

# Development and investigation of means of transportation, storage, gasification and refueling of cryogen liquids of space systems

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## ABSTRACT

The paper describes the development of hydrogen, oxygen, LNG (tank cars, container cars) stationary devices based on the existing constructions. The investigation results of liquid hydrogen losses on experimental cryogenic storage and transport tanks with different thermal insulation (multilayer-vacuum, powder-vacuum, screen-vacuum (with a nitrogen screen of different designs)) are presented.

The paper presents the results of research on obtaining and maintaining pressure in the tank of a gasification plant with hydrogen supercritical parameters for long-term product delivery to the customer at variable or constant flowrate, both using an external source of hydrogen and a part of the hydrogen supplied to the consumer as a heat carrier.

The paper presents a method and equipment of refueling the Orbiter fuel tanks with high-purity hydrogen for variable hydrogen mass and different number of tanks.

**Keywords:** tank car, tank container, storage tank, thermal insulation of the tank, gasifier of liquid hydrogen, supercritical parameters of cryogenic liquid, power supply system of the orbiter.

## INTRODUCTION

The steady progress of the development of large carrier rockets [1] led to the need to switch to liquid hydrogen and oxygen, requiring ground-based and onboard cryogenic systems [2]. At this stage, the demand for systems of transportation, storage, gasification, and filling of the low-boiling component of the space systems emerged [3-7].

The power supply system of a lunar orbiter in the "N1-LZ" program and the "Buran" orbiter in the "Energia - Buran" program was based on electrochemical generators (EG) with hydrogen-oxygen fuel cell with matrix electrolyte. Such a generator transformed the chemical energy of the fuel to electricity and water [8]. The electrochemical generators "Volna" and "Foton" used cryogenic components (high-purity oxygen and hydrogen) as fuel cells. This decision was related to the requirement to have the required power capacity of the electrochemical generators of the orbiter's power supply system [9].

The Federal Target Program "Development of Spaceports for the Period 2017-2025 to Support the Space Activities of the Russian Federation" envisages the construction and commissioning of a rocket-space complex for launching the carrier rocket "Angara" at the "Vostochny" spaceport launching spacecrafts using boosters working on cryogenic components: liquid oxygen and liquid hydrogen.

Due to the relevance of these tasks, the main goal of those research projects was two-fold. The first subgoal was the investigation of in-tank processes in the subcritical and supercritical zones taking into thermal-physical and transportation properties. The second subgoal was the development of means of transportation, long-term storage, gasification, and refueling for ground space infrastructure installations.

Cryogenic tank cars for delivering liquid hydrogen (tank cars 8G514 and ZVC) and liquid oxygen (tank cars 8G512 and 8G513), which were developed as a part of the "N1-LZ" Lunar program in Russia at the end of the 1960s, did not meet the engineering requirements of the current stage of space program development. The reasons for this are as follows [10, 11]:

1. High losses of cryogenic components during transportation (1.6 % daily loss for hydrogen and 1.3 % daily loss for oxygen);
2. Low mass of the transported liquid oxygen and low working pressure in the transport tank;
3. Contamination of high-purity components by adulterants during the processes of transporting cryogenic liquids to a space complex;
4. Lack of devices for safe discharge of hydrogen vapor in the atmosphere for both the normal hydrogen transportation and emergencies (losses of vacuum in the insulation cavity of the tank) in conditions of transportation of a rocket fuel component;
5. Lack of transportation equipment capable of multimodal (mixed) transportation of cryogenic components of rocket fuels.

The following research and development projects on creating modern equipment for systems of transportation, long-term storage, gasification, and refueling space systems by low-boiling components had to be carried out to address these issues.

### **Transportation of cryogenic components**

The following research was carried out:

1. Determination of evaporation capacity of liquid hydrogen on test general-purpose tank cars ZVC-100M and ZVC-100M2, of liquid oxygen, nitrogen, argon on tank cars 15-558S-03, 15-558S-04, of liquified natural gas on the tank car 15-5106, of the liquid hydrogen tank container KTsv-20/1,2, of the liquid natural gas tanks KTsm-35/06, KTsm-40/07.
2. Investigation of accumulation of impurities in the liquid hydrogen during transportation from the manufacturer to the launch complex. Also, a method justifying the need to take into account the accumulation of impurities at each stage of the fuel component delivery (filling the transportation tank, transportation, draining the transportation tank).

3. Discharge regimes of hydrogen and LNG vapor in the atmosphere during normal transportation and emergencies in conditions railway transportation of cryogenic rocket fuel components (losses of vacuum in the thermal insulation cavity of the transport tank) were investigated, and safety measures were proposed. Also, parameters of a safe drainage device for hydrogen and LNG vapor atmosphere discharge in the condition of transportation of hazardous substances were determined.
4. Investigation of multimodal (mixed) transportation of cryogenic liquids in container tanks [12].

