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ҰЛТТЫҚ ҒЫЛЫМ АКАДЕМИЯСЫ» РҚБ
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# RESEARCH OF THE STRESS-STRAIN STATE OF THE BUCKET ELEVATOR NODE CHAIN

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**Abstract.** One of the directions of development of the exploration, oil and gas and mining industries is to increase the productivity of equipment by increasing the technical level and production efficiency. Aluminum production is one of the fastest growing industries. In search of new directions for the development of aluminum production technology, there are numerous studies aimed at the widespread industrial introduction and modernization of electrolyzers. The alumina acceptance unit of the bucket elevator at the electrolysis plant provides for the transportation of alumina, which gets into the moving parts of the elevator chain, which leads to their jamming and premature accelerated wear of the connecting bushings. Based on computer modeling using the APM FEM program, a study of the stress-strain state of two variants was performed: plate and anchor chains with the application of acting loads, namely, the weight of the bucket with the load and the chain tension. As a result of statistical calculation, the equivalent Mises stress decreased by 2.44 times and the safety margin coefficient increased by 2.5 times. Thus, the replacement of the plate chain with the anchor of the alumina acceptance unit of the bucket elevator based on studies of the stress-strain state will increase the service life by 2.5 times and reduce the cost of preventive maintenance.

**Keywords:** productivity, service life, bucket elevator, chain, stress-strain state, modeling

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## ШӨМІШ ЭЛЕВАТОРЫНЫҢ ТҮЙІН ТІЗБЕГІНІҢ КЕРНЕУЛІ ДЕФОРМАЦИЯЛАНҒАН КҮЙІН ЗЕРТТЕУ

**Аннотация.** Геологиялық барлау, мұнай-газ және тау-кен өндіру салаларын дамыту бағыттарының бірі өндірістің техникалық деңгейі мен тиімділігін арттыру негізінде жабдықтардың өнімділігін арттыру болып табылады. Алюминий өндірісі ең жылдам дамып келе жатқан салаларға жатады. Алюминий өндіру техникасын дамытудың жаңа бағыттарын іздеуде электролизерлерді кеңінен өнеркәсіптік енгізу мен жаңғыртуға бағытталған көптеген зерттеулер бар. Электролиз зауытындағы шөміш элеваторының глиноземді қабылдау қондырғысы элеваторлар тізбегінің жылжымалы бөліктеріне түсетін глиноземді тасымалдауды қарастырады, бұл олардың кептелуіне және байланыстырушы втулкалардың мерзімінен бұрын тез тозуына әкеледі. APM FEM бағдарламасын қолдана отырып, компьютерлік модельдеу негізінде екі нұсқаның кернеулі-деформацияланған күйін зерттеу жүргізілді: жұмыс жүктемелерін қолдана отырып, пластиналық және якорь тізбектері, атап айтқанда шелектің салмағы және тізбектің керілуі. Статистикалық есептеу нәтижесінде Мизес бойынша эквивалентті кернеу 2,44 есе азайды және беріктік бойынша қор коэффициенті 2,5 есе өсті. Осылайша, кернеулі деформацияланған жағдайды зерттеу негізінде пластиналық тізбекті Шелек элеваторының алюминий тотығын қабылдау қондырғысына ауыстыру қызмет ету мерзімін 2,5 есеге арттырады және шығындарды азайтады.

**Түйін сөздер:** өнімділік, қызмет ету мерзімі, шөміш элеваторы, тізбек, кернеулі деформацияланған күй, модельдеу

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# ИССЛЕДОВАНИЕ НАПРЯЖЕННО-ДЕФОРМИРОВАННОГО СОСТОЯНИЯ ЦЕПИ УЗЛА КОВШОВОГО ЭЛЕВАТОРА

