Areas of activities:

• carrying out of research-and-development, design-and-experimental, and technological operations, as well as development of technical solutions, ensuring safe and reliable operation of main and technological pipelines, buildings, and structures (facilities) of Transneft, PSC, and Transneft system organizations (TSO);
• development of interstate, national, and industry standards, as well as other normative documents, in the field of construction and operation of main and technological pipelines, as well as pipeline transportation facilities;
• formation and maintenance of an information system for assessing the conformity of equipment and materials; carrying out of technical documentation examination and laboratory tests for compliance with the requirements of national, interstate, and foreign standards, as well as with the requirements of normative documents of Transneft, PSC; development of standard programs, organization and/or participation in the activities for addition (extension of certification) of the products into the Core products register;
• provision of expert-consulting and engineering services in the field of design, construction, and operation of main, field, distribution, technological pipelines, and other facilities of the fuel and energy complex;
• scientific and technological support for construction of the facilities of Transneft, PSC;
• assessment of the technical state of pipelines, development of the methods for increasing the transmission capacity of main pipelines;
• control, coordination, and provision of implementation of the activities on realization of the innovative development program of Transneft, PSC, including search, development, approbation and introduction of innovative products and technologies;
• development of the documents in the field of industrial and fire safety, as well as the documents for prevention and elimination of emergencies in the field of environmental protection;
• assurance of the status of Pipeline Transport Institute, in the external market as a national research center, carrying out a wide range of operations in the field of hydrocarbons pipeline transportation.

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The direction of metrological assurance development for pipeline ILI in the framework of conformity assessment

by Dr Y.V.Lisin*, O.V.Aralov¹, S.I.Vorobyev¹, and S.V. Ermish²
¹ Pipeline Transport Institute, Moscow, Russian Federation
² Transneft Diascan, JSC, Lukhovitsy, Moscow Region, Russian Federation

The article is devoted to the main development directions of metrological assurance for ILI(ILI) in Transneft within the industry system for assessing conformity.

A brief overview is given of the results of analysing international, Russian, and American standards establishing the requirements for classifying pipeline defects. Methods of guaranteeing reliable measurement results for ILI in the Russian Federation are examined, and specifically the main features of the concept of metrological assurance for ILI in Pipeline Transport Institute (hereafter referred to as the Concept).

The steps necessary to implement the Concept are enumerated: mandatory metrological requirements, measurement methods, standard defect measures, and ILI tools (measuring instruments), and information about the testing areas is provided for ILI tools in Russia and the USA. This article presents the results of Pipeline Transport Institute’s work setting-up a reference database of defects and developing regulatory documents. The expected results of implementing measures in accordance with the Concept are also stated, including obligatory metrological requirements for measurements taken during an ILI, a reference database of standard defect measures with specified metrological characteristics, a normative database for metrological evaluation of ILI tools, and an accredited metrological testing area for the tools. The positive effects of implementing the Concept in Russia are described, in particular regarding consumer protections from unreliable ILI results.

Key words: in-line inspection, ILI tool, metrological assurance, obligatory metrological requirements, conformity assessment

Reliability of measurements taken during an ILI

One of the conditions for ensuring pipeline reliability and preventing accidents is monitoring the technical state of trunk pipelines. The most effective method of monitoring is ILI(ILI) which helps to obtain information about defects, welds, and features in pipelines and their location through the use of ILI tools. The geometric dimensions of the defects calculated during an ILI and their subsequent interpretation are used as the initial data to calculate a pipeline’s strength and durability, and the time-frame for eliminating any defects that are found. Determining defect parameters with minimum error is the most important aspect of ensuring the pipeline’s reliability.

The accuracy of pipeline calculations is ensured by the reliability of the results of measurements taken during ILI. For more than 10 years the Pipeline

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Transport Institute has been performing calculations to determine the safe service life of pipelines in long-term operation (over 30 years) according to its own methods, as well as according to American and European standards NG-18, ASME B31.G-2009, DNV RP-F101, API 579/ASME FFS-1, and BS 7910:2013.

As a rule, manufacturers of ILI tools in Russia, Europe, and the United States form their metrological assurance only by means of calibration, and certificates of calibration are issued as approvals. It is therefore impossible to confirm the reliability of their measurement results with reference to national standards. Also, in the absence of generally accepted 'rules' or mandatory metrological requirements, it is impossible to assess the compliance of measurement results obtained during an ILI.

In the Russian Federation, measurement accuracy is guaranteed by the provisions of the Federal law On Assurance of Measurement Uniformity and the regulations it contains. Measurement accuracy is achieved by:

- establishing and complying with mandatory metrological requirements, including indicators of measurement accuracy;
- applying the regulatory framework (international and national standards);
- applying standards based on national standards;
- testing measuring tools to approve their type;
- calibrating measuring tools;
- using measurement techniques.

The Concept of metrological assurance for ILI

To implement these measures, the Pipeline Transport Institute developed the Concept of metrological assurance for ILI within the industry's conformity assessment system, which includes the requirements of the above-referenced Federal law. So far, measurements taken during ILIs have not been included within the scope of state regulation ensuring measurement uniformity. To solve this problem, the Pipeline Transport Institute developed compulsory metrological requirements based on the experience of previously conducted studies in the field of metrology. Accuracy indicators were thus established for measuring:

- flow cross-section diameter;
- distance travelled;
- pipe wall thickness using ultrasonic and magnetic methods, etc.

These mandatory metrological requirements have been introduced to Federal regulations and the Safety rules for hazardous production facilities of trunk pipelines, which is a binding regulatory document at the Federal level in the Russian Federation.

A brief overview of the requirements for classifying defects

In order to establish unified requirements for classifying defects, taking into account standard practices in Europe and the USA, the Pipeline Transport Institute analysed the following international, Russian, and American standards:

- American Petroleum Institute (API) standard API STD 1163: ILI systems qualification;
- National Association of Corrosion Engineers (NACE) standard NACE SP0102-2010: Standard practice: ILI of pipelines;
- Pipeline Operators’ Forum (POF) document Specifications and requirements for intelligent pig inspection of pipelines (2009);
- Russian standards for ILI of pipelines.

Based on this analysis, it became clear that approaches to classification in Russian and international practice are broadly similar. There are, however, some differences, for instance:
Crack defect. According to the Russian classification, this is a rupture in the pipe’s metal surface, characterized by a sharp tip and high ratio of length to width and to opening; while according to international classification, it is a flat, two-dimensional feature with displacement of fracture surfaces.

Buckle defect. According to the Russian classification, this is the

<table>
<thead>
<tr>
<th>No</th>
<th>Measurement method</th>
<th>Parameter</th>
<th>Requirements of Russian regulatory documentation</th>
<th>Requirements of POF 2009: Specifications and requirements for intelligent pig inspection of pipelines</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Magnetic</td>
<td>Error in anomaly length measurement</td>
<td>From 15 to 30 mm for corrosion, pits, grooves, laps, cavities</td>
<td>From 10 to 20 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>From (0.1 \cdot L or 30) to (0.1 \cdot L or 50) mm (which is more) for cracks</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Error in anomaly width measurement</td>
<td>From 15 to 30 mm for corrosion, pits, grooves, laps, cavities</td>
<td>From 10 to 20 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>50 mm for cross cracks</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Error in anomaly depth measurement</td>
<td>From 0.1 \cdot \delta to 0.2 \cdot \delta for corrosion, pits, grooves, laps, cavities</td>
<td>From 10 to 15 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.15 \cdot \delta for cracks</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Profilometry</td>
<td>Error in dent length measurement</td>
<td>20 mm</td>
<td>10 % of internal diameter</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Error in dent width measurement</td>
<td>40 mm</td>
<td>10 % of internal diameter</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Error in dent depth measurement</td>
<td>From 2 to 3 mm</td>
<td>1 % of internal diameter</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dent registration threshold</td>
<td>From 3 to 6 mm</td>
<td>2 % of internal diameter</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Error in inner diameter measurement</td>
<td>From 0.003 \cdot D_H to 0.005 \cdot \delta</td>
<td>1 % of internal diameter</td>
</tr>
</tbody>
</table>

Fig.1. ILI tool characteristics in Russian and international regulatory documentation:

\[ L \text{ – length of the defect or crack zone, mm;} \]
\[ D_H \text{ – external pipe diameter, mm;} \]
\[ \delta \text{ – nominal wall thickness of pipe, mm.} \]

- Crack defect. According to the Russian classification, this is a rupture in the pipe’s metal surface, characterized by a sharp tip and high ratio of length to width and to opening; while according to international classification, it is a flat, two-dimensional feature with displacement of fracture surfaces.
- Buckle defect. According to the Russian classification, this is the
deformation of the pipe wall due to external impact, in the form of convexity and concavity that are larger than the wall thickness. According to the international classification, it is partial collapse of the pipe due to excessive bending or compression caused by soil instability, landslides, erosion, frost heaving, earthquakes etc.

- Corrosive loss of metal defect. This is, according to the Russian classification, a pipe section with a measured reduction in wall thickness, as a result of corrosion damage; while according to the international classification, it is any pipeline anomaly arising due to metal loss. The loss of metal is usually the result of corrosion or the formation of grooves, notches, scores and scratches.

For reference, 24 defect types are defined in Russian documentation and 17 in international documentation. In many cases the defect definitions developed by PJSC Transneft more accurately reflect their characteristics for interpretation.

It should also be noted that some criteria for ILI tools in Russia, Europe, and the USA differ both by boundary values (minimum and maximum limits of measuring range) and by the way errors are expressed (in a percentage of the parameter and in millimetres for Europe and the USA; by formulae that include defect length, pipeline diameter, wall thickness, etc., for Russia).

The Pipeline Transport Institute is developing a national standard Metrological assurance of ILI to establish a unified set of requirements for classifying and schematizing defects that is aligned with international requirements.

**Measurement methods and methodology of interpreting defects**

Based on research results, the Pipeline Transport Institute has developed measurement methods for ILI:

- for measuring the pipeline flow cross-section diameter;
- for measuring the defect length;
- for measuring the depth of external-type defects by the position in the pipe wall, etc.

With regard to methods for measuring the defect depth, the pipe wall thickness at a defect-free section is determined by ultrasonic thickness measurement, as well as the remaining pipe wall thickness at the section with the defect. An ultrasonic pulse, emitted by the piezoelectric transducer, passes through an intermediate couplant, enters the object under inspection, is reflected from its rear wall and returns to the receiving sensor of the piezoelectric transducer. Given the known speed of sound, the thickness of the object is thus calculated according to the measured delay time of the ultrasonic pulse relative to its emission.

The mathematical data processing method is the calculation of the defect depth $h_D$ in the pipe wall (Fig.2) from the difference between the pipe wall thickness at the defect-free section $t$ and the residual pipe wall thickness $t_{res}$ at the section with the defect.

The defect depth $h_D$ in the pipe wall is found according to the formula:

$$ h_D = t - t_{res} $$

where $t_{res}$ is the residual pipe wall thickness and $t$ is the defect-free pipe wall thickness.

The measurement result is presented in the documents providing for its use in the following form:
where $\Delta h$ is the characteristic of error in the pipe wall defect depth measurement, in mm.

The error margin when measuring defect depth in the pipe wall $\Delta h$ is calculated in the following way:

$$\Delta h = \sqrt{\left( \frac{c h}{t^2} \Delta t \right)^2 + \left( \frac{c h}{t_{res}} \Delta t_{res} \right)^2} \quad (3)$$

where:

- $t_{res}$ is the residual pipe wall thickness, mm;
- $t$ is the defect-free pipe wall thickness, mm;
- $\Delta t_{res}$ is the error in measuring the residual pipe wall thickness, mm;
- $\Delta t$ is the error in measuring the defect-free pipe wall thickness, mm.

In order to analyse and evaluate technical solutions with respect to metrological assurance for interpreting results from using ILI tools, the Pipeline Transport Institute has organized expert metrological examination of data interpretation methods for trunk pipeline ILI.

**Defect measures and reference database of defects**

The Pipeline Transport Institute has developed documents to regulate:

- the nomenclature of defect measures with normalized metrological characteristics;
- the manufacture, storage and control of metrological characteristics of defect measures;
- the provision of equipment to the department for manufacturing, testing, and verifying metrological characteristics of defect measures.

The basis for storing and transmitting units of length when calibrating ILI tools is the set of standard samples which forms the defect-reference database, which is a set of defect measures, in the form of pipe lengths, consisting of pipe sections with various wall thicknesses, containing natural or artificial defects in geometry and in the pipe wall, as well as defects in welds in accordance with the classification of pipeline defects.

The metrological characteristics of these defects (length, width, depth) are known, and their nomenclature is consistent with the results of ILIs over more than 940,000 km of trunk pipelines, carried out by PJSC Transneft in Russia, Europe, Middle East, Latin America, and South America.

Defect measures are calibrated in accordance with verification methods, thus ensuring the traceability of the following measurements in the progression: the state standard from the state verification scheme → legal
entity standards (defect measures, signal generators) → working measuring instrument (ILI tool). This also ensures the transferring of the length, time, and electromagnetic oscillation attenuation unit dimensions with metrological characteristics.

The given reference database of defect measures acts as the basis of the metrological testing area for verifying and calibrating ILI tools (hereafter - metrological testing area).

At present the Pipeline Transport Institute has carried out tests to approve the type of nine defect measures with diameters ranging from 159 mm to 1220 mm, containing 45 defects of four types (notch, dent, metal loss, non-uniform thickness).

The defect reference database is also used to improve methods of interpreting defects, which define:

- the rules for interpreting data from ILIs, including pipe sections, defects, connective and structural components, weldable fittings, repair structures, and other features of the pipeline, detected as a result of running ILI tools;
- the rules for interpreting combined defects during data processing of ILI tools of various types, using data about defects from a specialized defects database;
- the rules for defining and recording defect repair methods.

Fig. 4. Defect test pipes.

Metrological test areas for ILI tools

PJSC Transneft’s metrological test facility consists of a liquid test rig and dry pull-through test rig. This test rig consists of pipelines of various diameters (from 159 mm to 1220 mm) and wall thicknesses (from 4 mm to 29 mm). The liquid used is 30% aqueous glycerin solution, with properties as close as possible to petroleum products, which enables the test rig to be in operation year-round. The dry pull-through test rig is designed for calibrating magnetic-type tools and simulating gaseous environments. The test rig is equipped with more than 11,200 of the various defects that can appear in oil, oil product, and gas pipelines. The design of the testing area allows the defects to be changed using flanged inserts.

The metrological test facility is currently being accredited with official state body for the recognition of the test facility’s competence. This is conducted to provide confidence in the measurement results at the level of the Russian Federation, and also to make them recognisable by other countries, including the Russian Federation’s trading partners.

In Houston, Texas (USA) the PRCI Technology Development Center set-up a testing area with a similar purpose in 2012. It incorporates three standard sizes of the pipeline under inspection (300, 400, and 600 mm) and 1100 pipes with real defects, a dry pull-through test, rig and a liquid test rig for ILI tools.
ILI tools

The following ILI tools were tested for type approval:

- Inspection system from the CMC series - multi-channel caliper tool;
- Inspection system from the UD series - ultrasonic thickness tool for WM (wall-thickness measurement);
- Inspection system from the DMC series - magnetic thickness tool for TFI (transverse-field inspection) and MFL method (magnetic-field leakage);
- Inspection system from the CDC series - combined thickness tool, formed of three sections: MFL, ultrasonic WM, and ultrasonic CD (crack detector, an ultrasonic inspection method, designed to detect and measure crack parameters in the pipe wall and longitudinal welds);
- Inspection system from the DCP series - combined ultrasonic thickness gauge that includes two sections: ultrasonic WM and ultrasonic CD.

The methods of calibrating these ILI tools, developed during testing, provide two possible sets of verification tools, comprising:

- Defect measures in the form of the pipe sections mentioned above;
- Serially-produced standards (thickness and length measures).
Results

The main results of the Pipeline Transport Institute’s activities described above are:

- unified state mandatory metrological requirements for measurements taken during ILIs;
- a unique reference database for defect measures with specified metrological characteristics;
- a normative framework for metrological evaluation of ILI tools;
- an accredited metrological test facility for ILI tools.

Future plans

To further develop this system, the Pipeline Transport Institute will carry out the following measures in 2017-2020:

- expanding the reference database by creating new defect measures using various methods of manufactured defects: mechanical (milling, welding, drilling notches) and using additive technologies (3D-printer);
- inter-laboratory comparisons of measurement units contained in defect measures, with the engagement of leading international metrology institutes, for example, the Dutch National Metrology Institute VSL;
- testing ILI tools in the interests of...

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>PJSC Transneft test facility, Russia</th>
<th>PRCI Technology Development Center, USA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipeline diameter range</td>
<td>6 - 48 in (159 - 1220 mm) 11 standard sizes</td>
<td>12 in, 16 in, 24 in (300, 400, 600 mm) 3 standard sizes</td>
</tr>
<tr>
<td>Number and type of defects for testing in-line inspection tools</td>
<td>More than 11,200 artificial and natural defects, including over 6,500 defects of the pipe base metal</td>
<td>1100 pipe samples with natural defects</td>
</tr>
<tr>
<td>Test facility features</td>
<td>3 circular and 4 semi-circular test loops of various diameters</td>
<td>Dry pull-through test rig ILI tools of 3 standard sizes (12 in, 16 in, 24 in)</td>
</tr>
<tr>
<td></td>
<td>Dry pull-through test rigs for ILI tools of various standard sizes</td>
<td>Liquid testing facility for ILI tools of 2 standard sizes (6 in, 12 in)</td>
</tr>
<tr>
<td></td>
<td>1.5D, 3D, 5D bends</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Aerial crossing</td>
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Russian and foreign customers;
• development of international standards.

Conclusion

This approach, within the industry system of conformity assessment, will allow for independence and impartiality when implementing metrological assurance of ILI, when testing, verifying (calibrating) ILI tools, etc. The approach will also involve the future exchange of technological information with leading Russian and foreign organizations in the field of ILI, and the joint development and adoption of normative procedures and standards.

It will also ensure consumer protection from unreliable results of ILI and, as a consequence, prevention of:

• the risks associated with pipeline incidents occurring because of dangerous undetected defects;
• additional financial costs in connection with the unnecessary replacement of pipelines due to inaccurately defined (classified) defects, as well as remediying environmental damage due to pipeline accidents;
• risks to reputation (the risk of losing business reputation) due to non-performance of hydrocarbon transportation services promised to the consumer;
• the use ILI tools and software which do not meet technical and metrological requirements for measuring instruments.

The activities examined within the framework of the industry system of conformity assessment provide increased accuracy and reliability for ILI results and reduce the risk of pipeline accidents. ILI measurements included in state regulation allow to establish unified, transparent, and obligatory requirements for all market participants.

References

2. Federal Agency on technical regulation and metrology (Rosstandart). ww.gost.ru/wps/portal/
4. JSC Transneft Diascan http://diascan.transneft.ru
5. PRCI (Pipeline Research Council International) https://www.prci.org/1.aspx
7. NACE (National Association of Corrosion Engineers) SP0102-2010 Standard Practice. ILI of Pipelines.
8. POF (Pipeline Operators Forum, 2009). Specifications and requirements for intelligent pig inspection of pipelines.
Listing of forthcoming industry events

The World Future Energy Summit
15-18 January 2018
ADNEC, Abu Dhabi, UAE
https://www.worldfutureenergysummit.com
The foremost platform dedicated to innovation, digitalisation and transformation in the global energy mix.

PPIM 2018 · The Pipeline Pigging & Integrity Management Conference
29 January 2018 - 1 February 2018
Houston, Texas, USA
clarion.org
Now in its 30th year, this conference, and its accompanying exhibition, form the industry’s primary forum devoted to pigging for maintenance and inspection, as well as pipeline integrity evaluation and repair. Organized by Clarion Technical Conferences and Tiratsoo Technical.

Energy Mexico Oil Gas Power
30 January 2018 – 1 February 2018
Mexico City, Mexico
http://www.energymexico.mx
Energy Mexico Oil Gas Power Expo & Congress is first event combining an international level exhibition with a world-class conference featuring the foremost experts in the national and international energy sector. The event floor will showcase the latest technologies, equipment and services available on the market.

Subsea Expo
7-9 February 2018
Aberdeen, UK
https://www.subseaexpo.com
Subsea Expo is the world’s foremost subsea exhibition and conference and is free to attend. Registration gives you access to the exhibition and all of the conference sessions.

EGYPS 2018
12-14 February 2018
Cairo, Egypt
https://www.egyps.com
EGYPS 2018 provides the opportunity to gain insights into the upcoming oil and gas opportunities in Egypt and North Africa, from new regulations, investment opportunities, project requirements to short and long term strategic plans and priorities that will help form strategic partnerships and enhance industry collaboration in the region.

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A systematic approach to developing measures for preventing and containing the consequences of accidents on oil pipelines in the Russian Federation’s Arctic zone

by Roman Y. Shestakov, Ilmar R. Aysmatullin, Vladislav N. Slepnev*, and Sergey A. Polovkov
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The Zapolyarye - Purpe trunk oil pipeline runs through an area with an arctic climate (Yamalo-Nenets autonomous region), which is characterized by a prolonged, harsh, winter and relatively short but warm summer. In these conditions, the technology for transporting crude hydrocarbons necessarily includes preliminary heating to +60°C of the high-viscosity oil mix which is to be pumped. However, in the case of damage to the pipeline system, a ‘hot’ oil spill could cause the deformation of permafrost soils, as could subsequent actions to deal with the emergency situation and its consequences. This deformation would lead to irreparable damage to the Arctic environment and may result in more accidents on the trunk pipeline. In order to develop protective measures, the sections of the pipeline which are potentially most dangerous must be identified; the possible volume of an oil spill in the case of an accident should be calculated; and the route it would spread should be predicted.

