REVIEW OF INVESTIGATIONS UNDER WAY ON THE LARGE-SCALE TSNIIMASH BALLISTIC FACILITY

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Summary—The large-scale TsNIIMASH ballistic facility was built in 1992 through modernization of the large shock tunnel. Having 0.5 m caliber, the facility is 200 m long. Each experiment on the facility envisages an explosion of stoichiometric hydrogen-oxygen mixture, up to 300 cub. m by volume. In the air-evacuated ballistic channel 60 m long, the expanding explosion products of the detonating gas mixture boost gyrostabilized steel plates 0.5m in diam which travel along the channel on a magnetic suspension without a mechanical contact with the walls. The case is unique in combining the ballistic facility geometric dimensions with the plate high-precise motion. Results of experiments on graphite crystalline conversion into diamond are given. Investigations to use the shock tunnel for hypervelocity launch of compact projectiles are discussed.

INTRODUCTION

The large-scale TsNIIMASH ballistic facility was developed in 1992 through modernization of the large shock tunnel built back in 1958 (see Fig. 1). The tunnel is 200 m long. The diameter 0.5 m is strictly similar along the whole length. Given the wall thickness of 60 mm, the tunnel made of low-carbon structural steel of ultimate strength of 460 MPa can be safely filled with gas at 150 ata. In pulsed operation in its local segments, the tunnel can withstand surplus pressure of up to 300 ata without failure.

Originally we intended to use the tunnel in designing a mock-up of a launcher to inject in orbit small projectiles. We planned to launch 0.5-1 kg projectiles to 10-11 km/sec in the experiments on the facility. The projectiles were supposed to be preliminarily boosted to 4.5 km/sec in the tunnel with the use of gyrostabilized plate-shaped sabots (see Fig. 3) accelerated

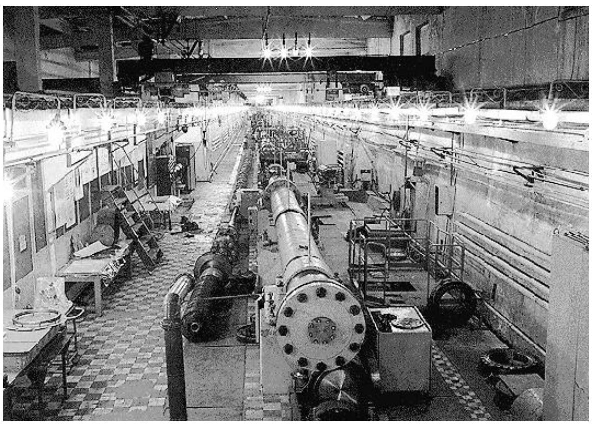

Fig. 1. TsNIIMASH large-scale ballistic facility.

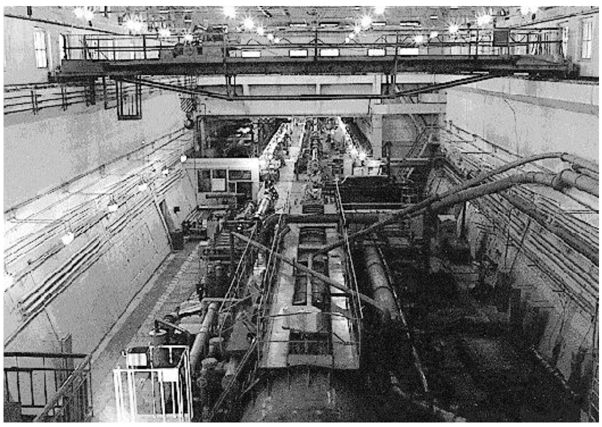

Fig. 2. Vacuum chamber of ballistic facility.

through the gasdynamic expansion of the stoichiometric hydrogen/oxygen mixture combustion products. The stoichiometric mixture was to be generated in the tunnel through the injection of oxygen and hydrogen gaseous jets through the tunnel end flange injectors at high pressure, much as in a rocket engine combustion chamber.