**Аннотация.** Одним из направлений развития геологоразведочной, нефтегазовой и горнодобывающей отраслей является повышение производительности оборудования на основе улучшения технического уровня и эффективности производства. Производство алюминия относится к наиболее быстро развивающимся отраслям промышленности. В поисках новых направлений развития техники производства алюминия имеются многочисленные исследования, направленные на широкое промышленное внедрение и модернизация электролизёров. Узел приёмки глинозёма ковшового элеватора на электролизном заводе предусматривает транспортировку глинозёма, который попадает в подвижные части цепи элеваторов, что приводит к их заклиниванию и преждевременному ускоренному износу соединительных втулок. На основании компьютерного моделирования с применением программы APM FEM выполнено исследование напряженно-деформированного состояния двух вариантов: пластинчатой и якорной цепей с приложением действующих нагрузок, а именно масса ковша с грузом и натяжение цепи. В результате статистического расчёта уменьшилось эквивалентное напряжение по Мизесу в 2,44 раза и увеличился коэффициент запаса прочности в 2,5 раза. Таким образом, замена пластинчатой цепи на якорную узла приёмки глинозёма ковшового элеватора на основании исследований напряженно-деформированного состояния повысит срок эксплуатации в 2,5 раза и уменьшит затраты на планово-предупредительный ремонт.

**Ключевые слова:** производительность, срок эксплуатации, ковшовый элеватор, цепь, напряженно-деформированное состояние, моделирование

## Introduction

Aluminum production is one of the fastest growing industries. In the aluminum industry, as in other sectors of the economy, the growth of metal production is carried out on the basis of increasing the technical level and production efficiency.

Currently, aluminum and its alloys are used in almost all branches of modern technology. The most important consumption of aluminum and its alloys is the aviation and automotive industries, railway and water transport, mechanical engineering, electrical industry and instrumentation, industrial and civil construction, chemical industry, production of consumer goods.

In search of new trends in technology aluminium production made a significant amount of design and experimental-industrial works aimed at a wide industrial introduction of powerful cells (Chalykh et. al., 2005: 6; Glushkevich et. al., 2009: 4; Ma et. al, 2019: 4).

Aluminum has a lot of properties that make it one of the most used materials in the world. It is widely distributed in nature, taking the first place among metals. It would seem that there should be no difficulties with its production. But the high chemical activity of the metal leads to the fact that it cannot be found in its pure form, and it is difficult, energy–intensive and costly to produce. The production of aluminum from all minerals containing it is expensive and unprofitable. It is extracted from bauxite, which contain up to 50 % aluminum oxides and lie directly on the surface of the earth in significant masses.

Aluminum ores have a rather complex chemical composition. They contain alumina in the amount of 30–70 % of the total weight, silica, which can be up to 20%, iron oxide in the range from 2 to 50 %, titanium (up to 10 %).

Alumina, which is aluminum oxide, consists of hydroxides, corundum and kaolinite. Recently, aluminum oxides have been obtained from nephelins, which also contain sodium, potassium, silicon, and alunite oxides. To produce 1 ton of pure aluminum, about two tons of alumina are needed, which, in turn, is obtained from about 4.5 tons of bauxite.

The origin of production Danish physicist H. Oersted was the first to isolate aluminum in its free form in 1825. The chemical reaction took place with aluminum chloride and potassium amalgam, instead of which two years later the German chemist Wehler used metallic potassium.

Potassium is a fairly expensive material, so in the industrial production of aluminum, the Frenchman St. Clair Deville used sodium instead of potassium in 1854, an element much cheaper and resistant double chloride of aluminum and sodium. N.N. Beketov was able to displace aluminum from molten cryolite with magnesium. In the late eighties of the same century, this chemical reaction was used by the Germans at the first aluminum plant.

In the second half of the XVIII century, about 20 tons of pure metal were obtained by chemical methods. It was very expensive aluminum. The production of aluminum by electrolysis originated in 1886, when almost identical patent applications were filed simultaneously by the founders of this method, the American scientist Ch. Hall and the Frenchman P. Eru. They proposed to dissolve alumina in molten cryolite, and then obtain aluminum by electrolysis.

This was the beginning of the aluminum industry, which has become one of the largest branches of metallurgy for more than a century. The process consists of three stages.

The first of the aluminum ores, whether it is bauxite or nepheline, produces alumina — aluminum oxide $Al_2O_3$. Then industrial aluminum is isolated from the oxide with a degree of purification of 99.5 %, which is not enough for some purposes. Therefore, aluminum is refined at the last stage. Aluminum production is completed by its purification to 99.99 %.

**Research materials and methods**

There are three methods for obtaining aluminum oxide from ores: acidic; electrolytic; alkaline (Meng 2000: 4; Perez-Aparicio et. al., 2014: 16).