This article examines the most dangerous possible incident, where the main factor affecting the spread and accumulation of spilled oil would be the topography of the area. A guillotine rupture of the pipeline was chosen as the event triggering the spill, because this type of failure would cause the greatest volume of transported liquid to be spilled. Modelling allows the furthest places where the liquid could drain and accumulate to be assessed. In order to exclude the threat of oil entering bodies of water, the necessity of constructing permanent barriers is indicated, which would prevent the spill from spreading. In order to save time in mobilizing technology and equipment to the site of the emergency situation, the creation of base stations is recommended: technically equipped bases, which would be located in the immediate vicinity of the most vulnerable sections of the pipeline route.

The systematic approach described in this article allows us to obtain the fullest and most realistic picture of events in the case of an accident on the trunk pipeline. These results may be used to develop protective measures aimed at minimising damage and at reducing as much as possible the impact of a possible oil spill on the fragile natural balance of the Arctic. The results may also be relevant when planning new trunk pipelines and reconstructing existing pipelines, and for setting-up a system of protective structures.

Introduction

In January 2017, the Zapolyarye - Purpe trunk oil pipeline was brought into operation - the northernmost pipeline in the Transneft system. The geographical location of the pipeline is shown in Fig.1. The pipeline’s operating conditions significantly limit the possibility of eliminating the consequences of a possible oil spill.

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accident in the system and, among other issues, they greatly complicate the process of containing the oil spill.

The Zapolyarye – Purpe trunk pipeline runs through an area with an arctic climate, whose features include an extended harsh winter and relatively short, but warm summer. The overall direction of the route is from North to South. The region where the pipeline is constructed is distinguished by its extremely difficult geology: more than 50% of the area is made up of permafrost soils, 70% of which are boggy and waterlogged.

The crude blend designated for pumping has high viscosity and a pour-point of +17°C. Accordingly, specially equipped heating stations are placed along the route in order that it may be heated to +60°C [1].

If an emergency situation, the impact of ‘hot’ crude and the oil spill containment works could cause deformation to the permafrost soils of the Arctic, which would not only disturb the delicate balance of the unique climate system and cause irreversible damage to the natural environment of the region, but could also lead to further accidents on the pipeline.

Consequently, issues connected with preventing accidents and minimizing their consequences are of paramount importance, starting from the climatic conditions and the topography of the area: evaluating the risk of damage to the pipeline occurring; selecting and developing methods of the spill containment; and erecting protective structures with this aim in mind.

The above-mentioned points testify to the necessity of forming a systematic approach to forecasting accidents on the trunk pipeline in the Arctic zone of the Russian Federation, and preparing to put in place optimum measures to reduce the possible area of oil contamination and, correspondingly, to minimize damage to the environment.

**Research methods**

The Zapolyarye - Purpe pipeline was constructed using mainly above-ground methods. This choice can be explained because, among other reasons, when using underground methods to build a trunk line designed for transporting hot oil, at sections where permafrost soils are widespread, circular thawing zones will form around the pipeline, leading to the development of extended waterlogged zones along the pipe. This in turn provokes the active development of erosional processes leading to soil deformation, which may trigger non-uniform displacements of the pipeline, and thus threaten its integrity. As such, an emergency situation may arise. Similar processes may also be caused by an accidental spill of hot oil. Moreover, soil deformation can be caused by works carried out for the oil-spill containment and elimination, and for oil-contaminated soil remediation.

In forming a systematic approach to
forecasting accidents on trunk pipelines in the Arctic zone, it is advisable to begin by identifying sections of the pipeline which are potentially at risk from accidents. In the context of this article, the procedure for evaluating the risk of an accident arising has been used in order to solve this task. However, it is first worth describing the most likely incidents on an oil pipeline which could have the consequence of an oil spill.

Toward this end, 107 incidents were analysed on the linear sections of trunk pipelines in the period from 1998 to 2010, including such sections of trunk pipeline as underwater crossings and joints at the position of air valves, shut-off and control valves, and launching and receiving stations for cleaning and diagnostic devices (utility and intelligent pigs). Of these, 97 incidents were connected to oil leaks in the linear sections of the oil pipelines, and seven incidents were linked to oil leaks in the areas where features of the trunk pipeline were located (joints at the position of air valves, shut-off, and control valves, and pig launching/receiving stations); three incidents were linked with oil leaks at underwater crossings of the trunk pipeline (Fig.2).

In the majority of the incidents examined, (87%) the oil spill did not lead to ignition. In 14 cases (13%) ignition of the liquid being transported did occur. Of these, ignition took place most often during scheduled or repair work at the linear

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**Fig. 2 Distribution of incidents by location:**

- blue: incidents linked to oil leaks in linear sections;
- red: incidents linked to oil leaks in the area around the location of features;
- green: incidents linked to oil leaks at underwater crossings.

107 incidents were analysed.

**Fig.3. Distribution of incidents by ignition:**

- red: incidents without ignition;
- blue: incidents with ignition.

107 incidents were analysed.

**Fig.4. Distribution of incidents by casualties.**

- blue: incidents with casualties;
- red: incidents without casualties.

107 incidents were analysed.
sections of trunk pipeline, including joints at the position of air-valves, shut-off and control valves, and pig launching/receiving stations (Fig. 3).

Casualties were avoided in almost all – 104 out of 107 – of the incidents examined (Fig. 4).

Based on these data, to evaluate the risk of an accident arising at a pipeline, a hypothetical scenario will be examined where oil ignition does not occur and there are no human casualties (supposing, for example, the area where the trunk pipeline is located to be sparsely populated). In this case the greatest damage to the environment would be caused exactly by oil contamination.

Risk is a combination (product) of the probability (or frequency) of damage being inflicted, and the severity of that damage [2]. In a general form, the formula for risk can be presented as:

\[ R = \sum_{i=1}^{N} p_i U_i \]

where

- \( R \) = risk;
- \( N \) = the quantity of discrete values of possible damages (of one type, one dimension) or groups combining them;
- \( U_i \) = the discrete value of the damage (severity of the damage) to the health and life of the worker;
- \( p_i \) = the probability that this value of damage will occur (be inflicted).

In order to calculate the degree of damage an accident at a trunk pipeline may cause, two specific (per the unit of the pipeline length) indicators are taken as characteristic:

- specific expected losses of oil in the case of an accident;
- specific expected environmental damage from the accident.

Risk evaluation was carried out using the software Toxi+Risc version 4.4.1, and damage was evaluated in accordance with methodological recommendations [3].

Based on the results of the risk evaluation, all sections of the trunk pipeline (the design length of one section is 1 km) were characterized as having a low or, more rarely, a medium relative degree of danger of failure. The medium degree was determined by the probability of oil ingress into a body of water. Moreover, it is worth noting in particular that it was impossible to identify by using risk evaluation the most dangerous section of the pipeline, which can be explained by the use of the newest methods and innovative technologies in constructing the Zapolyarye - Purpe trunk pipeline, as well as by stringent quality requirements for the works. Therefore, it was decided to carry out further modelling of the pipeline section located in conditions with numerous bodies of water in close proximity to the oil trunk line route.

For the modelling, a guillotine rupture in the pipeline was chosen as the accident situation, causing the largest oil spill into the surrounding environment. The length of the experimental section of the pipeline was 11 km, and points of possible outflow were set at every 500 m. Depending on the purpose of modelling, the interval between points could be reduced, and their number increased. Only the accuracy of the initial topography data was limited. The total volume of spilled oil can be estimated using the formula:

\[ V = V_1 + V_2 + V_3 \]

where:

- \( V_1 \) = the volume of oil (or oil-product) leaked in a pressure flow, i.e. from the moment when damage occurs to the pumping stop, cu m;
- \( V_2 \) = the volume of oil (or oil-product) leaked in a pressureless flow, i.e. from the moment of the pumping stop to the closure of the pipeline valves, cu m;
- \( V_3 \) = the volume of oil (or oil-product) leaked from the moment of the pipeline valves closure to the
leakage stop (until the moment emergency response team arrives and the leak is eliminated, or until the total emptying of the isolated section of the trunk pipeline), in \( \text{cu m} \).

The volume of oil leaked from each point was calculated taking into account the time needed to close valves and the topography in accordance with guidelines [4], as well as with the programme Risk - oil - pipeline, approved by the letter of the Gosgortekhnadzor [the Federal Mining and Industrial Inspectorate] of Russia on 07.07.1999 No 10-03/418. The volume of possible oil leaks is presented in Table 1.

Modelling was carried out using the module Oil-product spill (onshore) in the software complex ArcGIS (hereinafter - Module). The results of laser scanning of the area along the pipeline route were taken as initial data for the topography. Using contour lines and elevations, and ArcGIS processing, a regular topography grid was obtained (in GRID format). The topography conversion is shown in Fig.5.

However, the topography obtained in the process of modelling does not represent many particular features of the area through which the pipeline runs. An understanding of these can be gained from real photos of the route (for example, in Fig.6).

In order to adjust the relief model, information from satellite images and maps was used, which is freely available in the Internet. Bodies of water located in close proximity to the pipeline route were plotted on the terrain map. The module used enables modelling under the condition of oil reaching a hard surface. Therefore, in the examined case of the area being significantly water-logged, the following assumption was used: upon reaching a body of water, oil would not flow out of its limits. For that, bodies of water are presented on the terrain as depressions in the ground. The process of topography adjusting is presented in Fig.7.

For visual clarity, the final version of the topography is presented in 3D format (Fig.8). Satellite images can be used as the mount instead of a map (Fig.9).

The procedure of the Express-evaluation module was used for modelling, as it helps to identify the furthest places from the pipeline route where the oil could drain and accumulate.

The following assumptions were made in this method of modelling [5]:

- oil flows down in the terrain in the direction of the steepest descent;

<table>
<thead>
<tr>
<th>Point no.</th>
<th>Volume of oil leak in the case of a guillotine rupture, in ( \text{cu m} )</th>
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<tbody>
<tr>
<td>1</td>
<td>1576</td>
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<tr>
<td>2</td>
<td>2346</td>
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<tr>
<td>3</td>
<td>2825</td>
</tr>
<tr>
<td>4</td>
<td>3128</td>
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<td>3000</td>
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<td>6</td>
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<td>3309</td>
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<td>8</td>
<td>3320</td>
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<td>9</td>
<td>3658</td>
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<td>10</td>
<td>3697</td>
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<td>3739</td>
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<td>12</td>
<td>3834</td>
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<td>21</td>
<td>1581</td>
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<td>22</td>
<td>1541</td>
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</table>

Table 1. The volume of possible oil leakage in the case of a guillotine rupture in the pipeline.
• where the oil reaches a local depression, it will fill up to the spillover point;
• where the capacity of the local depression is insufficient to contain the volume of the spill, the minimum height at the edge of the basin of the local depression is calculated. Further calculation continues according to point 1, where the remaining volume of oil is defined as the difference between the initial volume and the capacity of the local depression;
• if the capacity of the local depression if sufficient to hold the volume of spilled oil, the total volume of the spill is calculated by adding the volumes contained in separate cells of the terrain (neighbouring cells) up to the spillover moment;
• processes of evaporation and infiltration of the oil product are not considered here.

Research results

The modelling results are presented in Fig.10.

Places where it would be possible for an oil spill to enter bodies of water are circled in red. In the conditions examined here, these are the zones should be protected as a priority, and are in maximum need of the development and installation of protective measures and structures.

In order to exclude the possibility of oil reaching bodies of water, it is necessary to construct permanent barriers, which would prevent a spill from spreading. Considering the distinctive features of the environment in the Arctic zone of the Russian Federation, such barriers would have to be erected with minimal earthworks, and where possible without them entirely. In this article, two options for such structures are demonstrated as proposals for technical improvement:

Protective embankments (Fig.11) — the structure consists of a foundation laid on weak soil (bog of the first or second type). The foundation is made of logs firmly fastened to each other. Non-woven synthetic material (NSM) is used to cover the foundation, and sand ballast is spread on this, and it is subsequently sewn up with synthetic thread.

Geweb could serve as an alternative option for protective structures (this is often used in Arctic zone conditions in the Russian Federation when constructing temporary
roads). Cells of the web are filled with soil proper to the area. Depending on the necessary change in the topography elevation the Geoweb can be laid down in one or in several layers. An example overview of this protective structure is shown in Fig.12.

These suggestions should not be taken as a definitive solution to the issue of protective structures at the pipeline sections with high risk of accident.

Fig.6. The area where the Zapolyarye — Purpe trunk pipeline is constructed.

Fig.7. The process of topographic adjustment (left-right).
.overlay of the map; topography adjusting; topography for modelling.
However, they may serve as a starting point for further studies.

Moreover, in order to save time when mobilizing machines and equipment to the site of an emergency situation, it is proposed to establish the base stations — technically equipped bases located in the immediate vicinity of the most vulnerable sections of the pipeline route, and which in the case of an accident would allow a quick and full oil spill response.

In order to check the effectiveness of suggestions to set up additional protective facilities at accident-prone sections of the pipeline, remodelling was performed with 0.5-m high protective structures plotted on the route. The result of remodelling is shown in Fig.13 and a 3D projection is shown in Fig.14.

**Discussion**

An evaluation of the damage caused by an oil spill was carried out according to guidelines [3]. Overall, the damage from an accident at a dangerous production facility can be expressed in the formula:

\[
P_a = P_{pp} + P_{la} + P_{as} + P_{ns} + P_{mol} + P_{stp}
\]

where:
Fig. 11. Structural concept of the protective embankment
1 - foundation made of firmly fastened logs;
2 - synthetic material;
3 - sand ballast;
4 - synthetic threads.

Fig. 12. Overview of Geoweb.

$p_a$ - the total damage from the accident, in roubles;
$p_{pp}$ - direct losses to the organisation running the dangerous production facility, in roubles;
$p_{la}$ - the expense of containing and eliminating the incident, and investigating it, in roubles;
$p_{se}$ - the social-economic losses (expenses as a result of deaths and injury to people), in roubles;
$p_v$ - the indirect damage, in roubles;
$p_{ec}$ - the ecological damage (caused to features of the surrounding environment), in roubles;
$p_{lcp}$ - losses from the decrease of labour resources as a result of people’s deaths or disability in roubles.
The economic effect of the measures described in the article has been estimated approximately by comparing the magnitude of damage from oil reaching bodies of water and the size of expenditure for installing protective structures.

Considering the design documentation and the conditions of use of the Zapolyarye - Purpe trunk pipeline, the maximum mass of a possible spill at the pipeline would be 3,734 t. The mass of oil entering the water is taken to be 75% of the mass of the possible spill and therefore equals 2,800 t.

The potential damage from contaminating
the environment as a result of an accident at bodies of water would be in the region of 16.5 billion roubles. The cost of works to construct a containment boundary at a distance of 1 km would be approximately 5 million roubles. Taking into account the area topography, the required reserve of protective facilities would be 20 km. Total expenses for setting up protective structures would be around 100 million roubles.

It can thus be seen that, if the protective measures described in this article are put into place, and if their implementation successfully prevents oil from reaching bodies of water, the economic effect of setting up these protective structures in areas where there is a high risk of damage to pipelines located in the Arctic zone of the Russian Federation, would total approximately 16.4 billion roubles.

Conclusions

The approach described in the article has a methodical character and allows the fullest and most realistic picture to be obtained of events’ escalation in the case of an accident at a trunk pipeline. The results obtained may be used to develop protective measures aimed at minimising damage and reducing the impact of a possible oil spill on the fragile natural balance of the Arctic. They may also be relevant when planning new trunk pipelines and when reconstructing pipelines currently in use, and when setting up systems of protective structures.

Acknowledgements

The authors would like to express their thanks to colleagues at the department of geotechnical inspection for facilities control at the Pipeline Transport Institute, and personally to the head of the department, T. I. Kuznetsov, as well as to the director of the centre for monitoring and geoinformational systems of pipeline transport facilities at the Pipeline Transport Institute, V. I. Surikov, for providing the initial data used to build the model of the area relief.

References

3. RD 03-496-02. Methodical recommendations for evaluating damage from accidents at dangerous manufacturing facilities.
Listing of forthcoming industry events (continued from p 172)

Pipeline Coating
13-15 February 2018
Vienna, Austria
https://www.ami.international/events/upcoming
10th Global Conference on Pipeline Coating provides a unique forum for the world’s leading pipeline contractors, operators, pipe mills and pipe coaters, engineers and specifiers, researchers, raw materials and machinery suppliers to debate the latest pipeline protection technology and worldwide industry trends.

Offshore Arabia 2018; 9th Offshore Arabia Conference and Exhibition
28 February 2018 - 01 March 2018
Dubai, UAE
http://offshorearabia.ae/about-us/
This event will provide the opportunity to showcase the ‘state of the art’ technology and know-how of the Oil and Gas and the Marine and Maritime sector. The event will also reflect every organization’s commitment to marine and the environment.

GEO 2018
5 March 2018 – 8 March 2018
Manama, Bahrain
http://geo2018.com/
13th Middle East Geosciences Conference and Exhibition is the showcase of oil & gas exploration technology and services in the Middle East, attracting NOCs, IOCs and major operating companies.

IHS Energy CERAWeek
5-9 March 2018
Houston, Texas, USA
http://ceraweek.com
IHS CERAWeek is the annual international gathering of energy industry leaders, experts, government officials and policymakers, leaders from the technology, financial, and industrial communities - and energy technology innovators.

13th Pipeline Technology Conference
12-14 March 2018
Berlin, Germany
www.pipeline-conference.com
The conference and exhibition on high-pressure pipeline systems. The 13th PTC offers opportunities for operators as well as technology and service providers to exchange latest onshore and offshore technologies and new developments supporting the energy strategies world-wide.

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Possible ways to achieving high-accuracy sizing of defects discovered by ILI tools

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The main goal of in-line inspection (ILI) is (according to the seven basic ILI quality metrics [1]) to correctly detect, locate, and identify all types of defects present in a pipeline and to size them in a fashion which allows statistical assessment of their true sizes. If achieved, the last fact opens the door widely to meaningful usage of the most sophisticated methods of structural mechanics (which were developed spending worldwide billions of $$$ but not used yet to its fullest in the pipeline industry) and obtaining most-accurate values possible of pipeline residual strength, probability of failure, and residual lifetime. This, in its turn, permits using predictive-maintenance technology in pipeline operation, introducing optimal inspections and repair logistics, and maximizing the long-term utility of the asset (in our case, the pipeline system).

The paper describes the methodology developed by the authors of a holistic innovative approach to ILI data generation and data management, which dramatically increases ILI inspection capabilities. This methodology, to a large extent, decreases the existing uncertainties and minimizes scatter of the input parameters and, thereby, makes predictions based on ILI data less conservative. As a result, this permits creation of safe solutions and avoidance of dangerous errors in predictions which include assessment of pipeline inspection frequency and safety margins.

According to the API 1163 Standard [2], the ILI measurement results are characterized by three parameters of statistical nature: tolerance, certainty, and the confidence level. Tolerance is the range with which anomalies dimension or characteristic is sized, and certainty is the probability that a reported anomaly characteristic is within a stated tolerance. Confidence level (CL) is a statistical term used to describe the mathematical certainty with which a statement is made, and indicates the confidence with which the tolerance and certainty levels are satisfied. The paper discusses the statistical sources of these probabilities and how they should be interpreted and handled. The paper contains recommendations on how to approach different practical problems, and illustrates each case with real-life examples.

Key words: pipelines, defects, in-line inspection, measurement errors, statistical analysis.

According to API 1163, ILI measurement results are characterized by three parameters of statistical nature: tolerance, certainty, and confidence level. Tolerance is the range with which anomalies dimension or characteristic is sized, and certainty is the probability that a reported anomaly characteristic is within a stated tolerance. Confidence level (CL) is a statistical term used to describe the mathematical certainty with which a statement is made.

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and indicates the confidence with which the tolerance and certainty levels are satisfied. Each of the parameters will now be considered separately.

The accuracy of any ILI tool is characterized by the tolerance of the measurements for a given certainty, which are found via its measurement error (ME). It is assumed that any measurement of the defect parameter made by using an ILI tool is, with probability $p$, inside the limits $\pm k \cdot wt$, where $k$ is a portion of pipe wall thickness $wt$. For instance, for HR ILI tools, the tolerance for defect depth is 10% $wt$ ($k = 0.1$) with probability $p = 0.8$ (80% confidence interval). This can be expressed as:

$$P(X - \mu \leq k \cdot wt) = 1 - \alpha = p \quad (*)$$

where $X$ is the error of a single arbitrary measurement of the defect depth; $\mu$ is the mathematical expectation of the ME; $\alpha = 1 - p$ is the confidence level; $p$ is the certainty according to API 1163 [2]; $k \cdot wt$ is the statistical accuracy (tolerance, according to API 1163 [2]).

Usually it is assumed that MEs are normally distributed with zero mathematical expectation. In this case the graphical interpretation of the ME distribution for different values of certainty $p$ has the form as given in Fig.1. The random value ME is inside the symmetrical interval, as related to the origin, $\pm k \cdot wt$; $k \cdot wt$, with probability $p = 1 - \alpha$. For instance, $p = 0.8$, then 80% of all MEs will be inside the interval $[\pm k \cdot wt; k \cdot wt]$. Hence, the total area of the tails is equal to $\alpha$. The interval is symmetric; therefore, area of each tail is equal to $\alpha / 2$. According to the properties of the normal probability-density function (PDF), Equn (*) can be expressed as in Equn 1 (below) where $\Phi(x)$ is the standard normal cumulative distribution function (CDF).

