

A. SHTERTSER\*, O. STOYANOVSKII\*, B. ZLOBIN\*, Y. MESHCHERYAKOV\*, Y. SKORNYAKOV\*

## DESIGNING AND MANUFACTURING OF EXPLOSION CHAMBERS FOR SCIENTIFIC RESEARCH AND EXPLOSIVE WORKING OF MATERIALS

### PROJEKT I WYTWORZENIE KOMORY DO DETONACYJNEJ DLA CELÓW NAUKOWYCH ORAZ PRZEPROWADZENIE ZGRZEWANIA WYBUCHOWEGO DLA MATERIAŁÓW METALICZNYCH

The paper presents the experience in designing and manufacture of explosion chambers for researching purposes and technological applications gathered in Lavrentyev Institute of Hydrodynamics of Siberian Branch of Russian Academy of Sciences. The peculiarity of the developed explosion chambers is that they are all-metal units with a long service life (10 thousand explosions and more); they completely isolate blast effects (shock wave, seismic wave, etc.) and hence can be installed in laboratory rooms and industrial premises and, when necessary, can be disassembled and moved to a new place of exploitation. Presented examples illustrate the application of the explosion chambers in production of new materials, articles, and for elimination of ammunition.

*Keywords:* explosion chamber (EC), computational model, composed shell, technological applications

Praca prezentuje doświadczenia w projektowaniu i wytwarzaniu komór detonacyjnych dla celów naukowych i zastosowań technologicznych zebranych w Instytucie Lavrentyeva w Syberyjskim Instytucie Hydrodynamiki, Rosyjskiej Akademii Nauk. Cechą charakterystyczną zastosowanych komór detonacyjnych jest to, że są one wykonane całkowicie z metalu oraz posiadają długą gwarancję żywotności (10 000 detonacji, lub więcej); dodatkowo całkowicie izolują od otoczenia skutki detonacji (fale uderzeniowe, fale sejsmiczne, itd.) i stąd można je instalować w pomieszczeniach laboratoryjnych, na terenach powierzchni przemysłowych, i kiedy jest to konieczne, mogą zostać zdemontowane i przeniesione w inne miejsce. Przedstawione przykłady ilustrują zastosowanie komór detonacyjnych przy wytwarzaniu nowych materiałów i detali.

#### 1. Introduction

Design and manufacture of metal explosion chambers (EC) were initiated in Lavrentyev Institute of Hydrodynamics of Siberian Branch of Russian Academy of Sciences (LIH SB RAS) in 1960ies, substantially immediately after the Institute establishment. Initially, creation of EC was caused by the need in researching in the explosion physics area. Later, the activities of EC development were continued in the Special Design Office of High-Rate Hydrodynamics (now Design and Technology Branch of LIH SB RAS); note that not only researching facilities were designed, but also technological chambers purposed for explosive working of materials. The design was attended by the researches of the strain-stress state of a chamber body (shell) under the conditions of impulse loading [1-8]. Detailed description of various ECs and peculiarities of their functions is presented in [9]. It must be mentioned that in 1950ies the fundamentals for calculations of stresses arising in shells under explosive loading were developed by W.E. Baker [10]. Later on his book containing valuable information for researches and engineers working in the field of explosion physics was published [11].

ECs were developed not only in LIH SB RAS but also in other institutions. In particular, company DYNASAFE [12] and Special Materials Corporation [13] produce (for anti-terrorism control) the chambers for explosive charges movement from the point of detection (railway stations, airports, city roads, etc.) to a treatment site for elimination. These chambers are not designed for multiple utilizations and can resist only one unauthorized explosion. Design and manufacture of metal ECs for explosive charges up to 50 kg were carried out, for example, in the eighties in the Scientific and Production Center ANITIM (Barnaul, Russia) [14]. In Russia and Ukraine large-size chambers for the explosive charge above 100 kg were created [15]. In Moscow regional explosion center of shared use, a spherical explosion chamber is used; its diameter is 12 m, wall thickness (armour steel) is 100 mm, the chamber is designed for the charge explosion up to 1 t TNT [16].

