



COMPREHENSIVE ASSESSMENT OF THE IMPACT OF MECHANICAL IMPURITIES ON THE RELIABILITY INDICATORS OF DOWNHOLE PUMPING EQUIPMENT IN OIL PRODUCTION

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ABSTRACT

The article investigates the causes of failures of downhole pumping equipment (DPE) used in mechanized oil production, as well as methods for analyzing and forecasting its reliability. Despite continuous improvements in pump design and materials, a significant proportion of failures is associated with the effects of abrasive particles, corrosion, and cavitation. An analysis of domestic and foreign studies aimed at identifying patterns of failure mechanisms and increasing the mean time between repairs (MTBR) of pumps has been carried out. It has been determined that the key factor affecting the reduction in efficiency and durability of the equipment is the presence of mechanical impurities, as well as their concentration, shape, and grain-size distribution. Based on data from oil fields in Kazakhstan, Russia, and Azerbaijan, fuzzy clustering of operating conditions was performed, which allowed the identification of four groups of objects with different combinations of factors. Three-dimensional dependencies were constructed, and the results of the analysis formed the basis for fuzzy logic rules «if..., then...». The application of fuzzy cluster analysis confirmed the effectiveness of this method in solving diagnostic and optimization problems in oilfield equipment operation. Based on the results of the analysis, a new-generation filter element was developed, demonstrating significantly higher efficiency compared to leading global analogues and successfully implemented at one of the fields in Serbia. The results obtained can be used to improve the reliability of downhole pumps, reduce failure frequency, and form a knowledge base for managerial decision-making in oil production.

Keywords: oil production; downhole pumping equipment; failure; mean time between repairs; mechanical impurities; uncertainty; fuzzy cluster analysis; reliability; filter element.

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Introduction

Downhole pumping equipment (DPE), including sucker rod pumps (SRP) and electric submersible pumps (ESP), is the primary means of mechanized oil production. The reliability of pumping units directly determines well operating efficiency, production costs, and the mean time between repairs (MTBR).

Despite continuous improvements in design and materials, downhole pumps remain susceptible to various failures, necessitating a comprehensive analysis of their underlying causes.

The causes of downhole pump failures are diverse and depend on both design features of the equipment and operating conditions. The reliability of DPE is largely determined

by operational conditions and the physicochemical properties of the produced fluid. Pump unit failures result from the cumulative effect of mechanical, chemical, and thermodynamic factors, among which abrasive wear, corrosion, cavitation, scale and paraffin deposits, as well as misalignment and dynamic loads caused by changes in well operating modes, play a key role.

One of the most common failure types is abrasive wear of pump components. In this context the sources of mechanical impurities are rock particles, sand, clay, as well as products of casing and tubing string degradation. High concentrations of solid particles cause accelerated wear of working elements - plungers, cylinders, valves, and impellers.

The most critical task in the operation of pumping units is ensuring a stable technological regime, minimizing the impact of negative factors, and extending MTBR. Traditional

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diagnostic methods based on statistical failure analysis and routine inspections do not always provide sufficient accuracy and timeliness. Consequently, intelligent approaches using fuzzy logic, cluster analysis, and machine learning methods are gaining increasing importance.

These methods enable processing large volumes of operational data, account for uncertainty in input parameters, and identifying hidden patterns affecting pump system reliability. This approach is particularly relevant for analyzing relationships between geological and operational parameters, including fluid flow rate, mechanical impurity composition, viscosity, temperature, productivity index, and water cut.

The possibilities of applying fuzzy logic in oil production are discussed in detail in works [1–7].

In work [6], a fuzzy clustering algorithm is described, revealing its essence, role of fuzzification parameter, which directly affects the structure and stability of fuzzy clusters, determining the accuracy and stability of the results obtained.

Furthermore, modern data analysis techniques also enable clustering wells with similar operating conditions, simplifying the selection of optimal pump parameters and contributing to extended MTBR.

In this regard, the development and implementation of advanced methods for analyzing, forecasting, and preventing DPE failures is an urgent task in modern oil production.

Current state of research

Failures of oilfield equipment and their components are in a complex relationship due to a variety of objective and subjective causes. Studies [8, 9] provide classifications of SRP and ESP failures, distinguishing both objective and subjective factors.