Based on the research, a method and device for safe discharge of hydrogen and methane vapors during transportation in a container was developed. The method provides a safe discharge of hydrogen and methane vapors from the container to the atmosphere in the conditions of railway and automobile transportation.

The main concept and design of a new type of vehicle – tank container for multimodal transportation of cryogenic rocket fuel components (hydrogen, LNG, oxygen) were developed.

Figure 1 shows the developed and manufactured experimental tank car and container tank for transporting liquid hydrogen.



model ZVC-100



model ZVC-100M



model ZVC-100M2



tank container for liquid hydrogen

**Figure 1.** Tank cars for liquid hydrogen transportation

Table 1 shows the technical specification of experimental railway tank cars for the transportation of liquid hydrogen.

As seen from Table 1, daily evaporation of the new ZVC-100M2 was reduced down to 0,8 %, which is two times less than the evaporation of the ZVC-100 (1.6% per day). Besides, the transportable hydrogen mass was increased by 7.1 % up to 7.5 tons.

During the investigation, the processes of vacuum loss in the thermal insulation cavity of the insulation space of a transportation tank during railway transportation of liquid hydrogen were investigated, Fig. 2, Fig. 3.

Parameter name	Tank car model		
	ZVC-100	ZVC-100M	ZVC-100M2
Geometric volume, m <sup>3</sup>	119		
Working vessel pressure, MPa	0.25		
Transportable hydrogen mass, kg	7000	7000	7500
Bogie type	Three-axle	Three-axle	Two-axle
Type of thermal insulation	Multilayer powder-vacuum	Multilayer powder-vacuum	Multilayer vacuum insulation with partial powder filling
Liquid hydrogen evaporation losses, % per day.	1.6	1.2	0.7...0.8
Method of unloading hydrogen from the vessel	Top unloading with pressurization of an external source		
Tank mass, kg	87800	87800	73500
Tank clearance	1T		
Tank dimensions, mm:			
length	23600	23600	23600
width	3180	3180	3180
height	3770	3770	3770

**Table 1.** Technical specification of railway tank cars for transportation of liquid hydrogen

Recommendations on the design of transport device elements (installation of protection against breakdown by auto-coupling, design of safety devices in the vehicle container, choice of material for manufacturing the vessel shell) were made.

Table shows the results of studies of thermophysical parameters. The study results are used to determine the parameters of the flow capacity of the safety devices of the liquid hydrogen transport vessel.



**Figure 2.** Hydrogen vapor discharge via tank relief valves



**Figure3.** A tank shell is frozen due to vacuum loss

Parameter	Value
Initial hydrogen mass in the vessel, t	4.85
Initial vessel pressure, MPa	0.178
Relief valve pressure-to-discharge, MPa	0.765
Time of valve pressure discharge from 0.765 MPa to 0.70 MPa, s	173
Time until first discharge of the relief valve, min	41
Time of pressure increase from $1 \cdot 10^{-4}$ mmHg to atmospheric pressure value, h	2.5
Hydrogen full evaporation time, h	6
Minimum vessel shell temperature, K	75

**Table 2.** Results of experimental determination of thermal-physical parameters of vacuum loss on the ZVC-100M tank car

The existing equipment for transportation of oxygen separation products (nitrogen, oxygen, hydrogen) met none of the current requirements (transportable mass of cryogenic component, vessel working pressure, component transportation losses). So, research was carried out to determine the evaporation capacity of liquid oxygen for different thermal insulation types in the transport tank.

Based on investigation results, multilayer vacuum thermal insulation allowed achieving daily oxygen evaporation capacity as low as 0.17 % (Table .3), which 1.7 less than that of the 8G513 tank car. Besides, the transportable oxygen mass was increased by 1.4 times up to 50.7 t. During tests, the vessel pressure could be raised from 0.25 MPa to 0.50 MPa, which allowed reducing the liquid oxygen consumer drainage rate and increase the drainless cryogenic component transportation time.

