Modernization Strategies for the Main Frame Structure of TEM2 Shunting Locomotives to Prolong Service Life

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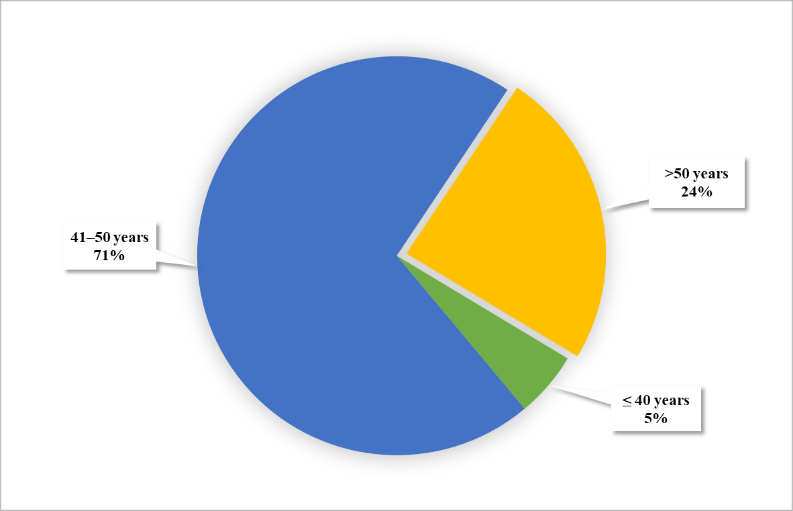
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**Abstract.** In this study, a structural analysis was conducted to assess the operational status of TEM2-type shunting locomotives that have been in use on Uzbekistan Railways for several decades. It was identified that approximately 24% of these locomotives have exceeded their normative service life of 50 years, as stipulated by national regulatory standards. Given the critical need to maintain safe and reliable operation, this article explores a modernization-based approach aimed at extending the service life of these aging locomotives. Mechanical degradation due to prolonged usage was addressed by employing ultrasonic testing techniques to measure the current thickness of frame components. A detailed finite element model of the locomotive frame was developed in SolidWorks to evaluate stress distribution and structural integrity. The assessment adhered to the criteria outlined in the GOST 34939 standard, which governs stress limits for locomotive structures. Preliminary results indicated that the stress levels in critical areas of the frame reached up to 158.2 MPa—significantly exceeding the maximum allowable limit of 141 MPa—thereby underscoring the necessity for structural reinforcement. To mitigate this issue, reinforcement elements were designed based on technical schematics and were installed via welding. Following reinforcement, stress values dropped to 133.2 MPa, and the safety factor improved from 2.8 to 3.0. This methodology has been practically implemented in the modernization of over 30 locomotives at the “O‘ztemiryo‘lmashta’mir” JSC repair facility. All welding procedures complied with national technical standards. The findings demonstrate that the proposed modernization strategy effectively reduces internal stresses, enhances structural reliability, and provides a sustainable solution for extending the operational lifespan of outdated locomotive fleets.

**Keywords:** shunting locomotive, finite element analysis, service life extension, stress-strain state, stress concentration factor, strength reserve coefficient, main frame modernization, residual resource.

# Introduction

In recent years, reforms have been carried out in the Republic of Uzbekistan to modernize the railway transport infrastructure, to construct new railway lines, and to technically and technologically update the existing systems. Within the framework of these reforms, more than 70 new modern mainline locomotives manufactured by the CRRC company of the People’s Republic of China were purchased by “O‘zbekiston temir yo‘llari” JSC. However, due to the fact that new shunting locomotives have not been purchased during the last 30 years, most of the shunting locomotives in the existing fleet have been in active operation for more than 40 years [1]. The lack of investment funds for the purchase of new shunting locomotives and the increase in transportation volume make the issue of effective and long-term use of these shunting locomotives an even more urgent problem. In order to study this problem in detail, as of 2025, the statistical data provided by the Locomotive Operation Department and locomotive depots within the structure of “O‘zbekiston temir yo‘llari” JSC were analyzed. Figure 1 below shows the classification of TEM2-type locomotives by year of manufacture. With the help of these analyses, the distribution of locomotives by year of production was studied, which makes it possible to assess their technical condition, ensure operational safety, and implement a strategy for the phased renewal of the locomotive fleet.



