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INFLUENCE OF MANUFACTURED-PART DESIGN AND GASKET MATERIAL ON THE TIGHTNESS OF FLANGED JOINTS UNDER SHARP THERMAL CYCLES IN THE ENVIRONMENT

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The results of 70 cycles of rigorous testing for resistance to thermal cycling of the medium are presented – temperature reduction of the supplied water $\delta T_{in.30\ sec}$ = 262°C over the first 30 sec of the process for two check valves of the type S23307-0160-65, DN 65 (body material St12Kh18N10T) as well as four of the same thermal cycles for a bellows-type stop valve S.KZSA-100-00-00-E-03, DN100 (body material St20). Sealing gaskets containing thermally expanded graphite are installed in the body–cap connector of all valves. At the completion of the tests, all three types of gaskets retained their integrity and serviceability. However, if the stop valve DN100, which structurally has an axisymmetric temperature distribution of the metal in the above-flow part of the body, retained its tightness throughout all thermal cycles, then out of 140 thermal cycles the check valves DN65, which do not have such an axisymmetric temperature distribution dynamics, had 18 brief (40–50 sec) weak seal failures in the front portion of the valve connector. The average difference of the temperature of the metal above the flow portion of the valve body in the front and back sectors was estimated as ΔT_{av} ~ 40°C in the presence of seal failure.

Gaskets, whose sealing material is thermally expanded graphite, which has high plasticity and elasticity properties, are used in the flange connectors of NPP pipeline fittings. The limit of elastic deformation is equal to 20–25%. In the first instance, this applies to graphite flange gaskets, which are manufactured by NPO UNIKhIMTEK in line with TU 5728-016-50187417-99, and spiral-wound gaskets by Soyuz-01 Firm in line with TU 38.314-25-8-91 [1]. NPO TsKTI conducted bench testing of two samples of check valves (S23307-0160-65 type), in whose housing–top connector gaskets PGF-D-V-12-03-113×74×5.3-I4 or SNP 1D-1 121×108×90×84×4.5 are installed (Fig. 1). The design documentation does not provide for the installation of a gasket in this connector, which made it difficult to maintain its tightness on sudden temperature changes.

A PGF gasket sealing graphite ring is made of thermally expanded graphite by winding thermally expanded graphite tape onto a mandrel, followed by cold pressing. An SNP gasket sealing ring is made in the form of alternating, wound spiral V-shaped layers with a specified angle of inclination and radius at the base of alternating layers of corrosion-resistant steel tape and filler consisting of thermally expanded graphite. The steel tape imparts high resilience to the gasket. The height of the graphite filler h_g exceeds that of the steel tape h_t. The height of the outer and inner steel rings h_{lim} is less than that of the steel tape h_t. This difference in the height of the gasket elements makes it possible for the plastic thermally expanded graphite to fill the micro-asperities of the sealing surfaces on compression, eliminating the need for lapping of the mating surfaces, and also limits the deformation to equalize the heights $h_t = h_{lim}$. The height of the graphite filler of both gaskets is equal to 5.3 mm, the height of the steel tape h_t of the SNP gasket is equal to 4.5 mm, the steel ring of the PGF gasket is equal to 3.8 mm, and SNP equals 4 mm.

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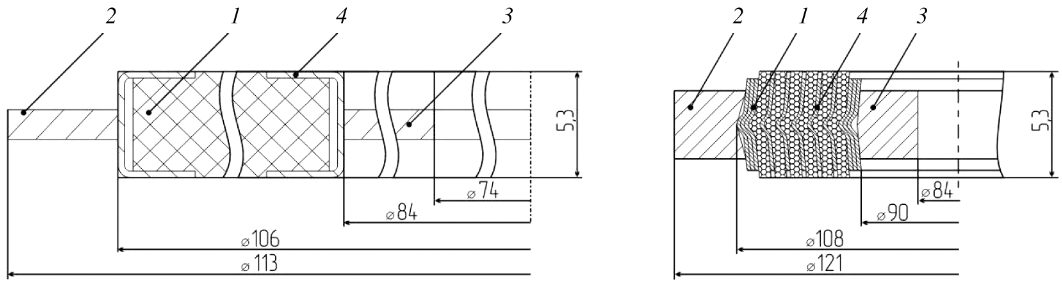
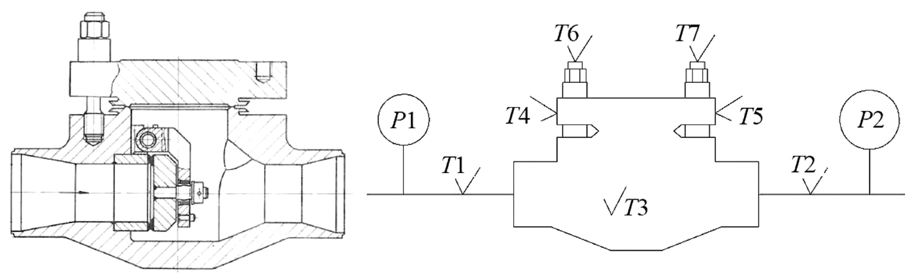


