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ANALYSIS AND GENERALIZATION OF THE RESULTS OF AN EXPERIMENTAL RESEARCH OF THE RECHARGEABLE BATTERIES OF SELF-GUIDED ELECTRIC TORPEDO CET-65 (USSR) IN POST-GUARANTEE TERMS OF EXPLOITATION

Об'єктом дослідження є процес зміни електротехнічних і тактико-технічних характеристик срібно-цинкових торпедних акумуляторних батарей в процесі їх післягарантійного зберігання.

Предметом дослідження є технічна геронтологія електротехнічних систем, а саме – срібно-цинкових акумуляторних батарей самонавідної електричної торпеди СЕТ-65 (СССР).

Наявні на озброєнні срібно-цинкові торпедні акумуляторні батареї знаходяться на післягарантійних термінах зберігання: від 30 років і більше. Минулі в ході такого періоду зміни їх параметрів, а також геронтологічні процеси, що протікають в них, мало вивчені. В умовах вимушеної експлуатації на післягарантійних термінах зберігання встає гостра необхідність проведення моніторингу їх стану. Виходячи з цього, виявлення закономірностей зміни електротехнічних характеристик срібно-цинкових торпедних акумуляторних батарей від їх строків зберігання і визначення впливу цих змін на основні тактико-технічні характеристики торпеди представляється важливою науково-прикладною задачею.

В роботі проаналізована модель життєвого циклу срібно-цинкових батарей. Це дозволяє прогнозувати зміни основних електротехнічних характеристик від термінів їх зберігання, а також вплив цих змін на основні тактико-технічні характеристики торпеди. Визначено залежності впливу терміну зберігання торпеди тривалістю більше 20 років на інтенсивність зменшення її швидкості і дальності її ходу. Встановлено, що вказані показники погіршуються до 20 % та до 17 % відповідно. Проведена корекція моделі життєвого циклу торпедної акумуляторної батареї. Встановлено, що, з урахуванням роботи автоматичної системи наведення, термін доцільної експлуатації торпедної акумуляторної батареї не повинен перевищувати 16 років. На основі геронтологічних змін джерел живлення торпедної акумуляторної батареї запропонована методика внесення поправок при проведенні торпедних стрільб. Це дозволить компенсувати збільшення розсіювання в боковому напрямку і по дальності, а також збільшення кута розрахункової точки зустрічі торпеди з ціллю. В свою чергу, це дозволить виконувати навчальні та бойові завдання, використовуючи наявні торпеди післягарантійних термінів зберігання.

Ключові слова: *торпеди післягарантійних термінів зберігання, срібно-цинкові акумуляторні батареї, геронтологічні зміни.*

1. Introduction

After Ukraine received the status of an independent state, its Navy inherited from the USSR a large number of various weapons, including torpedo. Subsequently, due to the lack of production facilities and the material and technical base necessary for production, repair and maintenance of torpedo weapon samples, the nomenclature of torpedoes was reduced to three. They include:

- 533 mm antisubmarine self-guided electric torpedo SET-65, 1965 of adoption for armament;
- 400 mm universal self-guided electric torpedo SET-72, 1972 of acceptance for armament;
- 533 mm long-range oxygen homing torpedo 53-65K, 1965 of adoption for armament.

The shelf life of these torpedoes exceeds the permissible period of their service. In order to maintain their technical readiness in the Ukrainian Navy, measures were repeatedly taken to modernize and extend the life of these torpedo-weapon models. However, due to the lack of necessary funding in full, it was not possible to carry out the restoration, modernization and timely renewal [1].

Most negatively this affected the power sources of anti-submarine torpedoes, since the terms of their storage and operation are strictly regulated by a number of guidelines and technical documents [2]. At the same time, there were no methods for predicting the change in electrical characteristics (EC) in torpedo silver-zinc rechargeable batteries (TRB) for operating periods exceeding 10 years. Models for the operation of torpedo tubes with storage periods exceeding the warranty period have not been developed. To do this, it was necessary to conduct research on their performance characteristics and develop ways to increase the corresponding characteristics to those declared in the technical documentation [2].