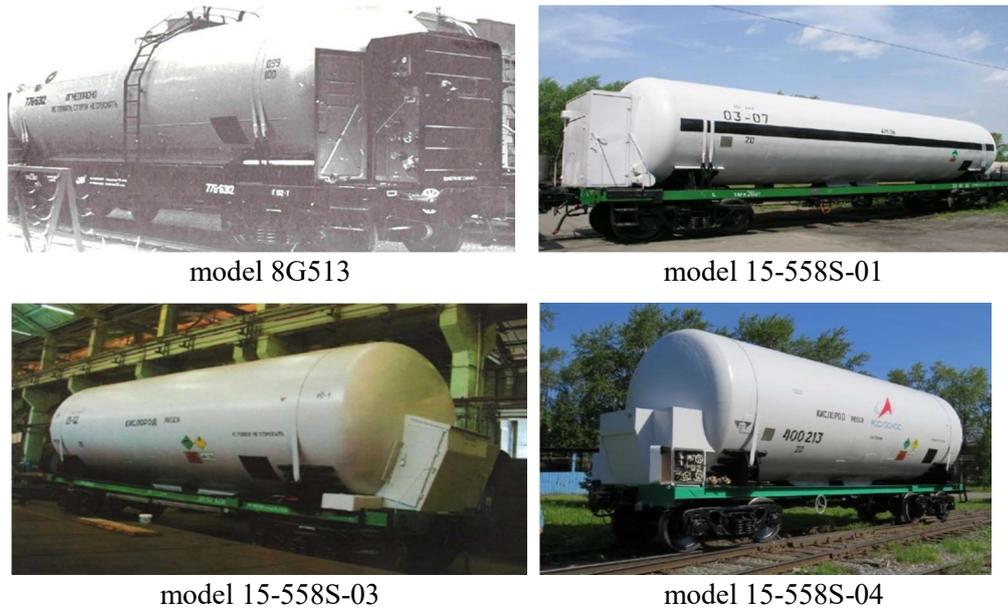
Parameter name	Cryogenic tank car model			
	8G513	15-588S-01	15-588S-03	15-588S-04
Geometric volume, m <sup>3</sup>	33.75	44.00	49.10	49.10
Vessel working pressure, MPa	0.25	0.50	0.50	0.50

Transportable product mass, t:				
oxygen	36.00	47.00	50.70	50.70
nitrogen	25.50	34.00	35.50	35.50
argon	36.00	55.00	57.60	57.60
Thermal insulation type	Powder-vacuum		Fiber-vacuum	Screen-vacuum
Product loss rate, % per day:				
argon	0.35	0.37	0.38	0.19
nitrogen	0.35	0.50	0.50	0.27
oxygen	0.30	0.35	0.34	0.17
Unloading method	Top unloading, with pressurization from the vaporizer			
Tank car clearance	02-VM	02-VM	02-VM	1-VM
Tank mass	35.30	37.80	34.50	34.77
Vessel material	AMtsS alloy (analog of 3003 alloy)	Steel 12Kh18N10T (analog of AISI 304)		
Shell material	Steel 09 G2S (analog of 13Mn6 steel)			
Tank overall dimensions, mm:				
Coupled length	12 570	14 730	12 020	12 020
width	3 000	3 040	3 246	3 246
height above rails	4 265	4 265	4 550	4 550
Vessel transportation pressure, MPa	Normal pressure	0.03–0.45		
Unloading rate, l/min	700–1000	500–800		

**Table 3.** Technical specifications of cryogenic tank cars

Figure 4 shows the developed and manufactured experimental cryogenic tank cars for transporting liquid oxygen, nitrogen, argon (15-558S-0, 15-558S-03, 15-558S-04).

The results of studies of different thermal insulation types (powder-vacuum, multilayer-vacuum (based on basalt mats), screen-vacuum) of different general-purpose industrial vessel for transporting liquid oxygen, nitrogen, argon allowed reducing the evaporation capacity of liquid oxygen and nitrogen in the 15-558S-04 tank with screen-vacuum thermal insulation by the factor of 1.2...1.4 [13, 14].



**Figure 4.** Tank cars for transportation of liquid oxygen, nitrogen, argon

### Liquefied natural gas transportation

Prospects of using liquefied natural gas (LNG) as rocket fuel in the space industry led to the need for transportation devices for delivering LNG to launch sites and rocket engine test facilities [10].



**Figure 5.** A railway tank car and container tank for LNG transportation

A novel cryogenic tank car and container tank, Fig. 5, were developed for LNG transportation. These devices are currently used in the space industry and for LNG export shipments in the Far East. Table 4 shows the technical specifications of these transportation devices.