a *b*

Fig. 1. Sealing gaskets PGF-D-V-12-03-113×74×5.3 (*a*) and SNP 1D-1 121×108×90×89×4.5 (*b*) containing thermally expanded graphite: *1*) O-ring, thermally expanded graphite; *2*, *3*) outer and inner steel ring, respectively; *4*) steel tape.



a *b*

Fig. 2. Check valve of th type C23307-0160-65, DN 65: overall view (*a*) and arrangement of measurement sensors (*b*); designations *P*1, *P*2, and *T*1–*T*7 correspond to P_{in}, P_{out}, T_{in}, T_{out}, T_{body}, T_{cap1}, T_{cap2}, T_{pin1}, T_{pin2}.

In 2004, testing was conducted on a stand at NPO TsKTI to determine the possibility of re-using PGF-D-V-15-P3-03-845×785×8 gaskets in a DN 800 valve after seal failure in a connector. The tests consisted of two series, each of which included 10 tests at 10 MPa and two tests for resistance to medium thermal changes with heating of the valve to 280°C for 6 h followed by 10 subsequent seal tests. Inspection of the gaskets between the series and after their completion showed satisfactory condition. The connector retained its tightness in all types of tests. But the tightness of a connector with these gaskets under sharp temperature reduction in the surrounding medium was not considered.

The purpose of testing two samples of check valves, similar to those installed at the Smolensk NPP, was to confirm experimentally the retention of the tightness of a body–cap connector using PGF and SNP gaskets with valves undergoing cycles with sharp temperature reduction in the surrounding medium (thermal cycles). The number of these cycles corresponded to their number for 20 years of operation of NPP units: five 4-year periods between overhauls of a unit. Each period included 14 thermal cycles (70 thermal cycles in total) with imitation of three operating regimes of the reactor:

Regime 1. Hydrotesting of check valves at 10.1 MPa and 130–150°C followed by reduction to 6.8 MPa and 20–40°C, respectively;

Regime 2. 12-fold imitation of the shutdown of a power unit at 8.5 MPa and 285°C and with temperature reduction of the water and valve body to 40°C;

Regime 3. One emergency situation with cold water supplied through a valve heated to 285°C and pressure increasing from 8.5 to 9.8 MPa. The hold-up at this pressure is equal to at least 12 sec, after which the pressure drops and the temperature of the valve drops to 40°C.

The design of the tested valve is characterized by a small height and substantial length of the chamber containing shutter (Fig. 2). This creates the prerequisites for uneven cooling of the front and back portions of the body (along the path of the medium). The unevenness is exacerbated by the low thermal conductivity of the material of the body made of 08Kh18N10T steel. In addition, the valve shutter opened by the flow of water creates a more intensive washing of the front part of the body with water and partially obscures the rear part of the shutter, which exacerbates this unevenness.