The latter method is the most common, developed in the same XVIII century, but since then has been repeatedly modified and significantly improved, used for processing of high-grade bauxite. This is how about 85% of alumina is obtained.

The technological process of aluminum electrolysis includes the following elements. Electrolysis housing, storage, supply and distribution of alumina, laying and replacement of lining, universal technological crane, foundry, computer control system, etc.

The basis of the technological process of obtaining primary aluminum at the Pavlodar electrolysis plant is the electrolysis of cryolite alumina melt.

Electrolysis is carried out in electrolyzers. The electrolyzer consists of cathode and anode devices. The cathode device is a metal casing lined with coal hearths and side blocks. Burnt anodes are suspended from above in the electrolyzer, which are fixed to the anode device.

The fired anodes are a mixture of coke and pitch binder, pre-fired at a temperature of approximately 1100 °C. The cathode is molten aluminum.

The electrolyte is a molten cryolite ($Na_3AlF_6$) with a small excess of $AlF_3$, in which alumina ($Al_2O_3$) is dissolved. Electrolysis is carried out at variable concentrations of alumina from about 1 to 8 % by weight. The process temperature is close to the melting point of this mixture and is 950–960 ° C. Molten aluminum at the electrolysis temperature is heavier than the electrolyte and is located at the bottom of the electrolyzer.

In essence, the electrolyte is not consumed during electrolysis, but certain losses still occur, mainly due to evaporation.

The electrolyte in modern electrolyzers usually contains the following components:

- from 6 to 13 % aluminum fluoride ($AlF_3$).
- from 4 to 6 % calcium fluoride ($CaF_2$).
- from 2 to 4 % alumina ($Al_2O_3$).

The depth of the electrolyte layer in the electrolyzer does not change any significantly, and is usually about 20 cm. The interpolar distance, in other words, the vertical distance between the bottom of the anode and the surface of the liquid metal layer is usually from 4 to 5 cm. Thus, in addition to its main functions of being a solvent for alumina and contributing to its electrolytic decomposition with the formation of aluminum, the electrolyte provides a physical separation between metallic aluminum formed at the cathode and carbon dioxide gas released at the anode.

It is important to maintain the concentration of alumina ($Al_2O_3$) in the electrolyte at a level of 2 to 4 % by weight. Too low concentration of alumina, caused by insufficient loading, can lead to an anodic effect, which disrupts the normal course of the electrolysis process, causing an increase in voltage in the electrolyzer. In this case, electrolytic decomposition of the fluoride compounds of the electrolyte occurs, and an electrically insulating layer of gas is formed under the anode, which increases the electrical resistance and, consequently, the voltage in the electrolyzer. The consequences of the anode effect are significant disturbances of the thermal balance in the electrolyzer, an increase in fluoride emissions, a decrease in the current and electricity utilization factor.

Thus, theoretically, only alumina and carbon of the anode are consumed for the electrolysis process, as well as electricity necessary not only for the electrolytic process — the decomposition of alumina, but also to maintain a high operating temperature. Practically, a certain amount of fluoride salts is also consumed, which evaporate and are absorbed into the lining. To maintain the required electrolyte composition, aluminum fluoride must be periodically injected into the electrolyzer.

Fluoride salts and alumina are supplied to the electrolyzers as raw materials. In the process of electrolysis, burnt anodes and electricity are consumed.It is necessary to achieve the maximum service life of the bath with the quantitative production of high-purity aluminum, i.e. also to achieve a high current output.

The amount of aluminum $P_т$ that can theoretically be obtained in the electrolysis process (Korvatsky et. al., 2008: 8) for a certain period of time *t*, determined by Faraday's law:

$$P_{Т} = I \times t \times q$$

where $P_т$ is the theoretical amount of aluminum, kg;

*I* – current strength, A;

*t* – time, h;

q is the electrochemical equivalent of aluminum, 0.336 g/(AЧ · h).

In practice, due to current leaks and secondary processes (in particular, the dissolution of aluminum in the electrolyte and its subsequent oxidation by anode gases), the amount of aluminum produced by the $P_{пр}$ is always less than this value. The ratio of the amount of metal actually obtained during electrolysis to its theoretically expected amount over the same time is called the current output.

