ISSN 1068-798X, Russian Engineering Research, 2017, Vol. 37, No. 5, pp. 397–400. © Allerton Press, Inc., 2017.
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# Reducing the Infiltration at Vacuum Chambers to Obtain Ultrahigh Vacuum

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**Abstract**—The design of electric heaters in ultrahigh-vacuum chambers is considered. Effective heat shielding of the tested product is proposed. The permissible operating time of the heating elements is determined.

*Keywords:* ultrahigh vacuum, vacuum chamber, heating element, heat shielding
**DOI:** 10.3103/S1068798X17050240

To ensure the sealing of spacecraft and hence their safe operation, extensive bench testing of their components is required [1, 2].

It is difficult to ensure ultrahigh vacuum because gases are liberated from metal structural components at a pressure $p < 1.3 \times 10^{-5}$ Pa. Such desorption hinders the generation of the pressure required in the technical specifications—$1.3 \times 10^{-8}$ Pa, say.

To reduce the gas load $Q$ (or the infiltration flux), high sealing of all the chamber components is required, and materials that release a minimum of gases under ultrahigh vacuum must be used. The exhaust system employed (especially in cryogenic conditions) must be of high productivity. To obtain a pressure $p = 1.3 \times 10^{-8}$ Pa in a large chamber, the gas load $Q = pS$ must exceed $3.9 \times 10^{-6}$ Pa m$^3$/s, and the exhaust rate $S$ of the cryogenic pump must be no less than $3 \times 10^2$ m$^3$/s.

Since solids are characterized by sorption, absorption, and chemosorption in normal conditions, forced desorption by heating all the chamber components to 550–600 K or more is required in order to ensure ultrahigh vacuum. This theoretical conclusion is confirmed experimentally by the operation of the system in Fig. 1, for example [3–6]. After operation for ten years, no failure or unsealing of the chamber components is seen.

The gas load associated with desorption of the internal surface of chamber *1* was calculated in [3].

In the present work, we determine the power of the electric heater and verify its operability.

To eliminate sparkover, high voltages (220 or 127 V) are not employed in the heating system for chamber *1*. In that case, it is expedient to use a multistep OSU-40 transformer (output voltage 4.5–21 V) as the power source for the Nichrome electric heaters. In accordance with the technical specifications, the power of heaters *3* and *4* in the cylindrical part of working chamber *1* and exhaust line *13*, which is made of Kh18N10T steel, must be no more than 15 kW at $T \leq 600$ K. The electric heaters consist of Kh20N80 Nichrome wire (diameter $d = 4$ mm; resistivity $\rho = 1.27\ \Omega$ mm$^2$/m), with 24 heating elements *3* (length

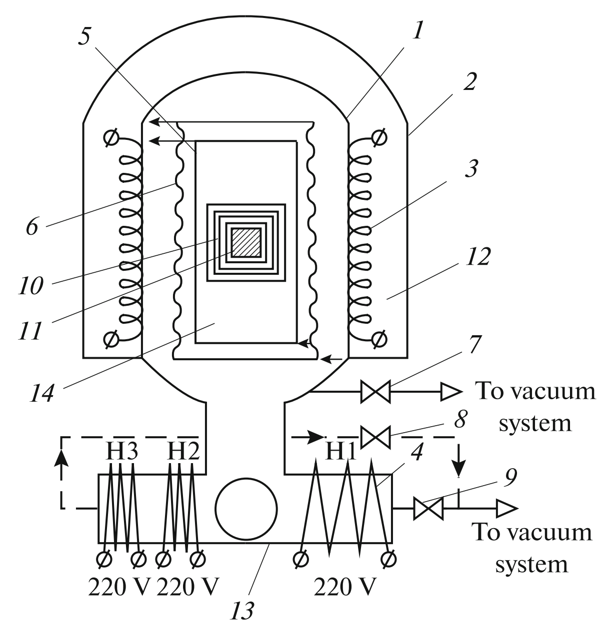


**Fig. 1.** Ultrahigh-vacuum chamber: (*1*) working chamber; (*2*) protective chamber; (*3*) heating system; (*4*) exhaust-line heater; (*5*) nitrogen screen; (*6*) helium cryogenic pump; (*7*–*9*) valves; (*10*) heat screens; (*11*) tested object; (*12*) high-vacuum cavity; (*13*) exhaust line; (*14*) working cavity.