The challenges related with the EC design are still topical, thus the investigations of the strain – stress state of the chamber are supported in different institutions in Russia [17-19] and in the other countries [20, 21] from 1990ies till now. Some institutions possess the numerical codes and methods for

\* DESIGN AND TECHNOLOGY BRANCH OF LAVRENTYEV INSTITUTE OF HYDRODYNAMICS SB RAS, NOVOSIBIRSK, RUSSIA

stress-strain state calculations. Certain organizations create EC not for sales but for their own purposes. For example, in [22] the special chamber for production of wBN is described. It has the volume of 200 cubic meters, can sustain the explosion of 10 kg HE and is under operation during 13 years. As there is a demand on movable EC engineers offer different designs of such equipment [23-26].

The main peculiarity of the ECs developed in LIH SB RAS is that they are fully metal, completely isolate the explosion action, can be installed in laboratories and industrial buildings and, when necessary, can be disassembled and moved to a new site of operation. Since 1976 and up to now, more than 90 explosion chambers of various design and purpose have been manufactured; the explosive charge value varies within the range from 150 g to 16 kg TNT. Increasingly stringent demands to environment protection stimulate rising interest toward explosion chambers since this equipment, being combined with special purification devices, enables to neutralize toxic components of explosion products [9, 27]. The present paper describes various modifications of the chambers and examples of their applications.

Among the targets which have the EC developers there is one to reduce the chamber mass in respect to the explosive charge mass. To do this, reliable methods of evaluation of the strain-stress state of the chamber shell are necessary. One technique, permitting evaluating the optimal chamber mass and sizes on the base of assigned explosive charge mass, is described below.

## 2. Computational model for the explosion chamber with the composed shell

It is known that, under the explosion loading, such a state of the EC shell is optimal when all occurring stresses are similar everywhere (so-called uniformly-loaded state). The simplest way to reach the uniformly-loaded state is when the shell is spherical. If the shape is different, the explosion causes flexural waves occur in the shell which may result in the significant (2, 3 times or more) overloading in the poles against the center. In particular, it is valid for the chambers with the composed shell which has the middle cylindrical part and semi-spherical, elliptic, or other-shaped covers on the end-faces. As compared to the spherical ones, such chambers are more preferable from the viewpoint of manufacture adaptability. According to our experience, it is possible, applying respective design solutions, to provide the uniformly-loaded state in the composed cases, too. For example, if the spherical covers are connected with the cylindrical part via bayonet locks, it prevents flexure waves passing, and stress concentration in the chamber poles is avoided. The computational model which enables to find the optimal mass  $m$  and size of the composite shell was developed for such uniformly-loaded explosion chambers.

### 2.1. Task statement

Under consideration is the shell of permanent thickness, with the cylindrical central part and semi-spherical covers on its end-faces. Fig. 1 presents the general view of the shell and its geometrical parameters. The composite shell has the

radius of the cylindrical part and spherical covers  $R$  and cylinder length  $H$ . The explosive charge of arbitrary mass  $M$  and specific explosion heat  $Q_0$  is situated on the shell symmetry axis. The wall thickness is  $\delta$  and is permanent in each point of the composed shell. The optimal shell mass  $m$  and sizes ( $R, H$ ) are sought, providing that the assigned strength for allowable stress is guaranteed. The solution is sought as a function  $m(R)$ , where  $m$  is the composed shell mass. The length  $H$  of the cylindrical part is expressed via  $R$  and proportion factor  $K_H$  as  $H = K_H \cdot R$ , whereas, as the radius is varied, the relative sizes of the shell elements remain permanent. In the formulas below, the values for the spherical element contain indices "S", for the cylindrical ones – indices "C".

