Methodology and results of experimental studies of precision weighing systems of refueling complexes of upper stages and spacecraft of space rockets

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Abstract. This article presents the main provisions of the new methodology, scientific and methodological approach and the results of experimental studies of precision weighing systems of refueling complexes of upper stages and spacecraft of space rockets. The article presents the following results of experimental studies of precision weighing systems: experimental substantiation of the provisions and conclusions of the metrological model of the refueling complex; experimental confirmation of the metrological characteristics of weighing devices of platform scales and platform two-channel scales in terms of weighing the delivered doses; experimental determination of the actual dose delivery error according to the indications of platform scales and two-channel platform scales with the supply of propellant components from transport and refueling containers; experimental testing of PC software in order to identify possible errors, as well as to make possible adjustments to the software for more accurate tracking of the main refueling operations; selection of optimal values of low flow rate for a more accurate cutoff of the dose and practicing the operator's actions at the stage of the cutoff operation; determination of cutoff errors based on statistical processing of experimental data. The article also presents in detail the experimental unique scientific installation created by the authors, identifies the directions of its practical application in testing new weighing systems, in research work and in the educational process.

1. Introduction

Experimental studies of precision weighing systems (WS) with the supply of propellant components directly from the transport and refueling container (TRC) using bench equipment simulating refueling complexes (RC), play a significant role in solving an important problem situation of increasing the accuracy of refueling complexes of upper stages and space vehicles (SV) space rockets (SR) [1-4]. These studies were carried out in the joint research laboratory of the Department of Transport installations of MADI and ZAO ELVES (Closed Joint Stock Company) under the scientific supervision of the leading researcher of the MADI research department, Candidate of Technical Sciences, Senior Researcher V.M. Shulga. When conducting experimental studies of precision weighing systems, the following goals were set: experimental substantiation of the provisions and conclusions of the metrological model of refueling complexes; experimental confirmation of the metrological characteristics of the weighing devices (WD) of the platform weighing device (PWD) and weighing device platform two-channel
(WDPTC) in terms of weighing the doses issued; experimental determination of the actual dose delivery error according to the indications of the PWD and WDPTC with the supply of RFC from the TRC; conducting experimental testing of the PC software in order to identify possible errors, as well as to make possible adjustments to the software for more accurate tracking of the main refueling operations; selection of optimal values of low flow rate for a more accurate cutoff of the dose and practicing the operator's actions at the stage of the cutoff operation; determination of cutoff errors based on statistical processing of experimental data.

Experimental studies were carried out by issuing control doses of water from a filling tank installed on the weighing module of the weighing system into a control container installed on a control balance. To carry out the experiment, we assembled experimental installations, the description of which is given in this article in Section 2 "Materials and Methods". Refueling complexes with a volume of 100 and 250 liters are used with PWD-500, with WDPTC-1000 - 250 liters, with WDPTC-2500 - 999 liters, with WDPTC-5000 - 2000 liters. For the dose of each nominal value, as a rule, 10 experimental points were obtained. Doses were dispensed at a constant pressure of 0.3 ± 0.001 MPa. In the experiments, a correction was introduced for the mass of displaced air in the filling tank and for the mass of displaced air from the control tank (CT). The actual mass of the i-th dose was calculated based on the readings of the control weights. When dispensing each i-th dose, the dose cut-off error was recorded, which is equal to the readings of the Icon board. The processing of the experimental results was carried out according to the method described in this article in Section 2 "Materials and Methods".

2. Materials and methods

Experimental installations and stands were created on the basis of the hydro laboratory. The stand includes main and auxiliary equipment. The main equipment includes: a pneumatic system, a water supply and drainage system, a set of high-precision control scales, a set of filling tanks, a set of control tanks (CT), gauges of excess pressure, temperature, humidity and atmospheric pressure, gas-hydraulic dispensing shields, sets of connecting hoses, weights of class M1 with a nominal value of 20 kg, a set of weights of 1 g - 1 kg and 1 kg - 10 kg class M1, weights of class M1 with a nominal value of 500 kg.

