Remote inspection by the magnetic tomography method (MTM) to prevent the risks imposed by exploitation of Arctic offshore pipelines

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Abstract. Cold climate areas that provide opportunities for the remote inspection of pipelines include the Barents Sea, the Russian Arctic, the Alaskan Chukchi Sea, the Beaufort Sea and the Canadian Arctic offshore. First, an analysis of several actual projects of contactless diagnostics using the magnetic tomography method of pipelines in Arctic conditions is done. Second, the Risk-Based Inspection methodology for Arctic offshore pipelines is discussed. It involves ensuring pipeline reliability on the basis of data on the technical condition of the metal in actual operating conditions. The magnetic tomography method allows not only to remotely identify areas of anomalies with metal defects, but also to register mechanical stress levels taking into account actual loads. This reduces the risk for the structure to come to the critical state in terms of exceeding local loads. Finally, magnetic tomography technology allows managing risks in cases of local corrosion, stress cracking or loss of stability of underwater pipelines in areas with free spanning. The qualitative indicators of the inspection include the probabilities of identifying, interpreting the degree of danger, missing a dangerous defect. The pipeline diagnostics report provides the parameters of reliability forecasting: the period of incident-free operation, safe working pressure, and pressure coefficient.

1. Introduction
The Arctic territories are primarily cold-water seas: the Barents Sea, the Russian Arctic, offshore Sakhalin Island, the Alaskan Chukchi Sea, the Beaufort Sea, the Canadian Arctic islands and offshore northeastern Canada currently represent the most important area of development of energy for the world. On the other hand, these are territories with very sensitive ecosystems, where any inaccurate man-made intervention can lead to disastrous consequences for the environment.

The operation of the oil and gas production facilities without proper control of the technical condition, are dangerous in any environment. The extremities of operating conditions, and the enormous length of the pipeline infrastructure facilities operating under pressure, introduce additional risks. The risks introduced by breakdowns, as well as their consequences not only for the environment, but also for personnel, are also much more severe also because less time is available for rescue operations.

Considering individual characteristics of a human body, at a water temperature of 0 to +5 °C, typical for the Arctic latitudes and areas with a cold climate, only 20 to 40 minutes are available for the effective
2. Remote inspection of pipelines in arctic conditions by the magnetic tomography method (MTM)

This report discusses the diagnostics of subsea pipelines in arctic conditions. To date, there is a number of methods for checking the technical condition of offshore fuel and energy facilities available at the market [2-6]. The main methods of inspecting such structures are visual inspection with the help of guided underwater robots (Remotely Operated underwater Vehicle – ROV), together with monitoring the state of electrochemical protection against corrosion (examining the state of sacrificial anodes), and in some areas – the LRUT (Long Range Ultrasonic Technology).

These methods are used for the so-called unpiggable pipelines. For some pipelines, it is possible to apply the in-line inspection that involves several magnetic or ultrasonic flaw detector shells, which allow highly accurate detection of different types of metal defects, their location and orientation relative to the axis of the pipeline [7]. On the basis of these conventional methods, the hazard degree of these defects is determined numerically, taking into account the information on the nominal loads impacting the object. This system of technical diagnostics is not without a number of drawbacks. Below are the main ones.

1. The primary (exploratory) detection of suspected cracks located in an unknown direction is difficult (they can occur in the longitudinal, transverse directions, and at an angle to the axis of the object, but the sensors are not omni-directional);
2. There is yet no generally accepted algorithm for assessing crack resistance and predicting the rate of development of crack-like defects based on the life-cycle mechanism in the form of a “bath”;
3. There are no uniform quantitative criteria for assessing the risk of the in-line inspection (ILI) of pipeline defects of various types that would take into account the specific operating conditions of pipelines.
4. The conventional in-line inspection does not at all provide methods for assessing the degree of degradation of metal properties in aggressive embrittlement (hydrogen) conditions, such as microbial induced corrosion (MIC) or stress-corrosion (SCC) and sulfide-stress cracking.
5. The latter applies to conditions of increased static or cyclic loads with stress-deformed state (SDS) anomalies. These are pipeline sections with free spanning, corrugation, stress-strain-torsion levels above acceptable ones, with loss of stability, for example, due to washout (removal) of soil during heavy rains, in landslide areas, on precipices, in ravines, in mountainous terrain, in zones of seismic activity, permafrost and mountain soils, mine workings, as well as underwater (offshore) pipelines.
6. The main problem of the in-line inspection is that the degree of stress concentration in a particular section of the pipeline is not taken into account, i.e. local stress concentrators are not considered. The engineers of the pipeline integrity service of the operating organization assess the stress on their responsibility by expert assessment [8].