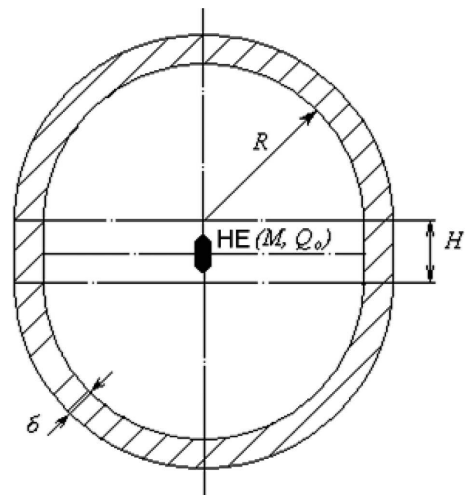


Fig. 1. Composed shell and its geometrical parameters:  $R$  is the radius of the cylindrical part and spherical cover,  $H$  is the cylindrical part length,  $\delta$  is the shell thickness. The explosive charge of mass  $M$  and specific explosion heat  $Q_0$  is situated in the shell center

Let us accept the following assumptions: the shell is treated as a thin-walled at  $R \geq 10 \delta$ . Similarly to [28], the formulas for thin-walled cases are used here. In [29] the author presents the numerical solution of the task of a non-spherical charge explosion; according to this solution, the front of the explosion wave replicates the charge shape at the distance of minimum 20 times above the charge size. In practice, in some cases, the charge shape is similar to the EC shell shape, thus the action of the explosion wave on the shell is quite uniform. It is valid, for example for cylindrical EC in which the frogs of railway points undergo the explosive hardening treatment [9]. In our calculations it is also assumed that the impulse is distributed uniformly over the composed shell surface. For each charge mass, the shell wall thickness is specially chosen in such a way to have the equivalent stresses occurring in it equal to the allowed value which we mean the elasticity limit at the cyclic loading. Re-distribution of the deformation energy between the shell's elements is ignored. Assume that the cylindrical part is deformed under the action of the pressure pulse distributed over its surface. Semi-spherical covers are also deformed only under the pressure pulse action onto their surface. Similar deformation pattern is observed in the shells with parts which do not have rigid connection to each other. The EC with such a shell was considered in [7]. In the spherical case, the two-axial stress state with equal meridional and circumferential stresses  $\sigma_{\phi S} = \sigma_{\theta S}$  occurs, since, in view

of the shell wall thinness assumption, stress  $\sigma_{rS}$ , acting along the shell radius, can be taken equal to zero. In the cylindrical case, the stress state is two-axial, too. There,  $\sigma_{rC} = 0$ ,  $\sigma_{\varphi C}$  are the circumferential stresses in the shell, whereas the axial stress  $\sigma_Z$  depends on the stresses in the semi-spherical covers and coincides with the meridional stresses on the end-face covers surface. The circumferential stresses in the cylinder are not similar in magnitude with the circumferential stresses in the semi-spheres. It corresponds to the case of the composite shell in which the parts are connected via the bayonette, as it transmits only the extension from the covers to the cylindrical part. Under the assumptions made it is possible to use the computational formulas and dependencies obtained in [7] to determine the optimal mass and size of the composed shell shown in Fig. 1.

## 2.2. Determination of explosion chamber mass and size

According to [9], the specific impulse  $I$  of the reflected shock wave is expressed as

$$I = \frac{2M \sqrt{2Q_0}}{S} \quad (1)$$

where  $M$  is the mass of the exploded explosive charge, kg;  $Q_0$  is the specific explosion heat, J/kg;  $S$  is the surface area under the impulse action, m<sup>2</sup>. The sphere surface area (total area of the internal surfaces of the spherical covers in Fig. 1 is  $S_S = 4\pi R^2$ . The area of the cylindrical shell surface is  $S_C = 2\pi RH$ . Hence in Eq. 1 the total area of composed shell surface is  $S = S_S + S_C$ . Conventionally, the full mass of the explosive charge  $M$  can be divided to two parts: the equivalent mass  $M_{ES}$  acting only on two semi-spherical parts, and the equivalent mass  $M_{EC}$  which acts only on the cylindrical part of the shell. Let us introduce for convenience the coefficients  $K_H = \frac{H}{R}$  and  $K_M = \frac{2}{2 + K_H} = 1 - \frac{K_H}{2 + K_H}$ . Then, by means of simple mathematical calculations we find, that

$$M_{ES} = \frac{2R}{2R + H} M = K_M \cdot M \text{ and } M_{EC} = \frac{H}{2R + H} M = (1 - K_M) \cdot M \quad (2)$$