The available silver-zinc TRBs are in various stages of storage: from 30 years or more. The changes in their parameters that passed during this period, as well as the

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processes taking place in them, have been little studied. In conditions of forced exploitation on post-warranty storage terms, there is an urgent need to monitor their condition, which in turn implies the following:

– prediction of changes in the basic EC of TRB;
– organizational and technical measures aimed at reducing the likelihood of manifestation of an abnormal effect;
– timely and safe disposal.

For the time being, all TRBs have expired their life in the Ukrainian Navy, and this makes it impossible to issue such torpedoes to warships and use them as intended [3].

Proceeding from this, the identification of the regularities of the change in the TRB of silver-zinc ECs from their storage terms and the determination of the effect of these changes on the main tactical and technical characteristics of the torpedo (speed and range) is an actual scientific and applied problem. And in the conditions of the hybrid war in Ukraine and the annexation of the Crimean peninsula – the urgency of this task is unconditional, since it is directly related to the combat readiness of a number of Ukrainian Navy warships.

2. The object of research and its technological audit

The object of research is the process of changing the ECs and TTCs of silver-zinc ECBs in the course of their post-warranty storage.

The subject of the study is the technical gerontology of electrotechnical systems, namely silver-zinc TAB CET-65 (Fig. 1) [4].

Fig. 1. CET-65 Torpedo (USSR)

By document [2], the lifetime of the TRB is determined by ten years of storage, during which:

– average repair (in 5 years);
– control checks (every 2.5 years).

That is, during the established service life, preventive measures are designed for the product aimed at maintaining the values of the main power indicators of the torpedo close to the nominal ones. At the same time, for TRB post-warranty terms of storage of operational documentation, neither a list of corresponding measures, nor their essence, nor their periodicity is stipulated.

Consequently, a contradiction is obtained, which consists in that, on the one hand, in the absence of an alternative, there is an urgent need for torpedo armament after post-warranty storage. On the other hand, there is a significant gap in the technical documentation that would regulate the procedure for checking, repairing, modernizing, preparing for combat use and directly using combat torpedoes.

At the moment, such a state of torpedo armament, which is on post-warranty terms of operation, is one of the main problems of the Ukrainian Navy.

3. The aim and objectives of research

The aim of research is to determination of the technically expedient storage times for silver-zinc TABs exposed to the effects of gerontological changes, on the basis of the dependence of the fall of the ETC on the storage time.

To achieve this goal, it is necessary to solve the following research tasks:

1. Identify the regularities of the influence of changes in the ETC of silver-zinc TABs of long storage periods on the main TTC of torpedo armament – on speed and range.
2. To predict the changes in the main energy indices of silver-zinc TABs from the time of their storage, as well as the effect of these changes on the speed and range of the torpedo.
3. To develop a methodical approach to the correction of the initial data of shooting by the CET-65 torpedoes taking into account the gerontological changes of silver-zinc TRB at various stages of its storage.

4. Research of existing solutions of the problem

The problem of deterioration of the technical characteristics of ammunition of various types and calibers due to natural aging (gerontological changes) of their elements due to long-term storage is not new, and the process itself is inevitable. Conditions and periods of storage, temperature regime, as well as immediate tightness of ammunition somehow influence the process of their aging, speeding up or slowing it down. It is this process that forces the transfer of existing ammunition into the category of those that have a long or post-warranty period of storage.

Over the past 15 years, only in Ukraine, a number of scientific experimental studies have been carried out to study the effect of this process, both on the technical state of the armament sample and on the TTC of such types of munitions as:

– automatic [5, 6];
– pistol [7, 8];
– artillery [9];
– tank ammunition [10];
– ammunition of naval nomenclature [11].

And if in the works listed above the main reason for carrying out the experimental studies was the depletion of the powder charges due to their long-term storage, then in the work on torpedo armament, this change was caused by the change in the ETC of the TRB. And TRB, as is known, is a radically different element than the powder charge.

Consequently, all approaches and patterns described in the above works should not be used in the process of studying torpedo weapons.

As for the latter, in the experimental studies [1, 12, 13], TRB was investigated for changes in their ETC due to natural aging of the corresponding nutrients. But only a few isolated studies have been described in these studies, while a comprehensive detailed analysis of the results obtained has not been carried out.

Also, other world scientific works can't be ignored.