To be ultimately accelerated, the projectile must separate from the plate-shaped sabots and be fired into the gascumulative acceleration channel 100 m long (see Fig. 4). On the operation principle, the gascumulative accelerator is similar to RAM-accelerator [1], with the only difference that condensed explosive is used instead of gaseous explosive mixture. The thick-wall tunnel with the inner diam of 100 mm was lined with a thin layer of the explosive, sandwiched with a damping layer. The thick-wall tunnel was fixed along the tunnel axis with plate-shaped supporting elements. The projectile was presumed to be accelerated in the gascumulative accelerator in vacuum through its conic tail symmetric compression (see Fig. 5) with the high-velocity detonation products converging to the tunnel axis, the explosive being initiated simultaneously throughout the entire perimeter of the channel, in synchronism with the projectile motion. The explosive were supposed to be initiated through the high-velocity impact with a liquid ejected through the nozzles (see Fig. 5) on the projectile side surface. The liquid ejection was powered by high-speed rotation of the projectile about its axis of symmetry. That the projectile under symmetric compression with the gas had gyroscopic moment was due to provide its stable motion along the gascumulative accelerator, without mechanical contact with the walls.

The projectiles accelerated in the gascumulative accelerator were planned to be thrown into the vacuum chamber 180 cubic meters (see Fig. 2) butt joined with the facility tunnel. The chamber was fitted with high-speed optical diagnostics instrumentation allowing to investigate projectile hypervelocity motion in the gaseous atmosphere. A projectile catcher weighing 10 tons, 8 m long, was installed on guide rails in the chamber, its retardation on recoil being realized through friction against the rails.

The work on preparation of the projectile gascumulative acceleration was nearly completed, however in early 1992 the financing of the program was stopped. This caused us to change the line of investigation and consider possible civil-purpose applications of the facility, for example, to realize material dynamic synthesis and processing technologies. Even in the early ballistic high-velocity launch experiments performed on the facility the gyrostabilized plates were used as impactors for target dynamic loading, and not as sabots for projectile preliminary acceleration.

UPGRADED LARGE-SCALE BALLISTIC FACILITY

In the experiments having been conducted on the facility by now, we launched steel plates 6 mm and 20 mm thick, weighing 9.1 kg and 30 kg correspondingly (see Fig. 3). The revolving

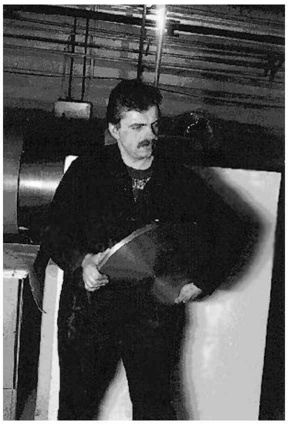

Fig. 3. Throwing discus.

Fig. 4. 100-mm ballistic gascumulative facility.

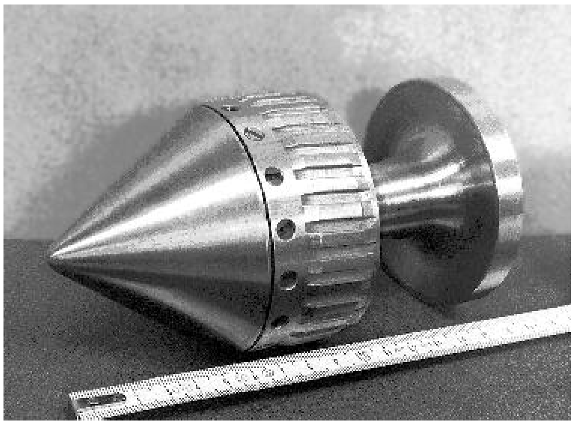

Fig. 5. Projectile for gascumulative accelerator.

magnetic field generated with an electromagnetic stator, mounted in the tunnel body, spins the plate in the tunnel on a string suspension up to the ultimate angular speed (200 rps) limited by their breaking strength. The considerable gyroscopic moment makes it possible to preserve its angular position on acceleration. At synchronous rotation of the magnetic field and plate, specially made of magnetosoft steel, the latter was magnetized. Due to conductivity of the steel, the plate held the magnetic field for some time dependent on the plate thickness. For those thicknesses in use the plate demagnitization time was in excess of the time of plate acceleration in the tunnel. When the magnetized plate moved along the tunnel, electric currents were induced in the electrically-conductive walls. The interaction of these currents with the magnetic field of the plate provided a way for the latter to travel in the tunnel on a magnetic suspension. The adjustment of the plate spin axis, such that its angular deflection from the axis of the tunnel was within 30 angular seconds, effected considerable reduction of lateral component of the resulting force of gas pressure with the result that the plate moved in a magnetic suspension without mechanical contact with the tunnel walls. The plate-to-wall clearance was about 0.5 mm.

