International Journal of Engineering & Technology, 7 (4.8) (2018) 103-108

International Journal of Engineering & Technology

Website:www.sciencepubco.com/index.php/IJET

Research paper

Functional Reliability Assessment of Water Transmission Buildings of Urban Water Supply Systems

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Abstract

Continuous operation of water supply systems of settlements, industrial and agricultural objects is one of the topical problems in Ukraine. The most costly, complicated and responsible for reliable water supply in modern water supply systems are the complexes of water transmission buildings, which include pump stations, water mains, pressure and regulation facilities. They are located on a large territory, hydraulically connected with each other and require an integrated assessment of reliability based on their constructive and functional indicators, as well as the normative consolidation of methods and indicators of reliability assessment. It is proposed to assess the functional reliability by constant coefficients of operational availability. They should be complied with the normative values of the operating efficiency factors. The numerical values of the operating efficiency factors for each of three categories of water supply systems in conditions of water supply reduction and limitation are determined on the basis of the present standards. The basic principles of the methodology of engineering calculations of functional reliability of water transmission buildings' complexes (WTBC) are theoretically substantiated. The expediency and reliability of the assessment of functional reliability is confirmed by calculations. Improvement of functional reliability of WTBC can be provided by rational design schemes and efficient operation with intensive rehabilitation.

Keywords: *coefficient of operating efficiency, operational availability coefficient, reliability, water transmission.*

1. Introduction

Continuous operation of water supply systems that provide settlements, industrial and agricultural objects by water of the required quality is one of the topic problems that currently faces the Ukrainian economy. Interruptions in water supply result inconveniences for users, improper operation, sanitation problems at places of water consumption, significant economic losses and even environmental disasters. Thus, the water supply break in the city results inconvenience and discomfort for the population, economic losses in production enterprises because of the reduced production or defective products, environmental threats because of forced emergency production breaks, etc.

The most costly, complicated and responsible for reliable water supply in modern water supply systems are the complexes of water transmission buildings, which include pump stations, water mains, pressure and regulation facilities (Fig. 1). They are located on a large area and are hydraulically connected with each other. Any failures of their operation result reduction and interruptions in water supply and changes in the operating modes of all other buildings of the water supply system. Therefore, providing the reliable and continuous operation of WTBC is important, as from economic, social and environmental point of views.

WTBC as the technological structures are characterized by constructive complexity, dynamism of the state and imperfect operation. Even for the average city, there are tens of kilometers of water pipes of different materials and diameters built in different years, several powerful pumping stations, pressure-regulating buildings by capacity of tens of thousands of m^3 [4], [9] [16], [1]. The parameters of WTBC buildings' parameters change with time because of aging and deterioration: increase of hydraulic resistance of pipes, wear of pumping units, formation of cracks in water tanks. The influence of external factors is not always predictable: corrosion activity of soils, soils subsidence and erosion, destructive influence of plants along the water main layout, economic activity of people, etc. The imperfection of the WTBC operation of existing water supply systems in the settlements of Ukraine is caused [16]:

- *reduction in water supply* because of economic water use by consumers (reduction of water consumption by industry, introduction of water meter accounting, rationalization of water consumption, increase of water and electricity tariffs, etc.);
- *increase of the accident rate and decrease of reliability of WTBC* because of aging and wear of buildings, pipelines and equipment, the insufficient level of their replacement or rehabilitation;
- *deterioration of hydraulic characteristics* of the pipelines (the growth of hydraulic resistance of the pipes, nonconstructive changes in the schemes of WTBC, water analysis of them, etc.);
- *reduction of total, but increase of specific energy consumption,* mainly because of aging and wear of pump units.

Such state of the WTBC indicates the need of their renovation, which provides not only the massive replacement of pipelines and equipment, but also changes in the design, reconstruction and modernization conditions taking into account existing problems and development trends, changes in WTBC parameters in the process of operation, as well as requirements of reliability and resource saving [16], [1]. It is obvious that the requirements of reliability of water supply system to city or to enterprise refer to WTBC.

