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AUTOMATION OF THE CALCULATION PROGRAMS

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Abstract. *A model and technology for the manufacture of lightweight and reliable welded cylinders have been developed, in which high-strength steels and domestic composite materials are used to reduce weight. The technology of creating a composite winding allows to obtain a combined design with operational characteristics that meet the requirements of national and international standards. Studies have shown that the service life of metal-plastic cylinders is at least 25 years, which corresponds to the service life of modern ships. It was found that the reinforcement of the welded metal body with the composite surface of the cylinders exceeds the durability of 20 times. The use of such models with a metal case reinforced with a fiberglass composite in vehicles has confirmed their high reliability, long service life and safety.*

Key words: *safety, reliability, cylinder, strengthening, composite, environment.*

Introduction.

Ukraine's post-war economy will require a lot of time and money to develop new technologies and equipment for alternative fuels. Therefore, Ukraine, simultaneously with the introduction of a natural gas saving regime, is constantly searching for alternative sources of its production and supply directions. However, many of them are related to the need to cross the marine areas: the Caspian, Black and Mediterranean Seas and the straits between them.

Today, the transportation of natural gas through marine areas remains an extremely urgent and complex problem. Three main technologies are used for the transportation of natural gas by sea: underwater pipelines, gas carriers in liquefied (LNG) or compressed (CNG) states, each of which has its advantages and disadvantages. For Ukraine, the transportation of compressed natural gas by sea will be of great importance [1,2].

The issue of transporting natural gas and using it as the main energy carrier is extremely relevant, and the choice of safe and reliable technology remains the main problem of this industry. Therefore, the creation of new or improvement of existing tanks, with the help of which it is possible to transport a large volume of gas at low costs, is a top priority.

Analysis of the status of research and publications.

With the growing focus on sustainability and renewables, the demand for CNG is gradually increasing. Large investments are needed in the development of infrastructure, as well as the improvement of gas storage and processing technologies themselves. CNG technology is an important step towards reducing the carbon footprint, global warming and climate change, as well as reducing air pollution and diversifying energy sources.

Consequently, CNG technology (Compressed Natural Gas - CNG) is a new technology for the marine transportation of natural gas on special vessels in a compressed state. At the same time, ships use a special transport system for loading and unloading gas, as well as for pre-treatment, compression and transportation in containers at high pressures [3].

This technology was first tested in the 1960s in the United States. In 1964, the first special vessel for the transport of liquefied natural gas from Algeria to England, called Methane Princess, was built at the Vickers Armstong Shipbuilders shipyard for the Shell Tankers UK operating company. The gas carrier with a cargo capacity of 34,500 cubic meters of methane had aluminum tanks, a steam turbine, in the boilers of which it was possible to dispose of boiled gas. However, it had certain disadvantages, such as the heavy weight of high-pressure cylinders, so given the long distances of transportation from gas-bearing regions to consumers, it did not become widely used.

In addition, the Canadian company TransCanada Pipeline offered the transportation of compressed gas by gas locomotive in the form of vertical cylinders from a gas pipe, which, for the purpose of reliability and safety of operation, were reinforced with fiberglass composite material. And to increase thevolume of transportation with the same mass of cylinders, EnerSea Transport proposed to place gas cylinders in cooled modules [1-3].

Crane & Stenning Technology Inc. proposed to replace gas cylinders with a long pipe, which is enclosed in a bay in the form of a part of the gas pipeline. This made it possible to reduce the safety factor from 2.5 for cylinders to 1.7, but these proposals do not have practical implementation.

There are a large number of marine shipping container designs in the world. They can be universal, specialized, refrigerated, for the transportation of liquids (oil, alcohol, etc.). Containers of all types have constant technical characteristics, a special design that ensures the transportation of cargo by one or more modes of transport without intermediate unloading from the container. By design, containers can be closed, open and tank containers.