To launch gyrostabilized plates we used the tunnel section 60 m long (see Fig. 6), which was adjusted so that the offset of its axis is not greater than 0.5 mm. In the experiments we have performed the boost section of the tunnel was air-evacuated or filled with gaseous hydrogen at low pressure. Of the rest of the tunnel, we used its section of up to 110 m in length, filled with oxygen/hydrogen mixture with an initial pressure, at most, 15 ata. The tunnel section containing oxygen/hydrogen mixture was separated from the boost section by a polyamidic diaphragm, only 0.2 mm thick. The detonation wave initiated in the section containing oxygen/hydrogen mixture propagated along the section from its end towards the projectile to be launched. When impacted by the wave front, the polyamidic diaphragm failed and burned up under the action of the high-temperature detonation products, further impacting the projectile at high velocity, with the result that the projectile was brought to high-rate accelerated motion, the rate of acceleration dying down with increasing velocity. As compared to the high-velocity launching scheme, originally projected for use, the detonation-induced acceleration scheme featured relatively low energy efficiency, but proved to be more simple and safe. The velocity of the projectile, launched in the tunnel, was measured with the use of pulse pressure transducers mounted in the tunnel body lengthwise. The instance the projectile flew past the transducer was registered in response to pressure step change with time.

The projectiles launched in the facility were retarded at the end of the boost section by a heavy anvil with a shock-absorber installed in the tunnel tail section 7 m long. On high-velocity impact of a projectile on the anvil, the end face of the latter suffered severe deformation and called for replacement after each experiment. A ring-shaped recess was designed into the tunnel

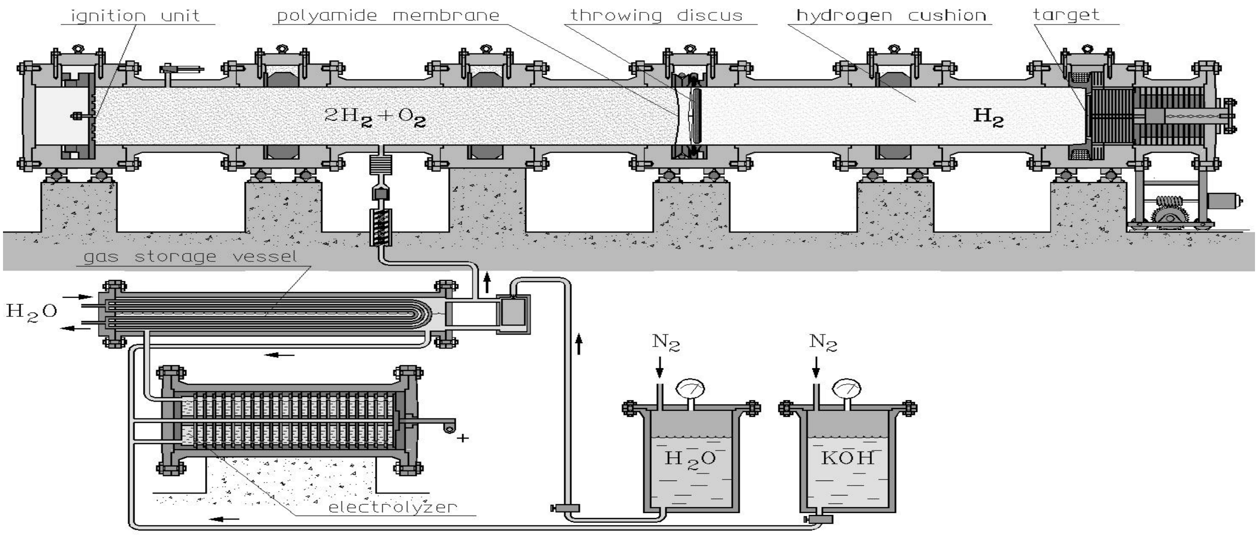

Fig. 6. Upgraded ballistic facility.