Authors (Yugay et. al., 2022: 4; Chalykh et. al., 2005: 6) evaluate the current output losses on baths with annealed anodes:

- reverse reaction between metal and $CO_2$ – 3–5 %;
- other reactions involving metal (with oxygen, carbon, with electrolyte components followed by evaporation, etc.) up to 1 %;
- electronic conductivity, short circuits, shunting up to 2 %;
- other losses up to 1 %.

According to this indicator, the quality of the work of the electrolysis shop, housing or electrolyzer is judged. In practice, the current output, depending on the type of electrolyzer and its power, is 88–96 %.

Increasing the current output is important because it reduces energy consumption and increases labor productivity.

Upon reaching full design capacity and mastering the guaranteed technological parameters, the production volume of the Pavlodar Electrolysis Plant will reach 300,000 tons of primary aluminum per year. The entire volume of primary aluminum produced, thanks to the modern technology and design of the electrolyzers used with burnt anodes at a current of 320 kA, will belong to the category of the highest quality with the content of the main component of aluminum 99.7 ... 99.8 %.

The technical level of primary aluminum produced is reflected by the level of price quotations on the London Metal Exchange. For primary aluminum with a content of 99.7 ... 99.8 % of the main component, the maximum value of quotations is set.

Thus, insignificant amounts of primary A7 grade aluminum are obtained. As a result of uncharacteristic violations of modern plants in the technology of service or the quality of incoming raw materials and materials, short periods of reduction in the grade of primary aluminum are possible, but in the total volume of production, the grade level is maintained at least A7.

Currently, there are three main types of electrolysis baths for the production of aluminum: electrolyzers with a self-firing anode with a side current supply, electrolyzers with a self-firing anode with an upper current supply and electrolyzers with pre-fired anodes.

The development of the design of aluminum electrolyzers was mainly along the way of increasing their capacity to 2475 kg / day and service life from 600–800 days to 2500–3000 days to due to an increase in current strength from 50–60 kA to 300–325 kA (table 1).

Table 1 – Technical parameters of electrolyzers

| Parameters | Until 2000 year | After 2000 year |
|---|---|---|
| 1. Current strength, kA | 50–60 | 300–325 |
| 2. "Operating time" of metal, kg/day | 385 | 2475 |
| 3. Electricity consumption, kW h/kg | 18,5–19,0 | 12,9–13,5 |
| 4. The ratio of the cathode and anode areas | 0,55 | 0,90 |
| 5. Man-hours per ton of aluminum | 5–8 | 1,7 |
| 6. Service life, days | 600–800 | 2500–3000 |

As you can see, the breakthrough was enormous, primarily due to the transition to better types of electrolyzers.

Currently, industrial series of electrolyzers with self-igniting anodes and a side current supply with a current strength from 60 to 170 kA are operating. The anode current density of the electrolyzers of this system is 0.7–1 A / cm2, the power consumption is from 14.5 to 22 kЧ· Wh / kg of aluminum.

**Results**

The alumina acceptance unit includes: two metal silos with a volume of 1000 $m^3$ each, with a diameter of 12 m; an unheated silo room with a plan size of 10 ×40 m; an unheated silo room with a plan size of 10×52 m; an unheated shelter of wagons with a plan size of 6×52 m; a heated operator room; a heated point heating.

Currently, the alumina required for the electrolysis production of aluminum at the Kazakhstan Electrolysis Plant is supplied from the Pavlodar aluminum plant by cement trucks.

The alumina acceptance unit at the electrolysis plant provides for the transportation of alumina to silos from hopper cars using elevators. The main indicator of the operability of the acceptance node is the coefficient of technical readiness of the equipment and is included in the frequency of scheduled preventive repairs.After commissioning of the alumina acceptance unit and to the present time, the repair services of the plant have faced the problem of frequent removal of elevators for repair, the main reason of which is the wear of the plate chain conveyor and the tensioning system (Abishev et. al., 2021: 7; Glushkevich et. al., 2009: 4; Zhang et. al., 2022: 1).

The reason for wear is the transported raw material – alumina, which has strong abrasive properties in its structure. In addition, the fine fraction of alumina and its fluidity also serves to accelerate the wear of the main components of the elevator.