In [14], an algorithm for determining the optimal torpedo configuration is presented, which would satisfy the requirements and criteria for its effectiveness. At the same time, studies of the optimal configuration of its TRB elements, both guarantee and post-guarantee terms of storage, were not conducted.

The authors of [15] developed a conceptual high-precision finite element model for a supercavitating torpedo. However, in the development of this model, a certain error was made in connection with the neglect of the effect of gerontological changes in torpedo elements during their aging on the main TTC and ETC of such torpedo.

The author of [16] generalized and analyzed the problem of aging of both munitions in general and torpedoes in particular, but no models or forecasts were proposed for their expedient use.

The rest of the vast majority of scientific papers, such as [17, 18], describes only current trends in the development of torpedo armaments in the world or presents a concise analysis of their main TTC. The effect on the TTC torpedoes of the aging processes of their elements in such works is not considered at all.

Thus, the results of the analysis show that in a relatively small number of scientific papers on this subject, experimental studies of the TRB torpedo SET-65 post-warranty terms of operation have not been carried out.

5. Methods of research

Theoretical studies [19] shows that during the long-term storage with TRB, changes occur that negatively affect their ETC such as capacitance, voltage, internal resistance. The obtained dependences of the change in the discharge time of the TRB from the change in its capacitance determined the influence of the torpedo storage time on the range of its travel. The dependence of the change in motor power on the voltage in turn caused the influence of such terms on the change in the speed of the torpedo.

Variation of the torpedo range from the shelf life TAB $\Delta L(\tau)$ is the ratio of the torpedo range on the warranty shelf life of the TRB L to the table values of the range of the torpedo L_T. This difference is defined in [1] and is represented as the expression:

$$L/L_T = L_T - 0.007\tau, \quad (1)$$

where L – the values of the range of the torpedo on the warranty terms of TRB storage; L_T – table values of torpedo range; τ – TRB shelf life.

Changing the speed of the torpedo from the TRB shelf life $\Delta V(\tau)$ is the ratio of the speed of the torpedo on the warranty TRB shelf life V to the table values of the speed of such torpedo V_T. This difference is also defined in [1] and is represented as the expression:

$$V/V_T = V_T - 0.009\tau, \quad (2)$$

where V – the speed of the torpedo on the TRB warranty shelf life; V_T – table values of the speed of the torpedo; τ – TRB shelf life. Based on the obtained data [1], the TRB life cycle model is developed (Fig. 2), which is described by a sixth-degree polynomial:

$$C = (-9.9888e^{-6})\tau^6 + 6.057e^{-4}\tau^5 + (-1.258e^{-2})\tau^4 +$$
$$+9.7436e^{-2}\tau^3 + (-0.25375)\tau^2 + (-0.22637)\tau + 239.98, \quad (3)$$

where C – TRB capacity; τ – TRB shelf life.

This model makes it possible to predict the changes in the main ETC of TRB from the time of their storage, and also to predict the impact of these changes on the speed and range of the torpedo. Such model makes it possible to determine the correction values for the initial parameters of torpedo firing.

This model includes three stages:

– the first – TRB capacity, which remains practically unchanged, the aging processes occurring inside the TRB are insignificant and their rate of flow is low. They do not have a significant effect on the ETC of TRB;

– the second – TRB capacity sharply decreases. The permissible minimum value of the capacity can be determined on the basis of the minimum permissible speed and range of the torpedo;

– the third stage – the values of the capacity can't provide the necessary speed and range of the torpedo, and, consequently, the use of TRB is not appropriate [19].

To confirm the theoretical obtained results, the JSC RPC «Luhansk battery-1» (Ukraine) developed a test program for batteries of СЦА-240 (А-187М) [20]. Summarizing the proposed order of TRB tests, the program of their conduct can be presented schematically (Fig. 3).