From Equn 1 it follows that the tolerance for the ILI tool is calculated according to:

$$k \cdot wt = z_{1-\alpha/2}\sigma$$

$$P(-k \cdot wt < X < k \cdot wt) = 1 - \alpha = 2\Phi\left(\frac{k \cdot wt}{\sigma}\right) - 1 \quad (1)$$

where $z_{1-\alpha/2}$ is the quantile of the standard normal distribution of level $1 - \alpha/2$.

Hence, with known ILI tool tolerance (from Equn 2) it is possible to define the standard deviation (SD) of tool MEs.

The meaning of the confidence level is in that when, for instance CL = 95%, the certainty = 80%, and the tolerance = 10% $wt$, then in 95% of the time conducting ILIs, 80% of the MEs will be within the boundaries $\pm 10% wt$. Visualization of this fact is given in Fig.2, which reflects results of 15 computer-simulated ILIs. In each of the virtual ILIs, 30 MEs were made. In Fig. 2 the rectangle represents a sample of MEs. The red vertical lines are sample medians (50% level quantile), and the boundaries of the rectangles are the 10% and the 90% sample quantile. The length of the rectangle embodies 80% of all the MEs. The horizontal lines represent the scatter of the MEs. From Fig.2 it can be seen than in one of the 15 sets of virtual ILIs the left boundary of the rectangle is out of the 10% $wt$ limit.

### Types of defect size adjustments

Over the years, the world pipeline industry has developed several engineering schools of thought (ESTs) regarding defect sizing (see, for instance, Refs 3, 10, 11). One of the ESTs is presented in the API 1163 Standard [2], and utilizes the unit curve concept (which is equivalent to accepting no bias in both ILI and verification instrument (VI) readings, no MEs in the VI readings and normal distribution of the ILI MEs). The other, most commonly used types of adjustment can be formalized as follows:

$$d_V = d_v (\sigma_V = 0) \quad (4)$$

$$d_{adj} = d_I \cdot k \quad (5)$$

<table>
<thead>
<tr>
<th>Unit curve (no bias admitted)</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_V = d_v (\sigma_V = 0) \quad (4)$</td>
<td></td>
</tr>
<tr>
<td>$d_{adj} = d_I \cdot k \quad (5)$</td>
<td></td>
</tr>
</tbody>
</table>
\[ d_{\text{adj}} = d_i + k\sigma_{\epsilon I} \]  
\[ \sigma_{\text{adj}} = k\sigma_{\epsilon I} \]  
\[ \sigma_{\text{adj}} = \sigma_{\epsilon I} + \Delta_{\text{adj}} \]  
\[ d_{\text{adj}} = \phi(d_i, d_V, \sigma_{\epsilon I}, \sigma_{\epsilon V}) \]  
\[ d_{\text{adj}} = d_i + \sqrt{\text{tol}_i^2 + \text{tol}_V^2} \]  

Probability of exceedance method

Here \( d_i, d_V \) are correspondingly the ILI tool and the VI measurements; \( \sigma_{\epsilon I}, \sigma_{\epsilon V} \) are correspondingly the SDs of the ILI tool and the VI measurement errors; \( \text{tol}_i, \text{tol}_V \) are correspondingly the tolerances for the ILI tool and the VI measurements; \( d_{\text{adj}}, \sigma_{\text{adj}}, \Delta_{\text{adj}} \) are correspondingly the adjusted ILI tool reading, adjusted SD, and the adjusting safety margin; \( k (k > 1) \) is a multiplicative safety coefficient.

We will now proceed to a description of each approach defined above.

The statement in Equn 3 surmises that both measurement instruments (ILI tool and VI) are free of any MEs.

Equation 4 means that the VI measurements do not contain MEs, i.e. VI is 'ideal', and this can never happen. The assumption that VI is ideal may lead to assigning de facto its MEs to the ILI tool, which will lead to an unjustified low assessment of its quality. This is especially important to account for when assessing possibilities of an ILI tool or of a candidate diagnostician. Hence, it is necessary to assess the MEs of each instrument separately.

The simplest types of adjustments are presented by Equns 5 and 6. They amount to multiplying the ILI readings ('raw' ILI data) by a coefficient, which is more than unity. Sometimes, this type adjustment is applied to the SD of ILI readings; see Equns 7 and 8. In Equn 8 the term is a safety margin added to the SD. In general, the adjusted ILI reading is a function of the readings of both ILI and VI instruments, and of the SDs of the MEs of both tools (Equn 9). The explicit expression which accounts for this is given by Equn 10, and Figs 1 and 3. According to them, the tolerance for the ILI readings is taken at the certainty (in API 1163 wording) of 80% (recently, some companies started to prefer 90%). Under the 80% certainty the tolerance for the ILI tool would be ± 1.28 \( \sigma_{\epsilon I} \) (see Equn 2). For the 90% certainty the tolerance is ± 1.65 \( \sigma_{\epsilon I} \).

The probability of exceedance approach per se (Equn 11) is a staple model in structural reliability theory, where it is widely used in conjunction with the random-function theory. When applied to the problem being discussed in this paper, the main problem is how to construct the PDF for the ME of the ILI tool, and whether to select the level of exceedance as a deterministic or a random value.

Full statistical analysis method of ILI results

This section describes a methodology for full statistical analysis of ILI results considering a more-general practical case, when the ILI tool measurements contain not only random ME, but also systemic ones (constant and multiplicative bias). The methodology consists of the actual ILI tool accuracy-assessment technique used in the process of a specific pipeline inspection, and the calibration technique of all (verified and unverified) ILI tool measurements for the purpose of...
obtaining more-accurate values of the measured defect parameters.

Consider the most-common practical case when the ILI tool possesses both random and systemic MEs, and the verification tool only random ME. The mathematical model of measurements in this case will have the form:

\[ p_t = \alpha + \beta p_i + \varepsilon_I \]
\[ p_v = p_u + \varepsilon_V \]  

where \( p_u \) is the true (unmeasurable) value of the parameter to be measured; \( p_i \) is the ILI tool reading; \( p_v \) is the VI reading; \( \alpha \) and \( \beta \) are, respectively, the intercept and the slope of the regression line (RL) of the ILI tool, related to constant systemic measurement errors: \( \alpha \) is the average bias, \( \beta \) is the multiplicative bias; \( \varepsilon_I \) is the random measurement error of ILI tool; \( \varepsilon_V \) is the random measurement error of the VI.

According to measurement model (Equation 12), the accuracy will be determined by statistical characteristics of measurement errors \( \varepsilon_I, \varepsilon_V \), in particular, only by their variances; the mathematical expectation of ME equals zero.

The methodology consists of subsequently solving the following sub-problems:

- assessment of the measurements model parameters (Equation 12) (constant ILI tool measurement bias);
- assessment of the ILI tool and VI MEs variance;
- assessment of the true sizes of verified defects;
- assessment of the calibration line parameters, using which it is possible to obtain more accurate values of the unverified ILI tool measurements.

This technique is based on variance and regression analysis, and consists in comparing the diagnostics results with the verification data, limited in scope. Its final goal is calibration of the diagnostic results for obtaining a more-accurate assessment of the true values of the defects parameters. The technique provides capability for:

- Assessment of the actual accuracy of the implemented ILI tool in real-life conditions of its operation.
- Improving the accuracy of all (verified and unverified) measurements of defects sizes based on joint analysis of the diagnostics results and the limited in scope verification. This leads to a significant savings of funds and labour.

Assessment of the constant bias of the ILI tool measurements

Method of moments

For assessing the average and the multiplicative bias of the ILI tool measurements, which are included in the measurement model (Equation 12), it is
necessary to build a scatter diagram of the verified measurements and determine the RL parameters of the ILI tool and the VI measurements. The VI measurements are assumed to be the independent variable (regressor). In this case the problem of assessing the regression line parameters is non-trivial, since the independent variables of the measurements regression model (Equn 12) contain ‘inherent’ errors (stochastic regressors). Therefore, the use of the classic least-squares method (LSM) becomes impossible because the assessment by LSM will be, in general, biased and inconsistent [8].

Provided that the VI ME is known in advance, the consistent assessments of parameters $\alpha$ and $\beta$ of the measurement model (Equn 12) has the form [4]:

$$
\hat{\sigma}_\varepsilon^2 = s_{IV}^2, \quad \hat{\sigma}_\varepsilon^2 > \sigma_{IV}^2
$$

(13)

where $\overline{p_I}, \overline{p_V}$ are the sample averages of the ILI tool and VI measurements respectively; $s_I^2$ is the unbiased sample variance of the ILI tool measurements; $s_V^2$ is the unbiased sample variance of the VI measurements; $s_{IV}^2$ is the ILI tool and the VI measurements covariance.

Assessment of the ILI instrument accuracy

The case when the ILI tool measurements do not contain a multiplicative bias

For this case, when in the measurements model (Equn 12) $\beta = 1$, the method of assessing the error variances $\hat{p}_p, \hat{e}_e$ was proposed by Grubbs [6]. According to his approach, the variance of the measurements, obtained using an arbitrary MI, consists of two parts:

- variance of the true values of the measured parameter (i.e. defect depths);
- variance of the ME of the measurement instrument used.

The sample assessment of the covariation between two MIs is a non-biased assessment of the true sizes of defects. Then, the assessment of the ME variance of each MI can be evaluated as the difference between the sample variance of measurements of the MI being assessed, and the sample assessment of the covariation of the measurements:

$$
\hat{\sigma}_{I}^2 = s_{IV}^2 - s_{II}^2 = \sigma_{IV}^2 - \sigma_{II}^2
$$

(14)

$$
\hat{\sigma}_{V}^2 = s_{IV}^2 - s_{IV}^2
$$

(15)

In the case when one of the assessments in Eqs 14 or 15 turns out to be negative, Thompson [9] suggested using the following assessments (on the premise, that $\hat{\sigma}_{I}^2$ is negative):

$$
\hat{\sigma}_{I}^2 = s_{IV}^2 - s_{II}^2 - 2s_{IV}^2
$$

(16)

where $\sigma_{II}^2$ is the true value of the defect parameter $p_p$, variance.

Considering that the unbiased sample variances of ILI tool and VI measurements $s_I^2, s_V^2$ are the unbiased assessments of theoretical variances $\sigma_I^2, \sigma_V^2$ respectively,
the assessment of ILI tool ME and the assessment of the defect parameters true values variances may be found from Eqn 16 by equations:

\[ \sigma_{IV}^2 = s_{IV}^2 - \frac{s_{IV}^2}{\beta} \]

\[ \sigma_{el}^2 = s_I^2 - \beta s_{IV} \]  \hspace{1cm} (17)

where \( \beta \) is the assessment of the RL slope.

In a number of real-life cases the assessments obtained with the use of Eqn 17 were negative. This occurs when, and only when [5]:

\[ s_I^2 (s_{IV}^2 - \sigma_{IV}^2) - s_{IV}^2 \leq 0 \]  \hspace{1cm} (18)

When assessments of the ME variance (Eqn 17) are negative, it is possible to use the method developed by Jaech [7], according to which:

\[ S = \sigma_{IV}^2 + \sigma_{el}^2 = s_{IV}^2 - \frac{s_{IV}^2}{\beta} + s_I^2 - \beta s_{IV} = \]

\[ s_{IV}^2 + s_I^2 - s_{IV} \left( \frac{1}{\beta} + \beta \right) = \]

\[ s_{IV}^2 + s_I^2 - s_{IV} \left( \frac{1 + \beta^2}{\beta} \right) \]  \hspace{1cm} (19)

The formulas in Eqn 19 are used when the ILI tool measurements do not contain a multiplicative bias. If \( \beta \neq 1 \), the Jaech method has to be modified in the following way. Zero-in on the expression for covariation, for which purpose modify formulas for \( S \) and \( f(x) \).

Now consider the sum of MEs variations, using Eqn 17:

\[ \sigma_{IV} = \frac{1}{l} \]

\[ \sigma_{el}^2 = S - \sigma_{IV}^2 \]

\[ S = \frac{n}{n-1} (s_I^2 + s_{IV}^2 - 2s_{IV}) \]

\[ I_0 = \int_0^1 x \cdot f(x) \, dx \]

\[ I_1 = \int_0^1 f(x) \, dx \]

\[ f(x) = \left[ s_{IV}^2 (1 - x)^2 + s_I^2 x^2 + s_{IV} x \left( 2x \frac{1 + \beta^2}{\beta} \right) \right]^{-n/2} \]  \hspace{1cm} (20)

The sum of \( S \) and function \( f(x) \) are interconnected; hence, expression for \( f(x) \) can be written as follows:

\[ f(x) = \left[ \frac{n}{n-1} s_I^2 + 2x(s_{IV} - s_I^2) + s_{IV}^2 \right]^{-n/2} \]  \hspace{1cm} (21)

Then, taking into consideration Eqn 20, Eqn 21 takes the form of Eqn 22 (below).

Therefore, when \( \beta \neq 1 \) in Eqn 19, \( S \) is calculated using Eqn 20 instead of Eqn 19 and Eqn 22 instead of \( f(x) \). Other equations of the Jaech method remain unchanged.

It should be noted, that in reality the sample covariation \( S_{IV} \) may also be negative. This happens only in the case when small values of one tool’s measurements are related to the large values of the other measurement tool. This is a sign to reject one of the tools as unsuitable for use.

**Example 1**

Initial data for simulating measurements of defects depth was obtained using Eqn
12 which has \( \alpha = 0, \beta = 1 \), and the Monte Carlo simulation method. Conduct an experiment which consists in modelling \( N = 10000 \) sets of pairs of measurements of defect depths. Applying the Grubbs method (or the modified Grubbs method) to each set of measurements, we find that in most cases the assessments of the MEs variances are negative (see Fig.4). Application in this case of the Jaech method or its modification allows obtaining only positive values of the MEs variance (see Fig.5).

Method of increasing the measurement accuracy (calibration) of defects parameters

Consider the method of assessing the true sizes of defects, and rewrite the measurements model (Equn 12) in matrix form:

\[
\begin{pmatrix}
    p_l - \alpha \\
    p_V
\end{pmatrix} =
\begin{pmatrix}
    \beta \\
    1
\end{pmatrix} p_v +
\begin{pmatrix}
    \epsilon_l \\
    \epsilon_V
\end{pmatrix}
\]

Denote:

\[
Y = \begin{pmatrix}
    p_l - \alpha \\
    p_V
\end{pmatrix}, \quad X = \begin{pmatrix}
    \beta \\
    1
\end{pmatrix}, \quad E = \begin{pmatrix}
    \epsilon_l \\
    \epsilon_V
\end{pmatrix}
\]

Then, the measurements model can be rewritten as:

\[
Y = p_v X + E \quad (23)
\]

Expression 23 is a generalized linear regression model, where \( p_v \) is the unknown parameter (the true value of the verified defect parameter).

According to the Aitken theorem [8], the best (effective) unbiased assessment of the unknown parameter \( p_v \) of Equn 23 is the assessment obtained using the generalized least-squares method (GLSM).

Assessment of the true size of the verified defect parameter shall assume the form:

\[
\hat{p}_v = p_V + c_1 r \quad (24)
\]

where \( c_1 = f(\hat{\beta}, \hat{\sigma}^2_I, \hat{\sigma}^2_{IV}) \). This function is determined from the assessment of the unknown parameter \( p_v \) with GLSM.

The final goal of this method is calibration of the raw ILI tool measurements, i.e. defining the calibration line parameters, with the help of which it is possible to adjust the defect parameters values of all other, unverified ILI tool measurements. If the calibrating experiment is performed on a sample of size \( n \), then the adjusted defect parameter value for the \((n+1)\)-th unverified measurement \( p_{I}^{n+1} \) is determined from equation:

\[
\hat{p}_v^{n+1} = \hat{\xi} + \hat{\gamma} p_I^{n+1} \quad (25)
\]

where \( \hat{\xi}, \hat{\gamma} \) are the calibration line parameters.

Some analysis results from real cases

Case 1: oil pipeline

Measurements of defect depths conducted by the ILI tool and the VI were used. Information about the accuracy of both the ILI tool and the VI are absent. This circumstance (here and everywhere...
below) is not an obstacle for assessing the accuracy of both tools. In the calculations 86 pairs of independent measurements (ILI + VI) of 86 defects were used. Calculations were conducted for cases, when:

- all measurements were verified (Fig.6);
- only 30 measurements were verified (Fig.7).

Comparing these cases, it can be seen that just 30 verification measurements yield results which are very close to the results obtained when total verification is performed.

Case 2: gas pipeline

Analysis of the ILI results was performed as requested by the pipeline operator. It shows (see Fig.8), that for some reason the ILI data are over-reporting: they have a considerable (though conservative) bias and a large variance. This could be the result of a 'safe' adjustment of the raw ILI data.

The difference between the variances of the ILI tool and the verification instrument was larger than 10%. According to the EPRI (USA) criteria, in such cases the ILI tool has to be recalibrated or the results rejected. Using the above algorithm allows the operator to independently assess the actual accuracy of the ILI tool as demonstrated on the specific inspected pipeline. The operator should provide for both measurements to be conducted independently.

Conclusions

The general methodology of statistical analysis of ILI data outlined here permits:

- Assessing the components of the total variance of the ILI technology, including attribution of measurement-error variance to the ILI tool and the verification tool.
- Constructing consistent assessments (with minimal bias) of true sizes of defect parameters and their variances for cases when information about the ILI tool and VI is available, by filtering the measurement results from statistical debris, outliers, and noise.
- Implementation of the approach described above, as it opens the door for a consistent solution of problems of residual strength, lifetime, reliability, and risk assessment of pipelines.

Usage of this methodology necessitates relatively insignificant expenditures, but yields substantial savings in pipeline operation and risk.

References


Listing of forthcoming industry events (continued from p 184)

Australasian Oil & Gas Exhibition & Conference (AOG)
14-16 March 2018
Perth, Australia
http://www.aogexpo.com.au
The annual Australasian Oil & Gas Exhibition & Conference (AOG) is the platform event for the Australian oil and gas industry featuring over 200 exhibiting brands. This event is a showcase of the latest products and attracts over 8,000 global visitors providing opportunities to network and learn about the latest technological and innovative breakthroughs which will drive the industry into the future.

5th East Africa Oil & Gas Summit and Exhibition
14-16 March 2018
Nairobi, Kenya
http://www.eaogs.com
The oil and gas show for the East Africa region with more than 2,500 participants, 380 companies and 30 countries. Hosted by the Ministry of Petroleum.

49th Annual Conference
15-18 March 2018
Stein Eriksen Lodge, Deer Valley, Utah, USA
https://psig.org
Advancing the state of the art of modelling, simulation, optimization, steady-state and transient flows, single and multiphase flows, and related subjects as applied to fluid pipeline systems.

continued on p 194
Listing of forthcoming industry events (continued from p 193)

Pumps & Valves
21-22 March 2018
Antwerp, Belgium
http://www.easyfairs.com
The trade show on industrial maintenance, asset management, shutdowns and production reliability. The exhibition that presents products and services such as: Control valves, Industrial pumps, Seals, valves, Processing equipment, e.g. mixers and stirrers, Filters & filtration, Services for governmental agencies, industry and pipeline operators and Piping & pipelines.

7th North Africa Petroleum Exhibition & Conference
25-28 March 2018
Oran, Algeria
http://napecdz.com
NAPEC is the oil and gas exhibition & conference in Africa focusing on the North Africa Market. dedicated to the Upstream, Midstream and Downstream activities.

OGWA
26-28 March 2018
Muscat, Oman
http://www.ogwaexpo.com
OGWA is a biennial international exhibition and conference that brings together local and international oil and gas companies from the GCC, technology and service providers, equipment suppliers, and other companies directly serving the industry’s requirements.

CIPE Beijing
27-29 March 2018
Beijing, China
China International Exhibition on Equipment of Pipeline and Oil & Gas Storage and Transportation

ciooe Beijing
27-29 March 2018
Beijing, China
18th China International Offshore Oil & Gas Exhibition is an annual Exhibition where plenty of useful goods can be displayed. Most of these are typically about energy, power, natural resources, oil and gas, petroleum, refining, petrochemicals and offshore technologies.

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A comprehensive study of steel properties in trunk oil and petroleum product pipelines with various service lives

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2 Transneft PJSC, Moscow, Russian Federation

The article examines the approaches of a number of scientific institutions to the degradation of mechanical properties in pipe steels which may occur over long-term service life. It also presents the results of research into the actual mechanical properties and chemical composition characteristics of pipe steels with various service lives. The classification (ranking) of pipe steels of various grades used by PJSC Transneft is presented according to the criteria of length, service life, manufacturer, regulatory documents for supply, etc.

The pipe steels are grouped according to their actual mechanical properties: ultimate strength, elongation, impact toughness, and chemical composition characteristics.

Key words: pipe steels, mechanical properties, pipe steel grouping, standard and special tests

The development of approaches to assessing changes in pipe steel characteristics while in operation

At the present, there are several approaches to assessing changes in pipeline steel characteristics over long-term operation have been developed; the best-known scientific institutions specializing in this field are:

• Nizhny Novgorod University (Research Institute for Physics and Technology at Lobachevsky State University of Nizhnyi Novgorod) analyses the physical mechanisms of ageing processes in low-carbon low-alloyed pipe steels used in trunk pipelines. Ageing is attributed to the diffusion-controlled movement of carbon atoms towards lattice defects and the formation of carbide particles at the grain boundaries [1]. The methodology of relaxation tests is suggested with an evaluation of the macro-elasticity limit, as the most sensitive parameter to ageing processes in pipe steels. The university is known for organizing the 2010 conference on ‘The problems of steel ageing and resources in trunk pipelines’.

• The I.P. Bardin Central Research Institute for Ferrous Metallurgy [2-8] studies the impact of long-term operation and hydraulic tests on the mechanical properties and fracture resistance characteristics of pipe steels. As such, the fracture...
Resistance characteristics of metal are shown to decrease. Pipe steel properties degrade due to local micro-stresses in the structure of the metal, deformational ageing processes and the build-up of defects such as micro-cracks. Here, authors employ the internal friction method to assess the concentration and mobility of point defects, dislocation structure, and the kinetics of initial stages of ageing.