**FIGURE 1.** Distribution of TEM2-type locomotives in the locomotive fleet of “O‘zbekiston temir yo‘llari” JSC by year of manufacture

According to the analysis of Figure 1 above, currently, based on the distribution of TEM2-type shunting locomotives in the locomotive fleet of “O‘zbekiston temir yo‘llari” JSC by year of manufacture, 5 percent of the locomotives are up to 40 years old, 71 percent are in the range of 41–50 years, and 24 percent have been in use for more than 50 years [2]. These indicators clearly show that a large part of the existing rolling stock has far exceeded the initial service life limit. The direct correlation between the year of manufacture and the number of units in operation confirms the high dependence on outdated, yet still operational, locomotives in the railway network. The graphical distribution of the service life of TEM2-type locomotives visually reflects the degree of structural aging and mechanical fatigue throughout the entire fleet. This information is of great importance in the development of maintenance plans and identification of modernization strategies to ensure the reliable and efficient operation of the railway infrastructure.

The service life of locomotives is usually determined by the manufacturing companies, depending on the type of locomotive. In addition, according to GOST 31428 standard, in the general technical requirements developed for “Shunting diesel locomotives with electric transmission” (specifically in clause 4.8), their reliability is defined to be up to 40 years [3]. In the Republic of Uzbekistan, based on existing normative-technical and regulatory documents, the service life of TEM2-type shunting locomotives is set at 50 years.

However, one of the pressing issues is the determination of the useful remaining safe service life of locomotives whose designated service life has expired, taking into account all factors affecting their operational longevity. To achieve this, relevant scientific research must be carried out.

The procedure for determining the service life and evaluating the remaining resource of locomotives is clearly stated in the normative document P.15.01-2009 titled “Locomotives. Procedure for extending the designated service life” [4]. Clause 3 of this document emphasizes that the issue of extending the service life is determined based on the resources of the main structural components of the locomotive — that is, the main frame, bogie frame, and load-bearing elements.

# Literature review

The durability and strength of the frame structures of traction rolling stock, in the context of limited investment funds for renewing the locomotive fleets whose service life is expiring and purchasing new railway rolling stock, has become the main subject of engineering scientific research. The main direction of recent research is the application of finite element analysis and multibody dynamics methods to evaluate and extend the service life of railway rolling stock frame structures under long-term use, fatigue, and the effect of repeated failures. Below are presented the analyses of scientific articles conducted by researchers in this direction.

Do and colleagues [5] (2021) proposed a hybrid approach to assess the fatigue of wagon bogie frames, taking into account actual loading conditions in modern engineering software. Their results showed the importance of dynamic forces in predicting the actual service life of the bogie frame structure within the framework of national standards. Xiu et al. [6] (2021) expanded the methodology by taking into account the traction and braking loads of railway rolling stock, which revealed that longitudinal forces significantly accelerate fatigue damage compared to only vertical loads.

A number of studies paid special attention to assessing the effect of welding works on the durability of locomotive frame structures during repair periods. Seo et al. [7] (2023), using the thermal model of rolling stock, analyzed the effect of multiple welded repairs on the fatigue strength of the structure, concluding that repeated welding’s can lead to the accumulation of residual stress in the structure, and as a result, reduce the service life of the frame.

Lan and Song [8] (2021) presented a methodology for simulating the fatigue of rolling stock frame structures using the Miner’s rule, which makes it possible to predict the initiation of fatigue cracks in bogie frames at an early stage. Oganyan et al. [9] (2021) emphasized the necessity of evaluating the useful remaining service life of locomotives whose service period has expired in order to ensure the operational safety of railway rolling stock, especially for locomotives that have been operating beyond the service period defined by the manufacturer. As a result of long-term operation, more advanced approaches to fatigue modeling were introduced to take into account structural damage.

Based on the results of these studies, the current research is aimed at assessing the static strength of the main frame of the TEM2 shunting locomotive using a full-scale finite element model in accordance with the requirements of GOST 34939 [10]. Such an approach makes it possible to evaluate the fatigue of the structure through the stress-strain state and strength reserve coefficient, and directly contributes to the development of modernization strategies aimed at extending the service life of the locomotive.