Using the Eq. (1) and (2), one can apply the formulas from [7] to calculate the parameters of the composed shell elements.

At first let us find the stresses emerging in a composed shell during explosion of the charge  $M$ . The meridional and circumferential stress in the semi-spherical covers can be defined as follows

$$\sigma_{\phi S} = \sigma_{\theta S} = \frac{1}{2\pi \sqrt{1 - \mu}} \cdot \frac{M_{ES} E \sqrt{Q_0}}{\rho \delta_S (R_S)^2 a_0} \quad (3)$$

And the circumferential stress in the cylindrical part of shell are found by the formula

$$\sigma_{\phi C} = \frac{M_{EC} E \sqrt{2Q_0}}{\pi \rho \delta_C H R_C a_0} \quad (4)$$

From now on, the following designations are used:  $\mu$  is the Poisson's coefficient,  $E$  is the Young's modulus,  $\rho$  is the density,  $a_0$  is the acoustic speed of the shell material.

The thicknesses of the semi-spherical covers and cylindrical part of the composed shell, with regard to Eq. (2-4) and under condition of  $R_S = R_C = R$ , are

$$\delta_S = \frac{1}{2\pi \sqrt{1 - \mu}} \cdot \frac{M E \sqrt{Q_0}}{\sigma_2 \rho R^2 a_0} \cdot K_M \quad (5)$$

$$\delta_C = \frac{M E \sqrt{2Q_0}}{\pi \rho \sigma_1 K_H R^2 a_0} \cdot (1 - K_M) \quad (6)$$

where  $\sigma_2$  is the axial stress in the cylindrical part of composed shell (they are equal to the meridional stress in the semi-spherical cover), and  $\sigma_1$  is the circumferential stress in the cylindrical part of composed shell. When equating the above formulas (to satisfy the condition of  $\delta_S = \delta_C = \delta$ ), we have

$$\sigma_1 = \sigma_2 \sqrt{2(1 - \mu)} \quad (7)$$

Since the calculation is referred to the allowed stresses which are reached in the cylinder part when all elements have the same thickness, it is possible to write  $\sigma_m = \sqrt{\sigma_1^2 + \sigma_2^2 - \sigma_1 \sigma_2}$ , where  $\sigma_m$  is the allowed equivalent stress, i.e. the parameter of material strength. When substituting the expression for  $\sigma_1$  in this formula and solving the square equation, we have:

$$\sigma_2 = \frac{\sigma_m}{\sqrt{2(1 - \mu) + 1 - \sqrt{2(1 - \mu)}}} \quad (8)$$

Using the Eqs. (5, 6) the dependence of masses of spherical and cylindrical shell elements on a size parameter  $R$  can be found as:

$$m_S = \frac{4}{3} \pi \rho \left[ (R + \delta_S)^3 - (R)^3 \right] = \frac{4}{3} \pi \rho \left[ \left( R + \frac{K_1 \cdot K_M}{R^2} \right)^3 - R^3 \right] \quad (9)$$

$$m_C(R) = \pi \rho H \left[ (R + \delta_C)^2 - R^2 \right] = \pi \rho \cdot K_H R \left[ \left( R + \frac{(1 - K_M) K_2}{R^2} \right)^2 - (R)^2 \right] \quad (10)$$

where

$$K_1 = \frac{1}{2\pi \sqrt{1 - \mu}} \cdot \frac{M E \sqrt{Q_0}}{\rho a_0 \sigma_2} \text{ and } K_2 = \frac{M E \sqrt{2Q_0}}{\pi \rho K_H a_0 \sigma_1} \quad (11)$$