body opposite the anvil end face. A thick-walled changeable shell, reinforced by a wire binding, was fitted into the recess with a shell-to-wall clearance. The shell absorbed shock-induced side loads and suffered severe plastic deformations. Owing to the clearance between the shell and the tunnel body, the side loads did not end in failure of the latter. The weight of the anvil was as large as 6.5 tons, resulting in low speed of its recoil on impact and consequent possibility to use for its retardation a rubber shock-absorber, ca. 2 m long, intervening between the anvil and the tunnel end flange. The movable rod of the shock absorber, 140 mm in diameter, was passed through the hole in the tunnel end flange. The recoil of the anvil should not exceed 1 m, lest the force to the end flange of the tunnel be more than tolerable limit of loading equal to 400 tons.

Because of the sizable caliber of the facility and the substantial energy of the launched plates, a rich variety of samples of different composition placed at different depths from the target end face can be exposed to dynamic loading simultaneously in each experiment. The impulse decay at propagation deep into the target allows to realize loading over a wide range of pressures in each experiment. The precision launching of the plates provides possibility to damp the high-velocity impact on the sample-containing target with a layer of gaseous hydrogen, allowing to realize time-resolved loading and off-loading of samples. This prevents the samples not only from shock-wave heating up, but from initiation of rupture stresses, thus precluding their failure. In so doing there is a possibility to control the temperature of the samples, regardless of the pressure being realized. The oriented shearing of the samples with the preset deformation velocity is realized by forcing them during loading against the fast-rotating flywheel surface mounted on the target. Arranging the samples equidistant from the flywheel spin axis, one can achieve shearing over a wide range of velocities in each experiment. The set of parameters realized in each ballistic experiment is unique and unattainable by other known methods. The short-term exposure of the samples to high pressure, together with their high-velocity shear deformation with no shock-wave heating up, makes it possible to synthesize in solids metastable polycrystalline states having amorphous or nanophase structure, possessing high magnetic, mechanical and catalytic parameters, as well as to perform solid powder compaction.

BALLISTIC DIAMOND DYNAMIC SYNTHESIS EXPERIMENTS

Within the period from October 1992 to June 1993 we performed on the facility 10 ballistic experiments on the development of the technology for launching gyrostabilized plates. Each experiment involved launching of plates 9.1 kg weight. In the process the launch velocity increased successively from experiment to experiment. To realize maximum velocity measuring 3.5 km/sec we exploded oxygen/hydrogen mixture of composition $4H_2:O_2$, 330 cub. m by volume, filling in the tunnel section 110 m long under 15 ata. The kinetic energy of the launched plates was in excess of 50 MJ.

The launched plates impacted on cast iron targets 30 kg weight (see Fig. 7,8,9). On ultimate-velocity impact the cast iron's carbon inclusions were partially converted into diamonds as a result of the shock-wave action on the cast iron [2]. Upon chemical treatment of the cast iron target subjected to the shock-wave loading, more than 250 g of diamond dust was extracted, the particle characteristic size being of about 2 μm.

In January and April, 1997, upon upgrading the facility we performed under the ISTC Project#30 two experiments aimed at demonstration of the possibility of graphite crystalline conversion into diamond under dynamic loading with shear. In the experiments we launched plates 30 kg weight to 1.4 km/sec and 1.6 km/sec correspondingly. In the process the high-velocity impact of the plate on the target incorporating graphite samples was damped by gaseous hydrogen, the tunnel boost section was previously filled with. This effected time-resolved loading of the graphite crystals to 26 GPa during 12 μs without shock-wave heating up and failure on relaxation. The shear deformation velocity reached 350 m/sec.