- The research team at Togliatti State University [9-12] specializes in using acoustic emission methods to inspect materials and structures, and to evaluate material resources.
- Representatives of Belgorod National Research University are conducting studies into the assessment of resource and the durability of pipeline materials with various functions, including those for nuclear industry.
- The team at the quality and reliability laboratory for gas pipeline and gas field equipment materials at the Baikov Institute of Metallurgy and Material Science, Russian Academy of Sciences [19] has shown that the mechanical properties of trunk oil pipeline steels observed on standard samples in pipes after both long-term operation and from emergency reserves are practically the same. Over long-term operation under design conditions, the efficiency of microscopic mechanisms of hardening and embrittlement in pipe steel remains practically unchanged. Substructural heterogeneity in pipe metal, acquired during production causes significant dispersion of impact toughness values at different stages of operation.

However, impact toughness characteristics are crucial when dealing with the laws of pipe metal degradation over long-term operation in trunk oil pipelines.

- ZAO Melnikov Central Research and Design Institute of Steel Structures [14-15] has also been working on assessing the tendency for deformational ageing.
- The scientific Institute of Energy Supply Transport has formulated recommendations [16-18] according to which operating pressure should be reduced in comparison to design pressure as the pipeline ages (up to 29% when operating life exceeds 30 years).

Overall, the extensive and diverse studies carried out nationally and abroad cannot offer a clear-cut answer as to how long-term operation affects the performance of trunk oil pipelines and petroleum-product pipelines.

**Systematic studies into the properties of structural low-alloyed steels**

Since 2000, Transneft PJSC and the Pipeline Transport Institute, in cooperation with Baikov Institute of Metallurgy and Material Science, and IMASH RAN (the Mechanical Engineering Research Institute of the Russian Academy of Sciences), have been conducting research into the actual properties of pipe steels, including durability and resources for pipelines in long-term operation [21].

The basic results of this research are:

- there was no evidence of significant change to structural parameters and basic mechanical properties, characterising the reduction in static deformation resistance and damage resistance in pipe metal;
- structural indications of low-cyclic fatigue only appear in natural and artificial defect zones and are purely local;
pipeline leakage or failure occur in zones of operational defects;

- strength characteristics (yield strength and ultimate strength) in steels of pipes that have been operated, before and after bench tests, and those from emergency reserve, are higher than the values stipulated in the technical specifications which were in force when the pipes were manufactured;

- ductility characteristics (relative elongation of pipe steels) after operation are significantly dispersed in relation to the value given in technical specifications, but reduction of cross-sectional area decreases insignificantly over the service life.

These studies showed that the least reliable steel grades were 19G, 14KhGS, and Ts. The growth of defects to critical size is possible in these steels at the design pressure and as the operating period increases.

Forming and implementing the program of testing and studying properties of pipe steels in long-term operation

The above-mentioned works were developed at Transneft PJSC’s facilities into the concept of studying the mechanical and chemical properties of pipe steels used in operational pipelines and those under construction. Subsequently, recommendations for improving the general regulatory framework and methods were developed, along with calculations of strength and durability.

The concept comprises the following main stages:

- grouping and ranking of pipe steels;
- systematising design indicators for long-term operational, modern, and prospective pipe steels;
- substantiating a list of testing methods, as well as ways of evaluating strength, durability, and reliability;
- developing a methodology for a calculating and experimentally assessing strength, durability, and reliability.

At the first stage, the aims were:

- to group pipe sections according to steel grade (criteria: composition, alloying elements, impurities), industry standards, technical specifications, manufacturer, technologies, and production year;
- to rank, according to use, intended function (linear pipelines, industrial pipelines, and berthing facilities), years of operation, scope of replacement;
- to analyse the presence, reliability, and completeness of mechanical and chemical properties.

Transneft PJSC uses a total of over 70 steel grades in the linear sections of oil and petroleum-product pipelines. Some of them are represented only by the strength class (for instance K52) corresponding to the steel grade.

In the Transneft system, two main groups of steel are used: carbon steels (carbon content of up to 0.24% without the introduction of special alloying elements) and low-alloyed structural steel grades (total content of alloying elements is no more than 2.5%).

The content of carbon and alloying elements determines the weldability of pipe steels, which is evaluated according to the of carbon equivalent criterion value $C_{eq}$.

Low-alloyed steel grades with silicon and manganese of type 17GS and its modifications 17G1S and 17G1S-U are used most frequently (Fig.1) (in all, 56% of the total length), followed by steel grades Ts (7%). Modern steel grades of strength class K52, K56, and K60
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an important factor when constructing and operating pipelines. Grades of steel such as steel 10, steel 20, steel 4, steel 3, and their equivalents (modifications) were used to produce pipes with small diameters, from 159 to 530 mm. Some steel grades (17G1S and 09G2S) were used for practically all standard pipe sizes.

For large-diameter pipes (from 530 to 1120 mm), the following grades were used: 10G2FBYu and steels of modern strength classes K56-R60.

The greatest range of pipe sections have service lives of between 5 to 10 years and 35 to 45 years. The percentage of pipe sections which have service life of over 30 years is no less than 57%, and a life of over 50 years it is less than 10% (Fig.2).

Of approximately 55 Russian and foreign producers (Fig.3), Russian manufacturers account for the greatest length of pipe products (73%). A significant proportion of pipes is manufactured by Chelyabinsk Pipe-Rolling Plant (49%), Vyksa Steel Works (14%), and Volzhsky Pipe Plant (8%).

Ukraine’s share in production amounts to 12.5% from the Novomoskovsk Pipe Plant and the Khartsyzsk Pipe Plant products, combined).

The first six producers (Chelyabinsk Pipe-Rolling Plant, Vyksa Steel Works, Volzhsky Pipe Plant, Chomutov Tube Rolling Mill, (Czech Republic), Novomoskovsk Pipe Plant and Khartsyzsk Pipe Plant) make up the principal share (over 90%) used in Transneft system’s pipelines.

There are over 200 technical specifications in total from various manufacturers and state standards which determine the supply of pipe sections to Transneft system pipelines (Fig.4). They include technical specifications from both Russian and foreign manufacturers. Moreover, pipe products may be manufactured by a number of rolling mills according to the same technical specifications and standards.

The greatest length of pipe sections was

---

**Fig.1. Classification of steel grades according to their use in Transneft PJSC's pipelines.**

**Fig.2. Ranking the length of the pipelines according to service life.**

**Fig.3. Volume of steel supplies from manufacturing plants.**

**Fig.4. Relation between pipeline length and technical specification for manufacture of steels of various grades.**

(10G2FBYu) comprise 14% in total, while St20 makes up 3%, 14KhGS is 2.5%, and 19G is 2.1%.

The relationship between standard sizes of pipe sections and the steel grade used is
constructed in compliance with the following technical specifications: TS 14-3-109-73 and TS 14-3-602-77, ChMTS 3-225-69, TS 1381-007-05757848-2005, TS 14-3-1138-82, TS 14-3-1270-84, TS 14-3-1573-96, and TS 14-3-1973-98 and to the GOST 20295-74 and GOST 20295-85 standards. There is a significant length of pipeline (14% of the total amount) for which data regarding technical specifications and standards is not available.

The values for the mechanical properties of steel grade 17G1S, manufactured to comply with various technical specifications, have significant scatter (Table 1, Fig.5). The values for ultimate strength range from 500 to 630 MPa, for yield strength from 348 to 580 MPa, and for impact toughness from 5.7 to 85 J/cm². The average values used in calculations for this steel grade were 578 MPa for the ultimate strength, and 410 MPa for the yield strength.

The same is true for other steel grades produced by various manufacturers.

These data indicate the possibility of reducing the actual mechanical properties in comparison to the requirements of the technical specifications, which can vary by as much as 10-20%. As such, in order to improve the accuracy of strength and longevity calculations based on actual characteristics, it is necessary to additionally take into account the year of manufacture and technology used to produce each steel grade. This is especially true when design characteristics for mechanical properties are found to be lower than those stipulated in technical specifications.

Up until the mid-1950s, carbon ferritic-pearlitic steels St.3, St.4, St.10, and St.20 were used to construct oil pipelines, with strength classes K30-K38. Subsequently hot-rolled steels of grades 19G, 16GN, 14KhGS began to be used with the aim of decreasing the steel’s liability to brittle

<table>
<thead>
<tr>
<th>No.</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Length, km</td>
<td>13,600 (22.6% of the total length)</td>
</tr>
<tr>
<td>2</td>
<td>Number of technical specifications - manufacturer</td>
<td>89</td>
</tr>
<tr>
<td>3</td>
<td>Ultimate strength, in MPa</td>
<td>from 500 to 630</td>
</tr>
<tr>
<td>4</td>
<td>Yield strength, in MPa</td>
<td>from 348 to 580</td>
</tr>
<tr>
<td>5</td>
<td>Impact toughness, J/cm²</td>
<td>from 5.7 to 85</td>
</tr>
</tbody>
</table>

Table 1. Values for mechanical properties of steel grade 17G1S.
Fracture and strengthening it by adding carbon, manganese, and chrome. These grades were, however, still subject to brittle fracture, in particular avalanche-type and extended-ve fractures.

In the 1960s and later, low-alloyed steels based on hot-rolled 17GS (normalized 17G1S, including 17G1S-U after synthetic slag treatment, with strength level up to K52) came into widespread use. This was made possible by reducing the content of detrimental impurities (sulphur and phosphorus) and carbon, and strengthening the steel using manganese and silicon, as well as grain refinement by heat treatment in normalization.

Steels of types 14G2SAF, 14G2AF, 16G2SAF, and 17G2A are characterized by carbonitride strengthening, smelting in oxygen steel-making converters and subsequent continuous casting, steel treatment in the ladle, control of the shape of non-metallic inclusions and further reduction of the sulphur and carbon content. These steels have K55-K60 strength classes, and significantly exceed silicon-manganese steels by their properties.

In micro-alloyed low-perlitic and ferritic steels of 10G2FBYu, 09G2FB and other types, grain boundary, substructural and dispersion strengthening are used. These steels undergo thermos-mechanical rolling and subsequent accelerated cooling. Controlled rolling modes allow strength and toughness to be increased while maintaining sufficient weldability.

Steel quality was further improved with the development of low-alloyed steels, for instance 08G2MFB and 08G2FBT, which have a lower carbon content and other types of structures (acicular ferrite, ferrite-bainite) which undergo thermos-mechanical rolling, and which have ultimate strength of up to 640 MPa.

Data on the chemical composition of steel grades (intervals for the content of alloying elements) are selected from reference books and scientific and technical literature on pipe steels. In the vast majority of cases, there are no actual results for determining the chemical composition of the steel in pipe sections.

Steel grades were grouped according to standard values for carbon, phosphorus, and sulphur content (Tables 2-3).

As a rule, the lower is the content of detrimental impurities, the higher are the ductility and toughness indicators.

In Figs 7-9, pipe steels are ranked based on the actual mechanical properties of steel grade, taking into account technical specification data for ultimate strength values (group interval of 50 MPa), relative elongation (group interval of 3%), and impact toughness (group interval of 20 J/cm²).

Assigning points to each of the groups was proposed as a way to make a generalised ranking by chemical composition parameters and actual mechanical properties. The higher is the group that

<table>
<thead>
<tr>
<th>Period</th>
<th>Steel Grades</th>
</tr>
</thead>
<tbody>
<tr>
<td>1940s-50s:</td>
<td>VSt3sp, VSt3sp2, VSt3sp4, St3 (St3sp), St3sp4, St3ps2, St4 (St4sp), Steel 10, Steel 20, St10PS, St20L</td>
</tr>
<tr>
<td>1950s-60s:</td>
<td>Low-alloyed steels with solid-solution strengthening</td>
</tr>
<tr>
<td></td>
<td>09G2S, 10G2S1, 13GS, 13G1S-U, 13GS-U, 17G1S, 17G1S-U, 17GS, 19G, 14GN, 16GN, 14KhGS</td>
</tr>
<tr>
<td>1960s-70s:</td>
<td>Low-alloyed steels with carbide strengthening</td>
</tr>
<tr>
<td></td>
<td>09GSF, 17G2SF</td>
</tr>
<tr>
<td>1970s-80s:</td>
<td>Low-alloyed steels with carbo-nitride strengthening</td>
</tr>
<tr>
<td></td>
<td>13G2AF, 14G2SAF, 15GSTYu, 16G2SAF</td>
</tr>
<tr>
<td>1980s-90s:</td>
<td>Low-alloyed perlite-reduced steels</td>
</tr>
<tr>
<td></td>
<td>08G1NFB, 08G2FB, 09G2FB, 10G2FB, 10G2FBYu, 10G2FBYu2, 12GSB, 12G2SB</td>
</tr>
<tr>
<td>2000s:</td>
<td>Bainitic steels</td>
</tr>
<tr>
<td></td>
<td>06GFBA</td>
</tr>
</tbody>
</table>

Fig. 6. Grouping of steel grades according to development year and production technology.
### Table 2. Grouping of steel grades according to content of detrimental impurities.

<table>
<thead>
<tr>
<th>No.</th>
<th>Maximum allowable content of detrimental impurities (S, P), %</th>
<th>Steels</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>over 0.045</td>
<td>St3, St3ps2, St3sp4, VSt3sp, VSt3sp2, VSt3sp4, VSt3sp5, St4</td>
</tr>
<tr>
<td>2</td>
<td>0.035 &lt; S,P ≤ 0.045</td>
<td>Steel 10, Steel 10ps, 10G2S1, 10G2SD (MK), 14GN, 14KhGS, 15GSTYu, 15G2S, 16GN, 17GS, 17G1S, 17G2SF, 19G</td>
</tr>
<tr>
<td>3</td>
<td>0.025 &lt; S,P ≤ 0.035</td>
<td>13G2AF, 14G2SAF, 17G1S-U Steel 20</td>
</tr>
<tr>
<td>4</td>
<td>0.015 &lt; S,P ≤ 0.025</td>
<td>08G1NFB, 08G2FB, 09GSF, 09G2FB, 10G2FB 10G2FBYu, 10G2B-TYu2, 12GSB, 12G2SB, 13GS, 13G1S-U, 13G1S-U, 16G2SAF</td>
</tr>
<tr>
<td>5</td>
<td>0.015 or less</td>
<td>06GFBAA</td>
</tr>
</tbody>
</table>

### Table 3. Grouping of steel grades according to carbon content.

<table>
<thead>
<tr>
<th>No.</th>
<th>Maximum allowable carbon content, 0.01%</th>
<th>Steel grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>22 and over</td>
<td>St3, St3ps2, St3sp4, VSt3sp, VSt3sp2, VSt3sp4, VSt3sp5, St4, 19G, Steel 20</td>
</tr>
<tr>
<td>2</td>
<td>16 ≤ C &lt; 22</td>
<td>14GN, 14KhGS, 14G2SAF, 15G2S, 15GSTYu, 16GN, 16G2SAF, 17GS, 17G1S, 17G1S-U, 17G2SF</td>
</tr>
<tr>
<td>3</td>
<td>10 ≤ C &lt; 16</td>
<td>08G2FB, 08G1NFB, 09GSF, 09G2S 09G2FB, Steel 10, Steel 10ps, 10G2S1, 10G2SD (MK) 10G2FB 10G2FBYu, 10G2B-TYu2, 12GSB, 12G2SB, 13GS, 13G1S-U, 13G1S-U, 13G2AF</td>
</tr>
<tr>
<td>4</td>
<td>Less than 10</td>
<td>06GFBAA</td>
</tr>
</tbody>
</table>

### Fig. 7. Grouping of steel grades by strength.

<table>
<thead>
<tr>
<th>No</th>
<th>VS, MPa</th>
<th>Steel grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>650 MPa and higher</td>
<td>17G2SF, 16G2SAF, 17G1S(K60), 15GSTYu</td>
</tr>
<tr>
<td>2</td>
<td>600 – 650 MPa</td>
<td>13G1S-U, 17G1S-U, 10G2FBYu, 06GFBAA, 14KhGS, 17GS, 17G1S</td>
</tr>
<tr>
<td>3</td>
<td>550 – 600 MPa</td>
<td>14KhGS, 17GS, 14KhGS, 13G1S-U, 17G1S, 16G2-U, 09G2S, 10G2SD, 19G, Z</td>
</tr>
<tr>
<td>4</td>
<td>500 – 550 MPa</td>
<td>17GS, 16G2-U, Z,17G1S, 14GN, 14KhGS, 19G, Steel 20</td>
</tr>
<tr>
<td>5</td>
<td>Lower than 500 MPa</td>
<td>Ts, St4, VSt3sp4, VSt3sp2, VSt4, Steel 20</td>
</tr>
</tbody>
</table>
the steel grade falls into, the higher is the score, and the final values were obtained by combining scores for each characteristic. The modern steel of the ferritic - bainitic class 06GFBAA (Fig.10) was found to be the best steel grade.

Transneft R&D, LLC together with Transneft Diascan, JSC, and the organizations of the Transneft system, has developed and continue to enlarge a database based on the results of actual mechanical properties of pipe steels from various manufacturers, using technical documents and he time of manufacture. At present, it contains the results of more than 19,000 different tests.

**Combined data on the mechanical properties of pipe steels**

In summarizing the results of the tests and studies that have been carried out, the following statistics can be formulated.

The largest guaranteed impact toughness values were found in modern steel grades of strength class K56-K60, 10G2FBYu, 09G2SF, 13G1S-U, and 17G1S-U; these results were taken from Mesnager sample tests. The lowest values were found in 14KhGS, Ts, 19G and carbon steels (Fig.11).
<table>
<thead>
<tr>
<th>No.</th>
<th>Grade</th>
<th>Manufacturer</th>
<th>Technical specifications (TU)</th>
<th>Scores for rating properties based on ranking results</th>
<th>Total score</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>06GFBA</td>
<td>Chelyabinsk Pipe-Rolling Plant</td>
<td>TS 14-3R-28-99</td>
<td>4 5 6 7 8 9 4</td>
<td>22</td>
</tr>
<tr>
<td>2</td>
<td>13G1S-U</td>
<td>Volzhsky Pipe Plant</td>
<td>TS 14-3-1973-98</td>
<td>4 5 6 4 2</td>
<td>21</td>
</tr>
<tr>
<td>3</td>
<td>10G2FBYu</td>
<td>Vyksa Steel Works</td>
<td>TS 14-4-1573-96</td>
<td>4 4 6 4 2</td>
<td>20</td>
</tr>
<tr>
<td>4</td>
<td>13G1S-U</td>
<td>Vyksa Steel Works</td>
<td>TS 14-4-1573-96</td>
<td>3 5 6 4 2</td>
<td>20</td>
</tr>
<tr>
<td>5</td>
<td>17G1S-U</td>
<td>Volzhsky Pipe Plant</td>
<td>TS 14-3-1973-98</td>
<td>4 5 6 3 1</td>
<td>19</td>
</tr>
<tr>
<td>6</td>
<td>17G1S (K60)</td>
<td>Volzhsky Pipe Plant</td>
<td>TS 14-3-721-78</td>
<td>5 3 6 2 1</td>
<td>17</td>
</tr>
<tr>
<td>7</td>
<td>10G2SD</td>
<td>Mariupol Steel and Iron Works n.a.Ilyich</td>
<td>TS 5/VII 1949</td>
<td>3 6 3 2 2</td>
<td>16</td>
</tr>
<tr>
<td>8</td>
<td>13G1S-U</td>
<td>Khartsyzk Pipe Plant</td>
<td>TS Ukraine 322-8-10-95</td>
<td>3 1 6 4 2</td>
<td>16</td>
</tr>
<tr>
<td>9</td>
<td>14KhGS</td>
<td>Khartsyzk Pipe Plant</td>
<td>TS 14-3-109-73</td>
<td>3 5 3 2 2</td>
<td>15</td>
</tr>
<tr>
<td>10</td>
<td>17G1S-U</td>
<td>Chelyabinsk Pipe-Rolling Plant</td>
<td>TS 14-3-1698-90</td>
<td>4 5 2 3 1</td>
<td>15</td>
</tr>
<tr>
<td>11</td>
<td>10G2SD</td>
<td>Mariupol Steel and Iron Works n.a.Ilyich</td>
<td>PTS (Provisional Technical Specifications) 06-05-8</td>
<td>3 6 1 2 2</td>
<td>14</td>
</tr>
<tr>
<td>12</td>
<td>16G2SAF</td>
<td>Novomoskovsk Pipe Plant</td>
<td>TS 14-3-602-77</td>
<td>5 2 2 4 1</td>
<td>14</td>
</tr>
<tr>
<td>13</td>
<td>17G1S</td>
<td>Chelyabinsk Pipe-Rolling Plant</td>
<td>TS 3-225-69</td>
<td>4 5 2 2 1</td>
<td>14</td>
</tr>
<tr>
<td>14</td>
<td>17G1S-U</td>
<td>Novomoskovsk Pipe Plant</td>
<td>TS 14-3-602-77</td>
<td>3 5 2 3 1</td>
<td>14</td>
</tr>
<tr>
<td>15</td>
<td>17G1S-U</td>
<td>Khartsyzk Pipe Plant</td>
<td>TS 14-3-602-77</td>
<td>4 4 2 3 1</td>
<td>14</td>
</tr>
<tr>
<td>16</td>
<td>17GS</td>
<td>Novomoskovsk Pipe Plant</td>
<td>MRTU (Inter-Republic Technical Specifications) 14-4-13-65</td>
<td>3 5 3 2 1</td>
<td>14</td>
</tr>
</tbody>
</table>

Fig. 10. Element of grouping steel grades by property:

- **column 5** - strength
- **column 6** - ductility
- **column 7** - toughness
- **column 8** - detrimental impurities
- **column 9** - carbon content
A significant safe margin of ductility can be seen in carbon steel grades 09G2S and 10G2S, while the lowest margin of ductility was found in 19G and 14KhGS (Fig.12).