Ukrainian scientists have also proposed a technology for transporting compressed natural gas on container ships equipped with standard sea containers containing containers with compressed gas [4, 5]. B.E. Paton, Ye.I. Kryzhanivskyi, V.V. Zaitsev, A. Dzhus, M.M. Savytskyi, O.H. Dzioba and others were involved in the research of CNG sea transportation systems, as well as the design, calculations and construction of container ships and movable pipelines [6-10].

Ukraine has declared its intention to achieve climate neutrality in 2060, which is 10 years later than the European goal. In July 2021, the Government approved Ukraine's new goal of reducing greenhouse gas emissions by 65% of 1990 levels by 2030. As of 2021, Ukraine has already reduced emissions by 62.5% since 1990, but this reduction was primarily due to the decline of industry after the collapse of the Soviet Union. This calls into question the possibility of achieving climate neutrality within the specified period, due to the not very ambitious goal of reducing GHG emissions. Despite the challenges of the war, some initiatives are being implemented at the national level that are designed to help Ukraine achieve its goals.

Natural gas is by far the most common and environmentally friendly energy source. Its projected reserves, energy and environmental characteristics ensure its dominance in the fuel and energy complex despite the war in our country. Due to its low cost, it is massively used as a fuel in internal combustion engines, which is one of the largest environmental pollutants, it generates 5-10 times less carbon monoxide, 3 times less aromatic hydrocarbons, 1.5-2.5 times less nitrogen oxides, 8-10 times less smoke than other fuels, which is of great importance in terms of environmental impact (Table1) [3].

Table 1 - The presence of harmful substances depending on the type of fuel

Fuel type	CO_2	C_xN_y	$N0_x$	Soot	$Pb0_2$	Benzo-pyrene
Gasoline	100	100	100	0	100	100
Gasoline + catalyst	20-30	15	25	0	0	55
Diesel fuel	12	15	50-85	100	0	55
Diesel + Natural Gas	8-13	8 -13	50-70	20-40	0	30-40
Propane	15-20	55-70	30-80	0	0	3-15
Natural Gas	5-15	1-15	25-55	0	0	3-15

A source: [3]

According to the Kyoto Protocol, more than 35% of CO_2 emissions are generated during the operation of internal combustion engines. Therefore, the use of natural gas in internal combustion engines is considered as an alternative solution to the problem of greenhouse gas emissions. Many studies have been conducted on the accumulation, storage and transportation of natural gas in cylinders. The design and manufacturing technology of light high-pressure cylinders have been developed, the conditions for their safe operation have been studied.

The results of the American Gas Association and the Institute of Electric Welding (EWI) named after E.O. Paton [10]. During field tests, the gas was released through a funnel-shaped hole formed by a bullet with a dense jet without ignition by firing gas filled with natural gas at a pressure of 200 atm. cylinders. The bullet, having lost its puncture force, remained in the cylinder, the destruction of which stopped at the depressurization stage.

Thus, high-pressure cylinders are a fairly reliable means for loading and storing natural gas under pressure. The main drawback is the high weight of large-capacity cylinders, which limits the deadweight of the gas carrier ship. With such transportation, the fuel consumed exceeded the delivered gas resource in terms of energy indicators.

To date, there are good results in the construction and operation of gas pipelines from welded pipes of large diameters, as well as new developments in combined structures. Thus, according to Knutsen O.A.S. Shipping, referred to by the author, the transportation of compressed gas by sea at distances of 500-3000 nautical miles is more economically feasible [11].

In addition, transportation by CNG gas carriers has other advantages:

1) use of offshore deposits;
2) diversification of sources and points of gas production;
3) the possibility of using unused offshore platforms for unloading;
4) relatively lower cost of infrastructure for loading/ unloading;
5) simplicity of the cargo system design;
6) a higher level of safety, and therefore it is possible to reduce the safety factor of cylinders;
7) the possibility of using unused container ships by converting existing containers;
8) environmentally friendly (green) loading/unloading technology;
9) use of technologies for the production of pipes and the construction of high-pressure gas pipelines (up to 250 atm.) to create cylinders of large volume and pressure;
10) low gas consumption with a large greenhouse effect.