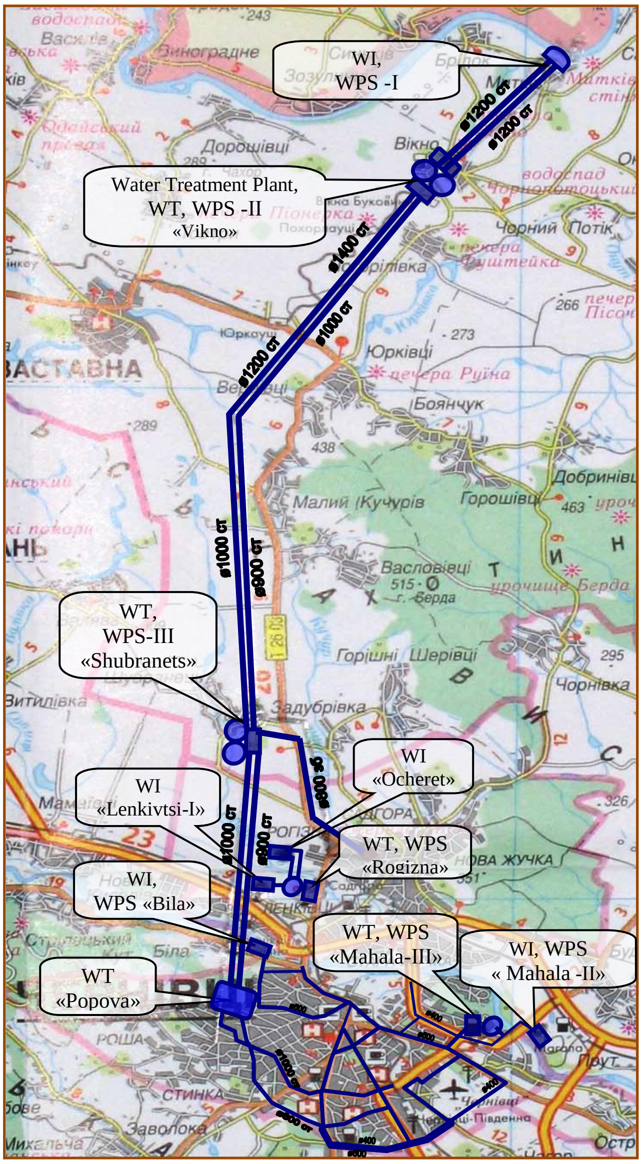


Fig. 1: Scheme of water transmission buildings' complex (WTBC) of the big city: WPS – water pumping station, WI – water intake, WT - water tanks

Problems of studying of reliability conditions of water supply systems were considered by such leading scientists as Abramov M., Alekseev M., Galperin Ye., Ilyin Y., Matyash O., Naymanov A., Naumenko I., Novohatniy V., Ukrainets M., Boryczko K., Janusz R., Kodikara J., Rajeev P., Rajani B., Robert D., Szpak D., Tchrzewska-Cieslak B., Zeman P. [4]-[15] and others. Each of these scientists made a certain contribution in the study of the processes of operation reliability of water supply buildings and their complexes. However, the issues of integrated assessment of the reliability of water transmission buildings based on their constructive and functional parameters, taking into account their changes during operation, remain unresolved. The researches in this direction [16], [18], [19], have been conducted at the National University of Water and Environmental Engineering in Rivne during recent years. At the same time, the normative fixing of the methods of reliability assessment of WTBC is important, especially at large distances of transmission and significant volumes of water consumption.

2. Main Body

The assessment of operational reliability of WTBC of water supply systems is based on a comprehensive analysis of continuous operation indicators of each individual element of the WTBC and their interaction in the scheme of the whole complex. It provides:
- determination of design indicators of WTBC's reliability;
- determination of normative indicators of WTBC's operational reliability and their numerical values;
- formation of methodology of engineering calculations of WTBC's operational reliability;
- creation of statistical database for the assessment and calculations of WTBC's operational reliability.