Since the composite shell mass consists of the sum of its elements masses, the final expression is:

$$m(R) = m_S(R) + m_C(R) \quad (12)$$

Thus, for the given values of explosive charge  $M$ , heat of explosion  $Q_0$ , parameter of composed shell shape  $K_H$  (see Fig. 1), material properties ( $\sigma_m$ ,  $\mu$ ,  $E$ ,  $\rho$ ,  $a_0$ ), and using the Eqs. (5-12) one can choose the suitable values of  $m$  and  $R$ . As a rule the shell size  $R$  follows from a type of works to be performed in explosion chamber, whereas chamber mass  $m$  and shell wall thickness  $\delta$  are calculated using Eqs. (9-12).

Evidently, the chamber mass depends on material strength  $\sigma_m$ . In [21] they use the high strength steel with a yield strength above 700 MPa. This enables to make EC for 8 kg of HE with a weight of 2 800 kg and a shell wall thickness of 30 mm. In our designs we use not expensive ordinary structural steels with  $\sigma_m = 200 - 300$  MPa. Note that we

make chambers sustaining 10 000 explosions and more. As the chamber shell undergoes the dynamic loading, the arising stresses depend on the impulse  $I$ , determined by formula (1). The peak pressure on the shell wall usually does not exceed 30 MPa and does not play an important role because of small pulse duration. The equations (1-12) permit to find chamber characteristics (wall thickness, mass, size) for any material chosen for EC manufacturing, but the strength parameter  $\sigma_m$  should be specified correctly, taking into account the necessary quantity of explosions to be made in a chamber.

### 3. Explosion chambers modifications and applications

A number of metal structures of the ECs have been developed for different technological applications and researching activities. As a rule, researching chambers are designed for relatively small explosive charges (150-200 g), they have special windows for optical shooting of fast processes. Fig. 2 shows the researching chamber KV-0.15 designed for the explosive charge of maximum 0.15 kg. The external diameter of the cylindrical part of the shell and its height are equal to 0.75 m. The chamber has a charging hutch with the diameter of 0.36 m and manual opening/closing, 8 measurement inputs and two antipode optical illuminators of 0.08 m in diameter. It is allowed to situate the maximal charge in the shell's center opposite to the illuminators. Inside the chamber, there is a working table, its diameter is 0.25 m. After each explosion, the chamber is blown with the compressed air (0.3 MPa), which is provided by two valves. The chamber mass is 800 kg. It is easy-serviceable and can be installed in rather small laboratory rooms.



Fig. 2. Explosion Chamber KV-0.15

Special ECs of individual structural design are developed for some researching purposes. Fig. 3 presents the plant for researching activities installed in Siberian Center of Synchrotron and TeraHerz Emission (Novosibirsk, Russia). The plant is de-

signed for 0.2 kg of explosive charge, the internal diameter of its cylindrical part is 0.98 m, the diameter of two charging hutches is 0.5 m. There is a pneumatic opening/closing mechanism, the plant mass is 2.7 t. Synchrotron emission enables to gather the unique information on the substance density distribution behind the detonation wave front.



Fig. 3. Explosion Chamber DVK-0.2

Technological ECs are purposed to solve industrial problems though they can also be utilized in scientific researches. The chamber KV-2 (Fig. 4) presents a typical example. This plant belongs to the vertical-type chambers and is designed for the concentrated charge up to 2.0 kg and for the flat charge up to 1.7 kg. The plant mass is 10.5 t, the internal diameter of the cylindrical part of the shell is 1.3 m, the working table diameter is 0.7 m, the height from the working table to the chamber pole is 1.67 m. The plant has a hydraulic drive for opening and closing. During the optical shooting, when the windows with special inserts are transparent, the maximal mass of the charge on the table in the case's center opposite to the illuminators is 0.5 kg. In addition to the researches, KV-2 is utilized for the explosive treatment of materials and can be used for the ammunition, such as shell fuse, destroy.