Pipeline operation possesses additional risks if there are stress-corrosion cracking defects (SCC) on unpiggable pipelines, where the use of the in-line inspection is impossible or inappropriate for any reasons. Such facilities include pipelines within gas compressor stations and oil pumping stations, underground gas storage (UGS) facilities, chemical and petrochemical plants, refineries, and a number of field pipelines. These unpiggable pipelines can comprise up to 70% of the total length of networks. The technology patented in the USA and Canada using the magnetic tomography method (MTM), regulated by the Russian guidance document RD 102-008-2002, is aimed at solving this problem [9].

The magnetic tomography method for such objects has certain advantages over the conventional diagnostic technologies that ensure its success [10-15], in particular:

1. Does not require special preparation of the pipeline, stopping it or changing its mode of operation;
2. Allows diagnosing areas inaccessible for in-pipe and contact methods of flaw detection;
3. Guarantees high accuracy of detection of areas with crack-like defects and stress-deformed state (SDS) anomalies (above 75%);
4. Demonstrates high performance (up to 7 km per day for 1 team of specialists with portable equipment, in some cases this can be even faster);
5. Wide range of detectable defects of the main and welded metal and high accuracy in assessing their danger degree, taking into account the existing loads;
6. Automatic route tracing followed by plotting the route on a topographic map of the area in absolute geographic coordinates;
7. Easy to organize automatic monitoring of the development of crack-like defects in areas of any length and within any time interval;
8. Low cost of services compared with the programs of pipe digging survey, taking into consideration the preparation of the metal surface for control and NDT for unpiggable pipelines.

As mentioned earlier, the pipeline facilities of the field infrastructure that transport gas, oily media, or water, are generally not fit for the in-line inspection. Sampling methods, conventional for such pipelines, be it the control of metal in pits, or with the help of witness samples (indicator plates inside the pipes), allow us to evaluate external and/or internal corrosion at certain points and are not able to reveal the state of the metal throughout, let alone the detection of the stress-corrosion cracking or sulfide-stress cracking (SCC) (figure 1).

![Image](a)
![Image](b)
![Image](c)
![Image](d)

**Figure 1.** Non-destructive evaluation (NDE) results in the control pits of the “Northern areas of Tyumen region - URAL-2” main gas pipeline with two stress-corrosion cracking defects (zones of transverse cracks) and their transverse cuts by a grinder to determine the depth. Where 1-st stress-corrosion cracking case: (a) - transverse crack zone and (b) - its transverse cut; 2-nd stress-corrosion cracking case: (c) - transverse crack zone and (d) - its transverse cut.
As an example of the detection of the stress-corrosion cracking defects, we present the results of the magnetic tomography method survey of a section of the main gas pipeline in Western Siberia (table 1). The total probability of detecting anomalies in areas with defects of the stress-corrosion cracking - zones of longitudinal cracks (ZLC) – the probability of detection (POD) reached 92%. All the stress-corrosion cracking defects indicated in the magnetic tomography method report were examined in control pits with the subsequent destructive control by means of cross-cutting with a tool (circular grinder) to determine the depth of cracks.

In addition to cracks in the longitudinal direction, the magnetic tomography method successfully detects both circumferential and angled defects, for example, micro-cracks of welded mounting connections and in spiral welded pipes.

**Table 1.** Verification of the magnetic tomography method data (detection of the stress-corrosion cracking defects) of the “Northern areas of Tyumen region - URAL-2” gas pipeline.

| № anomaly | Detected defects | Defects dimension, mm |
|-----------|------------------|----------------------|
| 5         | ZLC              | 20×5×1               |
| 5, 6      | ZLC              | 20×8×2,8             |
|           | ZLC              | -                    |
| 7, 8      | ZLC              | 130×160×0,5          |
| 7, 8 and 9| ZLC              | 1100×150×0,3; 110×40×1.5 |
|           | ZLC              | 200×460×2; 130×5×0,3 Corrosion up to 1,0 mm |
| 10        | ZLC              | 60×200×0,8; 50×50×0,8 |
| 11        | ZLC              | 150×40×1             |
| 11, 12    | ZLC t            | 60×40×1; Corrosion up to 1,0 mm |
|           | ZLC              | 100×200×0,5; Corrosion up to 0,6 mm |
| 13        | ZLC              | 390×200×0,3; Corrosion up to 1,0 mm |

Note: ZLC - zones of longitudinal cracks.