2.1. Estimated reliability indices of WTBC's operation

The following indicators are common [3], [4], [9], [13], [14], [16] to assess the reliable operation of water supply buildings:

• ***probability of failure-free operation R (t)*** - the probability that during time ***t*** the system or its element will preserve its operating parameters within permissible limits;

• ***failure intensity rate λ (t)*** - the conditional probability of failure initiation at time t, unless there has no been failures

$$\lambda(t) = -\frac{1}{R(t)} \cdot \frac{dR(t)}{dt}; \qquad (1)$$

$$R(t) = e^{-\int_0^t \lambda(t)dt}; \qquad (2)$$

• ***failure rate indicator z (t)*** - the ratio of mathematical expectation of failures' number of the renovated object during little operating time till the value of this nonfailure operating time

$$z(t) = \frac{d\Omega(t)}{dt} = \lim_{\Delta t \to 0} \frac{\Omega(t, t+\Delta t)}{\Delta t}, \qquad (3)$$

where ***Ω (t)*** is the function of failure rate;
Ω (t, t + Δ t) – the mathematical expectation of failures' number in the time interval ***(t, t + Δ t)***;

• ***renovation intensity μ(t)*** – the conditional probability of the object's renovation at time ***t***, if renovation has not been finished

$$\mu(t) = \frac{f_r(t)}{1-M(t)}, \qquad (4)$$

where ***fr (t)*** is the distribution density of the renovation time;
M(t) – the distribution function of the renovation time, or renovation probability

$$M(t) = 1 - e^{-\int_0^t \mu(t)dt}; \qquad (5)$$

• ***average failure time*** T_0 is the average value of the equipment operating time between the failures, if it is under renovation

$$T_o = \frac{1}{n} \cdot \sum_{i=1}^{n} t_i, \qquad (6)$$

where ***n*** – the equipment number failed during time ***t***;
t_i – the operation time between the first and second failures;

• ***average nonfailure operating time*** $T_{r.w}$ - the mathematical expectation of the random value of the operation time of the equipment between failures during time interval ***t*** = 0 ... ∞

$$T_{r.w} = \int_0^{\infty} R(t) \cdot dt; \qquad (7)$$

• ***availability factor A (t)*** is the probability that the object will be under operation at any time, except the planned periods during which the object's operation is not foreseen;

• ***operational availability factor*** A_{or} – the probability that an object at any time, except the planned periods, during which during which the object's operation is not foreseen, will be under operation and from this moment under nonfailure operation during the given time t_s

$$A_{or}(t_s) = A(t) \cdot R(t_s); \tag{8}$$

• ***coefficient of operating efficiency*** $K_{t.u}$ – the ratio of the mathematical expectation of the total time during which the objects (systems or their complexes) are under operation during certain operation period to the duration of this period; the mathematical expectation of the time when the object is under operation is the average time of the nonfailure operation $T_{r.w}$, then

$$K_{t.u} = \frac{T_{r.w}}{T_f}, \tag{9}$$

where T_f – duration of the operating period.

WTBC elements, as well as the whole water supply system, are referred to renovated objects. After performance the recovery and renovation works, these objects again able to perform the required functions with given quantitative and qualitative reliability indicators [2, 4, 9]. At the same time, the operating and recovery periods implement one after the other. Therefore, the stationary reliability indicators are used for practical calculations of the WTBC elements' reliability. These values of the reliability indicators vary with time, which are taken in conditions of the object's operation, when the valuesof its characteristics remain practically unchanged. It is often refers to indicators such as failure intensity rate λ, renovation intensity μ, failure rate z, and others. If values of indicators become constant, such dependencies had become of common practical application

$$R(t) = e^{-\lambda \cdot t}; \tag{10}$$

$$M(t) = 1 - e^{-\mu \cdot t}; \tag{11}$$

$$T_o = T_{r.w} = 1/\lambda. \tag{12}$$

Moreover, it is enough just to determine other common used indicators for practical calculations:

• ***specific failure rate indicator*** – the constant value of pipeline failure rate per unit of its length per unit time

$$z_o = \frac{n}{t \cdot \sum L}, \tag{13}$$

where n – failures number of pipelines during the observation period t, hours or years;
ΣL is the length of the WTBC pipelines, which are being monitored for failures, km.