The authors of [10, 11] performed a comprehensive analysis of ESP failures, identifying the main mechanisms of equipment failure: abrasive wear, cavitation, gas locking, corrosion, and motor overheating. The work emphasizes that the combination of geological conditions (gas content, water cut, sand production) and improper pump design selection is a key factor in reducing its performance.

Studies [12, 13] focus on SRPs, summarizing diagnostics and typical failures such as rod fatigue, cylinder and plunger wear, corrosion, and deposits. The authors highlight the need for intelligent monitoring systems. Methods of dynamogram analysis and mathematical modeling for fault detection are considered.

In [14], modern predictive analytics approaches for SRP failures using telemetry data and machine learning (LSTM models) are presented, demonstrating high efficiency in early fault detection. Practical application demonstrated the high efficiency of the proposed methodology for the early detection of anomalies, which allows increasing MTBR and reduction in operating expenses.

Thus, the conducted research covers a wide range of issues - from the systematization of traditional failure mechanisms to the implementation of digital monitoring and forecasting technologies. Collectively, these publications formed a relevant scientific framework for developing measures to improve the reliability of downhole pumps. The results of the conducted and summarized studies also indicated that the primary cause of failures in downhole pumping equipment (DPE) at the oil fields under consideration is the presence of mechanical impurities in the produced fluid. Their composi-

tion, particle size distribution, shape, and concentration in the fluid directly determine the nature of damage and the rate of degradation of equipment, the rate components. Precisely for this reason, the issue of comprehensive study regarding the influence of geological and technical factors on the operational characteristics of wells becomes paramount for ensuring the reliable and failure-free operation of pumps, such studies allow not only for the identification of the primary failure mechanisms, but also for the formulation of practical recommendations to enhance operational reliability [15, 16]

The conducted review shows that the modern research on downhole equipment failure covers a wide range of aspects - from analyzing traditional degradation mechanisms to implementing digital monitoring and forecasting methods. However, the reviewed works lack a unified system for classifying and grouping the vast array of factors affecting the reliability and efficiency of DPE. Furthermore, there is a lack of approach to determine which factors have the most decisive impact on the development process. Considering that the operational stability of pumps is largely determined by a combination of geological, physical, and technological conditions, the absence of such a classification framework complicates informed management decisions during field design and optimization. This review has enabled the evaluation of current research and the identification of issues requiring immediate attention. The review also suggests that the development of a system for the comprehensive assessment of mechanical impurity composition, their nature, and impact on DPE performance indicators remains insufficiently explored. Considering that equipment operates under conditions of uncertainty, there is a clear need to explore the possibility of implementing methods that account for and assume the presence of uncertainty.

In this regard, the present article proposes the application of the fuzzy set theory apparatus for solving the above-mentioned problems. This framework has proven to be an effective tool for analyzing development processes under conditions of insufficient and contradictory information regarding parameters that influence the choice of technological solutions [17-19]. The use of fuzzy cluster analysis methods will allow the identification of the most significant factors determining the reliability of pumping equipment and will form the basis for creating a robust decision support system under conditions of uncertainty.

Materials and methods

Analysis of scientific literature confirms that the application of fuzzy set theory allows successful solution of oilfield engineering tasks, including modeling, classification, data interpretation, and decision-making.

The methodology of fuzzy cluster analysis was developed by the researcher James Bezdek and is based on fuzzy set theory proposed by Lotfi Zadeh. Fuzzy cluster analysis is employed to group objects characterized by overlapping or «blurred» boundaries between classes.

Unlike traditional clustering, the Fuzzy C-Means (FCM) algorithm allows each object to belong to multiple clusters with varying membership degrees (ranging from 0 to 1).

The fuzzy C-Means (FCM) algorithm enables the distribution of each object across several groups depending on its degree of similarity to them.

This approach was previously applied to the classifica-

tion of hard-to-recover reserves [6, 20, 21]. It ensures more accurate identification of groups in the presence of complex non-linear dependencies between geo-technical operating conditions and operational efficiency metrics.

The study used data from oil fields in Kazakhstan, Russia, and Azerbaijan.

The following input parameters (clustering features) were selected:

- water cut of production well;
- fluid flowrate;
- mechanical impurity content;
- productivity index.