The main composition of the chain bucket elevator consists of:

- tension shoe with a height of 2660 mm;
- drive head;
- six linear boxes with a height of 2020 mm;
- four boxes with chain guides with a height of 2020 mm;
- two repair boxes with inspection hatches with a height of 2020 mm;
- a shortened box with a height of 664 mm;
- elevator chains with buckets 60.16 m long;
- the removed elevator drive.

The elevator chain consists of:

- two traction plate bushing-roller chains of type M315-2-160-1 according to STST 588-81 with a length of 60.16 m with riveted connecting strips;
- rounded buckets (188 pcs.) with a width of 400 mm and bucket fasteners on a chain.

Each bucket is attached to the chain by means of four M12×35 bolted joints with self-locking nuts with plastic inserts. The traction chain consists of segments that are connected to each other by means of connecting links.

Alumina during transportation gets into the moving parts of the elevator chain, which leads to their jamming and, as a consequence, premature accelerated wear of the connecting bushings, which must rotate when passing through the drive sprocket, tensioner, circling wheels. The jammed bushings tear off the fixed connecting axes, causing them to rotate and, as a result, there is friction between the axis and the connecting bar, the hole (wear) of the connecting bars increases, which ultimately threatens to break the entire chain of the elevator.

Plate chains consist of parallel plates connected pivotally by rollers located one from the other at a distance *t*, called the chain pitch. The elevator shelves consist of articulated beams of trough section and are attached to the chains with the help of fingers entering the holes of the bushings of plate chains.

A common disadvantage of plate chains is the small friction surface in the hinges, which causes high specific pressures, which are the cause of their wear. To reduce wear, hardened bushings are sometimes pressed into the eyelets of the hinge-plate chains. In addition to increasing wear resistance, this design of the chain allows it to be repaired by replacing the bushings.

According to the design and method of manufacture, chains are divided into welded, lamellar or articulated and special (cast ductile iron, etc.). A welded chain consists of oval mutually perpendicular links. This provides greater flexibility in all directions and allows the use of traction sprocket sprockets or drums of small diameters. Chains are made of steel bars of grades Steel2, Steel3 and steel 10. Parts with cracks, fractures, chips and other defects that reduce strength are not subject to restoration. Their number is usually small. The rollers and bushings of plate chains have one-sided wear and, in the absence of other defects, they can be reused with a 180° rotation relative to the hinge axis. At the same time, the steps of the links that have been lengthened due to the wear of these parts are restored. When the fit of the rollers and bushings in the plates is weakened, the strength of the joints can be restored by welding. It can be performed without disassembling the chain, excluding welding of bushings of the bushing-roller chain, which require disassembly into separate links. It is advisable to restore worn parts of traction plate chains of large sizes by surfacing, followed by mechanical and heat treatment. Simple articulated (non-tubular) conveyor chains are restored by surfacing holes.

**Discussion**

Modernization of the alumina acceptance unit of the bucket elevator consists mainly of replacing the plate chain with an anchor chain, in which there are no parts of rotation along the entire length of the chain.

This type of chains is widely used in cargo and traction devices. There are long-link and short-link chains.

The variety of types and high performance of round-link chains have made them popular and indispensable in many sectors of industry.

According to STST 228–79, anchor chains can be executed in two design versions and are made of three types:

1) normal strength – welded and forged from category 1a steel, calibers from 11 to 73 mm;

2) high strength – welded and forged from category 2a steel, calibers from 12.5 to 162 mm, cast from category 2b steel, calibers from 40 to 152 mm;

3) of particularly high strength – welded and forged from category 3a steel, calibers from 20.5 to 152 mm, cast from category 3b steel, calibers from 40 to 152 mm.

Computer modeling was performed using the APM FEM program (Donenbayev et. al., 2021: 6; Mussayev et. al., 2022: 13; Sherov et. al., 2021: 7; Sherov et. al., 2021: 8; Yin et al., 2021: 15) two variants: plate (option 1) and anchor (option 2) chains with the application of acting loads, namely the weight of the bucket with the load and the chain tension.

