau and Stanyukovich independently prove the fact of a surge in pressure, i.e., of cumulation at the front of a shockwave converging in a continuous medium [11].

The work in this country started following Kozyrev's suggestion. In 1946, he advanced the idea that the pressure and temperature sufficient for starting fusion in heavy isotopes of hydrogen may be achievable at the focal point of a spherical charge of an ordinary HE [12]. Furthermore, based on this idea, Kozyrev proposed the principal design of an explosion-driven fusion reactor that he called the spherical detonation-driven energy concentrator (SDEC).

The computational and theoretical work on GDTF was initiated at the All-USSR (currently Russian) Research Institute of Experimental Physics (VNIIEF) in 1951 by Ya B Zel'dovich, N A Popov, and V A Aleksandrov. E I Zababakhin paid constant attention to the progress of this work. Numerical estimates carried out in 1952 showed that an HE charge with a radius of 50 cm must produce the high temperatures (2 keV) required to start a self-sustained fusion reaction (ignition) if the spherically symmetric 'convergence' of the shell proceeds down to a radius of several tenths of a millimeter. Under this condition, it would be possible to ignite a thermonuclear explosion of $m \sim 10^{-3}$ g of a DT mixture [13].

The initial experimental work on GDTF started at the VNIIEF and was headed by L M Timonin and involved I G Proskurin, R S Osipov, and others. In 1958, A S Kozyrev and his co-workers Yu D Lavrovskii, M I Arifov, and S M Babadei joined the project. By the beginning of 1955, a group of physicists under Yu S Zamyatnin, with V M Gorbachev, N A Uvarov, D D Usenko, and others developed high-sensitivity instruments to measure weak neutron pulses (down to $\sim 10^4$ neutrons per pulse) using the so-called delayed registration technique (DRT) [14].

The first information on the GDTF work carried out in the USSR was presented in L A Artsimovich's report "Studies in controlled thermonuclear reactions in the USSR" published in the Proceedings of the 2nd International Conference on peaceful uses of atomic energy in Geneva in 1958. Then a letter on the subject "Fusions first for USSR" by A S Kozyrev, V A Aleksandrov, and N A Popov was published in *Nature* [15]. And finally, the paper "Ignition of a thermonuclear reaction at the focal point of a spherical charge of a high explosive" by a large team of authors (V A Aleksandrov, A S Kozyrev, N A Popov, V A Shcherbakov, et al.) was published in 1993 in *Chemical Physics* [16].

2. Computational and experimental studies in gas-dynamic thermonuclear fusion

The first experimental discovery of the generation of thermonuclear neutrons at the center of a spherical HE charge (with no quantitative measurements performed) dates back to 1954. A quantitative registration of thermonuclear neutrons formed under the same conditions by the delayed registration technique was carried out a year later. The physical arrangement of the HE charge that was chosen and justified by E I Zababakhin and N A Popov was the so-called multicascade system consisting of a sequence of relatively thin cascades fixed together into a whole structure by spokes. Each cascade was composed of shells made of a high-density material (Fe, U, etc.), light interlayers above them to reduce rigidity (e.g. plexiglass), and air gaps between the cascades. A specially adjusted ratio of shell masses was calculated by N A Popov in 1954. The neutron yield in experiments using this system was $10^7 - 10^8$ per pulse, and reached a maximum of 2×10^9 in an improved version of this system, which is more than four orders of magnitude less than the value predicted by symmetry-based calculations [14].

In 1959, E I Zababakhin proposed a new multilayer selfsimilar cumulation system, the so-called 'sloika,' composed of alternating layers with high and low density, without air gaps separating them and nonsymmetric elements such as spokes between layers [17].

Application of these systems for the purposes of GDTF resulted in increasing the neutron yield by two orders of magnitude and then to 10^{12} [14]. But even this level was lower by several orders of magnitude than the precalculated value. The sloika itself, extended to the internal boundary of the HE charge, consumed little energy and therefore energy extraction from the HE charge was executed by a relatively thin first (steel) cascade mounted on the cumulating system (the sloika) with nonsymmetric elements (spokes). In 1967, V A Shcherbakov suggested a new, more efficient system of energy extraction from a spherical HE charge by the central multilayer cumulating system. This system, consisting of a thicker (approximately three times thicker than the optimum shell thickness in the first cascade) and a steel shell more deeply placed, plus a foam plastic layer between this shell and the sloika (to replace spokes), resulted in approximately the same energy extraction as with an optimized first cascade. The effect of asymmetry of the steel shell was substantially reduced by its large thickness. It was shown that the effect of the different density of plastic foam on the dynamic processes in the system should be much reduced [18]. The efficiency of this new system of energy extraction was confirmed by experiments and the system was used in the majority of subsequent experiments.