• ***average renovation time*** T_r – the mathematical expectation of the renovation time, time needed to find and eliminate defects

$$T_r = 1/\mu; \tag{14}$$

• ***constant availability factor*** – the availability factor value determined for the object's operating conditions when the average failure rate and the average renovation time remain constant

$$A = \frac{T_o}{T_o + T_r} = \frac{\mu}{\mu + \lambda} = \frac{1}{1 + \frac{\lambda}{\mu}}. \tag{15}$$

The functional reliability should be considered as the ability of an object to perform its tasks. It is drinking water transmission to consumers of the design quantity for WTBC. This is the probability that during the given time WTBC will be able provide the design flow rates of the proper quality should not be lower than the design (normative) indicators. The values of these indicators should correspond to permissible water supply reduction according to the existing standards [1].

That's why the functional reliability of the WTBC should be assessed by the probability of failure-free operation ***R(t)*** and the operational availability factor A_{or}. These indicators characterize the ability of the production complex to preserve its operating parameters within the permissible limits. However, the operational availability factor A_{or} characterizes the reliability of the buildings' complex more accurately. It depends on the probability of failure-free operation ***R(t)*** and on the availability factor A, which depends on the WTBC scheme, i.e. the presence or absence of standby elements, their number and arrangement schemes.

2.2. Normative indicators of WTBC functional reliability

The reliable water supply system provides consumers by water of the proper quality with a temporary water supply reduction not below the permissible limits depending on its category. The existing standards [1] limit the duration of the water supply reduction up to 30% and the limitation on water supply (water supply reduction by more than 30%, and even its total absence during 3 days) according to the normatively determined terms depending on water supply system category:

- *1st category*: water supply reduction - no more than 3 days; water supply limitations - no more than 10 minutes;
- *2nd category*: water supply reduction - no more than 10 days; water supply limitations - no more than 6 hours;
- *3rd category*: water supply reduction - no more than 15 days; water supply limitations - no more than 24 hours.

Obviously, these requirements should be provided by conditions of proper functioning of water supply objects. They should be evaluated by appropriate indicators of functional reliability, reflecting the probability of performing a particular functional task within a certain period of time. This is the probability of continuous water transmission to the water supply objects of the sufficient quantity and the proper quality for a given period of time for WTBC.

The values of the quantitative indicators of functional reliability should not be less than normative. The coefficients of operating efficiency $K_{t.u}$ [2] can be accepted for these calculations. The average failure time $T_{r.w}$ is calculated by the equation (16) taking into account the duration of the operating period T_f the normative terms of the water supply reduction is up to 30% – [1] month and water supply limitations – 3 days [1]. The normative values of coefficients of operating efficiency $K_{t.u}$ for each category of water supply systems are given in Table. 1.

$$T_{r.w} = T_f - T_{ac}, \tag{16}$$

where T_{ac} – normative time of functioning of the water supply system at the elimination of emergency situations (Table 1).

The values of operating period duration are taken equal: for water supply reduction up to 30% – T_f = 30 days; water supply limitation – T_f = 3 days for determining the coefficients of operating efficiency $K_{t.u}$ by the equation (9).
Water supply systems and their elements refer to renovation objects. They become again operational and can perform the tasks after elimination the defects or emergency at the same level as before the emergency. The probability of the operation state of such objects, as specified in paragraph 2.1, should be determined by the complex reliability index - the operational availability fac-

tor A_{or}. It determines the probability that the object at any time will be able to operate and will continue to function in the same state during the given time interval t_s [2, 9]. It is the same time interval as for determining the coefficients of operating efficiency $K_{t.u}$, The normative duration of water supply reduction (one month) and water supply elimination (3 days) should be allowed.

Table 1: Normative values of coefficients of operating efficiency of water supply systems

Category	Normative terms T_{ac}		Coefficients of operating efficiency $K_{t.u}$ for	
	water supply reduction up to 30%	water supply limitation	water supply reduction up to 30%	water supply reduction up to 30%
I	3	10 minutes	0,90	0,9977
II	10	6 hours	0,67	0,917
III	15	24 hours	0,50	0,67

2.3. Theoretical principles of the engineering calculations' methodology of WTBC functional reliability

The reliability indicators values should be determined if they are constant by equations (10-15) for any element of WTBC (pumping units, valves, water mains, etc.). The parameter of failure intensity rate λ can be taken equal to parameter as the specific failure rate indicator z_o for practical calculations, so $\lambda = z_o$ [10, 11, 14, 15]. The failure intensity rate is λ = 0.00001...0.0003 1/h (for pipelines – 1/km/h), and renovation intensity is μ = 0.01...0.04 1/h [9, 16] for most WTBC objects. The ratio of these values is λ/μ = 0.00025...0.00625. The dependence $A = f(\lambda/\mu)$ is shown in Fig.2 for this range of values, which is practically a straight line.