Ancillary equipment includes: a beam crane with a lifting capacity of 2000 kg, a hydraulic trolley with a lifting capacity of 1.5 t, a hydraulic stacker with a lifting capacity of 1.5 t, a universal foundation with embedded parts designed for the installation of stationary weighing devices with Max up to 15,000 kg. The composition of the stand allows testing the methods and technologies of refueling in the dose range from 0.4 to 2500 kg. The description of the stand is given in [4, 9]. A mobile set of special bench equipment for research in the range from 40 to 10,000 kg has also been created. Experimental installations are simplified models of refueling complexes. In this case, the following rule should be adhered to: the maximum load of the check balance should be 2 ÷ 5 times less than the maximum load of the working weighing devices. This rule reflects the real conditions of refueling, under which the mass of the dispensed doses is 2 ÷ 10 times less than the mass of the filled with the refueling component. In all experiments, the total mass of the filling container with water should be equal to the gross mass of the refueling complex. If necessary, to fulfill this condition, the required number of weights is additionally placed on the platform of the weighing device. In all experiments, the devices used as check weights are adjusted immediately before work is carried out, and the adjustment is carried out in the range of delivery of control doses. The result is a high actual weighing accuracy on the checkweigher. Actual error values, as a rule, do not exceed the following values: ±1 g for VM24001 scales, ±5 g for special control scales (SKS) SKS-100, ±10 g for SKS-400, ±10 g for PWD-500, ±20 g for WDPTC-1000. Figure 1 shows a pneumohydraulic diagram of an experimental setup with a WDPTC-2500 working balance. This weighing device is intended for refueling complete with fuel filling station V = 999 l in the dose range from 200 to 1200 kg. The filling tanks are filled from the preparation tank E2 using the P1 pump. The required pressure in the system is generated and maintained using a pneumatic system. If the lines are spilled, the water is drained into the drain tank (DT). Dose cutoff is performed by valves V1 (high flow rate) and V2 (low flow rate, which is provided by the Throttle 1 nozzle).
A general view of the experimental setup is shown in Figure 2. The figure shows the WDPTC platform with a filling tank located on it; control rack based on a 19-inch cabinet; two mobile digital displays made in explosion-proof design; dispensing shield, which includes, along with other valves, cut-off valves and a nozzle. Figure 3 shows the 46” video wall panel included with the unit, which mirrors the PC monitor image and allows the refueling supervisor and commissioners to monitor the refueling process.

The panel displays information obtained during the development of the technology of filling the upper stage (dose of the oxidizer weighing 292.00 kg). The plant circuits similar in structure are used in experiments with the use of VD PWD-500 and WDPTC-1000. The difference lies in the volume of the filling and control tanks, the maximum load and the type of working and control weights. Table 1 shows the data for the equipment used in experiments with PWD-500 and WDPTC.

Figure 4 shows a variant of the installation with operating scales PWD-500 and a filling tank with $V = 250$ liters.
Figure 4. General view of the experimental setup for issuing control doses with the simultaneous use of weighing devices PWD-500 (main channel) and WDPTC-1000 (backup channel)

The installation, assembled in this version, was used to test the technology of work in case of emergency situations, therefore PWD-500 was installed on the WDPTC-1000 platform. A SKS-100 balance and a control container with $V = 50$ liters were used as control weights. The installation with WDPTC-5000 has a somewhat more complex scheme (see Figure 5). During research, filling tanks E1.1 and E1.2 are simultaneously filled with water from tanks E2.1 and E2.2 using pumps P1 and P2. A general view of the experimental setup (without check weights) is shown in Figure 6. The figure shows the WDPTC platform with two refueling tanks located on it; a control stand, a mobile digital display, a dispensing board, which, along with other valves, includes shut-off valves and a nozzle.

Figure 7 shows check scales WDPTC-1000 and PWD-500 with control tanks with $V = 1000 \text{ l}$ and $V = 500 \text{ l}$. This installation allows you to issue control doses of water weighing up to 1300 kg. Experimental equipment for the study of the metrological characteristics of the complex of refueling facilities for the RB and spacecraft of the ILV requires separate consideration. For these purposes, a mobile set of special bench equipment was created in the following composition: special control scales SKS-500 (Max = 500 kg); special control scales SKS-10 (Max = 10 t); capacity $V = 1 \text{ m}^3$; capacity $V = 10 \text{ m}^3$; pump with a maximum capacity of $16 \text{ m}^3/\text{h}$.