The lowest values for strength are observed in carbon steel grades. The greatest are found in steel grades 17G1S-U, its derivatives, and steel grades manufactured using controlled-rolling technology (Fig.13).

Fig.11. Minimum actual values for impact toughness KCV (-40) for various steel grades, J/cm².

Fig.12. Minimum actual values for elongation in different steel grades, %.

To assess the effect of alloying element content and impurities on the mechanical properties of various steel grades, and the relationship of the normative content of carbon and sulphur vs the actual values of mechanical properties, are plotted in Fig.14.

By analysing the above relationships, it can be concluded that impact toughness values for pipe steels increase when sulphur content is reduced. The influence of carbon was less noticeable.
Rather complex relationships were found for a certain drop in ductility when pipe steel strength increased, together with a simultaneous increase in the magnitude of reduction in area when elongation grew and in yield strength when ultimate strength grew for various steel grades. These are shown in Fig. 15.

It is important that the pipe metal characteristics used to calculate strength and durability were in fact the closest to the average values from the test results. The relative scatter in the characteristics studied within a series of tests is characterised by the value of the variation coefficient.

Analysis of the actual test results revealed a range of technical specifications from a number of manufacturers. For some characteristics, the value of the variation coefficient was significant (over 10%), which indicates a great heterogeneity of metal properties when transferred from sheet to sheet, and from pipe to pipe.

There are various combinations of manufacturer - technical specifications - steel grade for which test results are currently not available.

Conclusions and the way forward for future research

As opportunities for testing increase (given the availability of grades in pipe
sections for cutting during stoppages or replacements), and taking into account total length, it is necessary to select the templates and conduct tests and studies for specific combinations. These templates should be tested with both standard and specialized methods, including those developed by our partners in leading scientific institutions.

We plan to expand the area in which the mechanical properties obtained, based on the methods that can be applied when evaluating the strength and durability of pipe sections. This will be supported by performing verification bench tests using Transneft-Diascan JSC’s current and planned testing facilities [20]. The objectives for further research are:

- To expand knowledge of the problem of degradation in the characteristics of pipe steel metal during operation.

- To conduct tests of selected templates using existing methods of mechanical testing:
  - standard tests (tensile tests, impact bending, hardness measurement, etc.);
  - unified tests (calculation from deformation diagrams of work-hardening index, uniform reduction in area, fatigue strength, stress intensity factor, etc.);
  - special tests (ductility in Z-direction, indentation diagrams, anisotropy of properties in various directions).

- To develop new methods of assessing mechanical properties, and testing model samples:
  - taking into account surface layers;
  - research into the local properties of welded joints and damaged zones, microstructural studies;
  - estimation of local strain-stress state;
  - study of natural, artificial, dynamic and deformational ageing.

- To analyse the methods used for evaluating the destruction of pipe steels within a critical temperature interval.

- To verify existing methods through computational experiments.

- To develop new bench and full-scale test methods (with the involvement of leading scientific institutions).

References

Listing of forthcoming industry events (continued from p 194)

PVPC Expo Middle East
28-29 March 2018
Abu Dhabi, UAE
http://www.pvpcexpo.ae
This annual exhibition and conference brings together UAE and global leaders, buyers and suppliers to PVPC Expo Middle East to discuss the co-operation and further development of middle east market. It provides an unrivalled and highly valued opportunity for global related manufacturers, traders and Constructors to come together to interact with industry leaders and to share science and technology innovation, new products and market trends.

Technology for Future and Ageing Pipelines
11-12 April 2018
www.pipeline-technology.com
Het Pand Conference Centre, Gent, Belgium
Organized by Clarion Technical Conferences and Tiratsoo Technical in association with Lab. Soete of the Universteit Gent. For details, contact jriratsoo@gs-press.com.

NEFTEGAZ - see announcement on p 234
18th International Exhibition Equipment and Technologies for the Oil and Gas Industries
16-19 April 2018
Moscow, Russia
http://www.neftegaz-expo.ru/en
NEFTEGAZ is the efficient place for Russian and foreign oil and gas industry professionals to communicate, launch new projects, learn global trends and industry development prospects.

9th Mediterranean Offshore Conference & Exhibition
17 -19 April 2018
Alexandria, Egypt
http://www.moc-egypt.com
MOC Exhibition and Conference targets all the Mediterranean countries, with a special focus on the Southern shore. MOC Exhibition and Conference represents the trade event for any company of the energy industry because it stands internationally as the professional arena for the business and commercial relationships that bind the Northern and Southern shores of the Mediterranean Sea.

API Pipeline Conference and Cybernetics Symposium
24-26 April 2018
St Louis, Missouri, USA
http://www.api.org/events-and-training/calendar-of-events
API events are dedicated to standards development, making contacts, and open discussion on areas of interest. These meetings are hosts to some of the most knowledgeable minds in the industry, and they discuss issues that are important to both them and their companies. 

continued on p 233
Anisotropic pipelines in deep-sea mining: an approximate model for stability analysis

by Prof. D.G. Pavlou
Dept of Mechanical and Structural Engineering and Materials Science, University of Stavanger, Norway

FLOW-INDUCED INSTABILITY ANALYSIS of long, fibre-reinforced, pipes used for deep-sea mining applications is performed. The transfer-matrix method is implemented to the motion equation of a multi-layered anisotropic pipe for critical flow-velocity calculation. The mechanical properties of the laminated material as well as the mass of the hanged pump and the flow parameters are taken into account. Numerical results of representative examples are provided and discussed.

Key words: deep-sea mining, flow-induced instability, FRP pipes, composite materials

IN THE LAST DECADES mining activities in deep-sea are benefited from the offshore technology and advanced materials development. Deep-sea mining projects for depths up to 6 km are currently under development (for example, the Papua New Guinea, Blue Mining, and Blue Nodules projects). The lifting system in deep-sea mining installations consists of a flexible, free-span pipe, containing a sub-sea lift pump at its end.

Nowadays the trend for deep-sea pipes is the application of glass-fibre-reinforced polymeric materials (GFRP) due to their superior strength, excellent corrosion and fatigue resistance, and light weight (Fig.1). Apart from these important properties, low maintenance cost, low transportation cost, and ability for continuous pipeline manufacturing are additional advantages.

A typical lay-out of GFRP pipelines for offshore applications is shown in Fig.2. An interior liner is usually made from a thermoplastic. The next layer is made from a laminated glass- (or carbon-) fibre-reinforced polymeric material providing high strength to carry the service and installation loads. The exterior jacket protects the pipeline against wear.

The flexibility, the length and diameter, the mass of the lift pump, and the elastic properties of the anisotropic materials of the FRP layers are affecting the values of the critical flow velocity causing instability [1-4]. According to the author’s knowledge, flow-pipe interaction equations for deep-sea mining risers exist for pipes made by isotropic material. In the present work, the flow-pipe interaction equations of multilayered anisotropic FRP pipes [1-4] are formulated. Since the analytical solution is complicated, a simplified fluid-structure-interaction (FSI) model accounting for the effect of the internal flow is proposed. To this end the assumption of the one-phase flow is adopted and the interaction of the pipe with the external flow, as well as the material-damping effect [6], is ignored. The resulting governing fourth-order partial differential equation of motion is transformed to a system of four, first-order, differential equations. The transfer-matrix method is used for the correlation of the state vectors of two pipe
cross-sections. The global-transfer matrix of the pipe-pump system containing the boundary conditions, the material properties, and the flow parameters is derived. The condition for non-trivial solution is solved numerically, yielding the values of the flow velocity $U$ causing flow-induced pipeline instability.

**Brief description of the mechanical modelling of GFRP laminated materials**

Based on the Kirchhoff assumption, the correlation of strains $\epsilon_{xx}^o, \epsilon_{yy}^o, \gamma_{xy}^o$ and curvatures $k_{xx}^o, k_{yy}^o, k_{xy}^o$ of the middle plane of a laminate (Fig.3) with the corresponding force (per unit length) and moment (per unit length) resultants $N_x, N_y, N_{xy}, M_x, M_y, M_{xy}$ is given by Equn 1 (below) ([7, 8]).

The components $a_i, b_i, d_i$ of the above matrix can be derived by Equn 2 (below) in which:

$$A_{ij} = \sum_{k=1}^{N} Q_{jik} (z_k - z_{k-1})$$  \hspace{0.5cm} (3)

$$B_{ij} = \frac{1}{2} \sum_{k=1}^{N} Q_{jik} (z_k^2 - z_{k-1}^2)$$  \hspace{0.5cm} (4)

$$D_{ij} = \frac{1}{3} \sum_{k=1}^{N} Q_{jik} (z_k^3 - z_{k-1}^3)$$  \hspace{0.5cm} (5)

**Fig.1. Advantages of pipelines made from glass-fibre-reinforced polymeric materials.**

**Fig.2. Cross section of the pipe.**
In above equations, $N$ is the number of layers composing the laminate, $z_k$ represents the distances of any layer $k$ from the end surface of the laminate, and the parameters $Q_{ij}$ are given for each lamina by the $6 \cdot 11$ (below).

The parameters $m, n$ depend on the fibre-orientation angle $\theta$ of each lamina (Fig. 3):

\[
n = \cos \theta \quad (12)
\]
\[
n = \sin \theta \quad (13)
\]

The parameters $Q_{ij}$ are correlated to material properties in the principal coordinate system of each individual lamina composing the laminate:

\[
Q_{11} = \frac{E_1}{1-\nu_{12}\nu_{21}} \quad (14)
\]
\[
Q_{12} = \frac{\nu_{12}E_2}{1-\nu_{12}\nu_{21}} = \frac{\nu_{21}E_1}{1-\nu_{12}\nu_{21}} \quad (15)
\]
\[
Q_{22} = \frac{E_2}{1-\nu_{12}\nu_{21}} \quad (16)
\]
\[
Q_{66} = G_{12} \quad (17)
\]
\[
\nu_{11} = \frac{E_2}{E_1} \quad (18)
\]

$E_1, E_2$ are the elasticity moduli, $G_{12}$ is the shear modulus and $\nu_{12}, \nu_{21}$ are the Poisson’s ratios in the principal coordinate system $x_1, x_2$.

**Flow-pipe interaction modelling**

**Forces acting on a composite pipe element**

During fluid flow in a riser and lifting system (RLS – Fig. 4), the forces and moments acting on an elementary length of pipe are demonstrated in Fig. 5.

In the direction along the deformed pipe are acting:

(a) shear stresses $q$ due to the friction between the fluid and the interior cylindrical surface $\pi D l d s$; and
(b) longitudinal tension $T$.

\[
\bar{Q}_{11} = Q_{11} m^4 + 2 \left( Q_{12} + 2S_{66} \right) n^2 m^2 + Q_{22} n^4 \quad (6)
\]
\[
\bar{Q}_{12} = (Q_{11} + Q_{22} - 4Q_{66}) n^2 m^2 + Q_{12} \left( n^4 + m^4 \right) \quad (7)
\]
\[
\bar{Q}_{16} = (Q_{11} - Q_{12} - 2Q_{66}) nm^3 + (Q_{12} - Q_{22} + 2Q_{66}) n^3 m \quad (8)
\]
\[
\bar{Q}_{22} = Q_{11} n^4 + 2 \left( Q_{12} + 2Q_{66} \right) n^2 m^2 + Q_{12} m^4 \quad (9)
\]
\[
\bar{Q}_{26} = (Q_{11} - Q_{12} - 2Q_{66}) n^3 m + (Q_{12} - Q_{22} + 2Q_{66}) nm^3 \quad (10)
\]
\[
\bar{Q}_{66} = (Q_{11} + Q_{22} - 2Q_{12} - 2S_{66}) n^2 m^2 + Q_{66} \left( n^4 + m^4 \right) \quad (11)
\]
In the direction normal to the deformed pipe are acting:

(a) shear forces $Q$; and
(b) reaction forces $F$ between the fluid and the interior surface of the pipe, vertical gravity forces $mgdx$ due to the weight of the material of the corresponding pipe element, and vertical dynamic forces $ma^z_p$ due to the vertical motion of the elementary mass $m$ of the pipe ($a^z_p$ is the vertical acceleration).

In the $y$-direction are acting the bending moments $M_y$. Apart from the above forces, the deformation of the pipe yields a slope $\partial w / \partial x$ (with respect to $x$-axis). Assuming small slopes, i.e. $\cos(\partial w / \partial x) = 1$ and $\sin(\partial w / \partial x) = \partial w / \partial x$, the following equilibrium conditions of the forces projected on the axes $x$, $z$, $y$ can be obtained:

Equilibrium of forces projected in the $x$-direction:

$$\frac{\partial Q}{\partial x} + F + T \frac{\partial w}{\partial x} - mg = 0$$  \hspace{1cm} (19)

Equilibrium of forces projected in the $z$-direction:

$$\frac{\partial Q}{\partial x} + F + T \frac{\partial w}{\partial x} + \pi Dq \frac{\partial w}{\partial x} = ma^z_p$$  \hspace{1cm} (20)

Equilibrium of bending moments in the $y$-direction:

$$\frac{\partial M_y}{\partial x} = -Q$$  \hspace{1cm} (21)

Taking into account the following equation from the beam theory [e.g. Ref.2]:

$$\widehat{M}_y = -\widehat{EI}_y \frac{1}{\rho_y}$$  \hspace{1cm} (22)

Equn 21 can be written as follows:

$$\widehat{EI}_y \frac{\partial}{\partial x} \left( \frac{1}{\rho_y} \right) = Q$$  \hspace{1cm} (23)

where $\widehat{EI}_y$ is given [2] by the following formula:

$$\widehat{EI}_y = \frac{\pi D}{2} \left( \frac{D}{2a_{11}} + \frac{1}{d_{11}} \right)$$  \hspace{1cm} (24)

From the geometry it is well known that the curvature $1/\rho_y$ is associated with the deflection $w$ with the following relation:

$$\frac{1}{\rho_y} = \frac{\partial^2 w}{\partial x^2}$$  \hspace{1cm} (25)

Therefore, with the aid of above equation, Equn 23 yields:

$$Q = -\widehat{EI}_y \frac{\partial^2 w}{\partial x^2}$$  \hspace{1cm} (26)

Forces acting on a fluid element

In the direction along the axis of the deformed pipe, the forces acting on a fluid element shown in Fig.6 are:

(a) forces due to pressure $p$ acting on the cross-section area $A = \pi D^2 / 4$ ;
(b) shear forces $q$ due to friction of the fluid with the interior cylindrical surface of the pipe; and
(c) dynamic forces due to the motion of the fluid in $x$ and $z$ directions.

In the direction normal to the axis of deformed pipe, the forces acting on the fluid element are:

(a) reaction forces $F$ between the fluid and the interior surface of the pipe;
(b) the gravity forces $Mgdx$ due to the weight of the fluid element; and
(c) dynamic forces due to the motion of the fluid (in $x$ and $z$ directions).

Equilibrium of forces projected in the $x$-direction

$$-A \frac{\partial p}{\partial x} - q\pi D - F \frac{\partial w}{\partial x} - Mg = Ma_x^f \quad (27)$$

In above equation $a_x^f$ is the component of the acceleration of the fluid in the $x$-direction due to its flow in the $x$-direction, and because of the motion of the pipe in the $z$-direction.

Equilibrium of forces projected in the $z$-direction

$$-F - A \frac{\partial}{\partial x} \left( F \frac{\partial w}{\partial x} + q\pi D \frac{\partial w}{\partial x} \right) = Ma_z^f \quad (28)$$

where $a_z^f$ is the component of the acceleration of the fluid in the $z$-direction due to its flow in the $x$-direction, and due to the motion of the pipe in the $z$-direction.

Accelerations of the fluid and pipe elements

We consider that the motion of the pipe element takes place only in the $z$-direction. Therefore, its acceleration in the $x$-direction is:

$$a_x^p = 0 \quad (29)$$

As the velocity of the pipe element in the $z$-direction is $\partial w / \partial t$, its acceleration $a_z^p$ will be:

Fig. 5. Forces and moments acting on an elementary pipe element.

Fig. 6. Forces acting on a fluid element.
Neglecting quantities associated with tensioning, pressurization effects, and gravity – which are not important for the motion – and considering constant velocity $U$, the equilibrium equations of the pipe element (19), (20), (26) and the fluid element (27), (28) can be simplified as follows:

\[ F \frac{\partial w}{\partial x} = \pi D q \]  

(37)

\[ \frac{\partial Q}{\partial x} + F + \pi D q \frac{\partial w}{\partial x} = m \frac{\partial^2 w}{\partial t^2} \]  

(38)

\[ Q = -\hat{E} I_y \frac{\partial^4 w}{\partial x^4} \]  

(39)

\[ -q \pi D - F \frac{\partial w}{\partial x} = 0 \]  

(40)

\[ -F - q \pi D \frac{\partial w}{\partial x} = M \left[ \frac{\partial^2 w}{\partial t^2} + 2U \frac{\partial^2 w}{\partial x \partial t} + U^2 \frac{\partial^2 w}{\partial x^2} \right] \]  

(41)

With the aid of Equn 38, the following equation can be obtained:

\[ -F - \pi D q \frac{\partial w}{\partial x} = \frac{\partial Q}{\partial x} - m \frac{\partial^2 w}{\partial t^2} \]  

(42)

Combination of Equns 41 and 42 yields Equn 43 (see right). Taking into account Equn 39, Equn 43 can now be written as Equn 44 (see right) where $\hat{E} I_y$ is given by Equn 24.

The above homogeneous partial differential equation is the equation of motion describing the free vibration of the composite riser shown in Fig.4.
The transfer-matrix method

The transfer matrix of the riser

Using the following function with separated variables x and t,

\[ u(x,t) = R e^{u(x)} e^{i\omega t} \]  \hspace{1cm} (45)

the motion in Equn 44 yields the following characteristic Equn 46 (see below).

Following a standard mathematical procedure [9], the fourth-order differential Equn 46 can be transformed to the following matrix differential equation of the first order:

\[ \frac{d}{dx} \begin{bmatrix} Y_1 \\ Y_2 \end{bmatrix} = \begin{bmatrix} \Omega_r \end{bmatrix} \begin{bmatrix} Y_1 \\ Y_2 \end{bmatrix} \] \hspace{1cm} (47)

where:

\[ Y_1 = \begin{bmatrix} u(x) \\ u'(x) \\ u''(x) \\ u'''(x) \end{bmatrix} \] \hspace{1cm} (48)

and \( \begin{bmatrix} \Omega_r \end{bmatrix} \) is given by Equn 49 (below).

Therefore, the solution of the matrix Equn 47 can be written:

\[ \begin{bmatrix} Y_1 \\ Y_2 \end{bmatrix} = e^{\begin{bmatrix} \Omega_r \end{bmatrix} \frac{L}{x}} \begin{bmatrix} Y_1 \\ Y_2 \end{bmatrix} \] \hspace{1cm} (50)

where L is the length of the pipe segment 1-2. The matrices \( \{ Y_1 \}, \{ Y_2 \} \) denote the state vectors at \( x = 0 \) and \( x = L \) respectively:

\[ \frac{\partial Q}{\partial x} - m \frac{\partial^2 u}{\partial t^2} = M \frac{\partial^2 u}{\partial x^2} + 2MU \frac{\partial^2 u}{\partial t \partial x} + MU^2 \frac{\partial^2 u}{\partial x^2} \] \hspace{1cm} (43)

\[ \tilde{E}_I \frac{\partial^4 u}{\partial x^4} + \tilde{M} \frac{\partial^2 u}{\partial x^2} + \tilde{M} \frac{\partial^2 u}{\partial t^2} + (M + m) \frac{\partial^2 u}{\partial t^2} = 0 \] \hspace{1cm} (44)

\[ \tilde{E}_I \frac{d^4 u(x)}{dx^4} + \tilde{M} \frac{d^2 u(x)}{dx^2} + 2 \tilde{M} \frac{d^2 u}{dx \partial t} + \frac{d(\tilde{M} \omega^2 u(x))}{dx} = 0 \] \hspace{1cm} (46)

\[ \begin{bmatrix} \begin{array}{cccc} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ \frac{(M + m) \omega^2}{\tilde{E}_I} & -2\tilde{M} \omega i \tilde{E}_I & -\tilde{M} \omega^2 \tilde{E}_I & 0 \end{array} \end{bmatrix} \] \hspace{1cm} (49)

\[ \{ Y_1 \} = \begin{bmatrix} u(L + \ell) \\ u'(L + \ell) \\ u''(L + \ell) \\ u'''(L + \ell) \end{bmatrix} \] \hspace{1cm} (51)

**The transfer-matrix method**

The transfer matrix of the riser

Using the following function with separated variables x and t,

\[ u(x,t) = R e^{u(x)} e^{i\omega t} \]

the motion in Equn 44 yields the following characteristic Equn 46 (see below).

Following a standard mathematical procedure [9], the fourth-order differential Equn 46 can be transformed to the following matrix differential equation of the first order:

\[ \frac{d}{dx} \begin{bmatrix} Y_1 \\ Y_2 \end{bmatrix} = \begin{bmatrix} \Omega_r \end{bmatrix} \begin{bmatrix} Y_1 \\ Y_2 \end{bmatrix} \]

where:

\[ Y_1 = \begin{bmatrix} u(x) \\ u'(x) \\ u''(x) \\ u'''(x) \end{bmatrix} \]

and \( \begin{bmatrix} \Omega_r \end{bmatrix} \) is given by Equn 49 (below).