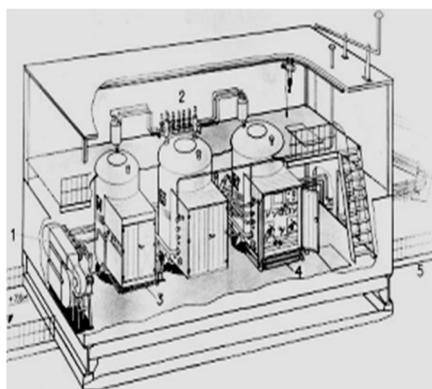
Parameter name	Tank car 15-5106	Container tank 40/0.7
Gross weight, t	-	30.48
Transportable product mass, t	23,5	14.2
Capacity, m <sup>3</sup>	65.4	40
Max permissible working pressure, MPa	0.5	0.7
Insulation type	Fiber-vacuum	Screen-vacuum
Evaporation loss rate, %/day	0.43	0.54
Drainless storage time, days	42	60

**Table 4.** Technical specifications of LNG tanks

### Development of high-purity cryogenic components' storage systems

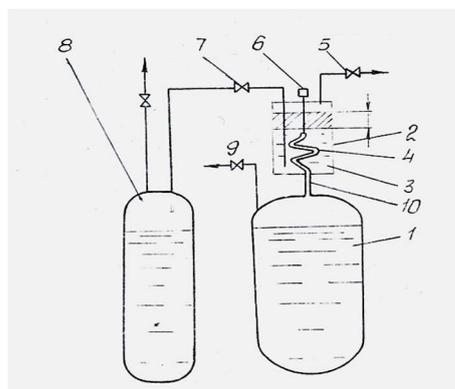
The following subjects were studied:

1. The purity of fuel cryogenic components during long-term storage (up to five months of storage in storage reservoirs);
2. Investigation and development of long-term drainless storage of liquid high-purity oxygen at pre-critical pressure in a storage reservoir;
3. Investigation and development of long-term drainless storage of liquid high-purity hydrogen at pre-critical pressure in a storage reservoir;
4. Investigation and development of devices for storage and unloading liquid hydrogen from a storage reservoir at supercritical pressure ( $P_p = 22.0$  MPa).



**Figure 6.** High-purity liquid oxygen storage layout:

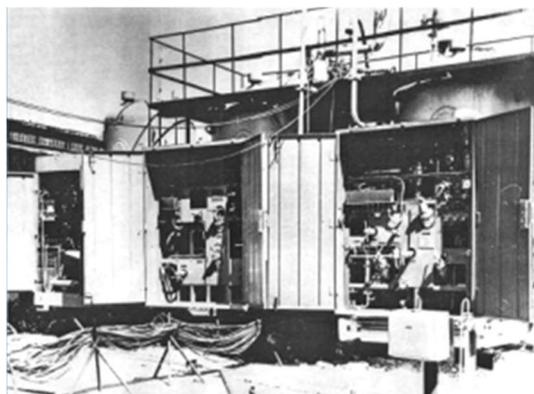
1 – gas heater; 2 – condensation system; 3, 4 – vaporizers; 5 – support frame; B2 – reservoir vessel; B3 – process oxygen vessel; B4 – liquid oxygen gasifier.



**Figure 7.** Pneumatic diagram of the high-purity oxygen reservoir

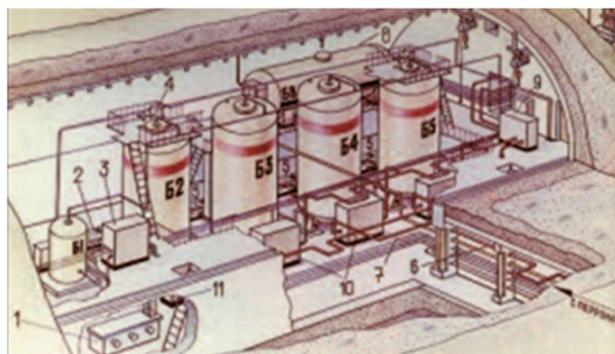
Investigation of storage duration of high-purity oxygen was done based on drainless storage, Fig. 6, using process oxygen as a cooling agent for condensation of vapor of high-purity oxygen, Fig. 7. The oxygen is supplied to the storage condenser located in the tank gas blanket with a lower boiling point than the boiling point of the high-purity oxygen.

The pressure in the storage reservoir was maintained in the range of 0.04–0.07 MPa, corresponding to the equilibrium temperature of 93.2–95.2 K. The process was maintained by periodic delivery of process oxygen, which boils at room temperature, in the condenser, Fig. 8. Drainless storage of high-purity oxygen eliminated nitrogen and argon contamination.