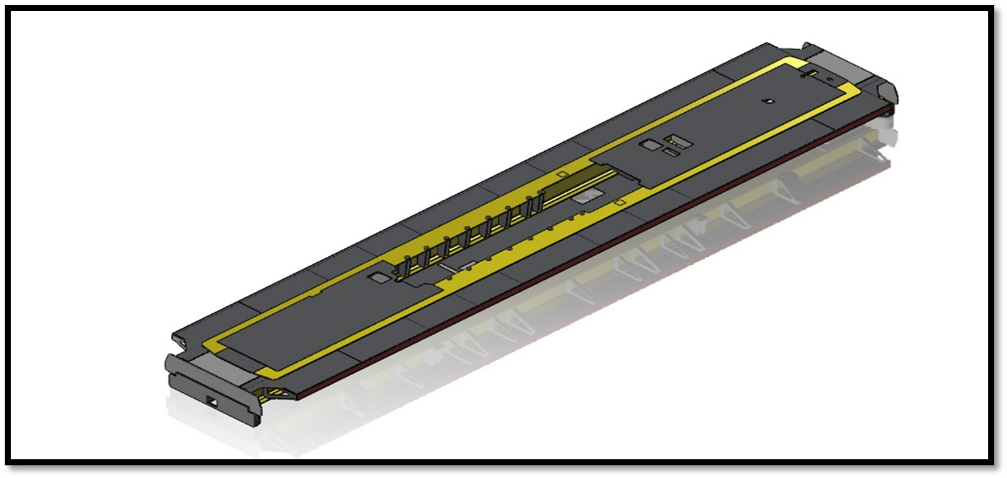
The research conducted by scientists from Tashkent State Transport University and Lanzhou Jiaotong University in Lanzhou, China, is aimed at increasing the efficiency of railway transport systems, ensuring operational safety, and improving the reliability characteristics of locomotives [11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23]. Their scientific research played a decisive role in the development of a methodology for assessing and extending the service life of railway rolling stock based on its residual resource. They also achieved significant results in modeling, characterizing, and controlling vibration-based railway transport systems. This served to further enrich the scientific foundations for improving the performance and durability of railway rolling stock.

# Materials and Methods

## Object Of Research

In this article, the object of the research is focused on the strength analysis of the main frame structure of the TEM2-type shunting locomotive, and taking into account the locations of high load formation in the structures, scientifically grounded technical solutions have been developed for modernization works aimed at increasing their durability and strength.

The metal thicknesses in the main frame structures of TEM2-type shunting locomotives No. 473, belonging to the “Termez” locomotive depot of “O‘zbekiston temir yo‘llari” JSC, and No. 784, owned by the “Navoi Uranium” State Enterprise, which have been in service for over 50 years, were measured using the ultrasonic method, taking into account evenly distributed corrosion factors. The inspection was carried out using the UT-1M type ultrasonic thickness gauge device, which had been previously calibrated. As a result of in-depth analyses, the most corroded areas in the main frames were identified, and the level of material corrosion in those sections was evaluated. Based on this data, a finite element model of the main frames was developed in a modern engineering software environment, closely approximating their actual condition. Figure 2 below presents the three-dimensional computational model of the main frame structure.



**FIGURE 2.** Three-dimensional computational model of the main frame structure of the TEM2 locomotive

The strength tests of the computational model of the main frame structure were carried out in accordance with the requirements of GOST 34939 [10]. This GOST specifies the permissible stress limits for calculation modes of locomotive frame structures, presented in Table 1.

**TABLE 1.** Allowable stresses for the main frame and bogie frame components of locomotives (as per GOST 34939)

|  |  |  |  |
| --- | --- | --- | --- |
| **Calculation modes** | | **Permissible stress for locomotive frame structures** | |
| **Main frame** | **Bogie frame** |
| **Mode I** | Ia | 0,9 σ0,2 | |
| Ib | 0,9 σ0,2 | 0,9 σ0,2 |
| **Mode II** |  | 0,6 σ0,2 | |
| **Mode III** |  | 0,6 σ0,2 | |
| **Mode IV** |  | 0,9 σ0,2 | |