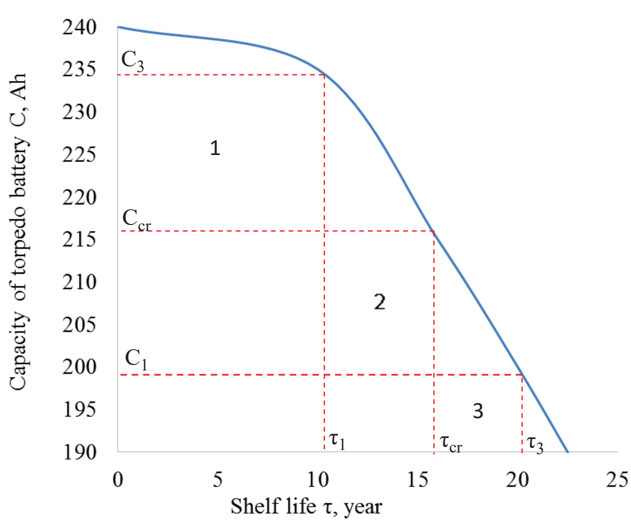

Fig. 2. TRB life cycle model

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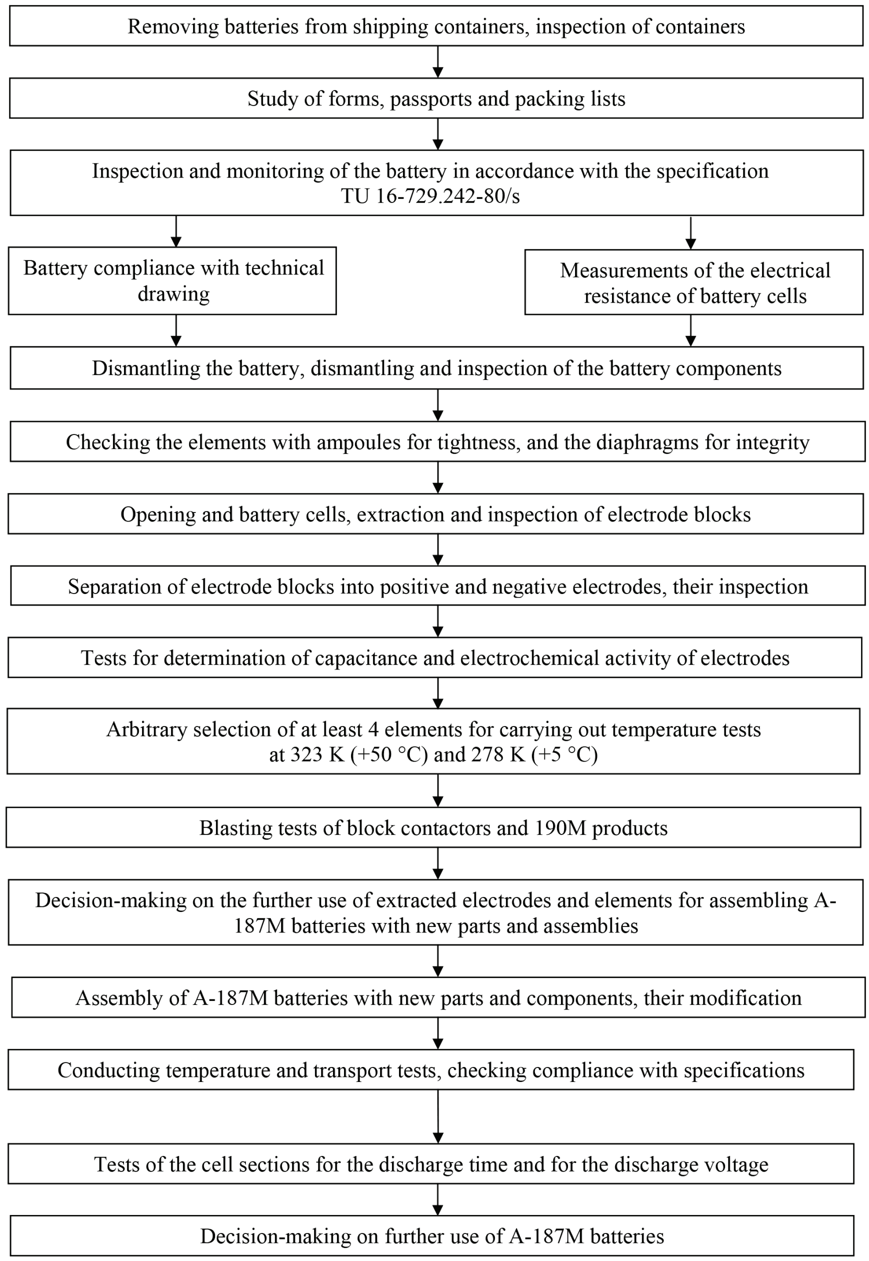

Fig. 3. Diagram of test program for batteries of СЦА-240 (А-187М)

The presented TRB test program is still the only document that not only regulates the procedure for checking TRB, but also provides an opportunity to extend their operation due to their finalization and modernization.