Later suggestions made by V G Ivoninskii, V M Gerasimov, and R S Osipov, and also by Yu M Styazhkin and V A Raevskii, led to a return to the cascade energy extraction from an HE charge in the version with a multicascade structure and a hybrid system, proposed by V P Ryabov, consisting of several cascades and the inner sloika. In 1969, V A Shcherbakov proposed a design of the central part with thicker light layers (approximately twice as thick as in the optimal self-similar sloika) and with intermediate-density layers placed above the heavy shell that compresses the gas at the center of the target. This resulted, for the same external asymmetry, in a more symmetric compression of the gas and in attenuation of the negative effect of mixing both in the thicker light layers and in the gas itself. All these effects were confirmed experimentally.

The use of thicker inner layers made of LiDT allowed obtaining the ignition of the thermonuclear process with total energy release exceeding the initiating energy of the HE explosion. The discrepancy between the values of the experimental and precalculated neutron yields necessitated the development of a new design and new technology of machining a high-accuracy and so-called high-precision spherical charge. The concept of such a charge was in fact worked out already in 1963 – 1964 together with A S Kozyrev, S M Babadei, E V Zotov, L D Ryabev, and others. In addition to choosing the sloika as design basis and a new system of energy extraction from an HE as described above, this charge implemented the switch to a liquid HE (LHE), which allowed eliminating density differences in the explosive material through the uniformity of the LHE and excluding technological joints and gaps between parts of the explosive charge.

The transition to a multipoint highly synchronized system of initiation developed by E V Zotov included an extremely uniform arrangement of nearly 1000 initiation points on the outer spherical surface of the charge following the symmetry of the regular dodecahedron (as suggested by V A Shcherbakov et al.); this allowed achieving highly accurate focusing that deviated from the assumed model geometry by not more than 0.1 mm. The accuracy of manufacturing the elements of this cumulating system was brought to the level of about 0.03 mm for outer layers of the system and about 0.003 mm for its inner elements [14].

The maximum neutron yield of 5×10^{13} neutrons, which was unprecedented at the time, was recorded on 10 December 1982 from the center of a target containing the DT gas, with the initial radius $r_0 \approx 1$ mm and initial density $\rho_0 \approx 0.1$ g cm^{-3}. Estimates showed that temperatures $T \approx 0.65$ keV and the maximum density $\rho \approx 80$ g cm^{-3} were reached in this experiment. The product $\rho r \approx 0.8$ g cm^{-2} is record high for inertial thermonuclear fusion and is sufficient for igniting the DT gas if the temperature is increased by a factor of 3 to 4. This specific version of the experiment was suggested by V M Danov together with A N Anisimov, L S Mkhitaryan, and some others. However, the experimental neutron yield was again found to be lower by 2 to 3 orders of magnitude than the calculated value [19].

To explain this difference, a hypothesis was advanced that the LHE charge has a systematic vertical component of asymmetry, which is probably caused by the effect of gravity on the LHE density and whose amplitude exceeds the random experiment-to-experiment variations caused by tolerances (these variations result in a yield instability of the order of tens of percent). This hypothesis was partly confirmed by dedicated experiments [16]. However, the presence of this systematic component of asymmetry may reduce the neutron yield by a factor of 2 to 4, not by orders of magnitude; moreover, the cause of this asymmetry was not established with certainty, and it was therefore unclear how to deal with it.

3. Manifestations of hydrodynamic instability in spherical compression

The discrepancy between the idealized calculation results and experimental values of neutron yield in GDTF systems can be explained by the effects, not taken into account in the calculations, of the asymmetry and mixing at the interface between materials of different densities. The extent to which these effects are included in the evaluation by available methods cannot result in adequate descriptions of the obtained experimental results.

Recently, researchers have started to account for the jet-shaped transport of the heavy material of the compressing shell into the central gas. Jets are formed via amplification and growth of small-scale perturbations whose initial causes are the structural features of the materials of central shells and of their surfaces. Calculations with this mechanism of polluting the gas and the consequent reduction of its maximum temperature taken into account are much more efficient than those using available theories of well-developed turbulence.

Calculations carried out so far with jet-caused mixing taken into account have led to nice results both for explaining the experimental neutron yield and for reducing this effect (and thus enhancing the neutron yield), provided the appropriate structural and technological improvements of GDTF systems are carried out.