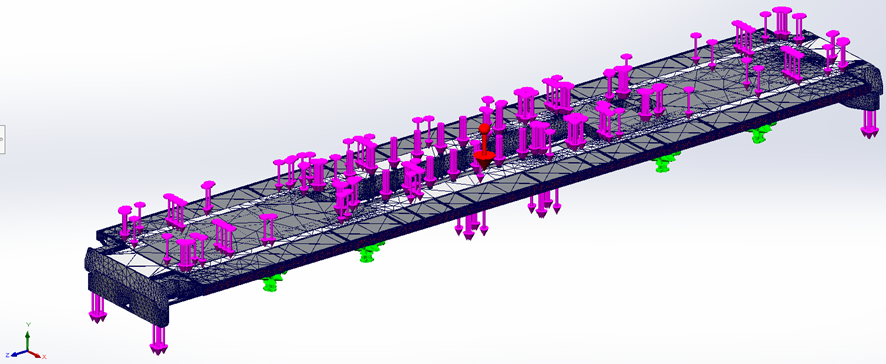
It was necessary to assess the current mechanical properties of the frame construction materials of TEM2-type shunting locomotives, which have been in service for more than 50 years as a result of long-term operation. The testing of samples taken from the frame structure of this type of expired service life locomotive was carried out in the testing laboratory of “O‘ztemiryo‘lmashta’mir” JSC, which holds accreditation certificate No. ML.0439. Based on Test Reports No. 43 and No. 15 dated 21.02.2024 by this laboratory, the values of the yield strength, ultimate tensile strength, relative elongation, and hardness of the material were determined. The test results show that the mechanical properties of the material used in the frame structure meet the requirements defined in the normative technical documents. Especially, if the yield strength of the material is not lower than the prescribed normative values, it can be concluded that the mechanical integrity of this material has been preserved. This, in turn, serves as a reliable basis for extending the residual service life of the locomotive or increasing its operational resource.

The III-design regime of the GOST 34939 standard is intended to account for static and dynamic loads arising during movement of the locomotive up to its design (i.e., maximum project-specified) speed along straight railway sections at various speeds. In this regime, the vertical, horizontal, and longitudinal forces acting on the frame structure during the actual operation of the train and the resulting stress-strain states are analyzed. Through this, it becomes possible to assess the strength and reliability of the main structural elements of the locomotive. The calculations performed in this regime are primarily focused on simulating the movement over straight and even railway sections and are of great importance in identifying the most heavily loaded areas of the main frames and assessing their strength condition.

The main frame structure and frame parts are manufactured by welding using St3 grade steel. According to its mechanical properties, the yield strength of the material is σ₀.₂ = 235 MPa. The strength calculation works were carried out based on the III Regime, and in this case, the permissible stress should not exceed 141 MPa. The calculation processes of the main frame structure were carried out based on the real operational conditions of the TEM2-type shunting locomotive and current normative requirements. The general stresses obtained as a result of the calculations must not exceed the permissible values specified in Table 1 for the corresponding calculation regimes.

# Results and Discussion

The finite element numerical model of the main frame of the TEM2-type shunting locomotive, developed using the SOLIDWORKS engineering software, consists of 773,241 finite elements and 1,564,562 nodes. The detailed mesh created for the model represents a fine-element mesh intended for solid bodies. This mesh structure was generated using a surface-based partitioning method, taking into account geometric irregularities, curves, and angles. The resulting mesh structure is shown in Figure 3.



**FIGURE 3.** The loading scheme of the finite element model of the locomotive main frame

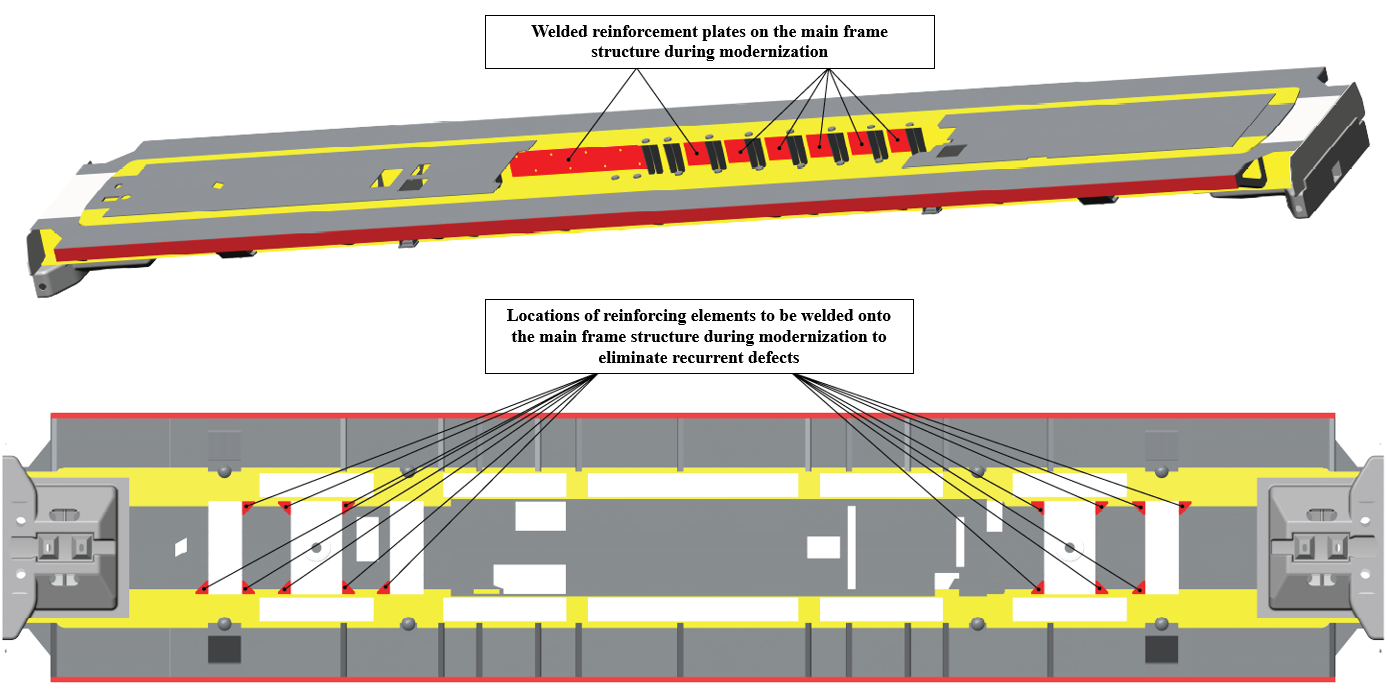
The results of the strength analysis of the main frame structure's computational model are presented in Figure 4, which shows the stress-strain state of the frame under static loading and evaluates the safety factor. Based on the analysis results, the highly loaded areas of the locomotive frame were identified. Such analysis serves to justify reinforcement measures for the main frame structure, extend its service life, and ensure safe operation.