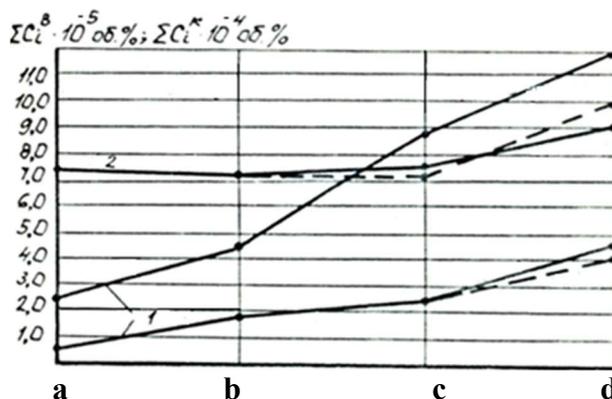
**Figure 8.** High-purity liquid oxygen storage facility

The investigation of the duration of the high-purity hydrogen in the storage vessel, Fig. 9, with the volume of 30 m<sup>3</sup> with the liquid nitrogen as a cooling agent supplied to the screen of the thermal insulation cavity of the storage vessel, revealed that the evaporation loss of liquid hydrogen was reduced to 0.3 % per day. This allowed limiting the liquid hydrogen contamination by impurities, oxygen, and nitrogen to  $4.5 \cdot 10^{-5}$  % according to the regulatory value (Figure10).

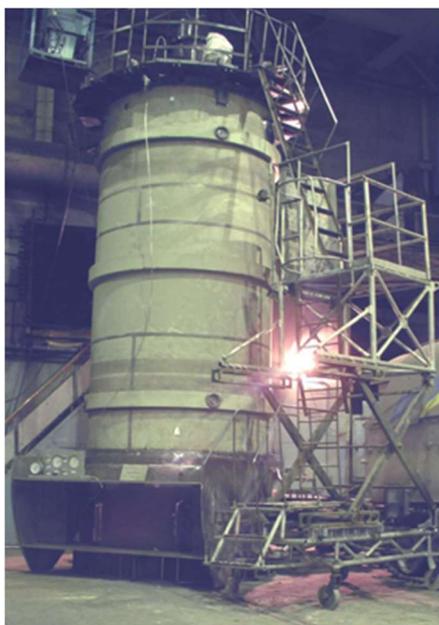


**Figure 9.** Liquid hydrogen storage with a block of vessels with nitrogen screens

Figure 9 shows 1–3 – armature blocks; 4, 5 – liquid hydrogen vessels; 6 – liquid hydrogen vessels’ supply pipelines; 7 – pipelines for unloading liquid hydrogen from vessels; 8 – liquid nitrogen process vessel; 9, 10 – storage vessels’ armature blocks; 11 – liquid hydrogen loading pipeline.



**Figure 10.** Plot of stage-wise change of concentration of impurities in liquid hydrogen (1) and oxygen (2) during delivery to the power supply system tanks (solid lines) and to electrochemical generators (dashed lines):  
*a*) component loaded in the tank; *b*) component unloaded from the tank; *c*) component delivered from the storage; *d*) component delivered to the tanks of the power supply system and to electrochemical generators



**Figure 11.** General view of the reservoir for storing liquid hydrogen at supercritical pressure  $P_{work} = 22.0$  MPa

We conducted an investigation and developed the structural designs of storage reservoirs to store liquid oxygen and nitrogen at supercritical working pressure [15].

Investigation of the process of storage and unloading liquid hydrogen, Fig. 11, from the reservoir at the pressure of  $P_{work}=22.0$  MPa was conducted at a special test site. The test site has a system for measuring the vessel wall temperature and a system for the regulated supply of a cooling agent to the vessel; the vessel thickness was 120 mm.

The cooling agent was supplied to the vessel screen located inside using the “accumulate-discharge” method of continuous discharge through the Laval nozzle, which created a vapor-liquid medium on the vessel screen. The vessel cooling rate corresponded to the regulation value of 30 K/hour.

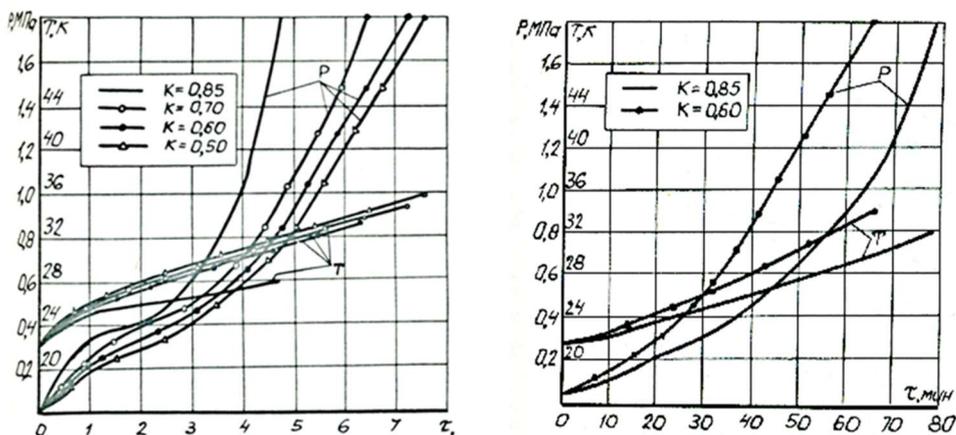
### **Gasification of liquid hydrogen**

The following research was carried out:

1. Reaching and maintaining supercritical parameters of hydrogen in the gasification plant tank during long-term (up to 140 hours) delivery at constant and variable flowrate using an external hydrogen coolant source and a part of hydrogen from the gasifier as a coolant source;
2. Investigation of transient processes in the hydrogen gasifier vessel vs. technical specifications of the consumer device;
3. Investigation of purity of hydrogen gasified and stored in the gas state for different gasification plants at supercritical parameters at launch and engineering complexes;
4. Process of removing hydrogen from tanks of an orbiter on launch and landing facilities.