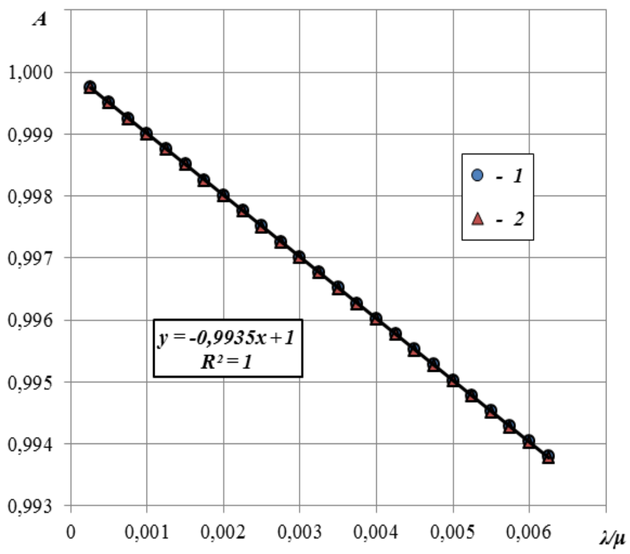


Fig. 2: Dependence of the constant availability coefficient A on the ratio of failure intensity rate λ and renovation intensity μ:

1 – calculation values by the equation (15); *2* – the same, by the equation (17)

Calculations have shown that in this values' interval and wider range, the constant availability coefficient A is the probability of nonfailure operation during the element renovation time T_r and can be determined by the equation

$$A = R(T_r) = e^{-\lambda \cdot T_r} = e^{-\frac{\lambda}{\mu}}. \quad (17)$$

However, the calculations' results of and by equation (15) and by equation (17) are sufficiently accurately approximated by the dependence

$$A = 1 - \frac{\lambda}{\mu}. \quad (18)$$

In this case, the maximum calculation error in the given range λ/μ does not exceed 0.004% in any of these equations (15, 17 or 18). The error increases if expand the range, that's unlikely for practical calculations, and makes: λ/μ = 0.01 – 0.01%; λ/μ = 0.05 – 0.25%; λ/μ = 1.0%. Thus, the practical calculations for computation the availability factor can be carried out using any of the following equations: 15, 17 or 18.

The probability of failure-free operation of the WTBC elements $R(t_s)$ should be calculated by the equation (10) for the range of their failures λ = 0,00001...0,0003 1/h (for pipelines - 1/km/h) and for the given limitation time in water supply t_s = 72 hours (3 days) and water supply resuction t_s = 720 hours (30 days), depending on which is shown in Fig. 3.

Obviously, the dependences $R(t_s) = f(\lambda, t_s)$ in the given range of values are sufficiently accurately approximated by straight lines too (Fig. 3)

$$R(t_s) = 1 - a \cdot \lambda, \quad (19)$$

where a is the coefficient, which depends on the given time of water supply limitation and reduction t_s .