6. Research results

On the basis of expressions (1) and (2), the corresponding dependences of the torpedo range (Fig. 4) and its speed (Fig. 5) on the TRB storage time are plotted.

Based on this, the following data were obtained for torpedoes with a 22-year TRB shelf life:

1. The capacity of such TRB is reduced by 20 %, which leads to a decrease in its discharge time to 10.8 min, which does not correspond to the data of the TTC (13 min).
2. The torpedo range with such TRB will decrease by 17 %, which corresponds to 2.5 km.
3. The voltage of the TRB is reduced by 18 %, which corresponds to 40 V [20].
4. With such voltage values, the torpedo motor's power ratings take unsatisfactory values equal to $1.8\cdot10^5$ W, at which the motor can't provide the required torpedo speed.
5. The speed of such torpedo will decrease by 20 %, which corresponds to 4 m/s (8 knots).

Limitations related to the operating conditions of on-board homing equipment, for normal operation of which a voltage drop of not more than 10 % is allowed, led to a forced correction of the TRB life cycle model. This value further limit the period of expedient operation of the TRB: taking into account this adjustment, such period should not exceed 16 years. One of the main results of the experimental study of the batteries of СЦА-240 (А-187М) was the data of tests of positive and negative electrodes, presented in Tables 1, 2, respectively.

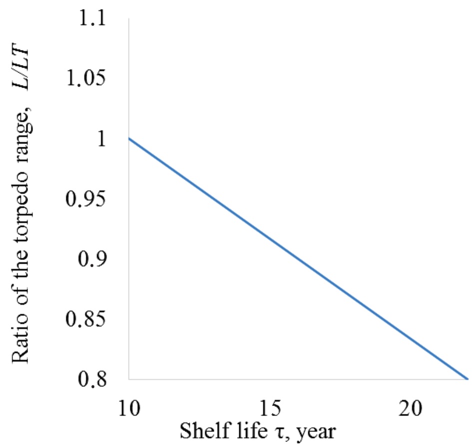

Fig. 4. Changing the torpedo range from the storage of torpedo batteries

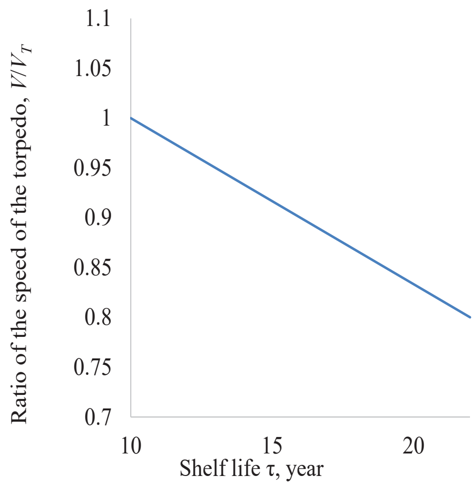

Fig. 5. Changing the speed of the torpedo from the time of storage of torpedo batteries

Table 1

Positive electrode test results

No. of element	Positive electrodes				Requirements for technical documentation
	No.	Mass, g	Discharge time, min	Appearance	
81086 (non-hermetic)	1	23.41	49′	Gray	The discharge time of positive electrodes should be at least 45′
	2	23.41	47′35″		
	3	23.26	48′30″		
	4	23.97	49′30″	Gray with brown spots	
	5	23.70	48′50″		
	6	23.56	48′		
	7	23.69	48′50″	Gray	
	8	23.15	46′30″		
	9	23.56	47′10″		
Average value		23.52	48′15″	–	
80647 (hermetic)	1	23.96	48′	Gray	
	2	23.64	46′45″		
	3	23.75	49′35″		
	4	23.50	47′45″	Gray with brown spots	
	5	23.17	46′		
	6	23.32	46′		
	7	23.40	46′40″	Gray	
	8	23.20	45′45″		
	9	23.44	46′15″		
Average value		23.49	47′	–	