Therefore, the solution of the matrix Equn 47 can be written:

\[ \begin{bmatrix} Y_1 \\ Y_2 \end{bmatrix} = e^{\begin{bmatrix} \Omega_r \end{bmatrix} \frac{L}{x}} \begin{bmatrix} Y_1 \\ Y_2 \end{bmatrix} \]

where \( L \) is the length of the pipe segment 1-2. The matrices \( \{ Y_1 \}, \{ Y_2 \} \) denote the state vectors at \( x = 0 \) and \( x = L \) respectively:

\[ \frac{\partial Q}{\partial x} - m \frac{\partial^2 u}{\partial t^2} = M \frac{\partial^2 u}{\partial x^2} + 2MU \frac{\partial^2 u}{\partial t \partial x} + MU^2 \frac{\partial^2 u}{\partial x^2} \] \hspace{1cm} (43)

\[ \tilde{E}_I \frac{\partial^4 u}{\partial x^4} + \tilde{M} \frac{\partial^2 u}{\partial x^2} + \tilde{M} \frac{\partial^2 u}{\partial t^2} + (M + m) \frac{\partial^2 u}{\partial t^2} = 0 \] \hspace{1cm} (44)

\[ \tilde{E}_I \frac{d^4 u(x)}{dx^4} + \tilde{M} \frac{d^2 u(x)}{dx^2} + 2 \tilde{M} \frac{d^2 u}{dx \partial t} + \frac{d(\tilde{M} \omega^2 u(x))}{dx} = 0 \] \hspace{1cm} (46)

\[ \begin{bmatrix} \begin{array}{cccc} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ \frac{(M + m) \omega^2}{\tilde{E}_I} & -2\tilde{M} \omega i \tilde{E}_I & -\tilde{M} \omega^2 \tilde{E}_I & 0 \end{array} \end{bmatrix} \] \hspace{1cm} (49)

\[ \{ Y_1 \} = \begin{bmatrix} u(L + \ell) \\ u'(L + \ell) \\ u''(L + \ell) \\ u'''(L + \ell) \end{bmatrix} \] \hspace{1cm} (51)
Global transfer matrix of the riser and lifting system

Combining Eqns 50 and 53 the following matrix equation can be obtained:

\[
[Y_e] \Omega p r L \{Y_e\} = \{\Omega\}.
\]  

or Eqn 57 (below).

In above equation \([I_{4x4}]\) is the unit matrix with size 4 x 4, and \([O_{4x1}]\) is a vector of size 4 x 1 containing zeros.

Boundary conditions

We assume that the RLS system 1-3 is fixed supported on the node-1 and has a free end on the node-3. Therefore, the boundary conditions of the system can be approximated as follows:

\[
\begin{align*}
  u(0) &= 0 \quad (58) \\
  u'(0) &= 0 \quad (59) \\
  u''(L) &= 0 \quad (60) \\
  u'''(L) &= 0 \quad (61)
\end{align*}
\]

The above conditions can be written as matrix equations in terms of the state vectors \(\{Y_1\}, \{Y_3\}\):

\[
\begin{align*}
  [B_1] \{Y_1\} &= \{O_{4x1}\} \quad (62) \\
  [B_3] \{Y_3\} &= \{O_{4x1}\} \quad (63)
\end{align*}
\]

where:

\[
[B_1] = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}
\]

\[
[B_3] = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
\]

Taking into account Eqns 62-65, the boundary conditions (58)-(61) can be modelled as follows:

\[
\begin{bmatrix} [B_1] & [O_{4x4}] \end{bmatrix} \begin{bmatrix} \{Y_1\} \\ \{Y_3\} \end{bmatrix} = \{O_{4x1}\} \quad (66)
\]

Combining the Eqns 57 and 66, the following global transfer-matrix equation can be obtained:

\[
\begin{align*}
  \begin{bmatrix} \Omega_p \end{bmatrix} &= \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ (M + m_p)\omega^2 & -2MU\omega & -MU^2 \\ E_p I_p & -E_p I_p & -E_p I_p & 0 \end{bmatrix} \\
  \begin{bmatrix} e^{(\Omega_p)\frac{1}{4}} & e^{(\Omega_p)\frac{1}{2}} & e^{(\Omega_p)L} & -I_{4x4} \end{bmatrix} & \begin{bmatrix} \{Y_1\} \\ \{Y_3\} \end{bmatrix} = \{O_{4x1}\} \quad (55)
\end{align*}
\]
\[
\begin{bmatrix}
-\Omega I^L & [\epsilon I^L]
\end{bmatrix}
\begin{bmatrix}
-B_1 \\
[B_2]
\end{bmatrix}
\begin{bmatrix}
\epsilon I^L \\
Y_1
\end{bmatrix} = \{O_{b_{44}}\}
\]

(67)

The condition for a non-trivial solution of the above equation is:

\[
\det\begin{bmatrix}
-\Omega I^L & [\epsilon I^L]
\end{bmatrix}
\begin{bmatrix}
-B_1 \\
[B_2]
\end{bmatrix} = 0
\]

(68)

Above equation can be solved numerically providing the values of \(\omega\) versus \(U\). Numerical results can be obtained with the aid of contemporary software packages like Mathematica. Critical values of the flow velocity causing dynamic instability are the values yielding the transition of \(\text{Im}\{\omega\}\) from a positive value (stability) to the negative one (instability) [1].

Implementation of the method on a representative example

An RLS system consisting of a multi-layered, glass-fibre-reinforced riser is considered for the implementation of the proposed methodology. The free-hanging riser has a length of \(L = 1000\) m and an inner diameter 100 mm. At the free end of the riser a heavy pump is hung. The riser consists of ten layers of S-Glass/Epoxy reinforced material with fibre orientation \(\pm 45^\circ\). The thickness of each lamina is 0.15 mm, and the mechanical properties in the principal directions are \(E_1 = 39\) MPa, \(E_2 = 6.6\) MPa, \(G_{12} = 3.8\) MPa, and \(\nu_{12} = 0.28\). The density of the composite material is \(2.1 \times 10^3\) kg/m\(^3\). The pump is simulated by a steel cylinder with a length \(l = 3.0\) m. A parametric study aiming to estimate the critical values of the flow velocity for several values of the pump mass \(m_p\) and the riser stiffness \(EI_{yy}\) is the subject of this implementation. To this end, the Equn 68 is solved with the aid of the contemporary software Mathematica. Starting from a small initial value \(U = 1\) m/s for the flow velocity, the natural frequency \(\omega\) is calculated incrementally for the values \(U = 0.1, 0.11, 0.12, 0.13, \ldots, 5.0\) m/s. In the first set of calculations the riser stiffness is constant \(EI_{yy} = 39157\) N/m\(^2\) in order to estimate the effect of the pump’s mass on the critical flow velocity \(U_{cr}\). For several values of the pump mass the values of \(U\) yielding transition of \(\text{Im}\{\omega\}\) from positive to negative values are plotted in Fig.9. In the second set of calculations the value of pump mass \(m_p = 8810\) kg is constant in order to estimate the effect of the riser stiffness on the \(U_{cr}\). The above results are plotted in Fig.10.

From Fig.9 it can be concluded that heavy pump increases the critical flow velocity, thus improving the dynamic stability of the RLS. Unlike the above effect, higher values of the riser stiffness tend to decrease the critical flow velocity (Fig.10). However, the above curve contains local peak and valleys, but the trend of \(U_{cr}\) reduction versus \(EI_{yy}\) is clear. In order to increase the flexibility of the riser, elastic
nodes can be used along the pipe. This conclusion fully agrees with the proposals of other researchers [10-13].

Conclusions

An analytical methodology for critical flow velocity estimation causing dynamic instability in riser and lifting systems (RLS) used for deep sea mining is presented.

The transfer-matrix method is used for the modelling of the system and the natural frequency calculation.

Heavy lifting pumps seem to increase the value of the critical flow velocity, thus improving the dynamic stability of the system.

Risers with high stiffnesses seem to decrease the critical flow velocity values, meaning that flexible pipes improve the dynamic behaviour of the system.

References

The use of digital technology to optimize oil pipeline transportation

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THE ARTICLE PRESENTS the results of developing digital technology to optimize ‘hot’ oil pumping. Digital technology is used to model and optimize oil pumping practices in a pipeline section by integrating the SmartTran software and the SCADA system. The problem of selecting optimum pumping practices without heating the oil was solved by D.T.Jefferson who determined the optimum pumping practices in a pipeline section for a fixed oil flow rate, providing that the cost of electricity used by all pumps per unit time was minimal.

The problem of optimizing ‘hot’ pumping has been studied by V.S. Yablonsky. The optimality criterion has been formulated for a fixed oil flow rate. It is not fulfilled when the pipeline throughput and the temperature in a section with several pump stations and heating points is changed.

The algorithm for solving this problem has been constructed with a new approach using the dynamic programming method. The search task is divided into several overlapping subtasks in order to find the optimal substructure. The object of each subtask is the cost function of pumps and preheaters at the stations of the pipeline section. The combination of working pumps and preheaters which gives the minimum cost for energy consumed is being searched for a solution.

The discussion presents the results of ‘hot’ pumping calculations for the Kasymov-Bolshoy Chagan section of the Uzen-Atyrau-Samara trunk oil pipeline. The calculation algorithm was implemented in the SmartTran software for modelling and optimizing ‘hot’ pumping. The initial calculation parameters were loaded from the SCADA system. The SmartTran software calculation results (oil pressure and temperature, pumps power, pumping and heating costs and other parameters) for ‘hot’ pumping are in accordance with the experimental data of the SCADA system.

Energy savings when operating pumps and preheaters can be found provided that the oil temperature in the pipeline section does not fall below the pumping safety conditions. The optimal practice calculation results demonstrate the economic efficiency of ‘hot’ pumping. Thus, the integration of SmartTran software with the SCADA system creates the digital technology for optimizing the technological practices of ‘hot’ oil pumping.

Key words: digital technology, pipeline transportation, optimality criterion, ‘hot’ pumping.

DIGITAL TECHNOLOGY processes SCADA system data using software and manages the technological oil pumping process in the pipeline. This technology monitors the operation of pumping units, preheaters, crude oil accepting and of floating tanks, shut-off valves, etc. All this increases the reliability of the pipeline operation.

This paper presents the results of digital technology development for optimizing oil transportation by integrating SmartTran software of JSC KBTU (hereafter referred

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to as SmartTran) and the SCADA system of JSC KazTransOil (hereafter SCADA system).

The problem of selecting optimum pumping practices through an oil pipeline without oil heating was first set up and solved by D.T. Jefferson [1, 2]. Jefferson examined an oil pipeline equipped with pumps that have different pressure boosting characteristics. Pressure is regulated at each pumping station. Technological limitations are imposed on the pressure value after the control valve and before the station. These limitations are expressed in the form of the following inequality:

\[
\sum_{i=1}^{n} p_{\text{mm}} - p_{0} + k_{i} \leq \sum_{i=1}^{k-1} M_{i} - p_{0} + k_{i}, \quad k = 1, 2, ..., n
\]

where \( n \) is the number of pipeline pump stations; \( p_{0} \) is the net suction head at the source pump station; \( M_{i} \) is the pressure loss at the pipeline section between \( i \) and \( i+1 \) stations; \( p_{\text{mm}} \) is the minimum permissible pressure before \( k+1 \) station; \( p_{\text{max}} \) is the maximum permissible pressure after \( k \) station; \( P_{k} \) is the differential pressure gained by \( i \) station.

In this case, the differential pressure \( P_{k} \) at each station can take any value from 0 to the maximum value \( P_{\text{max}} \).

The problem of identifying optimum practices is formulated as follows: at a fixed level of productivity, to find the distribution of differential pressures \( P_{i} \) between the pipeline stations, where the cost of electricity consumed per unit time by all pumping units will be minimal. The technological limitations should be taken into account (1):

\[
F = \sum_{i=1}^{n} N_{i} z_{i} \rightarrow \min
\]

where \( N_{i} \) is the power consumed by pumps at \( i \) station; \( z_{i} \) is the \( i \) station electricity cost.

To solve the optimization problem, Jefferson [2] uses the idea of dynamic programming. For each station with fixed capacity and a given differential pressure, one of the possible combinations to start the pumps must be chosen. In these conditions, the built-up pressure pumps a set output and consumes the least power. This optimization problem has been considered by V.I.Golosovker [3, 4].

In research by L.G.Shchepekov et al. [5 – 7], a solution is given to the optimization problem for oil pipeline systems using the linear programming method. The algorithms obtained are inferior to the dynamic programming algorithm when solving the problem for a pipeline section with a large number of stations [8].

S.Roberts [9] and J.Hedley [10] have shown the expediency of dynamic programming for solving optimization problems for complex multi-stage processes.

A solution to the problem of optimizing heated oil pumping was first obtained by V.S.Yablonsky et al. [11, 12]. According to V.S.Yablonsky et al. [12], the heating temperature will be optimal when the total cost of pumping and heating per unit length at the beginning of the section is equal to the total cost of pumping and heating per unit length at the end of the pipeline section.

The optimal condition for the fixed oil producing capacity in a pipeline section, as found by V.S.Yablonsky et al. [12], is written as:

\[
\rho \cdot Q \cdot g \cdot i_{n} \frac{z_{n}}{\eta_{n}} + k_{n} \cdot \pi \cdot D_{i} \cdot (T_{n} - T_{0}) \frac{z_{n}}{\eta_{0}} = \rho \cdot Q \cdot g \cdot i_{n} \frac{z_{n}}{\eta_{n}} + k_{n} \cdot \pi \cdot D_{i} \cdot (T_{n} - T_{0}) \frac{z_{n}}{\eta_{0}}
\]
where \( \rho \) is the oil density; \( Q \) is the volume flow rate; \( g \) is the acceleration of gravity; \( i_{H}, i_{k} \) are the hydraulic slopes in the initial and final pipeline sections; \( k_{H}, k_{k} \) are the heat-transfer coefficients in the initial and final pipeline sections; \( z_{H}, z_{\theta} \) are the costs of a unit of mechanical and thermal energy; \( \eta_{H}, \eta_{\theta} \) are the integral efficiency coefficients of pump stations and station preheaters; \( T_{H}, T_{k} \) is the initial and final oil temperature in the section; \( D_{i} \) is the internal diameter of the pipeline.

In studies [13] on heated oil pumping, the minimum total operating costs for pumping and heating are taken as the optimality criterion, and the target function is written as:

\[
S = \rho \cdot Q \cdot g \cdot H \cdot \frac{z_{H}}{\eta_{H}} + \rho \cdot Q \cdot c_{\rho} \cdot (T_{H} - T_{\theta}) \cdot \frac{z_{\theta}}{\eta_{\theta}} \Rightarrow \min
\]

\[
(4)
\]

where \( S \) is the total cost for oil pumping and heating in the section; \( H \) is the pump pressure, and \( c_{\rho} \) is the oil’s heat capacity.

Target functions and pumping optimization problems are also considered in studies [14 - 25]. V.S.Yablonsky et al.’s [12] optimal condition is formulated for a fixed oil producing capacity in the pipeline section, and is not fulfilled when the volume pumped is changed, and the oil temperature is regulated in a section with several pump stations and heating points.

The ‘hot’ pumping optimization problem

As is known, 80% of the energy consumed during ‘hot’ pumping is spent on the operation of pumps and preheaters [26]. Therefore, unlike in other studies, the optimization of ‘hot’ pumping is investigated by determining the optimal operating conditions for pumps and preheaters.

The optimality criterion for ‘hot’ oil pumping in a pipeline section with several stations is determined by the minimum value of the total energy cost used by pumps and preheaters per unit time:

\[
\sum_{i=1}^{k} \left( \sum_{j=1}^{m_{\text{PMP}}} c_{p} \cdot N^{\text{P}}_{ij} \cdot k_{ij} + c_{\text{fuel}} \cdot \frac{Q_{\text{fuel}}^{\text{P}}_{ij}}{Q_{\text{fuel}}^{\text{P}}_{ij}} \right) \rightarrow \min
\]

\[
(5)
\]

where \( m_{\text{PMP}} / m_{\text{fuel}} \) is the number of pumps/preheaters at \( i \) station; \( c_{p} / c_{\text{fuel}} \) is the electricity cost (tenge/(kWh))/fuel cost (tenge/kg) at \( i \) station; \( c_{p} / c_{\text{fuel}} \) is the integer variable, which has a value of 1 if the pump/preheater is in operation, and 0 otherwise; \( N^{\text{P}}_{ij} \) is the power consumption of \( j \) pumping unit of \( i \) station (kWh); \( k_{ij} \) is the ratio of rotor rotation frequency to the nominal frequency of the given pump; \( Q_{\text{fuel}}^{\text{P}}_{ij} \) is the rate fuel is supplied to \( j \) preheater at \( i \) station (kg/h).

The criterion (5) is considered together with pumping safety conditions:

- limitation on pressure at the entrance/exit of the station;
- condition for safe preheater operation;
- not allowing oil temperature in the pipeline to drop below the critical temperature (no-flow point).

The preheater’s safety conditions require the following limitations:

\[
Q_{\text{min},i}^{\text{fuel}} \leq Q_{\text{fuel}}^{\text{P}}_{ij} \leq Q_{\text{max},i}^{\text{fuel}}
\]

\[
(6)
\]
The differential in pressure for pumping through a group of pumps is determined by the formula:

\[
\Delta P^r (Q,k) = \begin{cases} 
0, & c_n = 0 \\
\rho g \left( \frac{Q}{c_n} - k \right), & c_n > 0 
\end{cases}
\]

where \(c_n\) is the number of operating pumps in a group; \(\rho\) is the density of oil being pumped; \(H(Q/c_n, k)\) is the dependence of the pressure on the flow rate of any pump in the group; \(k\) is the ratio of rotor rotations to the nominal frequency of an operating pump.

Given fixed oil flow, the function of pressure and power consumption generated by a pump or a group of pumps, in addition to the parameter \(k\), will have an independent variable in the temperature at the pump entrance (denoted by \(T_{in}\)).

Coefficients of pressure and efficiency characteristics for pumps depend on the toughness of the pumped oil, and the toughness in turn depends on the temperature. Therefore, for the pressure differential and the power consumed, the following dependencies are valid:

\[
\Delta P_{ij}^g = \Delta P_{ij}^g \left( k, T_{i} \right), \quad N_{ij}^{PU} = N_{ij}^{PU} \left( k, T_{i} \right) 
\]

The pressure differential satisfies the equation of the balance of pressures [27]:

\[
P_{in} + \sum_{i=1}^{m} \sum_{j=1}^{n^r} \Delta P_{ij}^g \left( T_{i} \right) = \sum_{i=1}^{k} \left( \Delta P_{i}^{OHS} + \Delta P_{i}^{PR} + \Delta P_{i}^{sec} \right) + \Delta P_{out} + P_{tank} 
\]

where \(P_{in}\) is the initial pressure; \(m^r\) is the number of pump groups at the station; \(\Delta P_{ij}^g\) is the pressure boost generated by the \(j\) group of pumps at the \(i\) station; \(\Delta P_{i}^{PR}\) is the pressure loss after the pressure regulator; \(\Delta P_{i}^{sec}\) is the loss of pressure in the pipeline, taking into account the drop in hydrostatic pressure between the \(i\) and \((i+1)\) station where the oil flow is \(Q_i\); \(\Delta P_{i}^{OHS}\) is the backpressure value at the final station entrance; \(P_{tank}\) is the pressure required to pump oil to the final tank; \(\Delta P_{i}^{OHS}\) are the pressure losses at oil heating stations.

In the case of 'hot' pumping, the pressure losses vary depending on the oil temperature at the station exit. The specified pressure parameters are functions of temperature:

\[
\Delta P_{i}^{sec} = \Delta P_{i}^{sec} \left( T_{i} + \Delta T_{i}^{OHS} \right), \quad \max_{-} \Delta P_{i}^{sec} = \max_{-} \Delta P_{i}^{sec} \left( T_{i} + \Delta T_{i}^{OHS} \right) 
\]

where \(T_{i}\) is the oil temperature at the entrance to the \(i\) station, \(\Delta T_{i}^{OHS}\) is the heating value at the oil heating station. The temperature at the exit to the station is equal to \((T_{i} + \Delta T_{i}^{OHS})\). The temperature at the exit to the next station can be calculated at a known flow rate, using the value of \((T_{i} + \Delta T_{i}^{OHS})\). This value is equal to the oil temperature at the exit of the initial station’s tanks.

The pressure limitations for safe pumping at the entrance and exit before the pressure regulator for the \(k\) station satisfy the conditions:

\[
P_{in}^k = P_{in} + \sum_{i=1}^{k-1} \sum_{j=1}^{n^r} \Delta P_{ij}^g - \sum_{i=1}^{k-1} \left( \Delta P_{i}^{OHS} + \Delta P_{i}^{PR} + \Delta P_{i}^{sec} \right) \geq P_{in}^{max} 
\]

\[
P_{out}^{k-1} = P_{in} + \sum_{i=1}^{n^r} \Delta P_{ij}^g - \Delta P_{i}^{OHS} \leq P_{out}^{max}
\]
When the preheater is located before the pumping station $T_{ik}^{inpum} = T_k + \Delta T_k^{OHS}$, the condition for cavitation-free operation for each $l$ group of pumps at the $k$ station is as follows:

$$P_{i_k}^{inpum} = P_{i_k}^{in} - \Delta P_{i_k}^{OHS} + \sum_{j=1}^{k-1} \Delta P_{i_j}^{n} \geq P_{i_k}^{min,p} \quad (11)$$

For the heated oil flow through each $i$ preheater there is a relationship of the type:

$$Q_{i_k}^{heat} = Q_{i_k}^{out} \left( \Delta P_{i_k}^{OHS}, g_{heating} \right) \quad (12)$$

where $\Delta P_{i_k}^{OHS}$ is the value of the pressure differential in the bypass pipe; $g_{heating} = \left( g_{1_k}, g_{2_k}, \ldots, g_{n_k} \right)$ is the vector denoting the operation of each preheater. The relationship can be determined taking into account the construction of the preheaters at the station.

