Analysis of the stress-strain state of the toroidal transition connecting the wall and the bottom of the tank

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Abstract. The interface zone of the wall and bottom of the vertical cylindrical steel tank (VST) is the most loaded part of the structure, which operates in a complex stress state. As a result of cyclic loads in places of stress concentration due to low-cycle fatigue and corrosive wear of the metal in the joint zone of the wall and the bottom of the VST the defects inevitably occur resulting in reliability decrease and service life of the tank. It is proposed to replace the T-shaped welding joint of the wall with the bottom with a part of the toroidal ring. At the same time to ensure the stability of the tank along the entire contour of the wall under the toroidal transition it is proposed to install a thrust bearing with fixing plates. The results of the calculations of the stress-strain state in the interface zone of the wall and the bottom showed that the proposed design will significantly reduce the occurring stresses, increase reliability, increase the period between repairs and extend the service life of tanks which will significantly reduce the cost of operating tank farms.

1 Introduction

The tank park of the Russian Federation with a capacity of more than 90 million m³, consists of 50,000 tanks, among which 45,000 are VST. Since more than half of all tanks were constructed before 1985, for trouble-free operation of such a number of tanks with a long service life large costs are required to perform repair works or to replace structures with new ones.

In addition, during the operation of tanks most of which have exhausted their service life, the risk of accidents that cause significant material and environmental damage increases. One of the main factors determining the occurrence of accidents on the VST are multifactor ultimate loads in the zone of interface of the wall with the bottom of the tank in combination with the lack of practical possibility of the performance of this T-joint defect detection.

In addition, at high voltages there are hidden welding defects in the T-joint area to be increased, resulting in micro cracks that together with the produced water accelerates corrosion processes. In the a result of such features of the operation of the interface zone of the wall with the bottom of the tank there are unacceptable defects that require the withdrawal of the tank from service and carrying out an extraordinary repair. It has been established that 30% of all repair work carried out in tank parks is repair of the interface zone of the wall with the tank bottom [1], and defects and stress concentrators formed in this part of the tanks significantly reduce the reliability and service life (Figure 1).
At present the issue of upgrading the design of the interface between the wall and the bottom of the VST is being discussed in various directions. But none of the proposed options found practical application. There developments of various non-standard design solutions for coupling the tank wall with the bottom are known.

In [2], the authors propose to construct a VST with a wall freely supported on the bottom instead of a rigid welded joint of the wall and bottom, and to make their connection in the form of a flexible compensation toroidal element located along the entire outer contour of the wall filled with an incompressible degassed liquid. The authors believe that with such a design the bending stresses will significantly decrease in the interface zone of the wall and the bottom.

In [3], the authors also propose to construct a VST with a wall freely supported on the bottom, and their connection should be performed with a corrugated compensation ring located along the entire inner contour of the wall which will reduce the stresses in the wall by about 2 times, and in the bottom almost to zero.

The author of work[4] believes that the most rational form of the welded joint when connecting the wall of the tank with the bottom is a welded joint of a concaved shape located on the inner side of the wall. Moreover the optimum value of the concavity of this joint should be 3-4 mm which according to the author’s calculations will lead to a decrease in stresses in the zone of connection of the tank wall with the bottom by 8-10% and to an increase in the time until micro cracks appear during operation.

In the work [5] it is proposed to perform the joint with a special T-shaped insert to increase the strength and corrosion resistance of the joint between the wall and the bottom of the VST.

In 1947 design organizations for Glavnetesbyt designed and built an experienced VST with a capacity of 2300 m³ with a toroidal edge on a spherical bottom [6]. With such interface of the wall and the bottom that is with the transition along a smooth curve from the cylinder to the sphere the stresses in the interface zone are reduced by about 25-30%, and the movements of the wall and the bottom during the filling of the tank occur smoothly.

The last example given is the closest analogue to the construction proposed in this paper. A distinctive feature of the proposed design is a thrust bearing installed along the entire contour of the wall under the toroidal transition, which will lead to a decrease in stresses in the joint zone of the wall and the bottom to 40%. In addition, such a structure can be used both in the construction of the VST and in its repair including VST of large volume.

2 Main part

When designing space structures, one should strive to ensure that there are no bending moments in the shell as the bending type of the stressed state is dangerous and technically disadvantageous for thin-
walled space structures. It is explained by the fact that the internal energy of the deformation of the shell during bending is much greater than during tension or compression.

In areas of sudden change in shape (surface fracture, precipitous change of the shell thickness), the magnitude of the deformations of the shell elements is different, and this in turns leads to bending.

To approach the moment less stress state of the shell, when the stress state depends only on normal and shear forces, the following conditions must be fulfilled: the shell must have a smoothly changing continuous surface; the edges of the shell should have the possibility to move freely in the direction normal to the middle surface.

The lower edge of the VST shell is rigidly connected by means of a welded T-joint with a horizontal bottom of the tank, therefore the edges of the shell cannot freely move in the direction normal to the middle surface that leads to the appearance of bending moments in the areas adjacent to the edges a sharp increase in the magnitude of the stress [7].

**Figure 2.** Design model for determination of the spatial movements of the structural parts of the tank (1 - wall; 2 - bottom; 3 - part of edge with width b3 - b31, interacting with artificial ground base; 3' - part of edge with width b31 lying on the base ring; 3'' - edging back (console of the edge) with width b32; 4 - support ring with width b4; SA, SB - vertical movements of the left (point A) and right (point B) of the upper edges of the ring; \( \theta \) - angle of internal roll of the ring; \( qA, qB \) - ground contact stresses under points, A and B, \( N_1 \) - the reaction acting from the side of the ring to the end of the console at the point C; \( N_2 \) - reaction acting from the side of the ring to the edge at the point B; \( C_1 \) - projection of point C on the axis O3X3; IPB - the initial position of the bottom) [1].