One of the main indicators of cylinders for transporting gas by sea is their small-size indicator, that is, the ratio of the mass of the cylinder to its useful volume (M/V). The cylinder, which is made of high-strength X80 pipe steel, has this indicator of 1,7. Equipped with these cylinders, a vessel with a capacity of 80 thousand tons will be able to transport up to 12 million m^3 of gas per voyage. This is considered a good indicator for a company that produces and supplies gas by its own means.

Our calculations show that this indicator can be significantly improved by using combined cylinders – a steel liner with a shell of composite material.

As can be seen from Table 2 composite material formed from epoxy-based fiberglass allows to improve M/V by 2,1-2,5 times and increase the capacity of the cargo system by 1,5-2 times, depending on the strength of the steel. The great advantage of the composite shell is its reliability. Tests confirm that the formation of a fatigue crack does not cause the destruction of the cylinder. The crack is formed only in the steel body of the cylinder, which leads to a pressure drop and the subsequent closure of the crack. That is, the gas is not completely released into the atmosphere. And the particle that came out of the cylinder seeps through the walls of the shell without destroying it.

Consequently, such a technology for strengthening cylinders is new and therefore requires detailed development: selection of materials, determination of design parameters, manufacturing technology, ensuring reliability of transportation, safety in operation, etc.

Methodology of Research.

The uniformity of welded joints and base metal under static loads is ensured provided that the strength limit is up to 2000 MPa. However, in the case of low-cycle loads, the requirements for the quality of welded joints are significantly increased. One of the key factors that starts the longevity of such joints is a sufficient margin of ductility.

The strength and ductility of high-strength and high-strength steels depend on the tempering stabilization modes after hardening. The effect of these modes due to the diffusion transition of carbon parts from the free state, fixed hardening in a solid solution, to the bound state (carbides). 30ХГСА steel was chosen for the study.

To study the effect of tempering temperature on the plastic properties of steel, experimental tests of the base metal at tempering temperatures of 500, 550 and 600 °C were carried out. The results of these tests are shown in Table 2.

As follows from the above results, in order to obtain a relative elongation δ_5 of at least 14%, which is required by the regulatory documents for the welded structure, the tempering temperature of 30ХГСА steel must be at least 550 °C.

On models of cylinders with a diameter of 229 mm, L=860 mm, it was previously established that at stresses of 950 MPa and a relative elongation $\delta \geq 14\%$, the required durability of welded cylinders N≥15000 load cycles is ensured. Moreover, after 15000 refueling-exhaust cycles, internal pressure tests of cylinders showed that their safety margin does not decrease. That is, in this cycle range, high resistance to fatigue failure is provided. It was also found that among the main reasons that affect the durability of welded structures under variable loads are:

- ✓ structural forms that can cause the appearance of a stress concentrator in weldedjoints;
- ✓ technological and metallurgical factors that create residual stresses and change the composition and chemical microinhomogeneity of the metal in the joint area during welding and heat treatment of the metal.

Table 2 - Test results of 30ХГСА steel samples

Sample No.	t, mm	b, mm	S, mm^2	$T_{tempering}$, °C	σ_c, MPa	$\sigma_{0,2}$, MPa	δ_5, %	E, GPa
1	3,5	20,1	70,35	500	1209	1135	10.8	194,4
2	3,58	19,95	71,62	500	1216	1162	11.7	191,99
3	3,54	19.85	69,7	550	957	868	15.2	192,66
4	3,53	19,8	69,89	550	959	870	14.8	201,36
5	3,57	19,85	70,68	550	987	889	14.9	195,99
6	3,52	19,9	69,65	600	968	873	14.6	198,15
7	3,48	19,85	68,88	600	945	839	15.4	194,94
8	3,57	19,9	71,49	600	958	865	15.8	196,67

Authoring

The main types of stress concentrators in welded structures are displacement of edges, dents, undercuts, cracks, pores, slag inclusions, lack of penetration, lack of fusion. It is generally known that even in a perfectly welded joint, the stress concentration coefficient is in the range of 1,3-2,5.

Further studies were performed on the above models, which performed well in previous experiments.