The bigger vertical-type chamber KV-5 for 5 kg of the explosive charge weights about 40t and has overall plane sizes 4.6×2.8 m and height 3.4 m in the close state and 4.3 m in the open state (Fig. 5). The working table of 1 m in diameter enables to treat quite large metal pieces or several articles together. Since 1991, more than 100 thousands bimetallic workpieces of plane bearings for diesel engines were manufactured by the explosive welding method in the KV-5 installed in Novosibirsk Factory of Measurement Equipment (Novosibirsk region, Russia) [30].



Fig. 4. Explosion Chamber KV-2

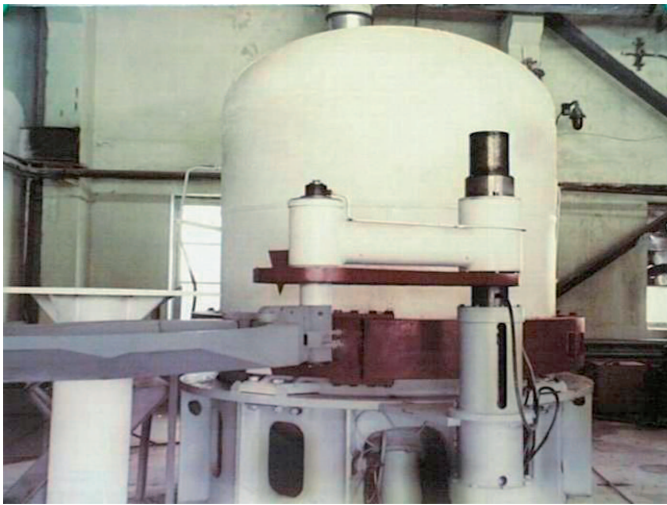


Fig. 5. Explosion Chamber KV-5

The ECs of a horizontal type, with the moving-out working table present and individual category. Initially, such chambers were designed for railway points strengthening by explosion [9]. For about 40 years this technology has been being utilized in Novosibirsk railway point factory where several horizontal ECs are installed. Later it turned out that such chambers can be utilized for other applications, too. For example, since 1995 the chamber KVG-8 designed for 8 kg of explosive charge has been operating in Norilsk mechanical factory (Fig. 6). The overall sizes of the plant with the extended table are: the length is 16.4 m, width 2.5 m, height 2.2 m. The cylindrical shell is 5.7 m in length, its internal diameter is 1.6 m. The plant mass (without ventilation system) is 48 t. In the chamber, bimetallic current leads to titanium electrodes are manufactured by the explosion method; these leads are used in electrolysis cells for nickel, titanium, and other metals production. The current lead presents a two-layer (copper/titanium)

tube with the external diameter of about 50 mm and length up to 1.3 m. The chamber permits manufacturing 12 tubes at one explosion. The other horizontal-type EC (KVG-16, for 16 kg of explosive charge) presents the double (by length) plant KVG-8. The open chamber length is 27.2 m, its weight is 76 t. The chamber was utilized for elimination of special pyrotechnic charges by explosion [27]. Within approximately two years, about 15 thousand explosions were organized in the chamber, with 16 kg of combustible mixture destroyed in each cycle.



Fig. 6. Explosion Chamber KVG-8

There are other modifications of the ECs. For example, facility Alfa-2 for 2 kg of explosive charge was developed especially to produce the diamond-graphite mixture from carbon-containing explosive charges. These facilities are utilized for nano-size diamonds production. The chamber mass is 6.8 t, its overall plane sizes are 2.0×2.5 m, height 4.5 m, inner volume is 2 m<sup>3</sup>. The working cycle is 10-15 minutes, hence more than 60 kg of the explosive substance can be treated during one working shift. Note that there are different technologies of diamond-graphite mixture production in which product synthesis takes place in different surrounding environment. Therefore the stress-strain state of the chamber's shell was studied for the explosions in carbon dioxide, air, and water-shell media [31].