Research on the creation and maintenance of supercritical parameters of hydrogen in the gasification plant vessel during continuous delivery to the consumer for a long period of time, both with continuous and periodic delivery, both using an external hydrogen source, Fig. 12a, and a part of the hydrogen from the tank going to the consumer as a coolant, Fig. 12b, was carried out on a special test stand, Fig. 13, 14. The test stand had equipment for coolant supply, hydrogen gasifier pressure, and temperature gauges, gauges for measuring gasified hydrogen flowrate, and chromatography instruments for analyzing the percentage of impurities in the gasified hydrogen supplied to the consumer.

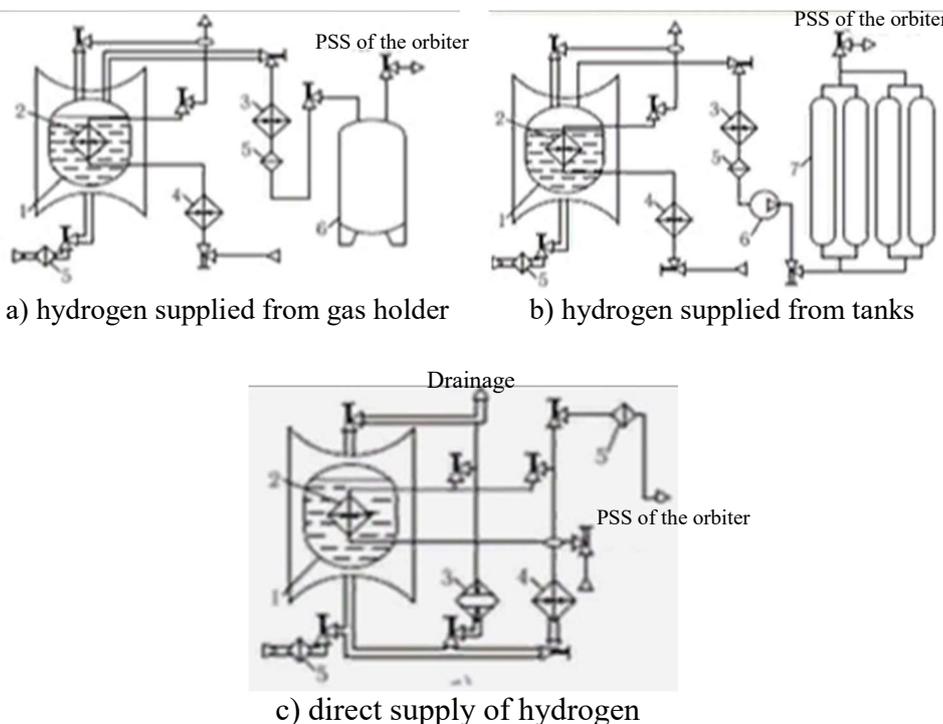
The study results allowed the creation of a liquid hydrogen gasifier with supercritical pressure of  $P=2.5$  MPa with periodic hydrogen flowrate from 0 to 2.16 kg/h, purity of 99.9999 % loaded in the electrochemical generators of the power supply system at the launch and engineering complexes.



a) Heat supply from an external source

b) Heat supply from the unloaded hydrogen

**Figure 12.** Measured hydrogen pressure and temperature in the vessel upon reaching the supercritical parameters of hydrogen