The Rayleigh – Taylor (RT) gravitational instability and turbulent mixing arise in response to the discontinuity of tangential velocities at the interface of different-density media as the interface undergoes acceleration on the side of the lighter material (e.g., as the compressing heavy shell is decelerated by the central light gas, and as the heavy envelopes of the sloika are decelerated or accelerated by the light layers) [20 – 23]. The instability of the interface between two different-density media also arises after a shockwave front passes through it (the Richtmayer – Meshkov instability [24 – 26]). At the VNIIEF, numerical modeling of developing hydrodynamic instabilities and turbulent mixing currently comprises a number of various methods, including special techniques for computing the evolution of small perturbations (SP) [27], two-dimensional and three-dimensional gas-dynamic methods, and methods based on various types of semiempirical models of well-developed turbulence. It should also be noted that instability and turbulent mixing depend essentially on the physical viscosity and strength of materials, which is especially important for the outer parts of GDTF systems. The positive effect of high strength and the refractory nature of the materials used was experimentally proved in [14].

Simultaneously with the work to increase the neutron yield in GDTF systems, the effects of perturbations of a prescribed spectral composition on this yield were studied at the VNIIEF (V E Kostyleva, R S Osipov, V A Kirdyashkin, and others). Among other things, this research helped to formulate the requirements for the accuracy of manufacturing the elements of the precision HE charge.

The strong dependence of the neutron yield on the symmetry of the converging shockwave was first observed for solid targets containing deuterium and tritium (the so-called thermonuclear indicator (TI) [28], a major role in whose development was played by V A Aleksandrov; of course, the thermonuclear ignition of the TI was not considered at the time).

Experiments with a precision-made GDTF charge showed that as the size of the central gas region decreases, the neutron yield first increases but then sharply decreases (although the results of idealized computations predicted that it should continue increasing); the neutron yield reaches its maximum value $N \sim 10^{13}$ for the initial radius of the gas region $r_0 \sim 1$ mm. Based on this, a conclusion was made in [29] that the linear asymmetry in a precision charge is of the order of the minimum radius of the gas-filled volume: $\Delta r \sim 0.1$, $r_0 \sim 0.1 - 0.15$ mm.

The increase in the neutron yield in experiments stems mostly from improvements in symmetry. However, ignition thresholds have never been achieved in any of the experiments conducted so far (the conditions closest to ignition were achieved in the 1982 experiment); even though the value of ρr already satisfies the critical condition, the temperature achieved is lower than that necessary for ignition by a factor of 3 to 4. The threshold may be attained by reducing the negative effect of mixing, by further reducing the asymmetry (by compensating for it, by eliminating the regular component of asymmetry, etc.) [16, 30, 31]. At the achieved level of asymmetry, it is possible to come closer to satisfying the ignition condition by increasing the size of the charge.

The method of igniting the gas following precompression to moderate densities (of the order of tens of grams per cm^3) by a focused shock wave may prove more promising because it does not suffer from the Rayleigh – Taylor instability and mixing effects while implementing the maximum compression of the gas by the shell required for ignition. It is still necessary, however, to somehow produce a moderately cold precompression followed by a sufficiently symmetric igniting shockwave. Unfortunately, so far there has been no experimental research into systems (not only GDTF) that could in the future ignite the target, for example, laser targets subjected to a dual pulse ensuring precompression and formation by a powerful focused shockwave [4].

Other possible sources of small-scale perturbations originate in the mesostructure of matter. The outer layers whose material has not yet melted are partly deformed. As we currently understand, the plastic flow of a continuous medium proceeds not as a deformation of the continuum but as movement at the mesolevel, of plasticity spots 1 to 100 μm in size. These spots are vortical in nature. The dispersion of the velocity of a free boundary, as the shockwave reaches it, was experimentally recorded and measured. This means that the nonuniformity of plastic flow at the mesolevel can act as a source of small-scale velocity perturbations. This flow can be metaphorically compared with the flow of a river about to freeze, carrying water mixed with small ice platelets. Consequently, this situation requires the use of improved models of viscoplastic flow. An extensive body of theoretical and experimental research in this field can be helpful here [32].

Plastic flow of molten inner shells at small radii can also act as a perturbation source. The cumulative flow converging toward the center is always accompanied by a shear, which in turn is a source of small-scale turbulence.