The key operational indicators were considered as output variables:

- mean time between repairs (MTBR);
- pump delivery coefficient.

This framework enabled comprehensive assessment of the relationship between operating conditions and actual equipment reliability.

Results and discussion

To determine the influence of factors governing the causes of pump failures on their performance indicators, an analysis of information regarding the geological and technological characteristics of operating conditions was performed. It demonstrated the possibility of establishing statistical dependencies in this specific case due to insufficient data. Therefore, to obtain a representation of the impact of key operational factors on pump efficiency indicators, a classification of operating conditions was conducted out using a fuzzy cluster analysis algorithm. To increase the reliability of the results, the analysis was carried out in stages. In the first stage, using data from fields in Kazakhstan and Russia (the training sample), a primary classification of operating conditions was conducted and the clusters were constructed. In the second stage, a similar analysis was performed with the addition of a data set from fields in Azerbaijan (the test sample), which enabled the comparative analysis and verification of the universality of the identified patterns.

It should be noted that the analysis didn't account for correlations between the concentration of mechanical impurities in the produced fluid and the water cut of the production well. During production from shallow reservoirs with uncon-

solidated sandstone, significant migration of mechanical impurities occurs due to the degradation of rock structures upon interaction with water. As a result of the clustering process, four groups of homogeneous data (clusters) were identified characterizing various combinations of operational factors (table 1). Membership functions were calculated for each cluster allowing for an assessment of the probability that specific operating conditions belong to one class or another. Table 2 presents the relative correspondence between input and output variables, clearly demonstrating the dependence of the mean time between repairs (MTBR) and the flow coefficient on the level of water cut, flow rate productivity, and mechanical impurity content.

For visualization purposes, the clustering results were presented as three-dimensional surfaces (figs. 1, 2), showing the variation in MTBR and the flow coefficient depending on the combination of factors. In the figures, the values of the output parameters are displayed in different colors, which allowed for the visual identification of the most favorable and unfavorable pump operation zones. The analysis showed that, for example, with low water cut, low flow rate, and low flow coefficient, but high mechanical impurity content, both the MTBR and the flow coefficient are minimized. Such dependence allowed for the formulation of fuzzy logic rules of «If..., Then...» type, which enables the use of analysis results in the development of expert systems for predicting pump failures.

IF water cut is LOW, fluid rate is LOW, and productivity index is LOW, and mechanical impurity content is HIGH, THEN MTBR and pump delivery coefficient are LOW.

IF water cut is LOW, fluid rate is LOW, productivity index is LOW, and mechanical impurity content is LOW, THEN MTBR and pump delivery coefficient are MEDIUM.

IF water cut is HIGH, fluid rate is MEDIUM, productivity index is LOW, and mechanical impurity content is LOW, THEN MTBR and pump delivery coefficient are HIGH.

IF water cut is HIGH, fluid rate is HIGH, productivity index is LOW, and mechanical impurity content is MEDIUM, THEN MTBR and pump delivery coefficient are HIGH.

The presented approach using fuzzy cluster analysis was taken into account in the development of a new generation filter element for specific operating conditions of a productive facility, which fundamentally differs in its characteristics from existing well filters [22]. The new filter element represents

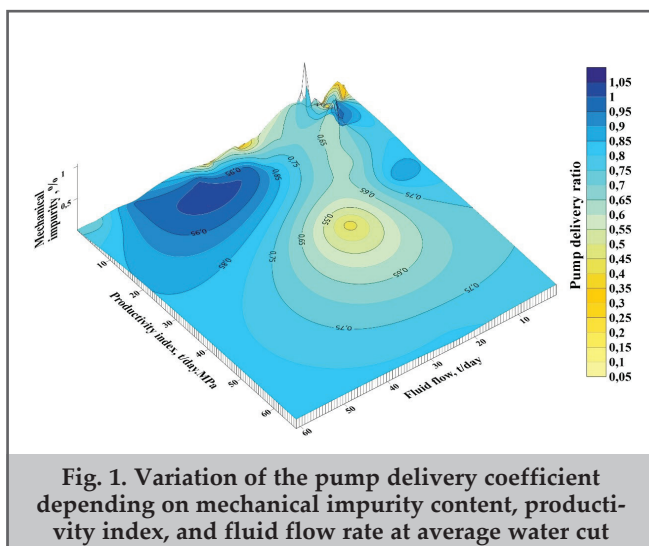


Fig. 1. Variation of the pump delivery coefficient depending on mechanical impurity content, productivity index, and fluid flow rate at average water cut