Discus projectile/striker Steel target with cast iron samples

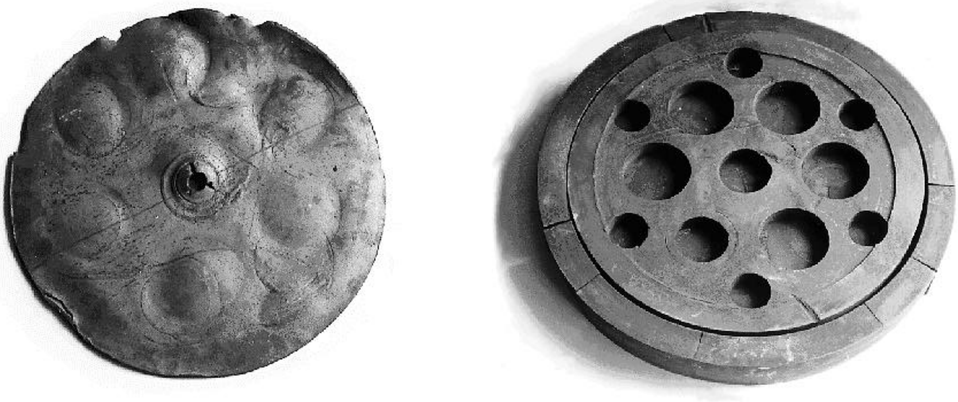

Fig. 7. High speed throwing: Experimental results (V=1.2 km/s).

Discus projectile/striker Cast iron target

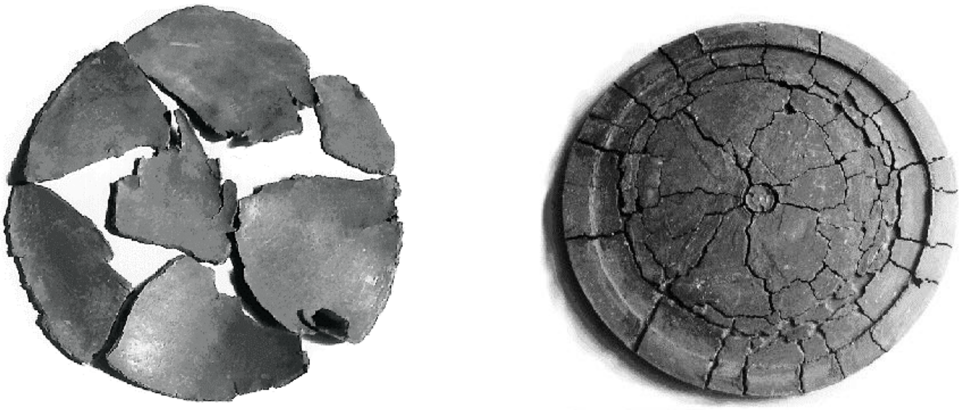

Fig. 8. High speed throwing: Experimental results (V=2 km/s).

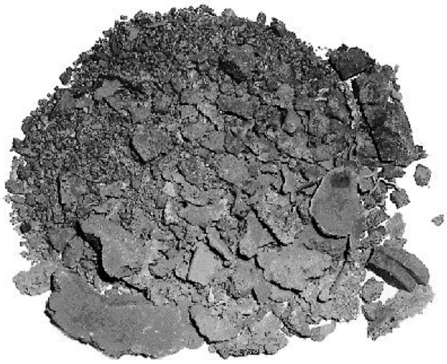

Fig. 9. High speed throwing:
Experimental results (V=3.5 km/s).

An oriented shear deformation of a compressed graphite sample, strictly along the plane of atomic layers, presents an opportunity for a coherent rearrangement of the graphite crystal lattice into the diamond one [3], whereby a fast relative gliding of atomic layers stimulates a practically simultaneous switch of carbon atoms in a layer into the new electron state with the formation of strong inter-layer covalent bonds, providing graphite crystal structure rearrangement. The chemically bound atomic layers then move as one rigid body, forming a planar nucleus of the diamond phase which goes on “encroaching” into the graphite crystal by additions of subsequent layers in the same way. This may result in a wave of crystal conversion of graphite into diamond, spreading through a compressed graphite crystal. The shear stress on the wave front (which constitutes the phase boundary) is due to be transmitted from the crystal surface through the newly formed diamond layer, thanks to its extremely high shear strength. In this case, in contrast with shock synthesis, no limits are imposed on the possible size of the synthesized diamond crystal. This provides a possibility to perform synthesis of large diamond crystals under dynamic loading.