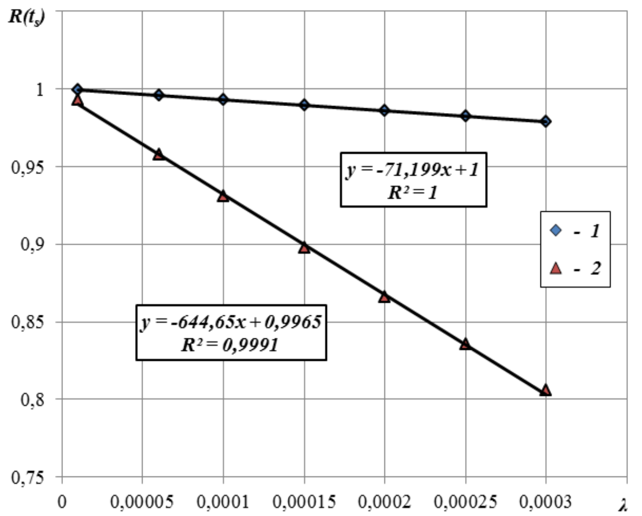


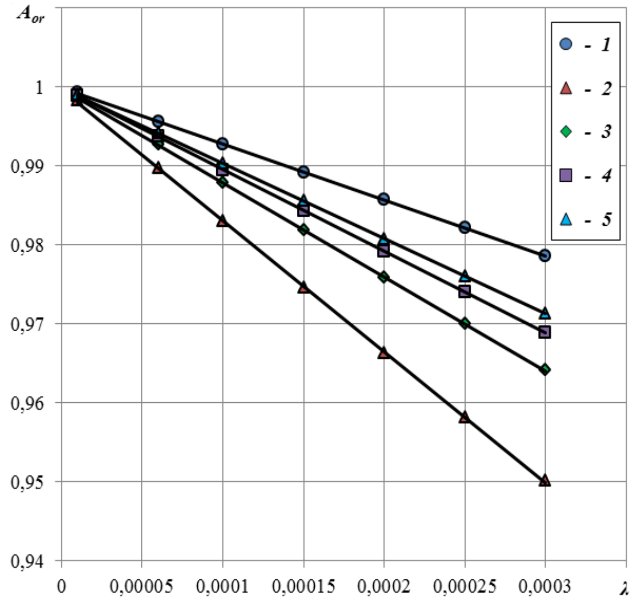
Fig. 3: Dependence of the probability of failure-free operation of the WTBC elements $R(t_s)$ on the failure intensity rate λ:

1 – calculation values for water supply limitations; *2* – calculation values for water supply reduction.

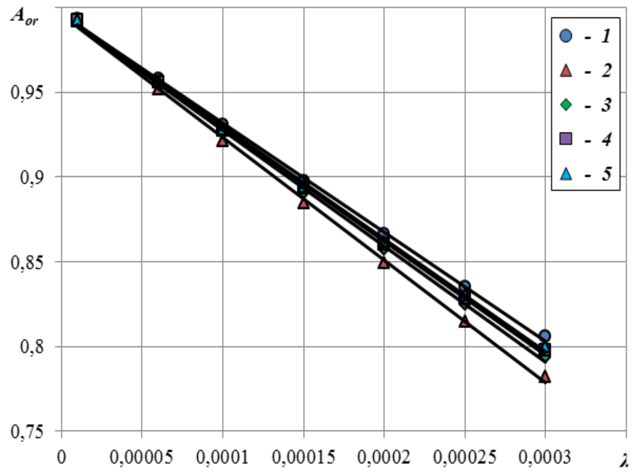
The diagrams in Fig. 4 show the changing of the availability coefficients depending on the failure intensity rate λ and the renovation intensity μ for conditions of water supply limitations and reductions. They show that the values of the operational availability coefficients A_{or} of WTBC individual elements make: A_{or} = 0.95...0.999 – for water supply limitation (within 3 days); A_{or} = 0.78...0.993 – for water supply reduction up to 30%. In case of the serial connection of the WTBC elements (for water mains length more than 1 km, location of valves and other equipment on them, etc.) will result the decrease of values $R(t_s)$ and A_{or}, because the calculated value of the constant availability coefficient of all WTBC will be determined as the multiplication of A_{or} of serially connected elements [4, 9, 16]. In this case, the value A_{or} of the section pipeline by length L, km, should be taken equal to A_{or} of 1 km pipeline in degree L. The general reliability of the complex of water transmission buildings is significantly increased [9, 16] because of duplication of water mains lines, their reserving, using tanks for emergency water storage. The estimated value of A_{or} of all WTBC will be determined by the equation

$$A_{or} = \prod_{i=1}^{m}\left(1-\prod_{j=1}^{n}\left(1-A_{or_{i,j}}\right)\right), \quad (20)$$

where $\boldsymbol{m}$ – the number of serially connected groups $\boldsymbol{i}$ of elements; $\boldsymbol{n}$ – the number of parallel connected elements $\boldsymbol{j}$ of the group $\boldsymbol{i}$; $\boldsymbol{A_{ori,j}}$ – coefficient of operational availability of the element $\boldsymbol{j}$ of the group $\boldsymbol{i}$.