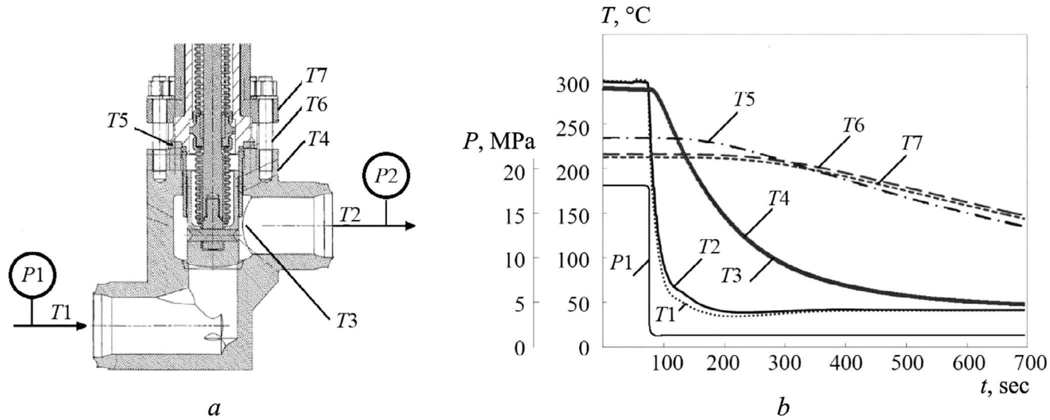


Fig. 3. Bellows-type stop valve S.KZSA-100-00-00-E-03, DN100: *a*) rough drawing; *b*) dynamics of parameters on thermal cycling; designations *P*1 and *T*1–*T*7 correspond to $P_{in} = P_{out}$, T_{in}, T_{out}, T_{body}, $T_{fl.l}$, T_g, T_{pin}, $T_{fl.u}$.

Test stand and measuring procedure. The tests were performed on two valves, arranged in parallel, using one of the two gaskets. Sections of pipes with diameter 76 × 5 mm and length 0.35 m were welded to the valve nozzles. Their outer ends were welded into prefabricated manifolds, whose ends were connected in a Z-shaped pattern to stand's pipelines for hot and chilled water, which was supplied to both valves at the same flow rate. Figure 2*b* shows the arrangement of the sensors for measuring pressure at the valve inlet and outlet, water temperature at valve inlet and outlet (T_{in}, T_{out}), the outer surface of the valve body T_{body}, the side surface of the caps T_{cap1}, T_{cap2}, and the upper end of the pins T_{pin1}, T_{pin2} in the front and back parts along the water flow. The water flow was measured in the supply pipelines. The parameters were recorded at the rate 1 Hz. The rise in the temperature of the supplied water did not exceed 3°C/min.

For comparison, here are the results of acceptance tests of a bellows-type stop valve S.KZSA DN 100 performed at NPO TsKTI: design pressure 18 MPa, body material – steel 20 (Fig. 3*a*). An O-ring made of thermally expanded graphite of the KGU type is installed in the body–bellows assembly connector with lock-type connecting surfaces.

The following were measured on the outer surface of the valve elements: the valve's body temperature T_{body}, the lower and upper flange temperatures $T_{fl.l}$ and $T_{fl.u}$, gasket lateral surface temperature T_g, and pin temperature T_{pin} as well as the pressure of the medium, the temperature of the medium at the inlet into the valve, and at the outlet from the valve with the four obligatory tests (in line with method 2) for resistance to thermal cycling of the environment. These tests were performed in line with a scenario close to the one under consideration but without pressure requirements (see Fig. 3*b*).

Results of pre-test checklist. The tested gaskets were installed in the valve's body–cap connectors, gradually tightening the nuts on the pins and incrementally increasing the torque *M* up to *M* = 110 N·m, as specified in the technical documentation for metal-to-metal factory seal. In the process of tightening, the gaps between the body and the valve cap were measured every 90° (see Table 1).

For the PGF gasket, the height of the graphite portion decreased to the height of the steel limiters at $M > 70$ N·m. For the SNP gasket, proportionality of the deformation of thermally expanded graphite to the applied moment at *M* = 50–90 N·m and deformation reduction at *M* = 90–110 N·m were noted, which is also associated with compression of a more rigid steel tape. At *M* = 110 N·m, the gasket was deformed by 1–1.1 mm.

Results of the investigations. Each thermal cycle ended once the pin–cap temperature difference started to decrease, assuming that subsequent cooling would not decompress the connector being tested, if this did not occur before the specified condition was met. In the course of the first of 14 thermal cycles, it was determined that for all of 2 × 2 = 4 pin–cap thermocouples installed on the front and back portions of the valves, the maximum of the specified temperature difference was observed 8–10 min after the chilled water arrived. It was characterized by the onset of a sharp reduction in T_{in}. For this reason, the duration of the dousing in all of the 56 subsequent cycles was limited to 11–12 min.