The difference between GDTF and other types of thermonuclear fusion lies in the energy cumulation degree, which can be crudely estimated from the temperature ratio $k = T_{\text{eff}}/T_{\text{HE}}$, where $T_{\text{eff}} = 2$ keV is the effective temperature of ignition of the DT mixture and $T_{\text{HE}} \sim 1$ eV. For GDTF, this gives $k \sim 10^3$. For the laser and ionic inertial fusion projects, the temperature in the evaporated part of the envelope is ~ 100 eV because $k \sim 10$. This difference is the cause of all the difficulties facing the feasibility of GDTF. As a result, no information obtained in studying laser thermonuclear fusion can be directly transferred to GDTF. Quite the reverse, the results obtained in more complicated conditions can be transferred to other forms of inertial thermonuclear fusion.

4. The effect of viscosity and strength on the stability of propagation of a shockwave and shells and on the mixing of materials at the interfaces

Strength may greatly influence the stability of motion of shells. For instance, it was shown as early as 1954 [33] that taking shear strength into account results in considerable damping of perturbations on a convergent steel shell 3 cm thick with the outer radius 12 cm placed under a constant pressure of 20 GPa. To explain the stability of the shockwave (SW) the behavior of small perturbations at the SW front was studied, including the envelopes of uranium and steel [34 – 36]. The studies were conducted with a plane and spherically converging SW by the method suggested in [34].

Perturbations of the shockwave in the material under study were introduced at the beveled surface of the wedge-shaped sample by a series of machined parallel cavities of a sinusoidal profile. The distance between these cavities determined the wavelength of perturbations at the SW front. The SW front shape was measured after it spread over the sample and reached the free surface. In the plane geometry case, a plane wedge was used, and in the spherical case, the difference in shell thickness was achieved by shifting the center of the inner spherical surface.

Propagation of the SW was studied with different wavelengths of harmonic perturbations at the wavefront. Experiments realized complete geometric modeling of the process of SW propagation, inclusive of reproducing the ratio of the initial amplitude a_0 and the perturbation wavelength λ.

The results of experiments showed that the relative amplitude of perturbations at a constant perturbation wavelength oscillates around the optically smooth SW front and is attenuated by approximately a factor of 10 after a path of approximately 3λ. In this way, it was concluded that plane and spherically converging SWs are stable. The progress of perturbations on the SW front was determined by the wavelength and amplitude of perturbations and by the parameters of the viscoplastic body [34, 37]. The results of measurements showed a certain degree of dispersion of the perturbation attenuation length, which depended on the value of the dynamic viscosity coefficient.

The viscosity data obtained for aluminum, lead, iron, and uranium showed that in the regions of solid state behind the SW front, an increase in viscosity with increasing the pressure follows fairly similar curves and corresponds to the viscosity coefficient from 2 kPa s to 12 – 14 kPa s [35, 36]. Similar changes in viscosity were also observed at lower deformation rates [38 – 40]. A considerable decrease in viscosity in the region above the melting curve was established, regardless of the type of material [35, 36]. We note that no mixing effects were observed in spherical-geometry experiments, although the steel shell was decelerated in measurement devices on collision with uranium, steel, or aluminum envelopes [41].

The process of convergence of envelopes is unstable under the assumption of an ideal compressible liquid [42]. According to Iordanskii's data [43], taking viscosity into account results in the exponential damping of perturbations on the converging shell. The corresponding exponent is a function of the viscosity coefficient and the perturbation harmonic number. Our estimate shows that the viscosity coefficient 2×10^3 kPa s results in damping harmonic perturbations for harmonics with $n > 10$.

The problem of the interdependence of two instability types — the Richtmayer – Meshkov (RM) and Rayleigh – Taylor (RT) instabilities — was discussed in [44]. We know that the RT instability in implosion scenarios arises when a heavy shell is decelerated (i.e., undergoes negative acceleration) when compressing the gas target. The implicit assumption here is that the acceleration $g(t)$ is a continuous function with the derivative bounded from above.

On the other hand, the general physical intuition suggests that a smooth acceleration can be represented with sufficient accuracy as a sequence of a large number of small pulses $p_i = g(t_i)\,\Delta t$ that arise as a result of the transmission of weak shockwaves across the interface. Perturbations generated by a single wave grow at the boundary in accordance with the RM regime; for instance, the amplitude of the interface distortion grows linearly and perturbations of the mass velocity tend to a constant value. But this feature contradicts the exponential growth of perturbations at the interface in the case of smooth deceleration, as a result of the RT instability.

This paradox is resolved as follows. An analytic solution was obtained in [44] for the Richtmayer problem (RM instability in the case of shockwave transmission across a curved interface between two media) that was numerically solved earlier in [22], which allowed the complete solution in the case of a weak SW. It was then found that if the solution succeeds in reaching the asymptotic mode in the time Δt between successive waves, then the evolution of perturbations at the interface can be reduced to the equation for an incompressible liquid and that the compressibility factor can be ignored if the interface perturbations are considered for sufficiently short wavelengths only.