a)



b)

Fig. 4: Dependence of the operational availability coefficient of WTBC elements $\boldsymbol{A_{or}}$ on the failure intensity rate $\boldsymbol{\lambda}$ and the renovation intensity $\boldsymbol{\mu}$ for such conditions:

a) water supply limitation; ***b***) water supply reduction:
1 – the calculated values of $\boldsymbol{R(t_s)}$ (for $\boldsymbol{\mu}$ = 0); ***2*** – calculated values of $\boldsymbol{A_{or}}$ at $\boldsymbol{\mu}$ = 0.01 1/h; ***3*** – the same for $\boldsymbol{\mu}$ = 0.02; ***4*** – the same for $\boldsymbol{\mu}$ = 0.03; ***5*** – the same for $\boldsymbol{\mu}$ = 0.04.

The calculations should be carried out on the basis of the design scheme of the WTBC (Fig. 5) for practical calculations in each case. The scheme reflects all the buildings, the main technological equipment and pipelines arrangement. The design scheme of the WTBC for calculating the reliability indicators should be determined taking into account their hydraulic interconnections with other elements of the water supply system (water supply networks, water tanks, etc.) with available reserving and duplication of separate buildings and water lines [9, 16].

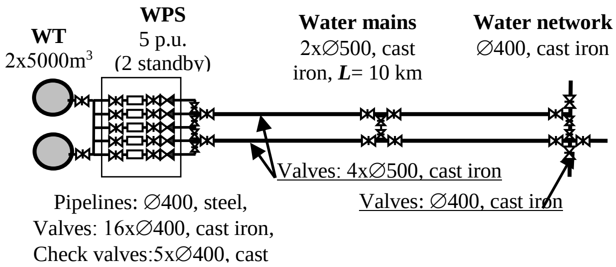


Fig. 5: Constructive scheme of typical WTBC settlements

The operational availability coefficients are determined for each of the WTBC elements (see Table 2). First it is necessary to calculate the value of the whole group of these elements at parallel arrangement of individual elements, which assembled in one building (for example, the pumping station), and then of the whole chain of such groups.

The values of the failure intensity rate $\boldsymbol{\lambda}$ and the renovation intensity $\boldsymbol{\mu}$ were taken according to [9, 16] calculating the reliability of certain elements of the WTBC (Table 2). The values of the failure intensity rate $\boldsymbol{A_{or}}$ were defined as the multiplication of their values for each element for the group of elements located serially within each building (Table 3). The $\boldsymbol{A_{or}}$ was determined by the equation (20) for buildings in which the group of elements are arranged in parallel. The presence of a cross connection on the water main allows to divide it into two parts (two lines of the pipelines before and after the connection), calculating them as a separate group of elements.

Table 2: Reliability indicators of WTBC's separate elements (Fig. 5)

Element	λ, 10^4 1/h, 1/km/h	A	$R(t_s)$ for conditios:		A_{or} for conditions:	
			a	***b***	***a***	***b***
Water tanks	0.57	0.99716	0.95979	0.99590	0.95706	0.99307
Valves	0.15	0.99963	0.98926	0.99892	0.98889	0.99855
Pumping unit Д 500-65	2.5	0.99379	0.83527	0.98216	0.83008	0.97606
Electric drive valve	0.6	0.99850	0.95772	0.99569	0.95629	0.99420
Check valve	0.8	0.99800	0.94403	0.99426	0.94214	0.99227
Steel pipeline, ∅400, L=20 m	0.15	0.99999	0.99978	0.99998	0.99977	0.99996
Control unit of the pumping unit	0.95	0.99763	0.93389	0.99318	0.93167	0.99083
Cast iron pipeline, ∅500, L= 5 km	0.52	0.98717	0.82928	0.98145	0.81864	0.96886
Steel pipeline, ∅500, L=10 m	0.2	0.99999	0.99986	0.99999	0.99985	0.99998

Notes: 1. The values of $\boldsymbol{R(t_s)}$ and $\boldsymbol{A_{or}}$ are given for conditions: ***a***) water supply reduction up to 30%; ***b***) water supply limitations.
2. The renovation intensity rate $\boldsymbol{\mu}$ is taken to be equal to: for equipment – 0.04 1/h; pipes and water tanks – 0.02 1/h.