The mode of dynamic loading required for the crystal conversion was achieved in the second ballistic experiment only. The results of pre- and after-loading graphite samples investigation by methods of material science verified that due to the high angular disorientation (about 1 degree) of the domains in the initial graphite samples the direct transition into diamond within macro-volume proceeded non-coherently in diffuse mode (and not in wave mode, as expected a priori), with the result that the graphite-to-diamond phase transition penetrated the samples only for a depth of not more than 0.3 mm (graphite samples cross-size was 20×20 mm). The graphite crystalline lattice coherent rearrangement into diamond was evidenced only within individual single-crystal domains sized about 10 μm (see Fig. 10). Relying on the performed investigations we came to the conclusion that for the graphite crystalline lattice coherent rearrangement into a diamond one in wave mode to be realized within the whole volume of a graphite sample up to 5 mm thick with the retention of its initial crystalline quality, it is necessary that only perfect graphite crystals are exposed to the dynamic loading with shear. The diamond dynamic synthesis experiments are planned to be continued on acquisition of large single crystals of graphite, presumed to be synthesized on the facility currently under development.

HYPERVELOCITY LAUNCHER

Based on the TsNIIMASH shock tunnel, the hypervelocity launcher (see Fig.11) was built in 1998 to perform laboratory testing of shield protection for the International Space Station Service Module. To realize hypervelocity launching, the convergent cone 3 m long, going to the acceleration channel 1 cm in diameter, 3 m long, is butt-jointed to the shock tunnel end. The tunnel section 20 m long together with the cone can be filled with stoichiometric mixture to 15 ata, while the acceleration channel is air-evacuated. The launched projectiles are thrown into the vacuum chamber. To measure velocities we use induction coils, which register metallic body passing through.

Leading with the work of Guderley, Landau, Stanyukovich [4] it is well known that detonation wave converging in a long-length cone produces gasdynamic flows at the cone vertex having extremely high density of energy sufficient, as expected before, even to initiate thermonuclear reactions. Casually and quantitatively, the effect of cumulation is conditioned by

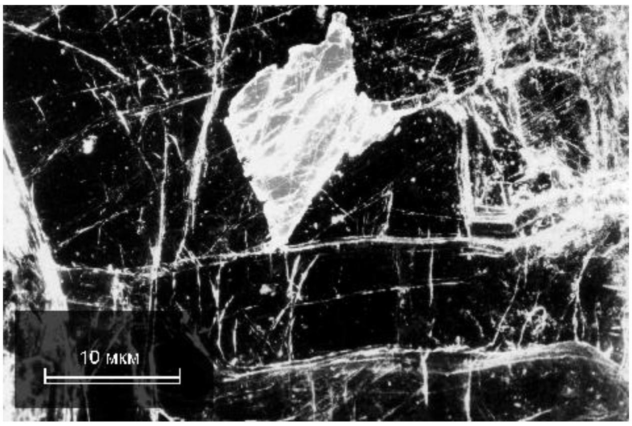

Fig. 10. Surface of a graphite sample subjected to loading.

the diminution of the shock wave front area in its passage through the convergent channel. This phenomenon was theoretically and experimentally studied as applied to the problem of controlled thermonuclear fusion [5]. As to the case of a cone-convergent spherical shock wave, analytical and numerical methods were developed to calculate gasdynamic properties realized under these conditions, as well as factors limiting energy cumulation (radiation, heat conduction, viscosity, hydrodynamic instabilities) were studied. A convergent plane shock wave was also investigated, e.g. as applied to the shock tunnel of TsNIIMASH [6]. Unlike a convergent spherical wave, for which smooth velocity increase in a power fashion is provided along the channel axis, in case of a plane wave Mach reflections from the cone walls are responsible for step increase in velocity, each step followed by smooth decay, so that the power fashion of velocity increase, realized for a spherical wave, is kept on average.