The dynamics of the measured parameters in one of the thermal cycles at the cooling stage in regime 2 is shown in Fig. 4. Just as in the boxes of the Smolensk NPP, the tested valves were not thermally insulated, which is why the initial

TABLE 1. Gap between Flanges on Installing Gaskets, mm

Torque, N·m	PGF gasket, mm				SNP gasket, mm			
	Angle, °							
	0	90	180	270	0	90	180	270
0*	19	19.3	19.5	19.4	18.4	18.4	18.2	18.2
10	18.5	18.5	18.7	18.7	–	–	–	–
30	18	18	18.3	18.35	–	–	–	–
50	18	18	17.7	17.8	18	17.9	18	18
70	17.6	17.7	17.7	17.7	17.8	17.8	17.6	17.6
90	17.7	17.8	17.7	17.7	17.6	17.6	17.4	17.3
110	17.6	17.7	17.7	17.7	17.5	17.3	17.3	17.2
Deformation,** mm	1.4/0.9	1.6/0.8	1.8/1	1.7/1	1/–	1.1/–	1.1/–	1/–

* $M = 0$ corresponds to uniform tightening of the nuts without the use of a wrench. ** Deformation from $M = 0/10$ N·m to $M = 110$ N·m.

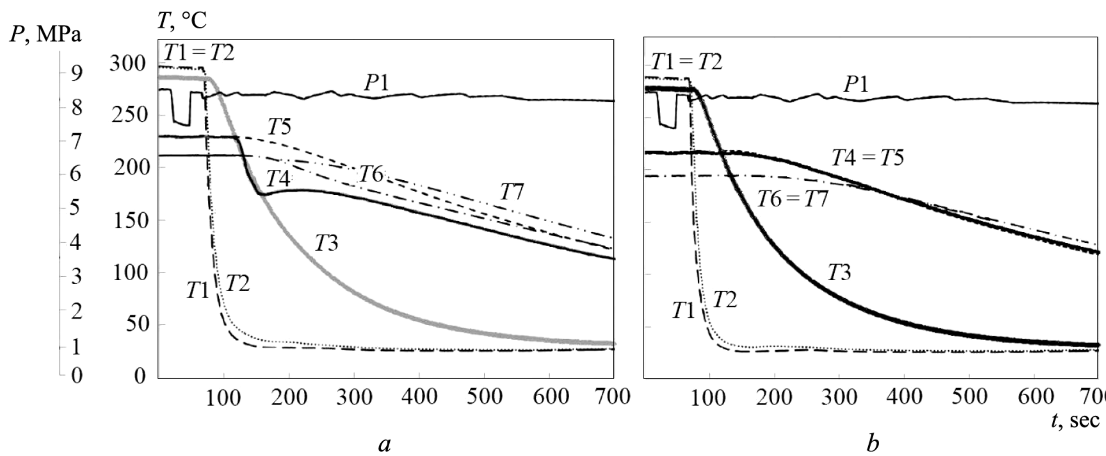


Fig. 4. Dynamics of the measured parameters in regime 2 with check valves (15th cycle in regimes 2 and 3) $G = 4.7$ kg/sec, $T_{in0} = 289$°C, $\delta T_{in.30\ sec} = 240$°C with PGF gasket (*a*) and SNP gasket (*b*); P, $T1$–$T7$ correspond to P_{in}, T_{in}, T_{out}, T_{body}, T_{cap1}, T_{cap2}, T_{pin1}, T_{pin2}.

temperature of the surfaces of the valve elements is lower. Neither of the gasket types passed the entire set of tests without the connector decompressing. However, on differentiation by regimes, they passed without seal failure all tests in regime 1 with the water temperature dropping for the first 30 sec of inundation by $\delta T_{in.30\ sec} = 8$–118°C.

In the course of 130 tests in regimes 2 and 3, the value of $\delta T_{in.30\ sec}$ was equal to 106–262°C. In addition, 45–60 sec into the process, 15 and three seal failures were observed in the valves with PGF and SNP gaskets, respectively, of which two and one failures occurred in regime 3. All seal failures were characterized by the condition $\delta T_{in.30\ sec} \geq 177$°C. Most of them occurred at $\delta T_{in.30\ sec} = 240$–250°C. However in the 51st test, there were no seal failures at $\delta T_{in.30\ sec} = 240$–262°C. Likewise, no correlation was found between seal failures and water flow through the valves, which in the first minute of filling in all experiments, both with and without seal failures, varied in the range $G = 2.3$–10 kg/sec and largely amounted to 4.5–5 kg/sec. It is assumed that at water velocity head corresponding to flow rates >2.3 kg/sec the valve shutter occupies an open position and further increases in the flow rate do not affect the hydrodynamics of the water flow with uneven laving of the front and back portions of the valve's body.