The results of experimental investigation of the RT instability on metal plates seem to have been first published in [45] and then in [46, 47]. In these papers, the plates were accelerated by explosion products through a gap (evacuated in [46], evacuated and filled with air in [47]). Increasing perturbations on the surface of a plate facing the explosion products were observed in [46]; erosion of the plate material on the loaded surface was observed in [47]. No erosion was observed if the gap was evacuated. Erosion was probably connected with the instability arising on the 'explosion products – air' interface. We note that the perturbation zone in the above experiments did not extend to the entire volume of the plates.

The effect of viscosity and surface tension on the RT instability was studied in [48] in the planar case. The results of that paper allow concluding that the impact of a steel plate against an aluminum one at the speed 2 km s^{-1} is accompanied by certain characteristic perturbations with the wave number $K = 2\pi/\lambda = 20$. The viscosity coefficients of aluminum and steel were assumed to be 2 kPa s^{-1}. But the instability failed to manifest itself in numerous experiments with the so-called measurement devices used at the VNIIEF mostly to measure the impact compressibility of materials [41, 49]. These experiments involved geometrically similar semispherical probe HE charges of the radii $R_{\varnothing} = 220$ and 300 mm. The accelerated steel shell was placed at approximately half the radius $R_{\varnothing}$. The symmetry of the SW shape was controlled and its velocity was measured in the samples after the steel or aluminum shield mounted at the radius (0.08 – 0.14) $R_{\varnothing}$.

The state of the shell at the initial phase of its acceleration by explosion products corresponds to the shock compression of iron and to its subsequent isentropic expansion. Experimental investigation showed that iron melting on the expansion isentrope begins at the pressure 140 GPa [50]. The so-called impact melting of iron sets in at a still higher pressure ~ 200 GPa [51]. In the case of reflection of explosion products (plane detonation wave) from iron (steel with low carbon content), a pressure of 40 GPa is produced.

This pressure of the convergent detonation wave in a spherical HE charge tends to increase with decreasing the radius as a result of cumulation [52], while the pressure of the convergent shockwave changes roughly as $P \sim r^{-0.9}$ [53]. If an iron envelope is inserted into the charge at a radius $R = 0.5\,R_{\varnothing}$, then the pressure of the first shockwave reaches 53 GPa; hence, the envelope remains solid. At subsequent stages of envelope acceleration, as it converges to the center and during its subsequent deceleration, the shell heats up additionally owing to the dissipation of its kinetic energy and conversion to heat [54]. After the shell impacts on the iron shield of the measurement unit at a radius $R < 0.15\,R_{\varnothing}$ in measurement charges [41, 49], the impact compression pressure in the shield reaches $P > 300$ GPa, which corresponds to the liquid state. This reduces the strength and viscosity of the materials, but their effect on the stability of motion of the shockwave and on mixing of materials at the contact interface is not observed for relatively small bases of SW motion.

Similar processes are typical of shells made of uranium. If a uranium shell is inserted into the spherical HE charge at the radius $R \sim 0.5\,R_{\varnothing}$, a shock compression pressure from 45 to 57 GPa is created on it [36], which corresponds to the area of the solid phase of uranium.

The symmetry of the detonation front in a spherical HE charge was conducted in the first measurements by recording the residual shape of a spherical aluminum core placed inside the charge [55]. This method, suggested by K I Shchelkin, is not only a method for evaluation of the symmetry of convergence of the shockwave (symmetry of implosion) but also an integral method of evaluating the degree of nonuniformity of the pressure distribution (dynamic disbalance) in the shock wave, which manifests itself both at the compression stage and at the stage of reflection from the SW center. The point is that a cavern was formed at the center of the core after the experiment was run, and the shape of this cavern was indicative of the symmetry of the shockwave front, while the texture of the material was a measure of the zone of turbulence and of energy dissipation during the compression and the subsequent expansion stage.

Measurements showed that the core retained its spherical shape but that its outer diameter increased by about 20% compared with the initial size. It was found that an almost spherical cavity was produced inside the core containing the hardened melt of the inner part of aluminum at the bottom [55]. The survival of the core in one piece was an indication that the implosion in the HE charge was highly symmetric.

Litvinov and Kozlov and coworkers placed spheres made of various materials inside a spherical HE charge and studied the changes in structure after impact loading [56]. Numerous experiments in which the authors varied the initiation of the HE charge failed to reveal any effects arising from various instability types. A spherically symmetric cavity with molten and fused inner surface was also produced in a number of experiments.