Results of calculation [7] confirm the possibility to realize the high gasdynamic properties on the developed hypervelocity ballistic facility. In the case under consideration the tunnel section, ca. 100 m long, together with the cone, is filled with stoichiometric mixture to the pressure of 10 atm. The detonation wave propagates over the mixture, transforming to a strong shock wave in the cone. Behind the front of the shock wave convergent in the cone the following parameters are realized when the front diameter reduces to ~1 cm: shock wave velocity - 13.6 km/sec, gas velocity - 12.6 km/sec, gas pressure - 9000 atm, gas temperature - 20000 K, gas density - 75 kg/cub.m. Due to the long length of the detonation area and consequent substantial mass of detonation products inflowing into the cone, the high thermodynamic parameters at the cone vertex are maintained for a sufficiently long time ranging up to several hundreds of microseconds. The high density of energy in the working gas is attained mainly through its translational motion, rather than through excitation of its internal degrees of freedom, as for adiabatic compression. At the acceleration channel outlet the calculated velocity of the aluminum projectile 2.7 g by mass exceeds 14 km/sec. When the gas moving behind the shock wave front impacts the projectile resting in the acceleration channel, the projectile experiences severe impact loading, and the reflected shock wave is developed in the working gas. The behind-front pressure reaches 13 GPa, several times greater than the ultimate dynamic strength of the aluminum alloy. Then the pressure declines rapidly (within 20 μs) to the level below the ultimate strength. In this time interval the projectile manages to gain not more than 5% of its kinetic energy. Thus, the launching process is contributed mainly by prolonged nondestructive action on the projectile along the whole length of the acceleration channel, rather than through attainment of extremely high degree of energy cumulation at the cone vertex, accompanied by pulsed acceleration of the projectile, as in explosion launching. In all likelihood, it will be difficult to realize the design behind-front energy density at the acceleration channel inlet due to the occurrence of a variety of gasdynamic instabilities.

In the first experiment, performed in July 1998, we launched the aluminum cylinder 1.3 cm long, 2.85 g by mass. The initial pressure of the hydrogen-oxygen mixture was 15 atm. The

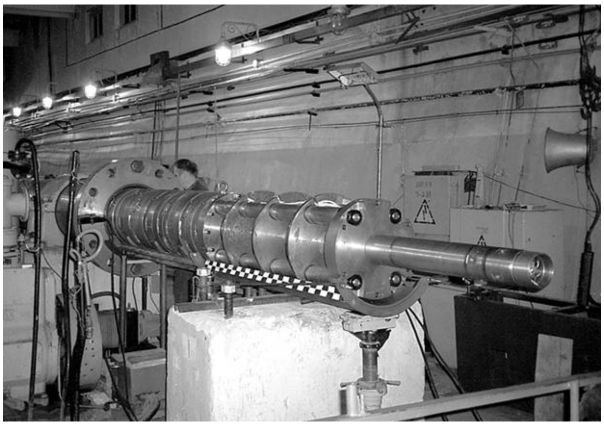

Fig. 11. Assembling of the hypervelocity ballistic facility.

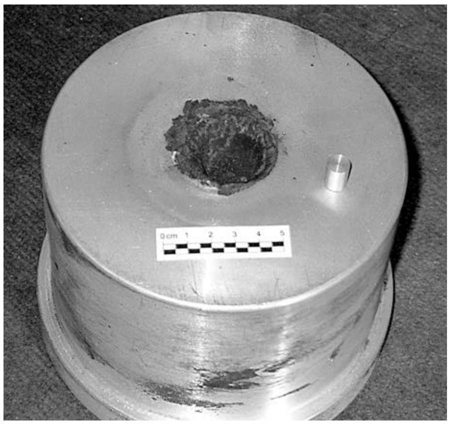

Fig. 12. Result of the first hypervelocity experiment.

damping layer of foam plastic was envisaged to prevent projectile failure. Unfortunately, in this experiment we did not manage to realize the design condition of launching. The measured projectile outlet velocity made up only 2.7 km/sec, what is far less than we anticipated. 2.9 μs after the projectile passing through, the coils registered plasma jet coming out from the acceleration channel, with the velocity of more than 30 km/sec. We consider this fact to be evidence that the energy cumulation behind the front of the detonation wave convergent in the cone was realized in this experiment. In the process the projectile was accelerated not through the interaction with the detonation wave, but by the action of prematurely-ignited mixture combustion products. In all likelihood, the premature ignition was conditioned by heating up of the walls nearby the cone vertex, as a result of concentration of light emission from the detonation wave front due to repeated reflection from the cone smooth walls. Figure 12 shows the crater formed on the impact of the projectile on the duralumin target.

To realize the design launch conditions in the next experiment we plan to fill the cone separately from the tunnel, with an inert (e.g. hydrogen/nitrogen) mixture, of the same pressure and density as the hydrogen/oxygen mixture in the tunnel.

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