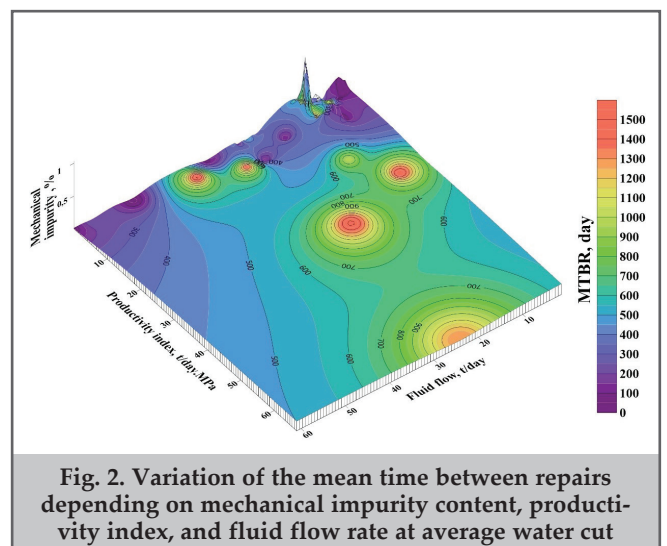


Fig. 2. Variation of the mean time between repairs depending on mechanical impurity content, productivity index, and fluid flow rate at average water cut

a labyrinth of interconnected channels, similar to a high-capacity pore space that does not impede the filtration of formation fluids. The flow of well production through the filter element ensures controlled removal of sand and mechanical impurities. The porous filtration cake formed around the filter element within the well perforation interval possesses natural «genetic» properties of the reservoir system and does not alter well completion efficiency or skin factor. Depending on the

physicochemical properties of the fluids saturating the productive formation, the filter element can be manufactured in either a hydrophilic or a hydrophobic configuration.

The new filter element technology enables the creation of a controlled modification of phase permeability aimed at reducing water content in well production. This is achieved, for example, by redistributing drawdown along the wellbore in wells with heterogeneous phase inflow, thereby decreasing