The results of these studies coincided with those of specially conducted experiments on evaluating the dissipation of energy in collapsing shells (with the outer radius 110 mm and the thickness 6.2 mm). The material of the shell — steel 3 — was scorched. Instead of an HE charge, the experiments used a semispherical insert between the explosive focusing system (FS) and the shell of the outer radius 220 mm made by gluing together sheets of plastic foam 40 mm in thickness of the density 0.35 ± 0.005 g cm^{-3}. The density differences in the plastic foam created conditions for triggering the hydrodynamic RM instability. The spherical shockwave in the plastic foam was generated by detonating 16 lens elements of the FS with the average thickness of the HE in them being 10 mm. An analysis of the experiments demonstrated that the shell was transformed into a semispherical core with a smooth spherical outer surface. The initial phase of the formation of a cumulative jet was observed at the center of the core. A relaxation zone was recorded near the core base. The core mass was practically equal to the mass of the initial shell. The core material had only a radial texture, which indicated that no turbulence was generated in the shell collapse. Furthermore, measurements of the amount of thermal energy stored in the core material (by measuring the temperature of water with the core submerged in it), and the evaluation of energy dissipation in the shell collapse due to the strength and viscosity coincided within acceptable accuracy.

A review of experimental studies of the effect of material strength on the development of the RT instability in the course of deceleration of convergent cylindrical shells is given in [54]. It was shown that steel and lead shells with prescribed perturbations become unstable when decelerated. The shell strength affects the shape and amplitude of perturbations at both the acceleration and the deceleration stages.

5. Conclusion

The thermonuclear ignition and burning of a DT gas as a result of spherically symmetric compression was implemented when the gas was compressed by a shell and by a focused shock wave [6]. Therefore, the problem of thermonuclear ignition has been resolved, once the energy is sufficiently high and the symmetry is sufficiently perfect.

A problem arises, however (and remains unresolved), when other much less powerful energy sources are used for compression: the energy of the explosion of chemical HE (GDTF) charges, laser radiation (laser thermonuclear fusion, LTF), beams of charged particles (ion-beam thermonuclear fusion, ITF), and magnetically cumulating systems (magnetically confined gas-dynamic compression, MAGC).

If the compression energy (typically known as the driver energy) is significantly reduced, the mass of the thermonuclear mixture available for ignition greatly diminishes, and hence its volume and the characteristic size of the ignition zone become smaller. As a result, requirements for the required symmetry and admissible width of the mixing zone become more stringent. If these requirements are not satisfied, the conditions under which ignition in GDTF systems is possible are ultimately not created. To satisfy the symmetry and mixing requirements in GDTF systems, a whole range of proposals have been made, which largely amount to reducing the initial asymmetry and creating systems less sensitive to asymmetry and mixing. This work continues. As regards the positive role of strength and viscosity in reducing asymmetry and mixing, this is important only for outer regions of GDTF systems, in which materials under compression retain their strength and do not transform into gases. But the main sources of asymmetry are likely to be outside, for example, the HE initiation system.

An analysis of the results of GDTF has already shown the need to conduct extensive numerical and theoretical studies of the main processes occurring in these systems — formation and growth of hydrodynamic instabilities, mixing, nonuniformity of elastoplastic flow, and detonation, i.e., of all pressing aspects of the modern dynamics of continuous media. Reassuring results have already been reported here. GDTF studies are a unique possibility to expand and test the numerical and theoretical models and methodology in gas dynamics at high pressures and temperatures.

The issue of the GDTF problem and of the identification of factors limiting the cumulation of energy in spherical devices with a convergent shockwave was one of the last discussed with V N Mineev. His span of interests included various fields in the physics of explosions and application of shock waves in research areas. From 1956 to 1978, Mineev took part in the Soviet Atomic Project at the VNIIEF Russian nuclear center, where he was one of the founding fathers of the experimental investigation of the viscosity and electric properties of condensed-matter materials under shock compression and later of the aspects of strength of materials and structures under dynamic loading. Mineev's work on the stability of safety protection and industrial structures under emergency conditions were extended further and gained wide recognition. His research projects at the Russian Academy of Sciences Joint Institute of High Temperatures mostly dealt with aspects of the safety of atomic power stations with the prevention of dire consequences of possible failures of their reactors.