Figure 5. Diagram of an experimental setup with WDPTC-5000

Before testing, the SKS-500 balance was adjusted, and their actual error did not exceed 10 g in the entire weighing range from 0 to 500 kg. SKS-500 complete with a capacity of 1 $\text{ m}^3$ made it possible to weigh doses in the range of 40 - 400 kg. For research in the range from 500 to 10,000 kg, special control scales SKS-10 with a maximum load of 10,000 kg were specially developed [5].
Table 1. Composition of experimental equipment

| Working scales | PWD-500 | WDPTC-1000 | WDPTC-2500 | WDPTC-5000 |
|----------------|---------|------------|------------|------------|
| Control scales | VM24001 | SKS-100    | SKS-100    | PWD-500    |
|                | SKS-400 | PWD-500    | WDPTC-1000 | WDPTC-1000 |
| Filling volume | 250     | 250        | 900        | 1800       |
| containers, liters |      | 900        |            |            |
| Control volume | 50      | 50         | 100        | 500        |
| capacity, liters |     | 200        | 500        | 1000       |
|                | 500     |            | 1000       |            |

Figure 6. Installation for experimental testing of the technology of filling products with WDPTC-5000

Figure 7. Check scales WDPTC-1000 and PWD-500

The scales used load cells of the SB4C4M7.5 type with a nominal load of 5000 kg. To complete the scales in terms of electronic equipment, an ADC-M unit and a TVM weight terminal were used. Based on the tests carried out for the purpose of type approval, the VSK-10 were registered with the Federal Information Fund for Ensuring the Uniformity of Measurements. The limits of permissible error of the balance are given in Table 2. The use of this equipment makes it possible to weigh the control doses of water dispensed by the filling complex in the range from 40 to 10000 kg. A series of three test dips showed that the actual error of the scales in the range of 10-10000 kg when loaded lies in the range from minus 0.4 kg to 0.0 kg, and when unloaded - from minus 0.4 kg to plus 0.3 kg. The set with the VSM-10 includes a plastic tank with $V = 10 \text{ m}^3$ and a submersible pump, the capacity of which in the real scheme was 6.5 m$^3$/hour, which made it possible to pump 10 tons of water from the control tank to the STRC complex in 1.5 hours.

Table 2. Limits of permissible error of scales

| Load range     | mpe, kg |
|----------------|---------|
| 20 to 500 kg   | ±1,0    |
| 500 to 2000 kg | ±2,0    |
| 2000 to 10000 kg | ±3,0    |

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The main task of research on experimental facilities is to determine the actual error in the dose delivery using the developed weighing equipment. Filling of spacecraft and booster blocks can be carried out: 1) at a constant pressure of the displacing gas in the refueling complex (filling tank); 2) with a constant gas mass in the refueling complex (the gas pipeline is closed). In the overwhelming majority of cases, refueling is performed at constant gas pressure. Option 2 is used for refueling small doses of propellant components into the tanks of small spacecraft or propulsion system (PS) for stabilization, orientation and launching (SOL) of the upper stage. On bench equipment, both refueling options can be tested. Let's consider the work according to the first option. The mass of the dispensed dose and the working excess pressure are set. The water temperature is measured. Corrections for the mass of the displaced air in the filling tank and the correction for the mass of displaced air from the control tank are calculated. The operator selects the number of the main channel, according to the indications of which the dose will be delivered, and enters it into the PC memory. During dispensing, the monitor screen displays indications of the main and reserve channels, and on digital displays in the «filling room» only the indications of the main channel are displayed, through which the dose is cut off. Let us denote by the letter I the readings of the main channel, and: Iinit - initial readings, Itek - current readings during dispensing, Ifin - final readings after the end of dispensing.

Consistently in accordance with the methodology substantiated and developed by V.M. Shulga, refueling operations are performed: 1) equipment test; 2) input of parameters (in this operation, the operator enters all the parameters of the refueling, in particular, MGD, MAIR.TRC and preliminaries - a part of the dose given out at a high flow rate); 3) filling of highways; 4) the passage of the mains (this operation is carried out until the complete disappearance of air bubbles in the transparent section of the issuing main); 5) control exposure; 6) delivery of a dose.

In parallel with the solution of this main task, the development of software is carried out, which is ultimately intended for the implementation of product filling technologies. On the bench equipment, the technology of weight dosing is being tested when refueling small-sized spacecraft. The minimum dose for these devices starts at 0.4 kg. For refueling small-sized devices, modular weighing devices (weighing device with dosing (WDD), weighing device with dosing and control container (WDDCC)) can be used, as well as mobile special control scales of the SKS type. The equipment is also used in the development of multi-portion weight dosing methods. The experimental development of work technologies in emergency situations deserves a separate discussion. These situations are also simulated on bench equipment, and the technology of work aimed at the successful completion of refueling is experimentally worked out.