**Table 1.** Characteristics of the OSU-40 transformer

| Stage | Voltage $U$, V | Power, $P_{tr}$, kW |
|---|---|---|
| 1 | 20.9 | 40 |
| 2 | 18.0 | 34 |
| 3 | 15.7 | 30 |
| 4 | 14.0 | 26 |
| 5 | 12.6 | 24 |
| 6 | 10.4 | 20 |

**Table 2.** Operational characteristics of the transformer

| Stage | $U$, V | $P_{tr}$, kW | $I_h$, A | $P_h$, kW | $P_c$, kW | $W$, W/cm$^2$ | $I_c$, A |
|---|---|---|---|---|---|---|---|
| 1 | 20.9 | 40 | 60 | 1.25 | 30.0 | 2.80 | 1440 |
| 2 | 18.0 | 34 | 52 | 0.93 | 22.0 | 2.10 | 1250 |
| 3 | 15.7 | 30 | 45 | 0.70 | 17.0 | 1.60 | 1100 |
| 4 | 14.0 | 26 | 40 | 0.56 | 13.0 | 1.30 | 960 |
| 5 | 12.6 | 24 | 36 | 0.46 | 11.0 | 1.05 | 860 |
| 6 | 10.4 | 20 | 30 | 0.32 | 7.5 | 0.73 | 720 |

1. The heating conditions of the working chamber ensure the required temperatures for all the metal structures in the stage. 2. Heating begins at the lowest stage and switches to the next at intervals of 15–20 min.

$l = 3.5$ m). The power source (transformer) is connected in parallel to the electric heaters outside the cylindrical part of the chamber, by means of special insulators.

Table 1 presents the characteristics of the OSU-40 transformer.

## CALCULATION OF THE ELECTRIC HEATER FOR THE WORKING CHAMBER

The transformer voltage $U = 20.9$ V; the power $P_{tr} = 40$ kW.

The cross-sectional area of the Nichrome wire $S = \pi d^2/4 = 12.6$ mm$^2$.

The resistance of the Nichrome wire $R_h = \rho l/S = 0.35\ \Omega$.

The current in a single heating element $I_h = U/R_h = 20.9/0.35 = 60$ A.

The power of a single heating element $P_h = I_h^2 R_h = 60^2 \times 0.35 = 1.26$ kW.

The surface area of a single heating element $S_{su} = \pi dl = 440$ cm$^2$.

The unit power $W = P_h/S_{su} = 2.86$ kW/cm$^2$.

The total power of the heating elements $P_\Sigma = nP_h = 30$ kW.

The total current in the electric heater $I_{\Sigma h} = nI_h = 1440$ A.

The operational characteristics of the other stages of the transformer are determined analogously (Table 2).

Kh20N80 Nichrome heaters *4* (length $i_c = 30$ m; diameter $d_c = 1$ mm) are used for degassing of the line *13*, with a voltage of 220 V and a current frequency of 50 Hz. Three heating coils H1, H2, and H3 are wound on the Nichrome housing of line *13*. The ceramic insulators around the Nichrome wire are covered by asbestos fabric to reduce heat losses to the atmosphere.

## CALCULATION OF THE POWER OF THE HEATING COILS

The cross-sectional area of the wire $S_c = \pi d_c^2/4 = 0.79$ mm$^2$.

The resistance of the wire $R_c = \rho l_c/S_c = 48\ \Omega$.

The current in the coil $I_c = U/R_c = 4.6$ A.

The power consumed $P_c = I^2 r = 1$ kW.

The surface area of the coil $S_{su.c} = \pi d_c l_c = 942$ cm$^2$.

The unit power of the coil $W_c = P_c/S_{su.c} = 1.1$ W/cm$^2$.

The total power of the lines is 3 kW.

To increase the power, we must add coils inside those already present. In that case, the temperature conditions are optimal, and the pressure at the end of the test cycle $p = 1.3 \times 10^{-8}$ Pa.

We proceed as follows to obtain ultrahigh vacuum with heating of the working chamber, lines *13*, all the metal structures of the chamber, the tested object *11* within the chamber, and the four Kh18N10T steel heat screens (thickness 1 mm).