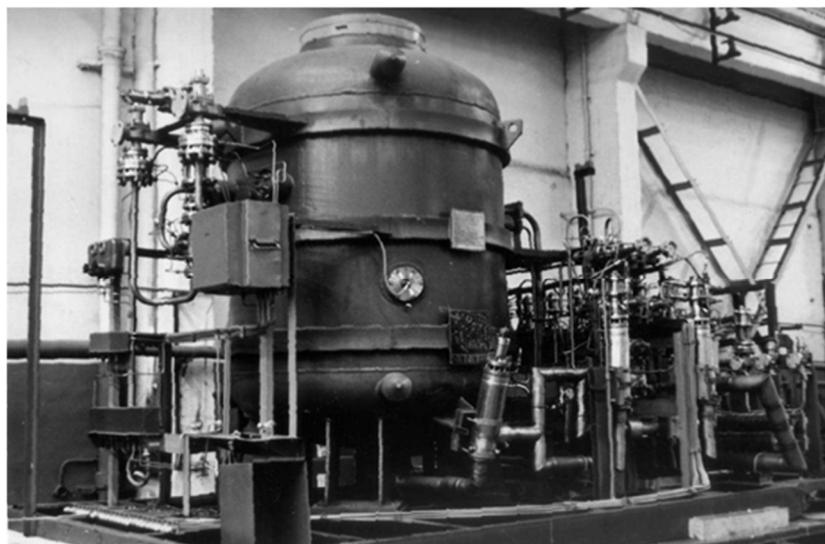
a) hydrogen supplied from gas holder

b) hydrogen supplied from tanks

c) direct supply of hydrogen

**Figure 13.** Schematic layout of the test rig for supplying hydrogen to the orbiter power supply chemical agents' storage and preprocessing subsystem.

1 – vessel, 2 – internal heat exchanger, 3 – vaporizer, 4 – external heat exchanger, 5 – filter, 6 (a) – gas holder storage, 6 (b) – compressor, 7 – storage receiver



**Figure 14.** Test rig for testing hydrogen gasification at supercritical parameters

### **Refueling tanks of the orbiter power supply tanks with liquid hydrogen and liquid oxygen**

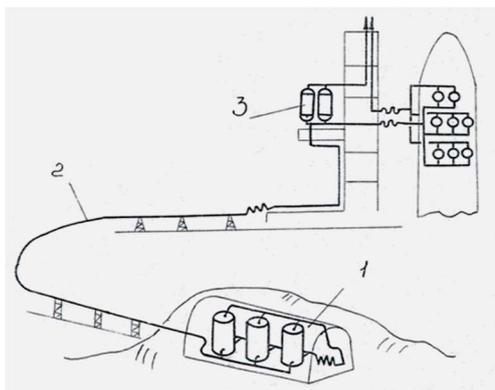
The following research was carried out:

1. Investigation and improvement of regimes of refueling a variable number of tanks of the orbiter power supply system with high-purity liquid hydrogen;
2. Investigation and improvement of regimes of refueling tanks of the orbiter power supply system with ultra-purity liquid oxygen for variable refueled oxygen mass (50, 75, 100 %);
3. Investigation and refinement of regimes of supplying gasified high-purity hydrogen and oxygen to the electrochemical generator of the orbiter power supply system.

Investigation and improvement of regimes of loading the orbiter's power supply system tanks were carried out on a special test rig. The test rig has standard tanks with input tank temperature and pressure gauges, a flowmeter at the input, a vessel for liquid hydrogen storage with temperature, pressure, and level gauges, as well as devices for delivering liquid hydrogen to the test rig from the manufacturer., Fig. 15.

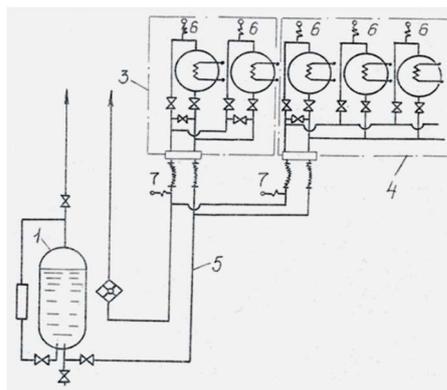
The study results confirmed the following:

- The possibility of loading 54 kg of hydrogen at a temperature of 23 K and flowrate of 0.06 kg/s in the tank for the refueling time from 20 to 40 minutes, Table 5;
- The possibility of refueling power supply system tanks with a variable number of tanks and variable hydrogen mass (50, 75, 100 %) (Figure 16).



**Figure 15.** Layout of the system for loading the tanks of the system of the orbiter power supply chemical agents' storage and preprocessing

1 – liquid hydrogen storage reservoirs,  
 2 – fueling system pipelines,  
 3 – intermediary vessels.