Table 1

Results of fuzzy cluster analysis and corresponding membership functions

| Water cut | Fluid flow, t/day | Productivity index, t/day. MPa | Mech. imp., % | MTBR | Pump delivery ratio | μ_1 | μ_2 | μ_3 | μ_4 | Cluster |
|-----------|-------------------|--------------------------------|---------------|------|---------------------|---------|---------|---------|---------|---------|
| 0.24 | 8 | 0.03 | 0.056 | 44 | 0.13 | 0.9992 | 0.0001 | 0.0001 | 0.0006 | 1 |
| 0.259 | 29 | 0.221 | 0.030 | 267 | | 0.9988 | 0.0001 | 0.0002 | 0.0009 | 1 |
| 0.185 | 2.7 | 2.7 | 0.2 | 98 | 0.323 | 0.9987 | 0.0002 | 0.0002 | 0.0009 | 1 |
| 0.33 | 7.46 | 8.82 | 0.2 | 1057 | 0.36 | 0.998 | 0.0002 | 0.0002 | 0.0016 | 1 |
| 0.11 | 5 | 0.02 | 0.086 | 298 | 0.2 | 0.99 | 0.0017 | 0.0017 | 0.0066 | 1 |
| 0.11 | 36 | 0.347 | 0.025 | 326 | | 0.9876 | 0.0021 | 0.0021 | 0.0082 | 1 |
| 0.09 | 30 | 0.14 | 0.063 | 451 | 0.5 | 0.9859 | 0.0024 | 0.0025 | 0.0092 | 1 |
| 0.37 | 9.52 | 3.94 | 0.2 | 1369 | 0.57 | 0.9832 | 0.0015 | 0.0015 | 0.0138 | 1 |
| 0.13 | 98 | 0.466 | 0.017 | 78 | | 0.9741 | 0.0044 | 0.0046 | 0.017 | 1 |
| 0.006 | 4.6 | 1.2 | 0.003 | 220 | 0.53 | 0.9594 | 0.0076 | 0.0078 | 0.0251 | 1 |
| 0.38 | 4.7 | 1.3 | 0.054 | 299 | 0.59 | 0.9578 | 0.0032 | 0.0037 | 0.0352 | 1 |
| 0.4 | 5 | 5 | 0.2 | 75 | 0.619 | 0.9367 | 0.005 | 0.005 | 0.0534 | 1 |
| 0.208 | 2.1 | 0.6 | 0.845 | 241 | 0.74 | 0.8738 | 0.0338 | 0.0213 | 0.0711 | 1 |
| 0.43 | 20 | 0.09 | 0.009 | 504 | 0.67 | 0.7731 | 0.0121 | 0.0161 | 0.1986 | 1 |
| 0.41 | 12 | 11.9 | 0.7 | 349 | 0.38 | 0.6799 | 0.0757 | 0.0394 | 0.2051 | 1 |
| 0.4 | 8.33 | 1.36 | 1 | 528 | 0.3 | 0.5242 | 0.1674 | 0.0736 | 0.2347 | 1 |
| 0.906 | 28.7 | 28.7 | 0.5 | 75 | 0.962 | 0 | 0.9952 | 0.0043 | 0.0005 | 2 |
| | | | | ⋮ | | | | | | |
| 0.77 | 57 | 0.43 | 0.004 | 229 | 0.71 | 0.0029 | 0.0283 | 0.2651 | 0.7037 | 4 |
| 0.5 | 20 | 0.144 | 0.0177 | 338 | | 0.247 | 0.0208 | 0.0311 | 0.7011 | 4 |
| 0.769 | 1.3 | 1.6 | 0.3 | 25 | 0.415 | 0.002 | 0.1222 | 0.177 | 0.6988 | 4 |
| 0.78 | 30 | 0.13 | 0.009 | 218 | 0.3 | 0.0019 | 0.0223 | 0.287 | 0.6889 | 4 |
| 0.75 | 24 | 66.7 | 0.1 | 1300 | 0.82 | 0.0066 | 0.0843 | 0.2306 | 0.6785 | 4 |
| 0.5 | 61 | 0.401 | 0.015 | 84 | | 0.2699 | 0.0259 | 0.0386 | 0.6655 | 4 |
| 0.526 | 1.9 | 1.9 | 0.5 | 69 | 0.220 | 0.2094 | 0.0968 | 0.0544 | 0.6394 | 4 |
| 0.49 | 5 | 0.02 | 0.005 | 275 | 0.11 | 0.3153 | 0.0216 | 0.0321 | 0.631 | 4 |
| 0.48 | 8 | 0.085 | 0.023 | 102 | | 0.3923 | 0.021 | 0.0298 | 0.5568 | 4 |

Table 2

Correspondence between input and output parameters

| Water cut | Fluid flow, t/day | Productivity index, t/day.MPa | Mech. imp., % | MTBR, days | Pump delivery ratio |
|-------------------|-------------------|-------------------------------|---------------------|----------------------|---------------------|
| 0.33-0.55 low | 7.46-12.5 low | 1.36-17.9 low | 0.7-1 high | 349-528 low | 0.3-0.38 low |
| | | | 0.2 low | 1006-1369 average | 0.36-0.7 average |
| 0.66-0.99 high | 0-24 average | 0-66.7 low | 0.05-0.2 low | 1103-1613 high | 0.31-0.99 high |
| | 33-55 high | 133-400 high | 0.4-1 high | 889-1461 high | 0.33-0.84 high |
| | | 1.92-58.3 low | 0.05-0.3 average | 895-1885 high | 0.47-0.99 high |

the overall water cut of the produced fluid. In addition, the applied technology limits the deposition of fine particles on the surface of the filter element, significantly enhancing its resistance to clogging and substantially extending the effective service life of the equipment. The primary purpose of this innovative product is to increase well productivity through controlled sand and mechanical impurity removal while preventing the formation of cavities in the wellbore reservoir zone. Furthermore, the filter can be used to reduce water inflow into the wellbore and may be additionally equipped with production-enhancement systems that facilitate fluid lifting from the wellbore by means of formation gas inflow. The described technical characteristics are critically important for the operation of wells at oil, gas, and gas-condensate fields. Water removal from the wellbore by produced gas can solve the problem of water-blocking of productive intervals, reduce water inflow when using filters with reverse-phase permeability, and limit sand production without loss of oil output over prolonged operating periods.