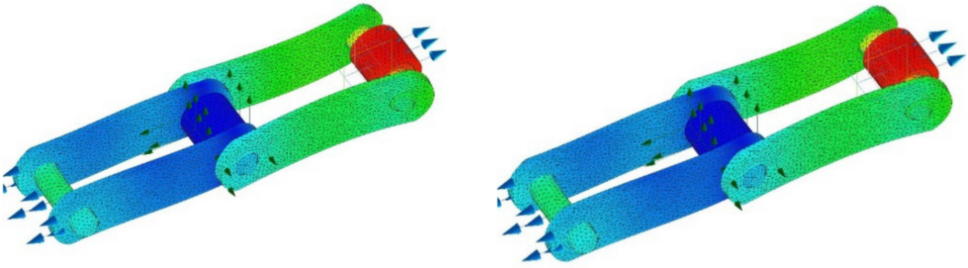
As a result of static calculation, the following were determined: equivalent stress by Mises; total linear displacement; coefficient of yield strength; coefficient of strength margin (Table 2).

Table 2 – Results of static calculation of plate (option 1) and anchor (option 2) chains

| Name | 1 option | | 2 option | |
|---|---|---|---|---|
| | Minimum value | Maximum value | Minimum value | Maximum value |
| Equivalent Mises voltage, MPa | 0,007 | 4,32 | 0,007 | 1,77 |
| Total linear displacement, mm | 0 | 0,0038 | 0 | 0,0001 |
| The coefficient of turnover margin | 55 | 31910 | 134 | 32850 |
| The coefficient of safety margin | 95 | 55673 | 234 | 57313 |

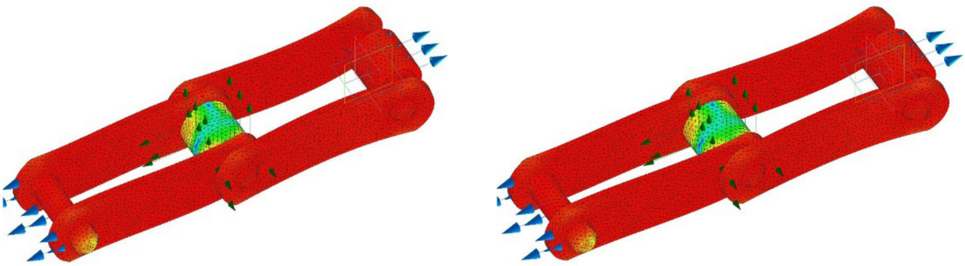
Figures 1 and 2 show maps of the results of statistical calculation of plate and anchor chains.

a) b)



Equivalent Mises voltage | Total linear displacement

c) d)

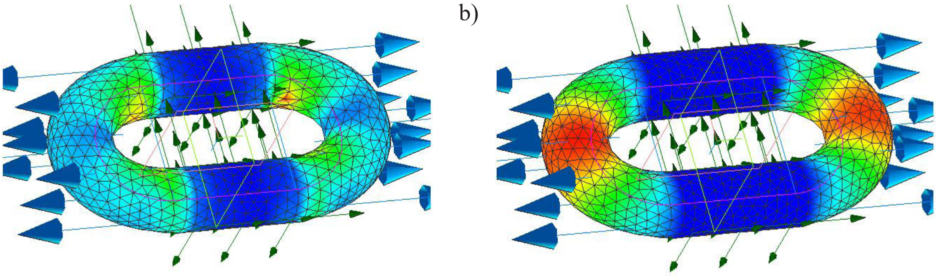


The coefficient of metal fluidity reserve | The coefficient of the margin of strength of the metal

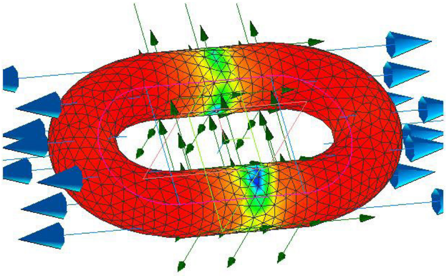
a – Equivalent Mises voltage; b – Total linear displacement; c – The coefficient of metal fluidity reserve; d – The coefficient of the margin of strength of the metal

Figure 1 – Map of the results of statistical calculation of the plate chain

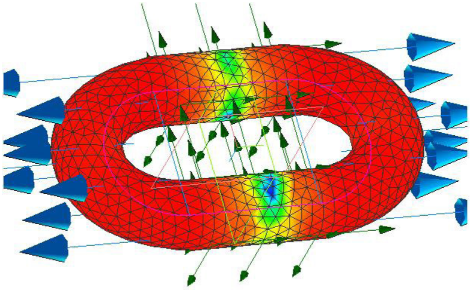
a) b)