It was accepted the parallel operation of 5 groups of elements (Table 3) with their triple multiplication (3 operating pump units) while determining the $\boldsymbol{A_{or}}$ coefficients for the pumping station in calculations according to the equation (20). Calculating the $\boldsymbol{A_{or}}$ of the water pipelines it is taken into account that two sections operate in parallel (groups of elements in Table 3) and in serial – one more pair of parallel sections.

Table 3: Reliability of the groups of WTBC elements (Fig. 5)

Building	Group of elements	A_{or} for conditions:	
		a	***b***
Water tanks	Water tank, valve, steel pipe ∅400, L=20 m	0.94621	0.99159
		0.99711*	**0.99993***
Pumping	Pumping unit, 2 valves, check	0.68887	0.95265

station	valve, steel pipe ∅400, L=20 m	**0.99128***	**1.00000***
Water mains	Cast iron pipe ∅500, L=5 km, cross connection (steel pipe ∅500, L=10 m), 5 valves,	0.77403	0.96181
		0.90048*	**0.99709***
WTBC in total:		**0,89005**	**0.99701**

Notes: 1. The value A_{or} is given for the same conditions as in Table 2.
2. * - the value of the coefficients A_{or} are for the whole building.

The data of the performed calculations of the WTBC's functional reliability and their comparison with the valuesof operating efficiency coefficients $K_{t.u}$ (Table 1) show that according to the WTBC scheme, shown in Fig. 5 water transmission in water supply systems of the 2nd and 3rd categories is allowed, because the values $K_{t.u}$ are greater than the recommended normative (Table 1). For example for conditions of water supply reduction up to 30% the coefficient value is 0.89 at the norm of 0.67 for the 2nd and 0.50 for the 3rd category of the water supply system; for water supply limitations is 0.9970, respectively, 0.917 and 0.67 for the 2nd and 0.50 for the 3rd category. The calculated valuesA_{or} of the whole system will be lower than the values A_{or} for WTBC taking into account the operation of water intake and treatment plants. This decrease is insignificant (approximately – 0.05% for conditions of water supply reduction and 0.004% for water supply limitation) as the additional calculations show.

As calculation results of reliability indicators show it is necessary to use the reliability of the WTBC's certain elements with higher reliability indices in order to put the WTBC according to the requirements of 1st category of water supply system. For example, to construct water mains from pipes with less failure intensity rate or to construct 2 cross connections on water mains. Among other options for improving the reliability of water supply system are installing reservoirs, with increasing the efficiency of emergency repair works, emergency water supplies in the city or with other WTBC from another water supply source.

Calculated using the above methodology, the values of the constant operational availability coefficients A_{or} essentially depend on such primary reliability indicators as the failure intensity rate λ, the renovation intensity μ and the specific failure rate parameter z_o. Their reliable values can be obtained on the basis of field observations on real water pipes, and statistical databases based on their basis for the estimation and calculations of the WTBC's functional reliability.

3. Conclusions

The calculations' result show that the functional reliability of the water transmission buildings' complexes (WTBC), determined using constant operational availability coefficients, corresponds to the coefficients of WTBC operating efficiency. These coefficients calculated according to the normative values of the time reduction limitation of water supply up to 30% and water supply limitations (up to 3 days) for each of the three categories of water supply systems. The expediency and reliability of such functional reliability assessment is confirmed by the theoretical substantiation of the main methodology provisions of engineering calculations of the WTBC functional reliability and by provided calculations. Improvement of the WTBC functional reliability can be provided by their rational design schemes and efficiency of operation, in particular, with low accident rate of pipelines and operability of carrying out of emergency repair works in the shortest possible time.

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