|  |
| --- |
| а) |
|  |
| b) |
|  |

**FIGURE 4.** Strength analysis of the main frame; a) stress–strain state, b) safety factor

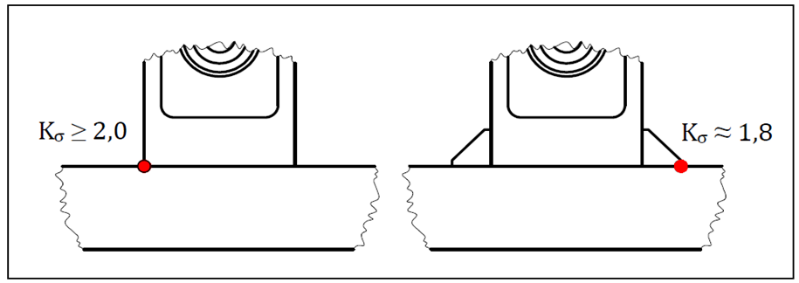
Based on the results of the strength analysis, the highly loaded areas in the main frame of the TEM2-type shunting locomotive were identified. The calculation results indicated the relatively weak zones of the frame in terms of strength and the high values of the stress-strain state occurring in them.

Taking into account all the above-mentioned factors, during the repair process of TEM2-type shunting locomotives that have been in service for more than 50 years in Uzbekistan Railways, the necessity arose to carry out reinforcement work in areas with a high stress-strain state in order to increase the strength of the main frames. For this purpose, regulatory-technical documents and design documentation aimed at ensuring the reliability of the main frame structure and extending its service life were developed. Figure 5 below shows the locations of the main frame structure of the TEM2-type locomotive, which has been in service for more than 50 years, that require reinforcement.



**FIGURE 5.** Reinforcement points of the main frame structure

During the modernization process, reinforcing elements were welded onto the main frame structure in order to eliminate the recurring defects that were identified. The results of evaluating the effect of these constructive technical solutions on the values of the stress concentration coefficient are presented in Figure 6 below.



**FIGURE 6.** Reduction of recurring defects in the main frame structure and change in the stress concentration coefficient during the modernization process

Shunting locomotives of the TEM2 type with more than 50 years of service life — No. 473, 846, 932, 1109, 1105, 2159, 2170, 2306, 2308, 2309, 2310, 2393, and 2557, which belong to “O‘zbekiston temir yo‘llari” JSC, as well as No. 784 belonging to the “Navoi Uranium” State Enterprise — underwent modernization of their main frame structures at the “O‘ztemiryo‘lmashta’mir” JSC enterprise based on the original design documentation. Figure 7 below shows the welded state of the reinforcing plates on the main frame structure according to the design drawings.