After placing the object in the chamber and connecting the temperature and pressure sensors and the monitoring instruments, the sealing of the chamber is tested. Then the exhaust system for the working chamber *14* and protective chamber *12* of the system is switched on, and heaters *3* and *4* are switched on, with simultaneous preliminary evacuation. The total gas flux to working chamber *1* is determined.

The walls of the working chamber and the lines are heated to 523 K after 16 h. Then the system is switched off. After 69 h, the chamber has cooled to 333 K.

When the chamber temperature is 303 K, the pressure in the working chamber is $3.9 \times 10^{-4}$ Pa. In the course of cooling, the total gas flux to the working chamber *1* is determined from the formula

$$Q = \frac{(p_2 - p_1)V}{\tau_2 - \tau_1},$$

where $p_2$ is the pressure when measurements of the gas flux begin (at time $\tau_2$); $p_1$ is the pressure when measurements of the gas flux end (at time $\tau_1$); $V$ is the chamber volume.

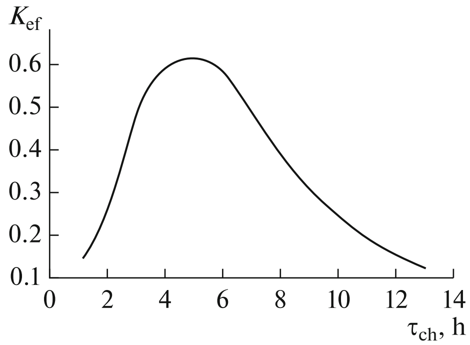


**Fig. 2.** Dependence of the effectiveness $K_{ef}$ of the heat screens on the chamber-heating time $\tau_{ch}$.

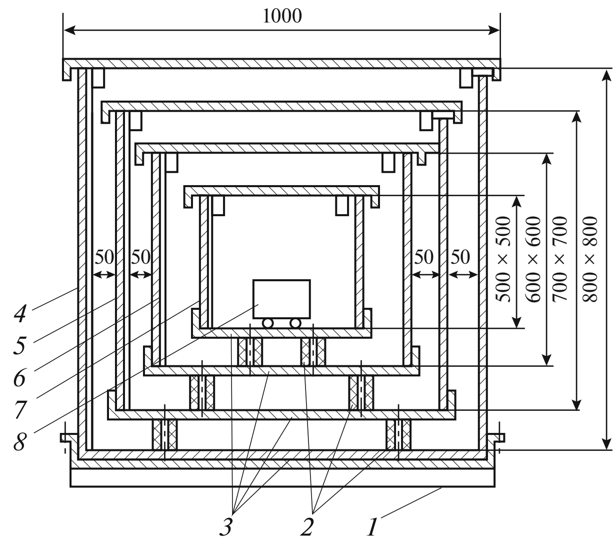


**Fig. 3.** Configuration of four heat screens: (*1*) base; (*2*) insulator; (*3*) floor; (*4*–*7*) screens; (*8*) part being tested.

When the chamber's wall temperature is $T_{1ch}$ = 403 K, the total gas flux to the working chamber is $Q_1 = 8 \times 10^{-5}$ Pa m$^3$/s. At $T_{2ch}$ = 371 K, $Q_2 = 6.65 \times 10^{-6}$ Pa m$^3$/s; at $T_{3ch}$ = 333 K, $Q_3 = 1 \times 10^{-6}$ Pa m$^3$/s. This indicates satisfactory purity and sealing of the working chamber, since the technical specifications require that $Q \leq 3.9 \times 10^{-6}$ Pa m$^3$/s.

In an ultrahigh-vacuum chamber with three heat screens, the components of the life-support system of spacecraft are tested. At the same time, the effectiveness of heat shielding of the tested objects is verified when the chamber is heated to $T_{ch}$ = 500–600 K. The effectiveness of heat shielding is assessed in terms of $K_{ef} = K_{sc}/K_{ns}$, where $K_{sc}$ is the heat removed from the part when using screens; $K_{ns}$ is the heat supplied to the part in the absence of screens.

In addition, we determine the permissible operating time of the heating elements. We find that, without the screens, there is a high probability of failure of the parts on account of overheating.

The first stage of the tests is operation of the working chamber's heating system for 14 h. The temperature is monitored by a regular thermocouple for the first 9 h; and by means of an IS-545A sensor with a nitrogen screen *5* (Fig. 1) for the next 5 h.