To reduce the impact of the stress concentrator, the following methods are known:

1) finalizing the joints with a cutter, cutter or abrasive wheel to ensure a smooth transition of the joints into the base metal, which is known to be especially effective for butt joints – the endurance limit increases by 40-60%;

2) rational design of welded joints by locating joints outside the most loaded sections of the structure.

To reduce the impact of residual stresses, the following technological methods are used:

- heat treatment by high tempering;
- formation of a pre-stressed state;
- plastic deformation of the seam – post-weld local and near-weld zone;
- pulse processing.

It is worth noting that the environment can affect the endurance resistance of materials both negatively and positively. The negative impact is exacerbated by an aggressive corrosive environment, which significantly reduces the endurance limit of metal products. A positive impact is created by the environment, which is the solid body itself. This phenomenon was first noticed when the holes in steel samples were welded with a material with a lower modulus of elasticity than in steel (for example, bronze electrodes). V.Gilde recommended changing the environment using solid polymeric materials with dispersed fillers, which hermetically cover welded joints and have a positive effect on their endurance. Such a material should have high adhesion to the metal, be plastic, have a lower modulus of elasticity and sufficient resistance to changes in loads so as not to break earlier than the metal. It has been established that the specified requirements are met by adhesives used in the industry for gluing metals. Among the adhesives made on the basis of compositions from thermosetting and thermoplastic synthetic resins, the most common are unsaturated polyesters based on compositions from thermosetting and thermoplastic synthetic resins. The positive effect here would be much more significant if the existing polymer adhesives had a higher strength. In fact, it is within 30-60 MPa.

Results and Discussion.

In this regard, it was decided to combine two methods of reinforcing welded joints on the selected models of cylinders, namely, the application of polymer adhesive and the creation of an environment in the form of a solid. This can be achieved by reinforcing the welded shell structure with a composite material.

The reinforcement efficiency will be most fully used when the reinforcement is performed by annular winding of the fiber material on a cylindrical shell made by rolling and welding with a longitudinal seam, i.e. in the direction of maximum forces.

The technology of manufacturing the composite shell is based on the technological principles developed in the manufacture of experimental ring samples, the quality assessment of which is confirmed by laboratory studies of the physical, mechanical and technological properties of composite materials.

Thermostatting of glass roofing bobbins for moisture removal was carried out in a furnace at a temperature 200 °C. Preparation of the binder fraction was carried out by weighing the components in the proportions specified in the instructions, stirring for 30 minutes and settling for 3 hours to remove air.

Sandblasting and degreasing of cylinder bodies with a solvent was carried out before applying a composite material to it.

The formation of the composite shell was carried out on a lathe equipped with such technological devices as a bobbin holder, a fiber path with a tray for binding and a regulator and a controller of the tension force of the technological belt. With the help of a fiber path, individual strands of glass roving are formed into a technological tape so that by the time of contact in each strand there is the same pre-tension force to ensure the compatible operation of all fibers during loading. In the future, the technological tape passes through the bath, where the impregnation of the fibers with a binder takes place.

The binder-formed and wetted processing tape passes through a braking device that is created by the force of friction-slip on the surface of the fingers. The electronic device controls the tension force, the value of which determines the density of the structure and the degree of application of the binder.

Designed and manufactured devices provide convenient quick installation on the machine and dismantling in order to clean and prevent it.

After setting the necessary parameters of the rotation speed and progress of the caliper, a layer-by-layer annular winding of the glass roofing is carried out until the calculated thickness of the composite material is reached.

An additional problem that needed to be solved when forming a composite shell on a welded body is the presence of reinforcement of welds protruding above the surface.

It has been established that the protrusion of the bead of welded annular seams above the surface does not affect the quality of the composite material, because the technological tape is laid parallel to these seams.

The presence of a roller protrusion in the longitudinal weld of the shell and possible technological deviations from the shape of the circle, such as dents or bulges in the zone of this connection, affect the level of stresses, that is, local stress concentrators are created, which, under cyclic loads during operation, significantly reduce the endurance life of the material.