Seal failures are unevenly distributed over the test period in regimes 2 and 3. So, all 15 seal failures of the PHF gasket occurred between thermal cycles 13 and 36. The next 29 thermal cycles in these regimes passed without seal failure. For SNP gaskets, seal failures were observed during thermal cycles 34, 35, and 58. All seal failures were noted in the front sector of the valve connector. Their duration was equal to 30–50 sec. For the thermal cycle shown in Fig. 4, seal failure occurred in a valve with a PGF gasket. Its onset is linked with a sharp reduction in the readings of the thermal-pairT_{cap1} due to the surface of the frontal part of the cap being laved with steam from the site of seal failure. It was caused by a sharp reduction of the height of the front sector of the valve body because of the larger reduction of its temperature as compared to the rest of the circumference of the body's sealing surface. The dynamics of steam-water leaks was recorded by a video camera, its termination was linked with the commencement of an increase in the readings of T_{cap1} of a thermal-pair (see Fig. 4*a*).

In this thermal cycle for a valve with an SNP gasket, the connector remained tight and a gradual reduction in the readings of all thermal-pairs was noted. The same was also observed for a valve with a PGF gasket in experiments without seal failure of its connector. On seal failure, the back portion of the cap retained a smooth dynamics of T_{cap2} reduction, which confirms the local character of seal failure in the gasket sector. The same dynamics of thermal-pair readings, both in the presence and absence of seal failures, was also observed during thermal cycles in regime 3.

Unlike check valves, the shutter of a DN 100 angle valve, on opening, blocked the upper part of its internal volume, where the stagnant zone of the hot water zone was situated. This resulted in uniform cooling round the circumference of the vertical axis of the upper part of the body. The complex hydrodynamics of the flow in the upper part of the check valve chamber did not provide such uniformity, and a high rate of relaxation of thermally expanded graphite in the front sector of the gasket was required to maintain the tightness of the tested connector.

Slow cooling of the cap of a check valve at a rate close to that of the top flange of the DN 100 valve shows that for these elements of the compared valves the inflow of chilled water to them is low. For this reason, valve elements added on gaskets are mainly cooled by radiative heat exchange between flange surfaces and heat conduction through a narrow gasket. This low negative heat flux, combined with the high thermal conductivity of the check valve's cap material, made it possible to evenly distribute the metal temperature throughout the cap volume even if it was uneven along the perimeter of the sealing surface of the valve body.

In line with the recommendations of [3], to obtain a high negative heat flux on the inner surface of the body of a DN 100 valve at the initial stage of its cooling, the water pressure was sharply reduced to 1.1 MPa. In accordance with the recommendations of [4], this effected surface boiling, with a high heat transfer coefficient, causing more intensive cooling of the internal surfaces of the valve. This made it possible to lower the temperature of the outer surface of the valve body by 105°C in the first minute versus 95°C in thermal cycles with a check valve, whose body is less massive but the thermal conductivity of the material is lower. Under such strict conditions, the DN 100 valve kept the tightness of the connector in all thermal cycles, while the check valve had several seal failures. The difference is associated with the nearly axisymmetric distribution of heat flow along the vertical part of the DN 100 valve body from the sealed surface of the body to the cold water flow turning point. In a check valve, this axial symmetry was absent because of unequal mixing temperature of initially hot and cold water laving the front and rear sectors of the inner surface of the above-flow part of the body. For this reason, if the specifications for the valve contain the possibility of a sharp drop in the temperature of the water passing through it, then its design must ensure on heat-exchange the heat flows through the metal from the sealed surface of the body to the flow path are axisymmetric.

Results of concluding investigation.. The final measurements of the gaps between the body and the valve cap showed compression of the PGF and SNP gaskets in the course of the tests by 0.4–0.6 and 0.2–0.3 mm, respectively. The latter reached deformation by 1.3 mm, corresponding to contact of the steel stops with the sealing surfaces of the body and cap. In addition, the nut moments at which the nuts shifted away from their place as the tightening became weaker remained equal to the initial value 110 ± 10 N·m.