3. The experimental studies of precision weighing systems of refuelling complexes of upper stages and spacecraft of space rockets

When solving the problem of increasing the accuracy of weighing rocket fuel components at the stage of experimental studies of precision weight measuring systems of refueling complexes of upper stages and spacecraft of space rockets, it is necessary to determine the main metrological characteristics of stationary weight measuring systems (SWMS). Weighing devices (WD) with a vertical capacity of V = 4.2 m³ are designed for filling the upper stage tanks at filling stations. The maximum load of the devices is limited to 3000 kg and 5500 kg for various types of aircraft WD. These loads correspond to the mass of fuel and oxidizer, which can be used to fill filling tanks with a volume of 4.2 m³ at a filling factor of 0.9. The absolute error of the WD did not exceed +0.1 kg ÷ -0.2 kg in the load range from 0 to 3000 kg during loading and unloading, while a slight nonlinearity of the readings was observed. A similar character of nonlinearity is also present in the characteristics of another type of aircraft WD with an absolute error of +0.1 kg ÷ -0.3 kg in the load range from 0 to 5500 kg during loading and unloading. In experimental studies, doses were dispensed using the mixed dosing method. The experimental research methodology was as follows: 500 kg of a component (fuel and oxidizer, respectively, for certain types of aircraft, were poured into the filling tank [9]. The platforms of the devices were loaded up to loads of 3000 and 5500 kg relative to the mass of the empty container. The main part of the dose was «given out» by removing the weights from the platform. The remaining 10 kg were dispensed as a component
into a drain container installed on a check balance with $M_{\text{ax}} = 250 \text{ kg}$, the error of which at loads of 10 ÷ 50 kg is $\pm 0.05 \text{ kg}$. Doses of the component were given out with a constant mass of helium in the filling tank and with a closed drain line in the drain tank. Therefore, the actual mass of the delivered dose was equal to the sum of the mass of the weights and the readings of the control weights for the $i$-th dose. During experiments with fuel, it was found that there is an incomplete filling of the lines. This meant that there were stagnant zones in the highway system, due to the fact that the highways from the filling tank were built into an essential highway system. The introduction of the «vacuuming of mains» operation into the refueling technology made it possible to ensure complete filling of the mains. In the oxidizer filling system, the lines were filled completely without evacuation. Since two doses of the component from one filling container are sequentially filled into the upper stages tanks of space rockets, two doses of the component were also dispensed sequentially during the tests. Three dispenses of two doses for fuel and oxidizer were carried out. The results of issuing control doses are presented that the absolute error in the delivery of amylin doses lies in the range from 0.0 kg to minus 0.4 kg, and the dose cutoff error by pneumatic valves lies in the range from minus 0.1 to plus 0.1 kg.

In general, the experimental values of the dose delivery error are much less than the permissible error of refueling the of upper stages tanks, equal to $\pm 6 \text{ kg}$ for a dose of 2000 kg, and less than the passport error of the aircraft WD in a special mode, equal to $\pm 2 \text{ kg}$. In relative units, the experimental values of the dose delivery error are within the range from 0.00% to $+ 0.02\%$.

In experiments on the «dose delivery» of a dose of 1000 kg using the aircraft VD, similar results are observed: the experimental error ($0.0 \pm -0.2 \text{ kg}$) is less than the permissible error of refueling ($\pm 3 \text{ kg}$) and the WDDF passport error in special mode ($\pm 1 \text{ kg}$). In relative units, the experimental values of the dose delivery error also lie in the range from 0.00% to minus 0.02%.

![Figure 8. Deviation of readings WS (WD) from the nominal value of the mass of the weights](image)

Experimental studies WS (WD) with a horizontal capacity $V = 10 \text{ m}^3$, designed for refueling upper stages tanks with naphthyl at the filling and neutralization station (FNS), the load range of which is limited by the capacity and is equal to 7000 kg., based on the dispensing doses weighing 6090 kg by the combined method: 6080 kg were “dispensed” by removing weights of class M1 from the platform, and the remaining 10 kg - with water into a control container installed on a SKS-400 control balance. Three days before the start of the active stage of experimental research on the platform WS (WD) 2000 kg weights were installed, which simulated the mass of the container. Then, 3 hours before the start of the dose of the propellant component, weights with a mass of 9000 kg were installed on the platform, simulating the intake of the component into the container. A container $V = 120 \text{ l}$ with water was also installed on the platform. The dose was cut off using a pneumatic valve [8]. Water was dispensed at a constant mass of air in the capacity; a correction was introduced for the mass of air displaced from the control capacity.