For each preheater, there is also the relationship of its heating value to the rate of oil flow through the preheater and the rate of fuel supplied to this preheater:

$$\Delta T_{i_k}^{heat} = C_{heating} Q_{i_k}^{heat} Q_{i_k}^{fuel} \quad (13)$$

where the constant $C_{heating}$ depends on the construction of the preheater, its condition, the fuel composition, and the time of year. This value is proportional to the preheater’s efficiency.

There is a specific temperature limit for the oil being pumped. It can be safely heated to this temperature in a preheater so that it does not decompose into separate fractions or evaporate. This value can be denoted as $T_{oil}^{max}$. In order to take this into account in the problem model, the following limitation is imposed for each $j$ preheater at the $i$ station:

$$T_j + \Delta T_{i_k}^{heat} = T_j + C_{heating} Q_{i_k}^{heat} Q_{i_k}^{fuel} \leq T_{oil}^{max} \quad (14)$$

Since the heated oil flows with rates $Q_{i_k}^{heat}$ from each preheater are then mixed with the unheated bypass flow at flow rate $Q = \sum Q_{i_k}^{hot}$ the total heating at the exit of the station at flow rate $Q$ is determined by the formula for mixing flows with different weight coefficients:

$$\Delta T_{OH}^{OHS} = \sum_{i=1}^{n} C_{i_k}^{heat} Q_{i_k}^{heat} \Delta T_{i_k}^{heat} \quad (15)$$

Using Eqs 12, 13, 15 the relationship of the heating value at the station to the values $\Delta P_{i_k}^{OHS}$, $g_{i_k}^{heat}$ and $Q_{i_k}^{heat}$ can be expressed thus:

$$\Delta T_{OH}^{OHS} = \frac{1}{Q} \sum_{i=1}^{n} C_{i_k}^{heat} Q_{i_k}^{heat} \left( Q_{i_k}^{heat} \left( \Delta P_{i_k}^{OHS}, g_{i_k}^{heat} \right) \right)^2$$

Each type of oil pumped in the section has a lower limit for cooling temperature $T_{oil}^{min}$. Usually its value is linked to the temperature at which oil flow is lost. For this reason it is necessary to impose the limitation:

$$T(s) > T_{oil}^{min} \quad (16)$$

where $T(s)$ is the value of oil temperature in a section.

Thus, the target function (5) and the pressure limitations (9) - (11) are formulated to
select optimum pumping practices for heated oil, as well as the temperature limitations (6), (14), (16). The main parameters of the problem are the following variables:

- \( c_{ij} \) - the optimum combination of pumps;
- \( g_{ij} \) - the optimum combination of preheaters;
- \( Q_{ij}^{fuel} \) - the necessary fuel supply to the preheater;
- \( \Delta P_{i}^{OHS} \) - loss of pressure in the heating station.

### Solution algorithm

The search task is performed using an approach based on dynamic programming and can be subdivided into a set of overlapping subtasks in order to find the optimal substructure. Using the solution to the problem for \( n \) pumps, it is possible to find solutions effectively for \( n + 1 \) pumps. A graph of pump operating conditions has been drawn up. Each graph unit contains data on the number of pumps used and their parameters, and the pressure drop in the pressure controller. The units of the graph are connected, based on pump pressure capacity characteristics and rotor rotation frequencies. The transition from the subtask solution to the solution of the general problem has been found and the correctness of this approach has been proved.

The object of each subtask is the function of the relationship of energy consumption cost to the pressure differential generated at the pump.

Naturally, \( P \geq 0 \). The optimum pressure is related to the pumping temperature. In the search for a solution, instead of continuous function \( S(P,T) \), its discrete version was used. The pressure value can be represented discretely with a fairly fine pitch \( \varepsilon_p = 0.01 \) bar, the temperature value is \( \varepsilon_T = 0.05^\circ C \).

The solution of the problem is stored in a discrete array \( \text{Info}(P,T) \) which for each value \( P \) contains a list of the necessary pumps at several previous stations.

The cost function \( S(P,T) \) and the solution array \( \text{Info}(P,T) \) for the pump can be written as:

\[
S(P,T) = \begin{cases} +\infty, & P \neq P_{\text{opt}} \\ z N^{P}(Q,T), & P = P_{\text{opt}} \\ \text{Info}(P,T) = \begin{cases} \emptyset, & P \neq P_{\text{opt}} \\ \text{pump number}, & P = P_{\text{opt}} \end{cases} \end{cases}
\]

(17)

where \( z \) is the cost of electricity at the station (tenge /kWh)), \( N_{\text{PU}} \) is the pump power (kW), \( Q \) is the flow rate passing through the pump.

The pressure differential generated by the pump is found to be:

\[
P_{\text{opt}} = \left[ \rho g H(Q,T) \right]
\]

where the operator \([ \ ]\) denotes rounding up to the nearest rational number in increments of \( \varepsilon_p \). The initial cost function is defined as follows:

\[
S_0^{-1}(P,T) = \begin{cases} 0, & P = P_0 \text{ and } T = T_n \\ +\varepsilon_T, & \text{otherwise} \end{cases}
\]

(18)

The 'combination' of two functions can be used to denote the function \( S(P) \), which for each \( P \) has value:

\[
S(P,T) = S^{A}(P,T) \cup S^{B}(P,T) = \min \left( S^{A}(P,T), S^{B}(P,T) \right)
\]
Similarly, the “combination” of two arrays denotes an array $\text{Info}(P,T)$ that for each $P$ has the value:

$$\text{Info}(P,T) = \text{Info}^A(P,T) \cup \text{Info}^B(P,T) = \begin{cases} \text{Info}^A(P,T), & S^A(P,T) \leq S^B(P,T) \\ \text{Info}^B(P,T), & S^A(P,T) > S^B(P,T) \end{cases}$$

The superposition of function $S^A$ on function $S^B$, denotes function $S(P,T)$, which for each $P$ has the value:

$$S(P,T) = S^A(P,T) \leftarrow S^B(P,T) = \min\left(S^A(P,T), S^A(P-P', T) + S^B(P', T)\right)$$

where the value of variable $P^*$ for a particular value $P$ is defined as:

$$P^* = \arg\min_{P' \in [0,\infty]} S^A(P-P', T) + S^B(P', T)$$

Likewise, the superposition of array $\text{Info}^B$ on array $\text{Info}^A$ is used to denote array $\text{Info}(P,T)$ which for each $P$ has the value:

$$\text{Info}(P,T) = \text{Info}^B(P,T) \leftarrow \text{Info}^A(P,T) = \begin{cases} \text{Info}^B(P,T), & S^A(P,T) \leq S^A(P-P', T) + S^B(P', T) \\ \text{Info}^A(P-P', T) + \text{Info}^B(P', T), & \text{otherwise} \end{cases}$$

The cost function $S_{\text{heat}}$ and the solution array $\text{Info}_{\text{heat}}(i)$ for each $i$ preheater are taken into account for modes using heating. The independent variables of these are as follows:

- The first independent variable $P$ indicates the pressure differential at the station;
- The second independent variable $T$ is the oil temperature at the entrance to the preheater; and
- The additional third independent variable $D_T$ is the increase in the total flow temperature using this preheater.

The preheater cost function has an additional index - the sample size of operating preheaters $v$ at the station from the set $m_{\text{heat}}$.

Naturally, $v \leq 2^{m_{\text{heat}}} - 1$.

The cost function for operating preheaters and its solution array are calculated as follows:

$$S_{\text{heat}}(P,T,\Delta T) = \begin{cases} z_{\text{heat}}\Delta Q_{\text{fuel}}(P,\Delta T) \in [Q_{\text{fuel},\text{min}}, Q_{\text{fuel},\text{max}}] & , T + \Delta T_{\text{heat}} \leq T_{\text{ref}} \\ +\infty, & \text{otherwise} \end{cases}$$

$$Q_{\text{fuel}}(P,\Delta T) = \frac{\Delta T_{\text{heat}}(P,\Delta T)}{C_{\text{fuel}}(P, g_{\text{fuel}}(v))}, \Delta T_{\text{heat}}(P,\Delta T) = \frac{Q}{Q_{\text{fuel}}(P, g_{\text{fuel}}(v))} - \Delta T$$ (19)

$$\text{Info}_{\text{heat}}(P,T,\Delta T) = \begin{cases} \text{"heater number"} & , Q_{\text{fuel}}(P,\Delta T) \in [Q_{\text{fuel},\text{min}}, Q_{\text{fuel},\text{max}}] \\ \text{"heater not working"}, & \text{otherwise} \end{cases}$$

where $Q_{\text{fuel}}(P,\Delta T)$ is the required fuel rate for the $i$ preheater when sampling, $\Delta T_{\text{heat}}$ is the heating temperature for the flow through a given preheater.

Vector $g_{\text{fuel}}(v)$ indicates the working combination of preheaters when sampling $v$. Since the superposition operation occurs for values $Q_{\text{fuel}}$ and $\Delta T_{\text{heat}}$ when solving $S_{\text{heat}}(P,T,\Delta T)$, the given solution automatically takes into account limitations to the fuel consumption of the preheater (6) and the maximum heating in the preheater (14).
After calculating all $S_{v^\text{heat}}$ and $\text{Info}_{v^\text{heat}}$, it is necessary to define the cost function $S_{v^\text{OHS}}$ and the solution array $\text{Info}_{v^\text{OHS}}$ for the total operation of the preheaters at the station for each sample $v$. Values $S_{v^\text{OHS}}$ and $\text{Info}_{v^\text{OHS}}$ are defined by the superposition of functions for all operating preheaters:

\[
S_{v^\text{OHS}}(P, T, \Delta T) = S_{v^\text{heat}}^\text{heat} \leftarrow S_{v^\text{heat}}^\text{heat,2} \leftarrow \ldots \leftarrow S_{v^\text{heat}}^\text{heat,\#}
\]

\[
\text{Info}_{v^\text{OHS}}(P, T, \Delta T) = \text{Info}_{v^\text{heat}}^\text{heat} \leftarrow \text{Info}_{v^\text{heat}}^\text{heat,2} \leftarrow \ldots \leftarrow \text{Info}_{v^\text{heat}}^\text{heat,\#}
\]

(20)

where $\text{g}_{\text{op}}(v)$ is the number of operating preheaters when sampling.

The superposition operation for the preheater cost function will take the following form (similar for the solution array):

\[
S^\text{heat,\#}(P, T, \Delta T) \leftarrow \left( S^\text{heat,\#} \right) = \min_{\Delta T \geq 0} \left( S^\text{heat,\#}(P, T, \Delta T) + S^\text{heat,\#}(P, T, \Delta T - \Delta T^*) \right)
\]

(21)

For any group of three values $(P, T, \Delta T)$, optimal station operation means the optimal sample of operating preheaters out of $m^\text{heat}$ preheaters. Therefore, the optimal cost function for the station is the combination of all possible cost functions from the samples $(2^m - 1)$ (similar for the solution array):

\[
S^\text{OHS}(P, T, \Delta T) = \bigcup_{v=1}^{2^m - 1} S_{v^\text{OHS}}(P, T, \Delta T)
\]

(22)

When none of the preheaters at the station operate, the calculated cost function and the solution array should be adjusted:

\[
S^\text{OHS}(0, T, 0) = 0, \quad \text{Info}^\text{OHS}(0, T, 0) = "heaters not working"
\]

Since, unlike the group of pumps, when the oil passes through the station the flow temperature increases and the pressure decreases, the superposition of the heating cost function $S^\text{OHS}$ onto the cost functions of the entire station takes the following form (similar for the solution array):

\[
S(P, T) = S^\text{heat}(P, T) \leftarrow \left( S^\text{OHS} \right) = \min_{P^*, \Delta T^* \geq 0} \left( S^\text{heat}(P + P^*, T - \Delta T^*) + S^\text{OHS}(P^*, T - \Delta T^*, \Delta T^*) \right)
\]

If the preheaters are located after the pumps, then the cost function at the station entrance and its solution array must first be superimposed with the cost function $S^\text{OHS}$ and only then with the cost functions of the pump group. Otherwise, the opposite should be done. If there are no preheaters at a station, there is no need to calculate function $S^\text{OHS}$ for it or to superimpose it on the cost function of the station.

The pressure differential and temperature drop at the section depend on the initial temperature. To properly trim the cost functions and solution arrays at the exit of the station and define the cost functions and solution array at the entrance of the next station, the discrete functions $\Delta P^\text{max}_i(T), \Delta T^\text{max}_i(T)$ and $\max_\Delta \Delta P^\text{max}_i(T), \max_\Delta \Delta T^\text{max}_i(T)$ should be calculated for each $i$ section in increments of $\varepsilon_i$.

Moreover, the function $\max_\Delta \Delta T^\text{max}_i(T)$ determines the maximum value of the temperature drop between the initial point and any point in the $i$ section.
It is thus possible to define functions \( P_{\text{out}}^{\text{min}}(T), P_{\text{out}}^{\text{max}}(T) \) for the minimum and maximum allowable pressure at the exit of the station:

\[
P_{\text{out}}^{\text{max}} \geq P_{\text{out}}^{\text{min}} = \max \left( P_{\text{out}}^{\text{min}} + \Delta P_{\text{sec}}^k, \max_0 \Delta P_{\text{sec}}^k \right) \\
P_{\text{out}}^{\text{min}} \leq P_{\text{out}}^{\text{max}} = \min \left( P_{\text{out}}^{\text{max}} - \Delta P_{\text{sec}}^k, P_{\text{out}}^{\text{max}} \right)
\]

In this case, the condition (16) for minimum required temperature at the exit of the station will take the following form:

\[
T_{\text{out}}^{\text{min}}(T) = T_{\text{oil}}^{\text{min}} + \max_0 \Delta T_{\text{sec}}^k(T)
\]

Cost function trimming at the exit of the station is found from \( P_{\text{out}}^{\text{min}}(T), P_{\text{out}}^{\text{max}}(T), T_{\text{out}}^{\text{min}}(T) \) and is denoted as a function which for each \( P \) and \( T \) has value:

\[
S^\text{cut} (P, T, \Delta P_{\text{sec}}^k, \Delta T_{\text{sec}}^k) = \begin{cases} 
+\infty, & P \notin [P_{\text{out}}^{\text{min}}(T), P_{\text{out}}^{\text{max}}(T)] \\
+\infty, & T < T_{\text{out}}^{\text{min}}(T) \\
S^*(P, T), & \text{otherwise}
\end{cases}
\]

The solution array is trimmed in the same way.

The pressure differential in the preheater will be added to the cost function and the solution array at the station exit. The changed pressure conditions (9) and (10) are automatically taken into account when it is trimmed.

The cost function at the entrance to the subsequent station is determined by the "shift" operation using the cost function at the station exit through \( \Delta P_{\text{sec}}^k(T) \) and \( \Delta T_{\text{sec}}^k(T) \). This function for each \( P \) and \( T \) has a value:

\[
S^\text{shift} (P, T, \Delta P_{\text{sec}}^k, \Delta T_{\text{sec}}^k) = \min_T \left( S^* \left( P + \Delta P_{\text{sec}}^k \left( T^* \right), T + \Delta T_{\text{sec}}^k \left( T^* \right) \right) \right)
\]

The shift operation is performed in the same way for the solution array.

All operations for finding the optimum practices of the 'hot' pumping method are thus defined above.

These operations are carried out for all stations except the last one in order of their location in the pipeline section:

\[
k = 1, 2, \ldots, m
\]

1. For \( i = 1 \) to \( m \):
   
   a. \( S^D_{\text{in}} \)

2. If \( m^{\text{heat}} > 0 \), then it is necessary to calculate \( S^\text{OHS} \) (19) – (22)

3. \( S^D_{\text{in}} (P, T) = S^D_{\text{in}} (P, T) \left\langle S^D_{\text{in}} (P, T) \left\langle \cdots \left\langle S^D_{\text{in}} (P, T) \right\rangle \right\rangle \right\rangle = \left\langle S^D_{\text{in}} (P, T) \right\rangle \right\rangle = \left\langle S^D_{\text{in}} (P, T) \right\rangle \right\rangle = \left\langle S^D_{\text{in}} (P, T) \right\rangle \right\rangle \) (23)

4. Calculation of functions \( \Delta P_{\text{sec}}^k(T), \Delta T_{\text{sec}}^k(T), \max_0 \Delta h_{\text{sec}}^k(T), \max_0 \Delta T_{\text{sec}}^k(T) \)

5. \( S^D_{\text{in}} (P, T) = \text{CUT} \left( S^D_{\text{in}} (P, T), P_{\text{out}}^{\text{min}}(P, T), P_{\text{out}}^{\text{max}}(P, T), T_{\text{out}}^{\text{min}}(P, T) \right) \)
6. \( S_n^{u,k+1}(P) = \text{SHIFT} \left( S_n^{u,k}(P,T), \Delta P_n^{\text{sec}}, \Delta T_n^{\text{sec}} \right) \)

7. \( k = k+1 \). If \( k \neq n+1 \), then go to step 1, otherwise exit the cycle

After the above cycle with initial condition (18) is carried out, the optimal final pressure and temperature are calculated as:

\[
\left( P^{opt}, T^{opt} \right) = \arg\min_{T \in \text{Final}, P \in \text{Final}} \left\{ S_n^{u,n+1}(P,T) \right\}
\]

The minimum cost per unit is the value of function \( S_n^{u,n+1}(P,T) \). The optimum combination of operating pumps and preheaters, as well as their operating practices and the required pressure differentials at the station, will be stored in the cell of the array.

**Discussion of calculation results**

Determining optimum oil pumping practices is important for reducing the power consumption of pumps and preheaters in the Uzen-Atyrau-Samara oil pipeline [25]. Taking into account the extent of electricity and heat consumption for ‘hot’ pumping, even a minor percentage reduction in costs can lead to significant energy savings [14], [23], [25].

Optimum ‘hot’ pumping practices are being sought at the Kasymov - Bolshoy Chagan section of this pipeline. Pumping occurs using the Kasymova and Inder station pumps, while oil heating takes place in the Sakharinii heating station as well as at these stations.

Based on criterion (5) and algorithm (23), SmartTran software was developed to model and optimize ‘hot’ pumping. SmartTran software was integrated with the SCADA fibre-optic system, i.e. parameters for ‘hot’ pumping practices were found by the SCADA system and represent the initial data for SmartTran calculations.

Figure 1 shows the distribution of pressure, the temperature of ‘hot’ pumping at the Kasymov-Bolshoy Chagan section, the operating pump parameters, and the oil heating temperature. The upper part of the figure shows the hydro-slope change. The middle part shows the distribution of pressure, while the lower part shows the distribution of oil and ground temperature. Operating pumps M2 and P2 at Kasymova station, and M2 and M3 at Inder station are marked in Fig.1. Oil is heated at Kasymova, Inder, and Sakharinii stations. The distributions of the hydro-slope, pressure and temperature of the oil blend in Fig.1 were obtained from SmartTran calculations. The points are the experimental data from the SCADA system. The concurrence of calculated data from SmartTran and the SCADA system should be noted.

The upper table (Fig.1) presents oil flow of 1782 t/h, power consumption of 5095 kW, specific electricity consumption of the pumps of 2.86 kWt/h, operating costs of the pumps of 87,000 tenge/h and of the preheater of 1,514,000 tenge/h, specific costs for pumping of 48.8 tenge/t and for heating of 85 tenge/t.

The lower table (Fig.1) shows the values calculated by SmartTran (oil pressure and temperature, pump power), which correspond to experimental data from the SCADA system with accuracy of 1 to 2%.

In the case of high flow rates, a drag reducing agent is introduced at Sakharinii in order to reduce the hydraulic resistance of the turbulent oil flow. This is due to the fact that at Sakharinii station, the pipeline switches from 1000 mm to 700 mm pipe.
diameter. Moreover, the average oil flow rate increases 2.04 times.

Figure 2 shows the results of SmartTran calculations and the experimental data of the SCADA system when the drag-reducing agent is added at Sakharnii with a concentration of 3 ppm.

The increase in oil flow to 1918.2 t/h leads to an increase in power consumption to 5,297 kW, in the cost of operating pumps to 905,000 tenge/h and the preheater to 2,192,000 tenge/h. However, the specific electricity consumption and pumping costs are reduced to 2.76 kWh/t and 47.2 tenge/t, respectively.

This can be explained by the influence of the drag reducing agent, which reduces the hydraulic resistance of the turbulent oil flow.

The specific costs of the preheater increase because a greater quantity of oil is heated. The correspondence between the calculated values for pump power, oil flow parameters and the experimental data from the SCADA system can also be noted here (Fig.2).

When ‘hot’ pumping, the main costs relate to heating oil. Optimization calculations were therefore carried out to determine an effective heating temperature for oil.

Figures 3 and 4 show the calculated data obtained for the same oil flow rate of 1779.2 t/h and ground temperature value.

The results of calculated data in Fig.3 were obtained from the experimental data of SCADA heating temperature at the Kasymova, Inder, and Sakharnii sections.

The results of calculated data in Fig.4 were obtained when the oil heating temperatures at Kasymova, Inder, and Sakharnii were found for optimal operating conditions for the pumps and the preheater. The optimal conditions were determined on the basis of criterion (5), satisfying the conditions for pressure (9) - (11), and oil preheating temperature (6), (14), (16).

In this case, the preheating temperature is adapted at Kasymova, Inder, and Sakharnii, so that the oil temperature at the Kasymov-Bolshoy Chagan section does not drop below 28°C. As can be seen from Fig.4, the heating temperatures are equal to 42.2°C at Kasymova, 37.7 °C at Inder, and 38.0 °C at Sakharnii.