Equivalent Mises voltage | Total linear displacement

c) 

The coefficient of metal fluidity reserve

d) 

The coefficient of the margin of strength of the metal

a – Equivalent Mises voltage; b – Total linear displacement; c – The coefficient of metal fluidity reserve; d – The coefficient of the margin of strength of the metal

Figure 2 – Map of the results of the statistical calculation of the anchor chain

Analysis of the results of statistical calculation showed that the equivalent Mises stress of the first option is 2.44 times less than the second, the total linear displacement is 38 times less than the second option relative to the first option, the yield strength coefficient of the second option is 2.4 times higher than the first, the strength margin coefficient of the second option is 2.5 times higher than the first, respectively, and the service life of the anchor the chain is 2.5 times higher than the plate chain, as well as the timing of preventive maintenance is reduced.

In addition, the price of one meter of a plate chain is 13400 tenge for an elevator, about 120 meters or 1 608 000 tenge is needed, and the cost of an anchor chain is 2300 per 1 m. respectively, 276 000 tenge, which is 5.82 times cheaper.

**Conclusions**

The advantage of choosing an anchor chain is in the absence of axes of rotation between the plates, where maximum wear occurs in plate chains along the entire length of the chain, due to friction, less economic feasibility and longer service life. In addition, the gaps between the axes and the chain plates are clogged with alumina, which is a good abrasive material and accelerates the wear process of the plate chain, as well as the economic feasibility of manufacturing and repair is less complicated.

Thus, when upgrading the alumina acceptance unit of the bucket elevator, namely, replacing the plate chain with an anchor chain based on stress-strain state studies will increase the service life by 2.5 times and reduce the cost of preventive maintenance.

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**M.S. Karabayev, M.Sh. Moyliev, E.M. Amirov, A.B. Yusupov, R.M. Sadirov**
FUNDAMENTAL PROBLEMS RELATED TO GOLD-ORE PROCESS IN THE CENTRAL KYZYLKUM, PROSPECTS FOR THEIR SOLUTIONS........................................................................156

**A.Zh. Kassenov, K.K. Abishev, A.S. Yanyushkin, B.N. Absadykov, D.A. Iskakova**
RESEARCH OF THE STRESS-STRAIN STATE OF THE BUCKET ELEVATOR NODE CHAIN........................................................................167

**M. Nurpeissova, B. Mingzhasarov, B. Burkhanov, D. Kyrgizbaeva, Zh. Nukarbekova**
INFLUENCE OF METEOROLOGICAL FACTORS ON THE ACCURACY OF MONITORING RESULTS........................................................................179

**A.R. Omarov, A.Zh. Zhussupbekov, A.S. Sarsembayeva, A.B. Issakulov, A.M. Buranbayeva**
NUMERICAL MODELLING MICRO PILES AND EVALUATION OF THE O-CELL TEST RESULTS........................................................................190

**V. Povetkin, A. Bukayeva, A. Nurmukhanova, A. Seitkhanov, M. Kerimzhanova**
IMPROVING THE DESIGN OF A CENTRIFUGAL GROUND PUMP IN ENRICHMENT PRODUCTION........................................................................202

**T.S. Salikhova, S.A. Glazyrin, T.K. Salikhov, A.Sh. Alimgazin, Z.A. Bimurzina**
DEVELOPMENT OF A TECHNOLOGICAL SCHEME OF A WASTE-FREE BIOENERGY PLANT FOR THE DISPOSAL OF WASTE........................................................................217

**B.T. Uakhitova, R.A. Zhokanov, Z.S. Sarkulova, M.M. Taizhigitova, N.B. Kurbangaliyeva**
STATISTICAL ANALYSIS AND QUANTIFICATION OF RISK DANGERS OF INJURIES...............230

**A.G. Fremd, A.J. Bibosinov, B.A. Iskakov**
DISTRIBUTION OF ZONES OF DECOMPRESSION OF THE EARTH'S CRUST AS AN INDICATOR OF THE OIL PROSPECTS OF THE TERRITORY OF THE CASPIAN REGION...............................242

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