An illustration and layout diagram of a reverse-phase permeability filter at a Western Siberian field are shown in figures 3 and 4, respectively.

The integration of a well operation method using an ESP installation and an innovative filter element is aimed at increasing the time between repairs, i.e., the mean time between ESP failures, and reducing operating costs for routine and major well repairs by reducing the number of failures due to the removal of mechanical impurities from the

productive formation.

The results of well operation using this technology at Western Siberian fields are presented in table 3.

At a field in Serbia, filters were placed in the wellbore zone. This resulted in an increase in the mean time between repairs, increased oil flow rate, and a reduction in mechanical impurities in the well output.

Sand control at this field had previously been performed by gravel packing in the near-wellbore zone. However, the gravel pack did not provide a long-term solution. A significant drawback of this technology was the introduction of large volumes of working fluid into the formation during installation, which subsequently required prolonged swabbing for removal, ultimately resulting in oil production losses. The productive reservoir is composed of unconsolidated sandstone, and its development is associated with suspended solids concentrations in well production exceeding permissible values of 500 mg/L. The effectiveness of the operations was evaluated based on the following criteria: reduction of produced solids to below 500 mg/L and achievement of an oil production increase of at least 2 t/day. Filters with packed elements and reverse-phase permeability were installed in three wells. After extended operation, the filters were retrieved and subjected to technical condition inspection. Subsequently, the equipment was reinstalled in other wells, one of which has been operating for more than four years. In all wells, the concentration of produced solid particles ranged from 125 to 180 mg/L. The field results demonstrated the high efficiency of filters with packed



Fig. 3. A reverse-phase permeability filter in a well

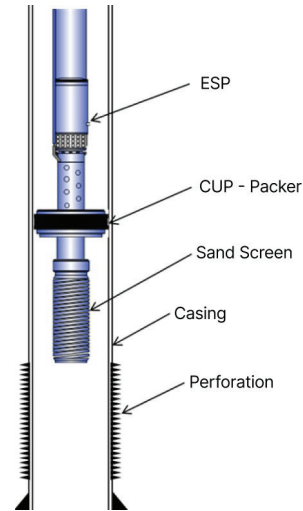


Fig. 4. Typical filter installation diagram under an ESP unit

| Field filter test results | | | | Table 3 |
|-----------------------------|--|------------------------|---|---------|
| Parameter | Before implementation | After implementation | Notes/Conclusions | |
| ESP | 1300 m | 1490 m | ESP deepened by +190 m | |
| Q_{liq} | Intermittent operation mode 11 m ³ /day | 32 m ³ /day | Switched from intermittent to continuous operation | |
| Q_{oil} | 3.1 t/day | 10 t/day | Average daily increase: +6.9 t/day | |
| Mechanical impurity content | Average over the last rolling year before implementation: 411.2 mg/L | Average: 173.8 mg/L | Reduction in mechanical impurity content by 58% compared to the previous rolling annual average | |
| Failure/day | 97 | 236 | Increase by 139 days | |

filter elements and reverse-phase permeability compared to the best existing solutions available on the global market. The achieved outcomes include a reduction in sand and mechani-

cal impurity production, compliance with oil production performance criteria, extension of the mean time between repairs, and the possibility of multiple reuse.

Conclusions

- Thus, the conducted studies made it possible to identify a set of factors determining the efficiency and reliability of downhole pump operation in the considered oil fields.
- The application of fuzzy cluster analysis enabled the investigation of equipment performance patterns under conditions of uncertainty and limited initial data. The obtained results provide a qualitative understanding of the influence of water cut, production rate, productivity index, and mechanical impurity content on the mean time between repairs and pump delivery coefficient. This approach makes it possible to form a knowledge base for managerial decision-making aimed at optimizing pump operation, developing equipment and technologies to reduce failure frequency, and improving the overall efficiency of oil production systems.
- Based on the conducted analysis, a next-generation filter element was developed, which demonstrated high efficiency compared to the best solutions currently available on the global market.
- Based on the analysis, a new generation filter element was created, which was successfully implemented in various modifications at fields in Western Siberia and the Republic of Serbia.

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