References

1. Vakhrameev Yu S, Mokhov V N, Popov N A *At. Energ.* **49** (2) 121 (1980) [*At. Energy* **49** 567 (1980)]
2. Avrorin E N, Feoktistov L P, Shibarshov L I *Fiz. Plazmy* **6** 965 (1980) [*Sov. J. Plasma Phys.* **6** 527 (1980)]
3. Shcherbakov V A *Fiz. Plazmy* **9** 409 (1983) [*Sov. J. Plasma Phys.* **9** 240 (1983)]
4. Shcherbakov V A *Voprosy At., Nauki Tekhn. Ser. Teor. Prikl. Fiz.* (2) 11 (1992)
5. Aleksandrova A G, Popov N A, Shcherbakov V A *Voprosy At. Nauki Tekhn. Ser. Yad.-Fiz. Issled.* **1** (2) 95 (2003)
6. Mokhov V N, in *Vysokie Plotnosti Energii* (High Energy Densities) (Sarov: RFYaTs – VNIIEF, 1997) p. 173
7. Winterberg F *Atomkernenerg. Kerntech.* **41** (1) 1 (1982)
8. Irving D *The German Atomic Bomb*: *The History of Nuclear Research in Nazi Germany* (New York: Da Capo Press, 1983) [Translated into Russian *Atomnaya bomba Adolfa Gitlera* (Moscow: YaUZA. EKSMO, 2004) p. 276]
9. Karlsch R *Hitlers Bombe* (München: Deutsche Verlags-Anstalt, 2005)
10. Guderley G *Zylinderachse, Luftfahrtforschung* **19** 302 (1942)
11. Landau L D, Stanyukovich K P *Dokl. Akad. Nauk SSSR* **46** (9) 399 (1945)
12. Kozyrev A S *Gazodinamicheskii Termoyadernyi Sintez* (Gas-Dynamic Thermonuclear Fusion) (Sarov: RFYaTs – VNIIEF, 2005)
13. Popov N A, in *Vysokie Plotnosti Energii* (High Energy Densities) (Sarov: RFYaTs – VNIIEF, 1997) p. 493
14. Babadei S M *Atom* (21) 36 (2002)
15. Kozyrev A S, Aleksandrov V A, Popov N A *Nature* **275** 476 (1978)
16. Aleksandrov V A et al. *Khim. Fiz.* **12** 745 (1993)
17. Zababakhin E I *Zh. Eksp. Teor. Fiz.* **49** 642 (1965) [*Sov. Phys. JETP* **22** 446 (1966)]
18. Shcherbakov V A *Khim. Fiz.* **14** 75 (1995)
19. Anisimov A N et al. *Khim. Fiz.* **12** 749 (1993)
20. Birkhoff G *Hydrodynamics* (Princeton: Princeton Univ. Press, 1950)
21. Belenkii S Z, Fradkin E S "Teoriya turbulentnogo peremeshivaniya" ("Theory of turbulent mixing") *Trudy Fiz. Inst. Akad. Nauk SSSR* **29** 207 (1965)
22. Richtmyer R D *Commun. Pure Appl. Math.* **13** 297 (1960)
23. Meshkov E E, Nikiforov V V, in *Vysokie Plotnosti Energii* (High Energy Densities) (Sarov: RFYaTs – VNIIEF, 1997) p. 188
24. Meshkov E E *Izv. Akad. Nauk SSSR. Ser. Mekh. Zhidk. Gaza* (5) 151 (1969)