The complete removal of the tightening did not result in noticeably larger gaps between the body and the valve cap (an increase of only up to 0.3 mm). Only the removal of the gaskets from the sockets and measuring the height of the graphite part of the gaskets every 90° showed significantly greater relaxation, especially for SNP gaskets, whose height increased to 4.9 mm, which is only 0.4 mm less than its initial value, while for PGF gaskets the increase in height is equal to 4.13 mm, which is 1.17 mm less than its initial value.

Visual inspection showed both gaskets to be in satisfactory condition with the formation of a layer of a graphite component along the outer diameter of the PGF gasket, which was the reason for relaxation lessening. The small drop in the height of the graphite part of the SNP gasket is associated with widening of the gap between the restrictive steel rings, i.e., with an increase in the area occupied by thermally expanded graphite between them. It is possible that the use of the nut tightening torque for the metal-to-metal factory seal specified in the technical documentation was excessive when applied to thermally expanded graphite, which led to a partial loss of elasticity.

Causes of connector seal failure in tested check valves. The first premise was associated with a significant difference Δh in the height of the metal level of the sealing surface of the above-flow portion of the body in the front and back sectors of the valve. In addition, a low height/length ratio of the above-flow part of the valve has an adverse effect. However, a large temperature difference is required in these sectors of the above-flow part of the valve body in order to achieve a dangerous height for the tested gaskets $\Delta h = 0.25$ mm:

$$\Delta T_{av} = \Delta h/\alpha h \sim 200°C, \quad (1)$$

where $h = 70$ mm is the height of the above-flow part of the body; $\alpha = 17 \cdot 10^{-6}$ K^{-1} [5] is the linear expansion coefficient of the valve body material. Such a high temperature difference is impossible.

The second version was used to consider the delay of local relaxation of thermally expanded graphite when the pressure on it changes (elastic aftereffect). Visual observation and subsequent measurement of condensed leaks of boiling water with similar parameters through a closed valve gate were used to assess the leak flow rate on seal failure of the valve connector ~0.2 g/sec and the mass velocity of the mainly non-jet outflow ~10^3 kg/(m^2·sec), which corresponds to the passage section of the outflow gap of 0.2 mm^2. The adduced area is represented as a 10 × 0.02 mm rectangular slot. The gap height 0.02 mm is 10 times smaller than the previously considered relaxation capacity of thermally expanded graphite, and the calculation according to Eq. (1) determines the actual difference of 20°C in the average temperature of the considered front and back sectors of the overflow part of the valve body.

The calculation performed using the ANSYS FLUENT program of the hydrodynamics of the water flow in a chamber with the valve shutter under the conditions of heat change, considered in Fig. 4, and the adopted full opening of the shutter showed a low mixing rate of water in the above-flow part of the chamber and a low intensity of cooling of the inner surface of this part at water speed not exceeding 0.05 m/sec. Under these conditions, in line with the recommendations of [6], the heat transfer coefficient on the inner surface of the considered part of the valve is determined by the ratios for natural water convection [4].

Weak cooling of the front and rear sectors of the lateral surface of the valve cap in the first 45 sec of chilled water supply with a drop in the temperature of the outer surface of the flow part of the valve body by 50°C is confirmed by the calculations (see Fig. 4). For this reason, the heat sink from the upper part of the body and the cap mainly occurred by heat conduction along the metal of the body and a narrow strip of a gasket made of thermally expanded graphite. An expert assessment gave the maximum value $\Delta T_{av} = 40°C$ with estimated error ±15–20°C, i.e., the results of the last two evaluations are in agreement.

Conclusions. The results of 70-cycle stand tests for resistance to thermal cycling of the medium showed that 1) both types of gaskets retain their integrity and serviceability under severe thermal cycling and that 2) short-term (40–50 sec) weak seal failures are present in the absence of axial symmetry of heat flows from the sealed surface of the body to the water-cooled internal surfaces of the flow parts of the valve when the temperature decreases during the first 30 sec of the process by $\delta T_{in.30\ sec} = 177–62°C$. To eliminate the considered seal failures, the design of the valve must provide on thermal cycling an axial symmetry of the decrease in the temperature of the metal along the height of the sealed portion of the valves.

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