Table 2

Results of negative electrode tests

No. of element	negative electrodes				Mercury content, %
	No.	Mass, g	Discharge time, min	Average discharge voltage, V	
81086 (non-hermetic)	1	16.6	19′24″	1.37	0.87
	2	16.7			
	3	16.5	21′40″	1.40	0.66
	4	16.6			
	5	16.6	22′42″	1.40	0.74
	6	16.7			
Average value		16.6	21′41″	1.39	0.76
80647 (hermetic)	1	16.7	22′20″	1.40	0.62
	2	16.6			
	3	16.8	23′12″	1.40	0.62
	4	16.6			
	5	16.8	20′05″	1.36	0.,68
	6	16.8			
Average value		16.7	21′54″	1.39	0.64
Requirements for technical documentation			not less than 17′	not less than 1.35	1–2.5

So in negative electrodes the content of mercury was reduced by 0.5 %, which is introduced into the active mass to ensure stability of the zinc electrode during storage, which does not correspond to technical documentation (1 %) [20].

It was also recorded a decline in its ETC to the boundary-permissible values in positive and negative electrodes, as a result of their long-term storage. Thus, the time of the control discharge of the positive electrodes of the TRB elements was 48 to 44 min, (at a rate of 45 min), and negative – from 19 to 16 min (at a rate of 17 min).

The above facts lead to a change in the ellipse of ship torpedo scattering during firing (Fig. 6):

– in range;
– in a lateral direction.

To compensate for this impact, it is necessary to make appropriate amendments:

– to make changes in the calculation of the maximum distance of the torpedo salvo and the conditions of «reaching» the torpedo to the target (the target reach);
– make changes in the calculation of the angle of the torpedo encounter at the calculated point of the torpedo encounter with the target (the lead angle).

On the basis of the developed technique [1], the initial data of torpedo firing were adjusted to take into account the gerontological changes in TRB. So for 50 % of torpedoes, ship dispersion in the lateral direction of the $B_L$and ship dispersion over the range of the B_R will exceed its values by 23 and 50 meters, respectively. For the remaining 50 % of the torpedoes, according to the normal distribution law of the random variable, these values will be 6 times larger and will be 138 and 300 m, respectively. This is 1/2 of the reaction channel length of the active channel of the automatic guidance system of the CET-65 torpedo and covers the response radii of the passive channel of the torpedo homing gear at target speeds of 9 to 18 knots.

It was also found that for the same target angle q_T, the angle of the meeting with the target θ and the lead angle φ, the value of the total distance traveled by the torpedo decreased by 15 % (2174 m). The main reason for this is precisely the gerontological changes in TRB. The value of the maximum distance of the torpedo salvo D_{mds} decreased by 1500 m, which is 15 % of its nominal value.

In determining the angle of the calculated point of encounter of the torpedo with the aim of φ, we obtained that the given angle, taking into account the gerontological changes of TRB φ_g, under the same shooting conditions, will differ from the true φ_t, and will be 9° (at $\varphi_i = 6.9°$).

In addition, it was established that the post-warranty retention aperture of the TRB had the lowest percentage of opening – 15–20 %, compared with 75–100 % of the apertures of the warranty shelf life. Visually, this difference is shown in Fig. 7.

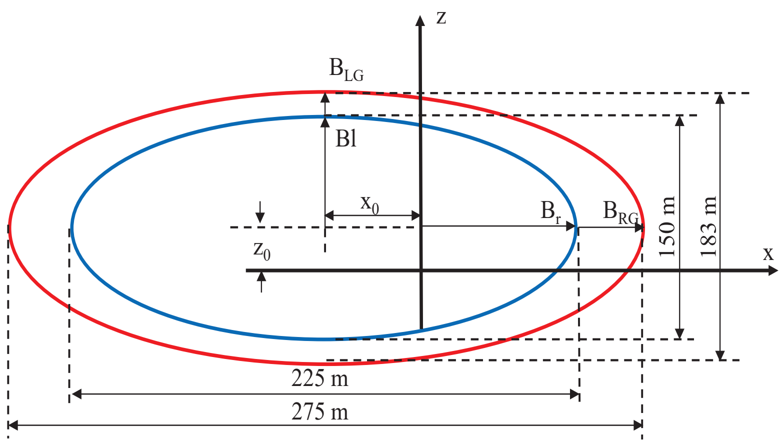

Fig. 6. Ellipse of polygon scattering of torpedoes taking into account gerontological changes in their rechargeable batteries

a *b*

Fig. 7. Comparative photos of diaphragm membrane blasting results: *a* – the warranty storage period; *b* – post-warranty storage period