25. Anuchina N N et al. *Izv. Akad. Nauk SSSR. Ser. Mekh. Zhidk. Gaza* (6) 157(1978)
26. Rozanov V B, Lebo I G, Zaitsev S G, Preprint FIAN No. 56 (Moscow: LPI SSSR, 1990)
27. Grishina G A, Bukharova V Ya, Zotova O M *Voprosy At., Nauki Tekhn. Ser. Metodiki Programmy Chislennogo Resheniya Zadach Mat. Fiz.* (3) 22 (1986)
28. Andryushin I A, Chernyshev A K, Yudin Yu A *Ukroshchenie Yadra* (Taming of the Nucleus) (Saransk: Krasnyi Oktyabr', 2003)
29. Kozyrev A S et al., in *Vysokie Plotnosti Energii* (High Energy Densities) (Sarov: RFYaTs – VNIIEF, 1997) p. 485
30. Anisimov A N, Danov V M, Mkhitaryan L S "O sostoyanii i perspektivakh GDTS" ("On current status and prospects for GDTF"), in *Zababakhinskie Nauchnye Chteniya 1992 Abstracts of Talks* (Zababakhin Science Sessions)
31. Zotova O M, Shcherbakov V A "O vliyanii vozmozhnoi raznoplotnosti ZhVV na simmetriyu sjatiya centralnoi ampuly s gazom pri ee vertikal'nyh smescheniyah" ("On the effect of possible density difference in LHE on the symmetry of compression of the vertically displaced central gas-containg ampule"), in *Zvenigorodskaya Konf. 1997* (Zvenigorod Conf. 1997)
32. *Osnovnye Dostizheniya RFYaTs – VNIIEF 2003* (Main Acievements of the RFYaTs – VNIIEF 2003) (Sarov: RFYaTs – VNIIEF, 2004) p. 7
33. Elliott L A *Proc. R. Soc. London* **139** 196 (1954)
34. Sakharov A D et al. *Dokl. Akad. Nauk SSSR* **159** 1019 (1964) [*Sov. Phys. Dokl.* **9** 1091 (1965)]
35. Mineev V N, Funtikov A I *Usp. Fiz. Nauk* **174** 727 (2004) [*Phys. Usp.* **47** 671 (2004)]
36. Mineev V N, Funtikov A I *Teplofiz. Vys. Temp.* **44** 943 (2006) [*High Temp.* **44** 941 (2006)]
37. Zaidel R M *Prikl. Mat. Tekh. Fiz.* (4) 30 (1967) [*J. Appl. Mech. Tech. Phys.* **8** (4) 20 (1967)]
38. Ogorodnikov V A et al. *Prikl. Mat. Tekh. Fiz.* (1) 5 (1995) [*J. Appl. Mech. Tech. Phys.* **36** 4 (1995)]
39. Ilyushin A A *Uchenye zapiski MGU Mekh.* **39** 11 (1940) (Moscow University Uchenye zapiski Mechanics)
40. Stepanov G V *Uprugoplasticheskoe Deformirovanie i Razrushenie Materialov pri Impul'snom Pogrujenii* (Elastoplastic Strain and Failyre of Materials under Pulse Loading) (Kiev: Nauk. dumka, 1991)
41. Al'tshuler L V et al. *Usp. Fiz. Nauk* **166** 575 (1996) [*Phys. Usp.* **39** 539 (1996)]
42. Sakharov A D *Atom* (1) 44 (1998)
43. Iordanskii S V *Prikl. Mat. Mekh.* **21** 465 (1957)
44. Zaidel R M *Izv. Akad. Nauk SSSR. Ser. Mekh. Zhidk. Gaza* (1) 111 (1972) [*Izv. AN SSSR. Ser. Mechanics of Liquids and Gases*]
45. Barnes J F et al. *J. Appl. Phys.* **45** 727 (1974)
46. Tsypkin V I et al. *Zh. Tekh. Fiz.* **45** 624 (1975) [*Sov. Phys. Tech. Phys.* **20** 387 (1975)]
47. Barnes J F et al. *J. Appl. Phys.* **51** 4678 (1980)
48. Bellman R, Pennington R H *Quart. Appl. Math.* **12** (2) 151 (1954)
49. Funtikov A I *Usp. Fiz. Nauk* **167** 1119 (1997) [*Phys. Usp.* **40** 1067 (1997)]
50. Funtikov A I, Osipov R S, Tsyganov V A *Teplofiz. Vys. Temp.* **37** 887 (1999) [*High Temp.* **37** 857 (1999)]
51. Funtikov A I *Teplofiz. Vys. Temp.* **41** 964 (2003) [*High Temp.* **41** 850 (2003)]
52. Zababakhin E I *Nekotorye Voprosy Gazodinamiki vzryva* (Some Aspects of Gas Dynamics of Explosions) (Snezhinsk: RFYaTs – VNIITF, 1997)
53. Zababakhin E I, Zababakhin I E *Yavleniya neogranichennoi kumulyatsii* (Unlimited Cumulation Phenomena) (M.: Nauka, 1988) [Translated into English (Moscow: Nauka Publ., 1990)]
54. Ivanov A G et al. *Prikl. Mat. Tekh. Fiz.* **35** (4) 163 (1994) [*J. Appl. Mech. Tech. Phys.* **35** 639 (1994)]
55. Altshuler L V et al. *Khim. Fiz.* **14** (2 – 3) 65 (1993)
56. Zhuchikhin V I *Pervaya Atomnaya* (First Atomic Bomb) (Moscow: IzdAT, 1993)
57. Rykovanov G N et al. (Composed) *Voprosy Sovremennoi Tekhnicheskoi Fiziki: K 70-letiyu so Dnya Rozhdeniya Akad. E N Avrorina: Izbrannye Trudy RFYaTs – VNIITF* (Aspects of Modern Technical Physics: Festschrift Volume on the 70th Anniversary of Acad. E N Avrorin: Selected Proceedings of RFYaTs – VNIITF) (Snezhinsk: Izd-vo RFYaTs – VNIITF, 2002)