Finally note the following. In many countries nowadays, much attention is devoted to the limitation of toxic exhaust from industrial enterprises. The explosion chambers enable to provide the needed level of environmental safety since they can be equipped with special devices for the purification of detonation products before their emission into atmosphere [9].

#### 4. Conclusions

Metal explosion chambers are the devices which effectively isolate such explosion factors as a shock wave, seismic action, and flying fragments of experimental or technologies assemblies. The chambers are rather commonly utilized as researching and technological equipment in the field of explosion welding, explosion strengthening, new materials synthesis, ammunition elimination, etc.

The methods of calculation of the stress-strain state of explosion chambers elements were developed; these techniques enable to determine the needed mass and size parameters of the devices for a given explosive charge mass. The computational techniques and many years' experience permit creating reliable custom-made equipment which guarantees high-level industrial and environmental safety.

#### Acknowledgements

The research was supported by the grants of the President of the Russian Federation for State Support of Leading Scientific Schools (nos. 246.2012.1 and 2695.2014.1).

#### REFERENCES

- [1] A.F. Demchuk, Method for designing explosion chambers, *Journal of Applied Mechanics and Technical Physics* **9**, 5, 558-559 (1968).
- [2] V.V. Adishchev, V.M. Kornev, Calculations of the shells of explosion chambers, *Combustion, Explosions, and Shock Waves* **15**, 6, 780-784 (1979).
- [3] A.A. Buzukov, Forces produced by an explosion in an air-filled explosion chamber, *Combustion, Explosion, and Shock Waves* **16**, 5, 555-559 (1980).
- [4] S.A. Zhdan, Dynamic load acting on the wall of explosion chamber, *Combustion, Explosion, and Shock Waves* **17**, 2, 241-244 (1981).
- [5] V.A. Mal'tsev, Yu.A. Konon, V.V. Adishchev, V.M. Kornev, Experimental study and analysis of the vibrations of an impulsively loaded thin-walled spherical shell, *Combustion, Explosion, and Shock Waves* **20**, 2, 214-218 (1984).
- [6] V.V. Sil'vestrov, A.V. Plastinin, N.N. Gorshkov, O.I. Stoyanovskii, Reaction of real explosion chamber to internal pulsed loading, *Combustion, Explosion, and Shock Waves* **30**, 2, 228-234 (1994).
- [7] U.P. Mesheriakov, A.A. Pikarevskii, O.I. Stoyanovskii, Calculation of maximum tension in poles of explosion chamber for explosion welding under conditions of real stressing, *Izvestia VolgGTU (Reports of Volgograd State Technical University)* **5**(65), 56-62 (2010), in Russian.
- [8] A.A. Pikarevskii, O.I. Stoyanovskii, Effect of shielding of a part of the casing of a technological explosion chamber on its stress state, *Journal of Applied Mechanics and Technical Physics* **54**, 2, 337-342 (2013).
- [9] A.F. Demchuk, V.P. Isakov, *Metal explosion chambers: monograph*. – Publishing house of Krasnoyarsk State University (2006), in Russian.
- [10] W.E. Baker, The elastic-plastic response of thin spherical shells to internal blast loading, *J. Appl. Mech.* **27**, 139-144 (1960).
- [11] W.E. Baker, P.A. Cox, J.J. Kulcsz, R.A. Srehlov, P.S. Westine, *Explosion Hazards and Evaluations*, Elsevier Science B.V. (1983).
- [12] <http://www.dynasafe.com>