This phenomenon will lead to late delivery of the electrolyte from the ampoule to the elements, untimely and incomplete wetting of the surface of the electrodes, as well as to delay the full reaction of the active masses. In turn, this will prevent the timely supply voltage of the power battery to the motor. In the final result, the speed of the torpedo and the angle of rotation of the rudders will not be sufficient for a timely exit to a given trajectory [13].

7. SWOT analysis of research results

Strengths. The results of a theoretical study on the fact that, due to gerontological changes in TRB for long periods of storage, their main ETC fall, were confirmed by the results of an experimental study.

The TRB torpedo life cycle model allows to predict:
– changes in the basic ETC of TRB from the time of their storage;
– the effect of these changes on the main TTC torpedoes – speed and range.

In turn, this allows to introduce corrections into the initial parameters of torpedo firing, taking into account the gerontological changes in the TRB elements.

The proposed model is adjusted taking into account the limitations associated with the operating conditions of onboard homing equipment.

The proposed method of making corrections during torpedo firing makes it possible to perform training and combat missions using the available torpedoes of post-warranty storage periods.

Weaknesses. Further experimental research, refinement and modernization of the TRB are complicated by the fact that the enterprise that conducted them is located in the temporarily occupied territory (Luhansk, Ukraine).

A limited number of both the CET-65 torpedoes themselves and the Ukrainian Navy ships equipped with the corresponding torpedo tubes do not give a full test of the results obtained in the course of the experimental study.

Opportunities. Test program TRB CET-65 is universal and can be used to study similar TRB of other types of torpedoes, both Ukrainian and imported.

Development of correction tables for shooting torpedoes of CET-65 for long periods of storage, depending on the duration of these terms.

Investigations of the effect of gerontological changes on the intensity of the loss of their physicochemical properties of the polyamide resin from which the diaphragms are made and the elements of the electric locks HX-10X1,5 TRB.

Threats. The fulfillment of the TRB test program is possible only in laboratory conditions with the participation of personnel of the appropriate qualification, which makes it impossible for it to be conducted by the forces and means of the crew of a warship or a military unit of the Ukrainian Navy. The lack of information on the effect on the intensity of gerontological changes of TRB storage conditions for torpedoes, temperature drops and humidity of the environment can lead to additional errors in the proposed model of the life cycle of TRB, and, consequently, to corrections of firing.

8. Conclusions

1. The regularities of the influence of changes in the ETC of silver-zinc TRB of long storage periods on the main TTC of the CET-65 torpedo have been revealed. It is established that under their action at a storage period of TRB at 22 years, the TRB capacity decreases by 20 %, and the discharge time drops to 10.8 min, which does not correspond to the nominal TTC (13 min). This leads to a decrease in the range of the torpedo by 17 %, which corresponds to 2.5 km. Also, the TRB voltage is reduced by 18 %, which corresponds to 40 V. With this value of the TRB voltage, the torpedo speed will decrease by 20 %, which corresponds to 4 m/s (8 knots).

2. A life-cycle model of silver-zinc TRB has been developed, which allows predicting the changes in the basic

ETC of TRB from the storage time, and also predicting the effect of these changes on the speed and range of the torpedo. This in turn allows to introduce corrections into the initial data of torpedo firing during their combat use, taking into account the gerontological changes in the TRB elements. Correction of the developed model of the TRB life cycle was made, taking into account the limitation related to the operating conditions of the onboard automatic guidance system, for normal operation of which a voltage drop of not more than 10 % is allowed. Taking into account this limitation, it is established that the period of expedient operation of silver-zinc TRB should not exceed 16 years.

3. On the basis of a comparative analysis of the accuracy of methods for solving the main task of the torpedo encounter, the effect of gerontological changes in the TRB power sources on the increase in the angle of the calculated point of the torpedo encounter with the target is determined. The value of this angle increases to 9.0° (by 23 %) compared to its nominal value of 6.9°.

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