The screens are most effective ($K_{ef}$ = 0.6) after heating for 4–7 h: with $T_{ch}$ = 518 K, the part is heated to 321 K, as against 383 K in the absence of the screens. Subsequently, the screens become less effective (Fig. 2). When the heating system is turned off, the part is at 463 K; over the next 4 h, on account of thermal inertia, it is heated to 473 K. The pressure in the working chamber is reduced from $1.5 \times 10^{-1}$ to $5 \times 10^{-3}$ Pa, by the operation only of the TMN-200 and VN-6G vacuum pumps.

In the second stage of the tests, the location of the temperature sensors is determined in the light of the nonuniform wall heating. As a result, it is decided to change the location of the sensor. The IS-545 sensor is mounted in the outer region of the chamber, in the upper section, where the temperature remains at 513 K throughout the tests. When using three screens, the chamber temperature is 513 K after 7 h, while the part is at 311 K. Thus, $K_{ef}$ = 0.65. With operation of the TMN-200 and VN-6G vacuum pumps, the pressure in the chamber falls from $3.5 \times 10^{-2}$ to $2.1 \times 10^{-4}$, while the total gas flux to the working chamber is $Q = 2.7 \times 10^{-6}$ Pa m$^3$/s when the chamber and the part are both at 328 K.

Tests using three screens without forced cooling show that, after the heating system is turned on, the temperature difference of the part in tests with and without the screens is 60 K after 6 h, 55 K after 9 h, 45 K after 14 h, and 35 K after 17 h. In other words, the effectiveness of the screens declines over time. The temperature of the part, the screens, and the chamber equalizes.

The heat screens increase the heating time of the chamber from 2 h to 5 h. The temperature of most of the heated parts is no more than 373 K.

Tests show that the heat supplied to the heat on chamber heating may be reduced by increasing the reflective properties of the screen surfaces. To that end, polished stainless-steel sheets may be used.

We also investigate the potential of forced cooling of the heat screens and additional screening of the tested parts. The simplest and most effective approach is to introduce a fourth 1000 × 1000 mm screen, which increases the effective heating time of the chamber by 2 h (Fig. 3).

First, the chamber is heated. Then screens *4*–*7* and the tested object *8* are heated. The temperature is higher for screen *4* than for screen *7*. After switching off the heating elements ($\tau_{off}$ in Fig. 4), screen *4* cools

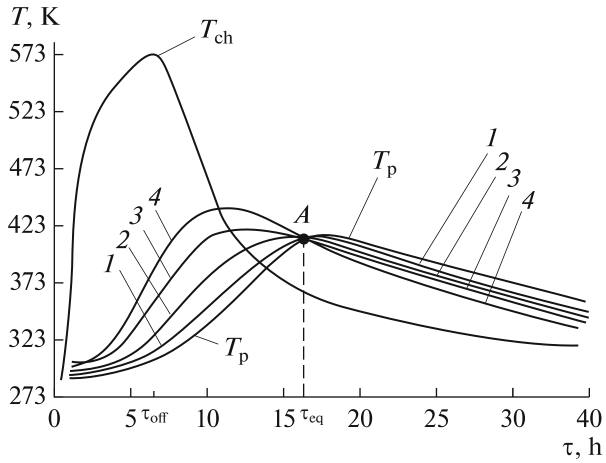


**Fig. 4.** Variation in the temperatures of the chamber ($T_{ch}$), the four heat screens (*1–4*), and the part being tested ($T_p$) over time τ: $\tau_{off}$ is the time at which the system is switched off; $\tau_{eq}$ is the time at which the temperature of the screens and the part equalize.

more rapidly than screen *7* (Fig. 3), while the temperature of the screens and the part equalize at some instant ($\tau_{eq}$ in Fig. 4). Then the temperature of screen *4* is again below that of screen *7*.

Thus, to obtain a pressure of $1.3 \times 10^{-8}$ Pa, it is sufficient to heat the chamber to $T_{ch} = 550$ K.

The proposed screening system and the selected transformer and heating system for the ultrahigh-vacuum chamber permit safe and reliable operation of components of spacecraft such as the Mir, Soyuz, Salyut, and Progress in tests at extremal temperatures.

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*Translated by Bernard Gilbert*