- [13] <http://www.npo-sm.ru/english/fontan.php>
- [14] V.A. Mal'tsev, Yu.A. Konon, L.B. Pervukhin, G.V. Stepanov, Opyt expluatatsii, rascheta i perspektivy sozdaniya vzryvnykh kamer, in: I.V. Yakovlev, V.F. Nesterenko (ed), *Proceed. of the 9-th Intern. Conf. on High Energy Rate Fabrication*, August 18-22, 1986, Novosibirsk, Lavrentyev Institute of Hydrodynamics (1986), in Russian.
- [15] V.V. Danilenko, *Explosion: physics, engineering, technology*, Moscow: Energoatomizdat (2010), in Russian.
- [16] <http://www.ckp-rf.ru/usu/73564>
- [17] A.G. Kazantsev, A.D. Chudnovskii, A.A. Silaev, L.B. Pervukhin, P.A. Nikolaenko, Stress state and strength of weld explosion-loaded vessels, *Tjazholoe Mashinostroenie* **11**, 26-29 (2010), in Russian.
- [18] A.G. Kazantsev, A.D. Chudnovskii, S.S. Smolyanin, L.B. Pervukhin, P.A. Nikolaenko, Stress and strain analysis and the durability of metal explosion-loaded vessels, *Zavodskaya Laboratorija* **76**, 12, 37-42 (2010), in Russian.
- [19] A.G. Kazantsev, S.S. Smolyaninov, L.B. Pervukhin, P.A. Nikolaenko, D.R. Kapustin, Stress and strain analysis of metal container with porous concrete protection under explosion-loading, *Tjazholoe Mashinostroenie* **8**, 27-32 (2011), in Russian.
- [20] V.P. Mukoid, Transient dynamic behavior of a closed gas-filled shell subjected to internal blast loading, *International Applied Mechanics* **35**, 3, 288-294 (1999).
- [21] D. Karlsson, Validate Simulation Techniques of a Mobile Explosive Containment Vessel, *Proceed. 5-th ANSA & μ ETA Intern. Conf.*, 5-7 June 2013, presentation 2A.2.karlsson, <http://www.beta-cae.gr/conference05.htm#proceedings>.
- [22] Masatada Araki, Multi-purpose explosion chamber with sound muffing and vibration cutting means, *High-Pressure Research: an International Journal* **5**, 1-6, 906-908 (1990).
- [23] Kim W. King, Explosion containment vessel, US patent No. 6644165 B1 dated 11.11.2003.
- [24] D.C. Abbe, J.L. Donovan, Portable explosion containment chamber, US patent No. 8621973 B2 dated 07.01.2014.
- [25] J.L. Donovan, Method and apparatus for containing and suppressing explosive detonations, US patent No. 5884569 A dated 23.03.1999.
- [26] D.C. Abbe, J.L. Donovan, Portable explosion containment chamber, US patent No. 20120312147 A1 dated 13.12.2012.
- [27] A.A. Shtertser, Yu.P. Meshcheryakov, A.F. Cherendin, O.I. Stoyanovskii, Explosion chambers – ecologically safe equipment, *Nanotechnologii. Ekologiya. Proizvodstvo (Nanotechnologies. Ecology. Production)* **2**, 90-91 (2010), in Russian.
- [28] Yu.V. Skorniyakov, Yu.P. Meshcheryakov, Definition of mass optimization of blasting chamber shells, *Izvestia Samarskogo Nauchnogo Centra RAN (Reports of Samara Scientific Centre RAS)* **13**, 4, 1110-1114 (2011), in Russian.
- [29] S.K. Godunov, *Chislennoe reshenie mnogomernykh zadach gasovoi dinamiki*, Moscow: Nauka (1976), in Russian.
- [30] A.A. Shtertser, B.S. Zlobin, V.Yu. Ulyanitskiy, S.B. Zlobin, Use of explosive technologies for production the sliding bearings of diesel engines, *Izvestia Samarskogo Nauchnogo Centra RAN (Reports of Samara Scientific Centre RAS)* **13**, 4, 1056-1060 (2011), in Russian.
- [31] V.V. Sil'vestrov, A.V. Plastinin, N.N. Gorshkov, Effect of the media surrounding an explosive charge on explosion chamber shell reaction, *Combustion, Explosion, and Shock Waves* **30**, 2, 222-227 (1994)