**Figure 16.** Pneumatic and hydraulic diagram of the system for loading the tanks of the system of the orbiter power supply chemical agents' storage and preprocessing

1 – intermediary vessel, 2 – vessel pressurization vaporizer, 3 – base block, 4 – modular block, 5 – fueling system pipelines, 6, 7 – temperature gauges

Tank #	Parameters before re-loading				Parameters taking into account re-loading			
	Flowrate, kg/S	Temperature, K	Hydrogen mass, kg	Fueling time, min	Flowrate, kg/S	Temperature, K	Hydrogen mass, kg	Fueling time, min
1	0.06	22.28	57.6	16	0.023	22.5	57.4	18
2	0.053	22.28	57.5	19	0.034	22.9	57.3	21
3	0.025	23.2	54.45	39	0.013	24.1	55.5	41
4	0.026	23.2	56.6	36	0.007	23.3	56.5	38
5	0.026	23.2	56.6	36	0.007	23.3	56.5	38
6	0.026	23.2	56.6	36	0.007	23.3	56.5	38
7	0.025	23.2	54.45	39	0.013	24.1	55.5	41
8	0.026	23.2	56.6	36	0.007	23.3	56.5	38

**Table 5.** Method of loading electrochemical generator tanks with liquid hydrogen

The study results enabled the following:

- Development and manufacture of devices for loading spacecraft tanks of the power supply system's electrochemical generators with high-purity oxygen and hydrogen, Fig. 15;
- Development and testing of systems for supplying gasified high-purity oxygen and hydrogen to the electrochemical generators, Fig. 17.

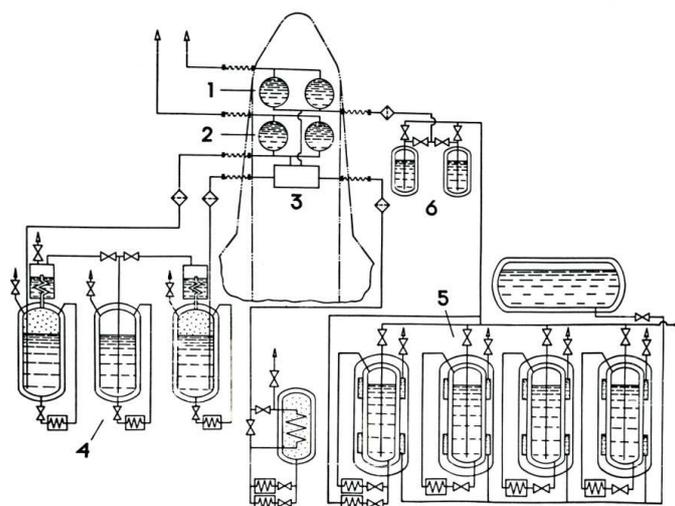
### CONCLUSION

As a result of the conducted research, equipment that meets the requirements for transportation, long-term storage, gasification, and refueling of tanks of rocket and space systems with high-purity liquid hydrogen and ultra-purity liquid oxygen was developed.

For cryogenic tank cars, the following loss reduction was achieved:

- The loss of liquid hydrogen in the ZVC-100M and ZVC-100M2 tank cars was reduced down to 0.8 % per day;
- The loss of liquid oxygen in the 15-558S-04 tank car was reduced down to 0.17 % per day.

For long-term (five months) storage of high-purity liquid oxygen at a launch site, a method and device for drainless were developed to preserve the oxygen purity and prevent oxygen loss. For long-term storage of high-purity hydrogen, a storage reservoir was developed. The reservoir storage is characterized by minimum daily liquid hydrogen losses and minimum contamination by nitrogen and oxygen.



**Figure 17.** Layout of the system for refueling tanks of the orbiter power supply system's electrochemical generators with liquid hydrogen and oxygen:  
**1** – hydrogen storage tanks; **2** – oxygen storage tanks; **3** – electrochemical generator of the orbiter power supply system; **4** – liquid oxygen reservoir; **5** – liquid hydrogen reservoir; **6** – intermediary liquid hydrogen vessels; **7** – liquid oxygen gasifier

Transient processes during storage, gasification, and delivery of hydrogen from the tank at supercritical parameters of cryogenic components were studied for two methods of reaching the hydrogen supercritical parameters. The first method was to use an external hydrogen source as a coolant, and the second method was to use a part of the supplied hydrogen from the gasifier tank. The transient process during the delivery of high-purity hydrogen from the gasifier tank at supercritical parameters for a long time with constant and variable flow rates was investigated.

Devices for liquid hydrogen and oxygen storage and unloading at supercritical working pressure ( $P_{\text{work}} = 22.0$  MPa) were developed, manufactured, and tested.

We developed a method and device for loading the tanks of the system of the orbiter power supply chemical agents' storage and preprocessing with high-purity hydrogen for a variable number of tanks (up to eight tanks) and loaded hydrogen mass (50, 75, 100 %) with hydrogen purity of 99.9999 %. The hydrogen is supplied to the electrochemical generators of the power supply system at launch and technical sites with a purity of 99.999 % and flowrate of 0...2.16 kg/h at a pressure of 1.4...1.8 MPa.

The accumulated experience allows developing mobile and stationary equipment aiding the implementation of the Federal Programs from 2020 to 2025.

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