|  |  |
| --- | --- |
|  |  |

**FIGURE 7.** Welded reinforcing plates on the areas of the main frame structure to be strengthened

The main goal of the frame structure reinforcement works is to reduce the values of the stress-strain state by decreasing the value of the stress concentration zone coefficient in relatively weak areas of the structure, to increase the reserve coefficient, and to ensure the operational reliability of locomotives whose service life has expired. In the following Figure 8, the results of the strength calculation considering the reinforcing elements aimed at increasing the strength of the main frame structure are presented.

|  |
| --- |
| a) |
|  |
| b) |
|  |

**FIGURE 8.** Strength analysis of the main frame considering the reinforcing elements for structural enhancement:   
a) stress–strain state, b) safety factor

According to the results of the FEA analysis, the strength analyses carried out on the main frame of the shunting locomotive whose service life has ended and the comparative analysis on the effectiveness of modernization technologies are presented in Table 2. It shows that the technical solutions of modernization performed for the main frame of the locomotive are structurally justified and that their impact on operational safety is positive.

**TABLE 2.** Strength Analysis Results of the Main Frame

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Structural condition of the main frame** | **Nominal stress, MPa** | **Stress concentration factor** | **Stress considering the stress concentration factor, MPa** | **Allowable stress, MPa** | **Strength safety factor** |
| Before reinforcement | 79,1 | 2,0 | 158,2 | 141 | 2,8 |
| After reinforcement | 74 | 1,8 | 133,2 | 141 | 3,0 |

As can be interpreted from the data in Table 2, prior to the implementation of reinforcement measures, the main frame exhibited a strength reserve factor of 2.8. The nominal stress was determined to be 79.1 MPa, while the actual stress, accounting for the stress concentration factor, reached 158.2 MPa. Since this value exceeds the allowable limit of 141 MPa, it implies reduced durability and constraints on the frame’s operational reliability. Following structural upgrades to the main frame, the strength reserve factor increased to 3.0, the nominal stress dropped to 74 MPa, and the actual stress was reduced to 133.2 MPa, remaining safely below the permissible threshold (133.2 < 141 MPa). This outcome not only validates the structural integrity for continued safe use, but also highlights the feasibility of extending the service life of shunting locomotives that have operated for over 50 years [24].

# Conclusion

In this scientific research, the strength of the main frame structure of TEM2-type shunting locomotives, which have been in operation for more than 50 years, was comprehensively evaluated by modeling using the finite element method in accordance with the requirements of GOST 34939. Taking into account the uniformly distributed corrosion factor formed as a result of long-term use, the full-volume 3D digital model of the main frame structure was created in the SolidWorks Simulation software based on the measured thickness using ultrasonic methods and the actual geometric changes caused by corrosion. An analysis of the stress-strain state was carried out under the most severe operating mode (Mode III).

According to the modeling results, it was determined that in some areas of the main frame structure, before modernization, the stress values exceeded the permissible limit (158.2 MPa > 141 MPa), which indicates a reduction in the safety margin of the structure and the necessity of modernization. After the implementation of additional modernization works, the maximum stresses were reduced to 133.2 MPa, which is below the standard permissible limit. As a result, the safety factor increased from 2.8 to 3.0, confirming the effectiveness of the applied modernization measures. A welding instruction for reinforcing plates (overlays) of the TEM2 locomotive’s main frame was developed, and the strength of the structure was ensured with a reduction of maximum stresses by 10–15%. In order to increase the reliability and strengthen the most heavily loaded areas of the frame structure, scientifically based normative-technical and design documents were developed and applied to extend the service life of TEM2 locomotives.A methodology for assessing the technical condition of the frame structures of TEM2-type locomotives operating on the railway network of the Republic of Uzbekistan, determining their residual life, and extending their service life beyond 50 years was developed and implemented at the “O‘ztemiryo‘lmashta’mir” JSC enterprise. As a result, the safe operational period of TEM2-type shunting locomotives with inventory numbers No. 473, 846, 932, 1105, 1109, 2159, 2170, 2306, 2308, 2309, 2310, 2393, and 2557, which belong to “O‘zbekiston temir yo‘llari” JSC, and No. 784 and 1526, which are under the balance of the Navoi Mining and Metallurgical Combine, was successfully extended up to 57 years.

This modernization serves as a technical solution for assessing the remaining service life and extending the useful safe operation period of locomotives nearing the end of their life in conditions where attracting investment funds is difficult. It contributes to ensuring the sustainable operation of railway transport in Uzbekistan.

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