By contrast, according to SCADA experimental data, the heating temperatures equalled 46.3°C at
Kasymova, 42.1°C at Inder, and 44.1°C at Sakharnii (Fig.3).

It can be noted that given optimum practices, the heating temperatures decrease by 4.1°C at Kasymova, by 5.4°C at Inder, and by 6.1°C at Sakharnii.

The total capacity of the pumps is 5091 kW (Fig.3) and 5088 kW (Fig.4).

Given optimum practices, the total costs for oil pumping and heating reduce from 2,201,000 tenge/h to 1,621,000 tenge/h, and unit costs from 123.7 tenge/t to 91.1 tenge/t.

Thus, the developed digital technology, by integrating SmartTran software with the SCADA system, makes it possible to determine the energy efficiency of ‘hot’ oil pumping.

**Conclusions**

Based on the results of these studies, the following conclusions can be drawn:

1. Optimizing ‘hot’ pumping practices includes identifying operating conditions for pumps and oil preheaters where the total...
energy cost value for pumps and fuel per unit time is minimal, and conditions for safe pumping are fulfilled. The expediency of minimizing the total cost, rather than the amount of energy consumed by pumps and preheaters, is explained by the fact that electricity and thermal energy have completely different costs. Therefore, it is reasonable to compare only expenditures from operating pumps and preheaters.

2. The solution algorithm is performed using the new approach of dynamic programming. The search problem is divided into a set of overlapping subtasks in order to find the optimal substructure. The object of each subtask is the cost function of pumps and preheaters at the stations of the pipeline section.

The combination of working pumps and preheaters which provides the minimum total expenditure is being searched for a solution.

Calculated results from SmartTran software (oil pressure and temperature, pump power), for ‘hot’ oil pumping at the Kasymov - Bolshoy Chagan section correspond to the experimental data of the SCADA system.

The optimal conditions were obtained on the basis of criterion (5), satisfying the conditions for pressure (9) - (11) and oil preheating temperature (6), (14), (16). Energy efficiency of pumps and preheaters was found provided that the oil temperature at the Kasymov-Bolshoy Chagan section did not drop below 28°C. It has been shown that the specific costs for pumping and heating were reduced from 123.7 tenge/t to 91.1 tenge/t. This constitutes a saving of 26.3%.

References
management problem. M. GRSU OG (Gubkin Russian State University of Oil and Gas) 37 pp.
20. V. A. Shabanov, O. V. Bondarenko, 2012. Target functions and criteria for oil pumping optimization through oil pipelines under VFD (variable frequency drive) of main line pumps. Oil and Gas Engineering 4 pp 10-17.
Listing of forthcoming industry events (continued from p 208)

IOGRPE - Iran Oil Show  
6-9 May 2018  
Tehran, Iran  
http://iran-oilshow.ir  
Iran oil show is the one of the largest exhibitions about oil and gas in the Middle East. It is a good opportunity to see the oil and gas market in Iran and other countries of the world.

16th International Exhibition for the Energy Industry  
10-12 May 2018  
Lahore, Pakistan  
http://www.pogeepakistan.com  
POGEE has become an important industry event. The annual growth in the number of exhibitors from around the world ascertains the immense investment potential in Pakistan’s energy sector. While showcasing the state-of-the-art machinery and technology, it brings together leaders and industry professionals.

Gas & Oil Technologies Expo and Conference  
22-25 May 2018  
Ufa, Russia  
http://www.gntexpo.ru  
The business platform with the participation of leading industry experts: representatives of science, government authorities, industry and business. The program of the Russian Petrochemical Forum includes: plenary session, international conference, seminars, round tables, thematic meetings.

15th Moscow International Oil and Gas Exhibition / MIOGE  
18-21 June 2018  
Moscow, Russia  
http://www.mioge.ru/en-GB  
MIOGE is Russia’s largest international exhibition of oil and gas equipment and technologies.

Oil & Gas Africa  
6-8 July 2018  
CTICC, Cape Town, South Africa  
http://oilgasafrcia.com  
Oil & Gas Africa is dedicated to developing the mid-stream and downstream sectors across the continent and features leading industry experts sharing a platform to discuss the latest challenges, market developments and opportunities.

The International Fair INNOPROM  
9-12 July 2018  
Ekaterinburg, Russia  
http://www.innoprom.com/en  
Russian’s leading metalworking and welding trade fair. It unites the key sectors of industry – industry automation, power engineering technologies, machine building and components for mechanical engineering, metalworking.
THE INDUSTRY’S KEY EVENT:
in the centre of attention, in the centre of Moscow

NATIONAL OIL AND GAS FORUM

16–18 April 2018
Expocentre Fairgrounds
Moscow, Russia
www.oilandgasforum.ru

18th International Exhibition
NEFTEGAZ 2018

16–19 April 2018
Expocentre Fairgrounds
Moscow, Russia
www.neftegaz-expo.ru
Modernizing the leak-detection system for MOL’s oil-products pipelines - Part 2

by F. Péterfalvi
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In Part 1 of this paper, published in the September issue, the author introduced MOL’s pipeline network, and went on to describe in detail the company’s licensing, operational, and safety requirements. Part 2 begins with a description of the company’s new approach to a leak-detection system (LDS) which has now been installed on a section of the network.

MOL’s new LDS for oil-product pipelines

The new LDS is the final stage of the ‘Operational system for oil product pipelines’ modernization project. It includes the pipeline system SCADA function, batch tracking and recording of transported oil products, monitoring the system infrastructure, and leak-detection modules.

Key features of the LDS project:

- introducing new leak-detection algorithms, and improving the accuracy of currently used ones;
- installing new, faster and more accurate Foundation Fieldbus pressure sensors at all stations;
- using new measuring instruments to determine the temperature profile along the entire length of the pipeline;
- installing new Coriolis flow meters in DN200 pipelines at Szajol receiving station and DN300 at Tiszajáváros (Fig.1) (Coriolis flow meters are used to determine the mass flow rate);
- integrating into the system additional isolation stations at Mezőszentgyörgy and Iregszemcse (Fig.2) in order to obtain a greater quantity of data about the pipelines;
- replacing out-of-date time servers with more precise and modern models;
- replacing time markers of the 16-bit analogue-to-digital converter with PLC modules supporting the 32-bit OMNI Flow communication;
- improving the system’s level of reliability in various ways, and upgrading batch tracking and calculation of oil-product transportation in accordance with the necessary requirements.

Defining the requirements for leak detection

Taking into account the assessment of LDS technologies (Table 1) and the existing conditions, an expert team has prepared a SCADA system project with a high level of availability, developed to account for the pipelines’ operational regime. These system works in parallel with independent algorithms, which provides a high level of availability and reliability in the new LDS. The pressure-wave method (PWM) acts as the main way of detecting third-party interference, since:

in combination with other methods (PDM, VBM, DMRT) it provides an optimal solution from the point of view of cost-quality ratio, as well as corresponding
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<td>Statistical analysis of volume balance and pressure</td>
<td>Analysis of rarefaction wave generated by a leak</td>
<td>Distributed sensing of temperature, noise / vibration or hydrocarbons</td>
<td></td>
</tr>
<tr>
<td>Application requirements</td>
<td>Measurements of ambient temperature, density or gas composition in addition to flow, pressure, temperature; SCADA and communication</td>
<td>Measurement of flow and pressure; SCADA and communication</td>
<td>Measurement of pressure, dedicated data acquisition equipment and communication</td>
<td>Installation of proprietary fibre optic sensing cable</td>
</tr>
<tr>
<td>Fluid application</td>
<td>For gas and liquid pipelines, onshore and offshore</td>
<td>For gas, liquid and multiphase pipelines onshore and offshore</td>
<td>For gas, liquid and multiphase pipelines onshore and offshore</td>
<td>For gas, liquid and multiphase pipelines, mostly onshore</td>
</tr>
<tr>
<td>Reliability</td>
<td>Medium, depending on model performance</td>
<td>High, designed to minimise false alarms</td>
<td>Low to medium, depending on tuning and system</td>
<td>Low to medium, depending on environmental factor and leak effect</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>Low to medium due to difficulty in maintaining high accuracy models</td>
<td>Medium</td>
<td>High, detecting small leaks and thefts quickly</td>
<td>Very high, detecting small leaks quickly</td>
</tr>
<tr>
<td>Robustness</td>
<td>Medium, loss of function due to missing data, slack flow or transient operations</td>
<td>High, can still detect leaks even if some instruments fail. Works under steady state, transient and shut in conditions</td>
<td>Medium, loss of function if pressure sensors are not available. Works under steady state, transient and shut in conditions</td>
<td>Low; may not detect leaks if cable is cut or if the hole is not located near the cable. Works under steady state, transient and shut in conditions</td>
</tr>
<tr>
<td>Leak location accuracy</td>
<td>Low</td>
<td>Medium</td>
<td>High, down to 100s of metres</td>
<td>Very high, down to 10s of metres</td>
</tr>
<tr>
<td>Calculation of leak size</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes, accurate only after leak calibration tests</td>
<td>No</td>
</tr>
<tr>
<td>Installation cost*</td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
<td>Very high if cable is to be installed</td>
</tr>
<tr>
<td>Maintenance cost</td>
<td>High, expert tuning required</td>
<td>Medium</td>
<td>Medium</td>
<td>Medium</td>
</tr>
<tr>
<td>Remarks</td>
<td>Suitable for existing and new pipelines if flow, pressure, gas composition / density and ambient temperature measurements are available</td>
<td>Good track record on both gas and liquid pipelines. Suitable for existing and new pipelines.</td>
<td>Requires pressure sensors only. Suitable for existing and new pipelines.</td>
<td>DAS / DVS can be used for intruder detection. Difficult test the performance. Difficult to retrofit.</td>
</tr>
</tbody>
</table>

*Installation cost has assumed that no field instruments exist on the pipeline. The cost for RTTM and Statistical systems would be reduced if field instruments are already in place.

Table 1. Comparative characteristics of pipeline leak-detection technologies (DMRT, SA, NP, and FO) [3]. (Note: (DAS – distributed acoustic sensing; DVS – distributed vibration sensing.)

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Thus the main elements and the basic specification for the new system are as follows:

- the principal method is PWM in conjunction with PDM (pressure-drop method), VBM (volume-balance method), and DMRT (dynamic modelling in real time)
- leak sensitivity:
  - in closed conditions (without transportation): 3-15 l/min
  - with transportation: 10-40 l/min
- leak localization accuracy: ±120 m in 0.1 sec with accurate time markers.
The accuracy depends on the pipe diameter, the length of the section, the position of valves, and distance between pressure sensors. Exact values were determined separately for each section.

Some technical characteristics of the

<table>
<thead>
<tr>
<th>No.</th>
<th>Location</th>
<th>Permissible number of errors and outages</th>
<th>Availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Tiszajúváros</td>
<td>3 errors - 24 hours / year</td>
<td>99.73%</td>
</tr>
<tr>
<td>2</td>
<td>Szajol</td>
<td>3 errors - 24 hours / year</td>
<td>99.73%</td>
</tr>
<tr>
<td>3</td>
<td>Szőny</td>
<td>3 errors - 24 hours / year</td>
<td>99.73%</td>
</tr>
<tr>
<td>4</td>
<td>Pécs</td>
<td>1 error - 8 hours / months</td>
<td>99.00%</td>
</tr>
<tr>
<td>5</td>
<td>Székesfehérvár</td>
<td>1 error - 8 hours / months</td>
<td>99.00%</td>
</tr>
<tr>
<td>6</td>
<td>Csepel</td>
<td>1 error - 8 hours / months</td>
<td>99.00%</td>
</tr>
<tr>
<td>7</td>
<td>Ferihegy</td>
<td>1 error - 8 hours / months</td>
<td>99.00%</td>
</tr>
<tr>
<td>8</td>
<td>Kecskemét</td>
<td>1 error - 8 hours / months</td>
<td>99.00%</td>
</tr>
<tr>
<td>9</td>
<td>Nyírbodánya</td>
<td>1 error - 8 hours / months</td>
<td>99.00%</td>
</tr>
<tr>
<td>10</td>
<td>Supply station, Százhalombatta</td>
<td>1 error - 8 hours / months</td>
<td>99.90%</td>
</tr>
<tr>
<td>11</td>
<td>Isolation stations</td>
<td>6 errors - 48 hours / year</td>
<td>99.45%</td>
</tr>
</tbody>
</table>

Table 2. Expected availability of the pipelines.

PWM used [8] are presented below:
- resolution of pressure measurement: ≈ 1 mbar at 63 bars
- total sampling time: 100 ms
- process 'noise' during operation:
- during work (pumping): ≈ 15 mbar

<table>
<thead>
<tr>
<th>Part of section (between two adjacent stations)</th>
<th>Diameter, mm</th>
<th>Length, km</th>
<th>Volume, m³</th>
<th>Minimal sensible leakage, l/min</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Shut-in/static condition</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Shut-in condition</td>
</tr>
<tr>
<td>Százhalombatta-Szőny DN150</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1201-1501</td>
<td>200</td>
<td>17.9</td>
<td>562</td>
<td>1.2</td>
</tr>
<tr>
<td>1501-1701</td>
<td>150</td>
<td>24.8</td>
<td>438</td>
<td>1</td>
</tr>
<tr>
<td>1701-1702</td>
<td>150</td>
<td>16.8</td>
<td>296</td>
<td>0.7</td>
</tr>
<tr>
<td>1702-7000</td>
<td>150</td>
<td>26.4</td>
<td>466</td>
<td>1</td>
</tr>
<tr>
<td>Százhalombatta-Szőny DN300</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1201-1501</td>
<td>300</td>
<td>18.4</td>
<td>1300</td>
<td>3</td>
</tr>
<tr>
<td>1501-1701</td>
<td>300</td>
<td>24.8</td>
<td>1753</td>
<td>4</td>
</tr>
<tr>
<td>1701-1702</td>
<td>300</td>
<td>16.9</td>
<td>1194</td>
<td>2.7</td>
</tr>
<tr>
<td>1702-7000</td>
<td>300</td>
<td>26.3</td>
<td>1859</td>
<td>4.3</td>
</tr>
</tbody>
</table>

Table 3. Specification of minimal leak detection for a section of the Százhalombatta-Szőny pipeline.
Some important aspects of the technical content of the EPC contract:

After carrying out the tender, the MOL company signed an EPC contract with a contractor (engineering, procurement and construction).

The PipeMan (Slovakia) LDS monitors all sections of the MOL’s oil product pipelines. However, its sensitivity level has proved to be lower than expected in the majority of sections with the exception of the Tiszaújváros-Százhalombatta pipeline for benzene and toluene transportation. The reduction in sensitivity is due to the low frequency and quality of the data received, which is limited by the installed instruments and the remote terminals (RT).

One of the aims of the project was to improve the effectiveness of PWM, providing the very best productivity of LDS with a reasonable investment cost. Among other aims one could mention the improvement of leak-detection methods as a whole.

Besides this, the project includes the replacement of the main equipment, as well as functions directly impacting the availability of pressure measuring sections. The facilities are equipped with no-break power sources (NBP), as well as with RT containers and boxes.

Table 2 displays the expected levels of availability for various pipelines.

In the previous system, pressure together with other analogue signals is converted into digital format before processing by PLC, SCADA, and LDS. The resolution of pressure data is presented as the minimum detectable change in pressure. Currently, data from all LDS pressure sensors (with the exception of the butane-transport pipeline) are provided with minimum resolution of 20-30 mbars (Fig.9).

Because the resolution of pressure data is one of the most important factors, directly influencing the sensitivity of the PWM, every pressure transducer in the LDS has been replaced together with RTs, which collect data from the transmitters. Figure 10 presents the new expected pressure resolution: after replacement, it is 4 mbar.

The actual sensitivity depends on the diameter and extent (volume) of the pipeline section under investigation. For each section, minimum detectable leaks were calculated with 4-mbar resolution, based on the following assumptions:

- in a closed state: ≈ 1 mbar
- the use of highly productive standard components:
  - full digital transmitters,
  - without ADC (analog-digital converter), 32-bit resolution FF (Foundation Fieldbus) PLC circuit board (≈ 1 mbar),
  - time of PLC FF cycle – 100 ms

Besides this, the project includes the replacement of the main equipment, as well as functions directly impacting the availability of pressure measuring sections. The facilities are equipped with no-break power sources (NBP), as well as with RT containers and boxes.

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Table 2 displays the expected levels of availability for various pipelines.
Table 3 presents an example of these characteristics.

Replacing RT for collection of pressure data makes it possible to achieve sweep frequency of 100 ms. Since the average speed of sound propagation in oil products is approximately 1,200 m/s, the given accuracy of ± 120 m (see above) will also be met.

The expected collection of high-resolution pressure data has not been possible due to the existing technical limitations of RTs. Therefore it has been necessary to replace RTs, while observing the following conditions:

- installing new transmitters at existing sections: 42 items
- installing new transmitters at new sections: 6 items
- replacing transmitters at existing sections: 162 items
- installing new telemetric RTs: 4 items
- replacing telemetric RTs: 68 items.

Further modernization measures include:

- improving the availability level of RTs at all isolation stations
- installing intelligent pigs
- upgrading the PipeMan batch-tracking system
- upgrading the module for calculating the transportation of oil products in accordance with new rules
- expanding the supervision system for all isolating valves and terminal/receiving stations by installing IP (inter-network protocol) video cameras at all sections
- increasing the quantity of clients of the Fast/Tools LOGIR SCADA platform for the oil product pipeline operation system (OOS)
- unifying the system for monitoring the state of isolation stations
- distance monitoring of the temperature of IT-infrastructure at terminal/receiving stations.

The test procedure

The principal aim of carrying out tests is to confirm that the LDS transmits a signal in the case of a liquid leak. One more aim is to check the signalization in the case of faults and in conditions of incorrect operation.

The choice of methods and parameters for testing depends on the operating conditions in the pipelines. Testing was ‘announced’ and conducted by extracting a controlled quantity of liquid from the pipeline (‘announcing’ the testing implies notifying the pipeline controller and exclusively testing the LDS).

The PWM tests were mainly carried out at isolation stations, but also directly at pipeline sections. Each subsequent test was performed with a lower leak-flow rate until the detection limit was reached. The PDM tests were conducted in closed conditions. The PWM tests were conducted in closed conditions and in a pumping regime. (Tests of the DMRT and VBM also counted on the volume of liquid leaking being around 1 m³ in real operating conditions. The minimum detectable leak flow rate was approximately 1.5 % of the nominal flow rate.)

Before the test results began to correspond to set expectations, multi-stage accurate adjustment and tuning of the system was necessary. During testing it became clear that the GPS coordinates of some
pipelines were not accurate. As a result, the location of the leak was also calculated incorrectly, and the values were indicated beyond the limits of the previously established parameters. However, in those pipelines where mapping was carried out at the same time as diagnostic studies, the accuracy of calculating leak location was found to be within the limits of the expected parameters. In future after carrying out inspections (using intelligent pigs), accurate measurements and mapping will be performed in every case, and the relevant information will be updated in the system’s database. When the tests were being planned and carried out, API Recommended Practice 1175 and 1130 were observed.

Conclusions

The introduction of a new LDS became a real test for the pipeline operators. It was necessary to find a balance between the high technical factors, the investment expenses, and other particular conditions. There is no such thing as an ideal technical solution.

It was necessary to introduce a new system for the MOL because the previous system was out-of-date, and its operation was accompanied by a multitude of shortcomings.

Taking into account the advantages and disadvantages of currently existing technologies, pipeline characteristics, and operating conditions, the expert team took the decision to use PWM as the basic principle, and determined new design factors for the system’s effectiveness. According to test results, the new system has justified calculated expectations of effectiveness, which indicates the given method has achieved its technical limit.

Acknowledgements

The author would like to thank Szilard Szellmann (of the Yokogawa) and Denes Ilinyi (of MOL) for their valuable advice and contribution to the successful management of the project. The article was reviewed by senior engineer Ferenc Torok.

References

Pipeline Transport Institute is a research and development center of the Transneft, PJSC, for carrying out of research-and-development and design-and-experimental operations, as well as development of new technologies, equipment, materials, and regulatory documentation in the field of design, construction, operation, and repair of the pipelines for transportation of oil and petroleum products.

Areas of activities:

- carrying out of research-and-development, design-and-experimental, and technological operations, as well as development of technical solutions, ensuring safe and reliable operation of main and technological pipelines, buildings, and structures (facilities) of Transneft, PJSC, and Transneft system organizations (TSO);
- development of interstate, national, and industry standards, as well as other normative documents, in the field of construction and operation of main and technological pipelines, as well as pipeline transportation facilities;
- formation and maintenance of an information system for assessing the conformity of equipment and materials; carrying out of technical documentation examination and laboratory tests for compliance with the requirements of national, interstate, and foreign standards, as well as with the requirements of normative documents of Transneft, PJSC; development of standard programs, organization and/or participation in the activities for addition (extension of certification) of the products into the Core products register;
- provision of expert-consulting and engineering services in the field of design, construction, and operation of main, field, distribution, technological pipelines, and other facilities of the fuel and energy complex;
- scientific and technological support for construction of the facilities of Transneft, PJSC;
- assessment of the technical state of pipelines, development of the methods for increasing the transmission capacity of main pipelines;
- control, coordination, and provision of implementation of the activities for realization of the innovative development program of Transneft, PJSC, including search, development, approbation and introduction of innovative products and technologies;
- development of the documents in the field of industrial and fire safety, as well as the documents for prevention and elimination of emergencies in the field of environmental protection;
- assurance of the status of Pipeline Transport Institute, in the external market as a national research center, carrying out a wide range of operations in the field of hydrocarbons pipeline transportation.

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