In addition, when winding the process tape, it is laid perpendicular to the longitudinal seam and loosely adjacent to the cylinder body. Therefore, such qualitative characteristics of the composite material as volume filling and percentage content of pores are locally violated in this area. To reduce the effect of the roller protrusion in the longitudinal weld of the shell, it must be removed. Improving the quality of the material formed on the modified metal case was confirmed in the course of laboratory tests.

The elements of the housings were made of sheet high-strength steels 30ХГСА and 25ХСНМФА by rolling a cylindrical shell, stamping hemispherical bottoms.

The elements of the housings were connected by welding the cylindrical shell with a longitudinal seam, and the hemispherical bottoms were welded to the shell with annular seams. A neck with a thread W27,8 under the valve was welded into one of the bottoms. The metal of the body made of 30ХГСА steel was hardened for strength of 950 MPa, and steel 25ХСНМФА – 1150 MPa.

The experimental batch of housings (Figure 1) was made of steel 30ХГСА with an outer diameter of 212 mm, and of steel 25ХСНМФА – 236 mm with a thickness of 3,5 mm, which provided an estimated margin of safety of the cylindrical part at the level of about 1,6, and hemispherical bottoms – 3,2.

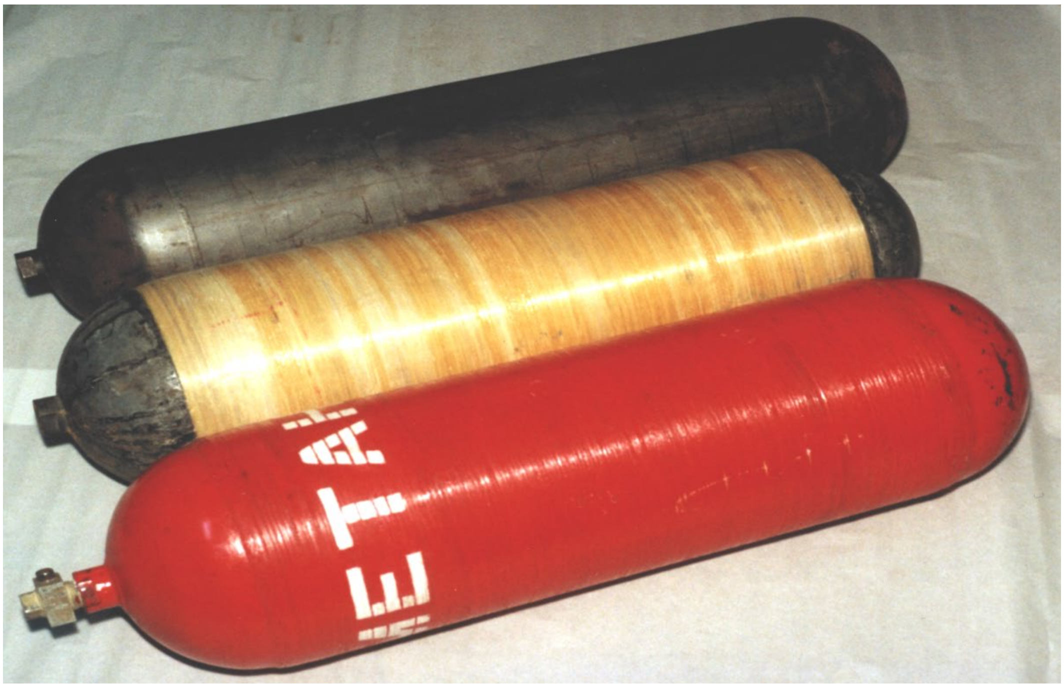

Figure 1 – Test samples of welded metal-plastic cylinders, reinforced with composite material

Authoring

This makes it possible not to cover hemispherical bottoms with composite material, because their safety margin is greater than the established requirements – K=2,6, and reinforce only the cylindrical part of the cylinder, which reduces the weight of the cylinder and at the same time reduces its laboriousness. To achieve a uniform margin of safety of the finished cylinder, reinforcement of the cylindrical part of the housings with a unidirectional annular composite material based on ES10 1618U10(168) roving and binding KDAHI was used. The worked-out technological modes on the test ring samples made it possible to prove the strength of the composite material in the ring direction to 950 MPa, that is, to ensure its uniformity with steel.