Averaging the error over 9 doses, starting with the second, gives a value of minus 0.54 kg, which is a systematic error. The dosing flow rate was 0.1 kg/sec. The standard deviation at a confidence level of 0.95 is equal to $S_{0.95} = \pm 0.1 \text{ kg}$ characterizes the random error due to the following components: random
error WS (WD) (dynamic and electromagnetic noise); random error due to valve operation. Thus, the absolute error in delivering a dose with a mass of 6090 kg, calculated as the sum of the systematic error and the standard deviation at a confidence level of 0.95, is equal to $\pm 0.64$ kg, or $\pm 0.011\%$ in relative units, which is in good agreement with the data shown in Figure 8.

4. Conclusion

In conclusion, it should be noted, that the developed and put into operation stationary weighing devices have an actual error, which is an order of magnitude less than the passport values of the permissible error limit. This gives grounds for increasing the accuracy of filling by approving the type of a single sample (or a series of WS) with higher metrological characteristics. Thus, the results of studies of stationary weighing devices developed and put into operation can serve as a basis for increasing the accuracy of weighing and dose delivery by implementing a scientific and methodological approach in accordance with [10] based on type approval of single samples WS (WD) (or a batch of aircraft WD), in operation, with higher metrological characteristics in the case of confirmation of these characteristics by experimental studies.

Designed, manufactured and tested in the course of scientific research and the above bench equipment formed the basis of a research laboratory created on the basis of the Department of Transport installations of MADI as part of the formation of a ground work for interaction of MADI with strategic industrial partners - AO M.V. Khrunichev (Joint Stock Company), AO Moven and AO TSENKI within the framework of the creation of a scientific and educational world level in terms of experimental development of equipment and scientific and methodological support of an innovative scientific and production center for research, development and technological work, projects and programs. In the research laboratory of the Department of Transport installations of MADI, along with the research described above, laboratory work of students and research of applicants, graduate students and doctoral students of MADI are also carried out.

References

[1] Denisov O E, Zolin A A, Ivanov M F, Kobyzev S B, Matveeva O P, Khlybov V F, Chugunkov V V 2016 *Launch equipment and technological processes of fuel preparation and rocket refueling: textbook. manual* (Moscow: Publishing house of MSTU named by N E Bauman)

[2] Vorobiev E V, Denisov O E and Kuznetsov V I 2014 *Design of special purpose vehicles: a tutorial* (Moscow: MADI)

[3] Technological objects of ground infrastructure of rocket and space technology (engineering manual) ed. I V Barmina (Moscow: Polygraph RPK, 2012)

[4] Investigation of the actual metrological characteristics of precision weighing systems and the results of substantiation and development of recommendations to improve the accuracy of filling spacecraft tanks and upper stages of space rockets with propellant components: research report (concluding) ed. V M Shulga (Moscow: MADI, 2019)

[5] Special control scales SKS. Specifications: TU 4274-034-45081993-13 (Moscow: Closed Joint Stock Company “Elves”, 2013)

[6] GOST R 8.736-2011 *State system for ensuring the uniformity of measurements. Multiple direct measurements. Methods for processing measurement results. Basic provisions* (Moscow: Standartinform Publishing House, 2013)

[7] Burdun G D, Markov B N 1984 *Fundamentals of Metrology* (Moscow: Standards Publishing House)

[8] Shut-off valves. Specifications: P 96261–00.025 M1 TV (SPb., ZNS 3T, 2009)

[9] Shulga V M, Nazarov V N, Borisov V G, Lebedev A G, Runov V V 2014 *Determination of the mass of doses of propellant components using WDDF-5 and WDDF-10 devices: measurement technique* (recommendation No. FR.1.28.2014.19022) (Moscow: Publishing house of Rosstandart)

[10] Federal Law of the Russian Federation dated 26.06.08 No. 102-F3.