Hydrostatic low-cycle load occurred during the tank filling creates large bending moments and lateral forces, which cause a one-time change in the geometry of the wall and the bottom of the tank. Due to this movement the wall becomes convex, and the bending moment causes a turn at the junction point between the wall and the bottom of the tank, which leads to a wave-like deformation of the bottom (Figure 2).

As a result of research of various structure options for mating the wall and the bottom of the RVS and studying the reasons why these structures have not found practical application, the following work goal was formulated.

To develop such a variant of the construction of the interface between the wall and the bottom of the VST, during the operation of which the following tasks should be optimally solved:
- the maximum possible reduction of tension in the zone of the joint between the wall and the bottom;
- ensuring smooth movement of the wall and the bottom of the VST during operation;
- ensuring the manufacturability of the construction, installations, diagnostics and repair of the zone of connection of the wall and the bottom;
- increasing in the overhaul period of the joint zone of the wall and the bottom of the tank;
- reducing the cost of repairing tanks and operating tank farms;
- ensuring the ability to use the proposed design as in the construction of VST, and in the re-pair;
- ensuring the possibility to use the proposed design for tanks of any volume, including tanks with a volume of 50000 m³.

To solve these tasks, it is proposed to replace the T-shaped welded joint of a cylindrical wall with a tapered bottom with a structural element in the form of a toroidal transition with a torus radius equal to the tank radius, with shelves which size is calculated depending on the sheet thickness and manufacturing technology walls of the first belt. (In accordance with the regulatory and technical documentation of the Russian Federation, the bottom of the VST, for tanks with a volume of more than 2000 m³, is constructed in the form of a cone with a ratio of 1: 100).

![Figure 3](image)

**Figure 3.** Connection of the wall and bottom of a vertical cylindrical steel tank (VST) by toroidal transition.

At the same time, to ensure the stability of the tank and reduce the amount of bending moment, it is proposed to mount a thrust bearing with fixing scarves installed with a step, which is calculated depending on the diameter of the VST and the thickness of the sheet metal of the first belt (Figure 3), along the entire contour of the wall on the Foundation of the tank under the toroidal transition.

The proposed construction is illustrated in Figure 3, where the wall (6) and the bottom (7) are interconnected by a toroidal transition (1). Along the entire contour of the wall, under the toroidal junction a thrust bearing (2) is installed which is connected to the stiffening plate (3) attached to the concrete ring (5) by means of fixed anchor bolts (4).

### 3 Research methodology

Calculations performed in the ANSYS software package allowed a comparative analysis of displacement deformations and stresses of the wall and bottom in the tank, where the wall and bottom are conjugated using a T-shaped welded joint and in the tank where the wall and bottom are connected by a toroidal junction.
a) displacement of the wall in the tank, where the wall and the bottom are connected with a T-shaped welded joint.

b) displacement of the wall in the tank, where the wall and the bottom are connected with the help of a toroidal transition.

**Figure 4.** The results of the determination of the spacy displacements of the VST wall.

a) stresses in the joint area of the wall and the bottom with a T-welded joint (up to 360 MPa).

b) stresses in the region of the wall and bottom joint using a toroidal transition with a thrust bearing (up to 196 MPa).

**Figure 5.** The results of the strength analysis in the program ANSYS.

The radial displacement of the wall in the standard construction is 25 mm (Figure 4a), in the proposed construction - 26 mm (Figure 4b). The increase in wall displacement of the proposed construction by 4% occurred due to the elimination of that part of the standard construction, which, by increasing stresses by 40%, restrained the wall movement.

The maximum stresses at some points of the protrusion of the bottom of the standard construction (calculated for steel 09G2S, the yield strength of which is 345 MPa) achieve 360 MPa (Figure 5a), and in the proposed construction the maximum stresses occurring in the interface zone of the wall and bottom are about 196 MPa (Figure 5b).

### 4 Choice of manufacturing method

For such a structural element as a toroidal transition, designed to mate the walls and the bottom of the VST, the choice of the optimal method of manufacturing has a direct impact on the possibility of rational construction of the technological process of manufacturing the structure, helps to reduce the specific metal consumption and reduce the cost of the product.
1) For the manufacture of a large batch of toroidal transitions, it is advisable to apply the methods of forming by the method of hot stamping and the method of breaking-in in a hot state. In this case the use of expensive heating and special shaping equipment, as well as large-sized metal-intensive die tooling are cost-effective.

2) To reduce the cost of the product, as a method of manufacturing an experimental batch of toroidal transitions, you can choose rotational-local rolling on a bending-correct machine, which in comparison with powerful bending presses reduces the cost of production preparation and is a less energy-intensive process of shaping. Since this type of manufacturing does not require consequent heat treatment the price of the product will be also significantly decreased.

5 Conclusion
Thus, the proposed design allows you:
1. To reduce the stresses in the zone of connection of the wall and the bottom to 40%;
2. To ensure smooth movement of the wall and the bottom in the process of filling-emptying the tank.
3. To significantly increase the time to the formation of plastic deformations of the wall and the bottom of the tank in the zone of their connection.
4. Significantly increase the time until the appearance of micro- and macrocracks, as well as slow down the corrosion of the metal in the zone of the joint between the wall and the bottom of the tank.
5. Increase the turnaround time in the zone of the joint between the wall and the bottom of the tank.
6. Extend the service life, improve the reliability and safety of tank farms.
7. Reduce the cost of repairing tanks and operating tank farms.
8. Use the proposed design for the construction of VST, as well as for its repair, including large tanks.

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