To conduct a full range of studies of the performance and durability of metal-plastic cylinders under conditions of repeated loads during refueling during operation and possible extreme situations, a pilot batch of cylinders was manufactured.

A full range of studies of the efficiency and durability of combined cylinders under conditions of multiple loads during refueling during operation and in possible extreme situations has been carried out. To confirm the technical solutions and calculation results, a set of tests was carried out.

The manufactured samples of metal-plastic cylinders have passed the full volume of laboratory and field tests, taking into account the requirements of domestic and foreign standards for products of this type.

The value of the actual safety factor of cylinders was determined during tests with a gradual increase in internal hydraulic pressure to failure at the installation for hydraulic tests.

To establish the safety margin of the steel body of the cylinder, their tests were carried out without reinforcement with a composite. The hulls collapsed viscously without the formation of fragments, and the presence of welds did not affect the nature and place of destruction (Figure 2).

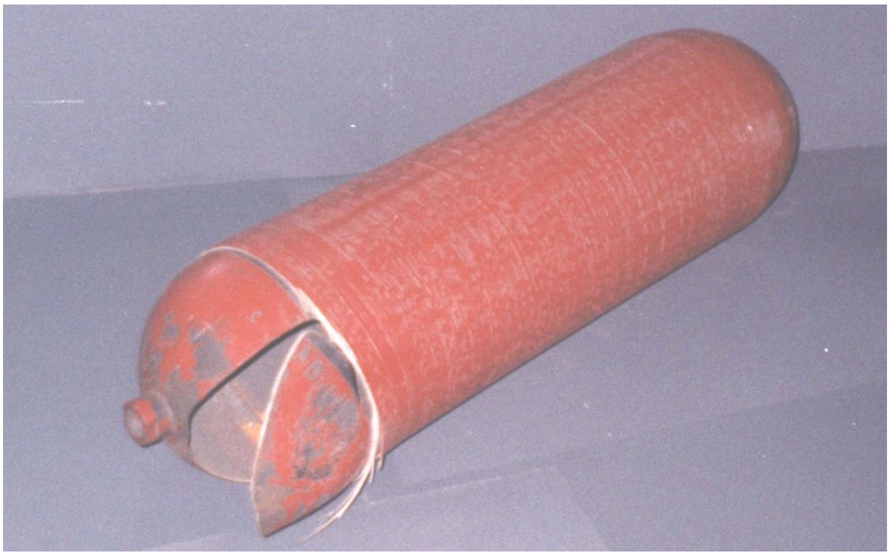

Figure 2 - Destruction of metal-plastic cylinders

Authoring

The destruction occurred at a pressure of 31,0 to 32,0 MPa. This confirmed the correctness of the selected modes of metal heat treatment, as well as calculations of the thickness of the steel housing.

When reinforcing cylinders with composite material 3,5 mm thick, they collapsed at a pressure of 58,0 to 61,0 MPa, which meets the requirements and confirms the results of theoretical calculations.

Under conditions of low cycle loads, the requirements for welded joints are increasing, therefore, in the course of testing the welding technology and heat treatment modes to determine the durability of welded housings, they were tested in the mode of cyclic loads by internal hydraulic pressure, which varied in several ranges (2,0-5,0; 2,0-8,0 and 2,0-15,0 MPa) with a frequency of not more than 10 cycles/min. Tests were carried out until the body was depressurized. After achieving the optimum welding and heat treatment parameters, the following test results were obtained:

1. when cycling in the range of 2,0-5,0 MPa of 30ХГСА steel casings – 30863 cycles;
2. when cycling in the range of 2,0-8,0 MPa of housings made of 30ХГСА steel (with mechanical treatment of welds by the vibrocoating method) – 5266 cycles;
3. when cycling in the range of 2,0-8,0 MPa of 30ХГСА steel casings – 50049 cycles;
4. when cycling in the range of 2,0-15,0 MPa of bodies made of steel 25ХСНМФА – 25846 cycles.

During the tests, the depressurization of welded housings occurred in the form of microcracks in the near-shore thermal impact zone at a distance of 3-7 mm from the fusion boundary, which opened under the action of pressure and caused leakage of the working fluid.

To determine the possible service life of cylinders, their tests were carried out in the mode of cyclic loads by internal hydraulic pressure, which varied in the ranges 2,0-20,0 and 2,0-22,0 MPa with a frequency of not more than 10 cycles/min. The tests were carried out before the cylinder depressurization. The following test results were obtained:

- ✓ when cycling in the range of 2.0-20.0 MPa cylinders with a welded body made of 25ХСНМФА steel –25 386 cycles;
- ✓ when cycling in the range of 2.0-22.0 MPa cylinders with a welded body made of 30ХГСА steel – 23 403 cycles.

In the mode of cyclic loads, the depressurization of cylinders occurred in the form of drip leakage, which stopped when the pressure dropped to a value of 5,0-15 MPa.

The residual safety factor after 15000 load cycles was determined by the static load of the cylinder before fracture and was 2,75 (fracture pressure 55,5 MPa).

At the same time, it was found that the cylinders lose their tightness after reaching at least 15000 load cycles. And this gives the right to operate them for at least 15 years. Thus, it is proved that welded cylinders, in case of reinforcement with composite material, are sufficiently durable.

Combined cylinders are also quite safe under dynamic load. The penetration of cylinders filled with methane up to 19,6 MPa, armor-piercing bullets of 7,62 caliber, or cumulative charges of UKZ-10 leads to damage to only one wall, forming an opening with smooth edges, in contrast to all-metal cylinders that are completely destroyed. In this case, the gas escapes through the hole without catching fire or exploding.

In a fire, cylinders with gas under pressure of 5 MPa, located horizontally above the surface of diesel fuel, are heated to 600-650 °C in 30 minutes. At the same time, the pressure in them rises to 18 MPa, which does not cause the destruction of cylinders. In cylinders with an initial gas pressure of 19,6 MPa, which were located vertically above the surface of diesel fuel, in such conditions the pressure increases to 55 MPa. In this case, the metal-plastic cylinder is destroyed not earlier than after 12 minutes, separating into two parts without fragments, while the all-metal cylinders are destroyed after 20 minutes, but with the formation of fragments.

In accordance with the requirements of transport safety, in order to exclude such extreme situations when cylinders of any design can break down during the fire of the vehicle, they are equipped with fuses that are triggered at a pressure of 30 MPa. To verify this, fire tests were carried out on the vehicle with cylinders installed on it, which were filled with gas at a pressure of 19.6 MPa.

The conducted climatic tests of cylinders in the range of limiting temperatures from minus 40 to plus 60 °C did not affect their strength and durability. Throwing the cylinder on the concrete floor from a height of 1,8 m does not affect their strength.

Summary and conclusions.

The tests carried out confirmed the reliability and safety of the developed cylinder design.

Compliance with the requirements of domestic and world standards for welded structures of high-pressure cylinders [12, 13] was achieved on the basis of the development of advanced welding technology using special activating fluxes, heat and machining modes, which ensured the uniformity of welded joints and the base metal, and durability – due to the reinforcement of welded housings with composite materials. Due to the complex of new developments, an increase in the operability of cylinders by more than 20 times and a decrease in their weight by 2-3 times was achieved. The cylinder has a stable mass index M/V=0,65 kg/l.

Consequently, the studies performed allow extrapolating their results to a wide range of cylinders of different geometric sizes by changing their diameters, lengths and wall thicknesses without replacing the main technological equipment. At the same time, it is possible to use existing equipment and materials that are provided to the industry of Ukraine, and further expand production with the production of up to several million cylinders per year, which will create hundreds of thousands of jobs in the metallurgical, chemical and engineering industries and ensure reliability and safety in the transportation and use of compressed natural gas in the reconstruction of our country.

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