Frequent causes of accidents are destruction due to micro cracks, and this is particularly relevant for newly built pipelines in unfriendly terrain (mountains, swamps). The reason is that such cracks appear in welded assembly joints in the zones of stress concentrators. That is why it is important not only to identify “defective” assembly joints, but also to identify those where, due to increased loads, there is a risk of an accident (figure 2). There are many of them, and it is impossible to repair them all at once, but it is important to point out the joints that create stress concentration, a possible origin of a breakdown. In such cases, it does not matter what caused the accident — deformation or imperfection of the metal, since the result is a destruction of the pipe.

Specialists on reliability conclude that such accidents at normal working pressure are caused by forces that imposed additional loads on the deformed bending areas during thermal cycles in the pipeline. As a result, the pipeline deforms again and again, which, in turn, leads to the growth of cracks until an accident occurs in the deformed area of the pipe. In world practice, pipeline accidents are frequent due to additional local loads that altogether exceed admissible load applied to the structure. In particular, the "zero inspection" of the Sabah–Sarawak Gas Pipeline (SSGP), a newly built main gas pipeline on Borneo Island (Malaysia), revealed a number of similar crack defects that were further confirmed by ultrasonic testing (UST) in verification pits.

According to the results of verification of the magnetic tomography method data, the probability of detection (POD) of defective joints requiring repair at this facility was 93%. Figure 3 shows the non-
destructive testing (NDT) pattern for the circular micro-crack in the control pit detected by the magnetic tomography method.

![Image](image_url)

**Figure 2.** Destruction of the welded joint due to the “circular crack” of the welded assembly joint in mountain terrain.

![Image](image_url)

**Figure 3.** The non-destructive testing (NDT) in the control pits of the Sabah–Sarawak Gas Pipeline (SSGP) in the areas of circular micro-cracks identified by the magnetic tomography method. Where (a) – eddy current testing in searching cracks and (b) – Ultrasonic testing in controlling whole wall thickness.

The undoubted advantage of the magnetic tomography method is the ability to monitor in real time the development of stress-corrosion cracking defects by installing special contactless sensors. The sensors monitor the growth of local mechanical stresses in the vicinity of the defects selected from the magnetic tomography method results that show the maximum stress concentration. For the pipes of the supply line of the gas-compressor station, by applying such sensors, it was possible not only to identify the stress-corrosion cracking defects (ZLC - zones of longitudinal cracks), but also correctly point out the particular defect among the seventeen other identified defects, the exact one which would lead to the destruction of the pipe during the resource tests (figure 4).
The use of in-line inspection may be not possible in all sections of offshore pipelines. There might be a jam of a flaw detector on pipelines with complex seabed geometry, and this may lead to a complete stop in the operation of the pipeline until the flaw detector is removed. In order to remove it, first a place where it is stuck must be found, and then complex diving works underwater must be carried out. This always implies huge financial costs and environmental threats. Often, when preparing for the flaw detector run and pipeline cavity cleaning, the internal anticorrosion coating of the pipeline is damaged, and there is a risk of ignition in the event of electrostatic charges.

Not all pipelines are subject to the in-line diagnosis, for example, unpiggable pipelines include discharge pipelines from oil or gas wells, gas compressor and oil pumping stations, underground gas storage facilities, refinery plants, gas-liquefying plants. The inability to control the technical condition of the pipeline increases the risks of operation breakdown, incidents, and emergencies.

For such objects, where the in-line inspection is difficult to do, or for pipelines that are not fit to the in-line inspection at all, the inspection by magnetic tomography method with the help of contactless scanning magnetometers, and its underwater implementation adapted for subsea objects (AQUA MTM) is perfectly applicable.

The essence of the magnetic tomography method lies in the interrelation of the parameters of the magnetic field of a pipeline with mechanical stress levels in the metal of the pipe, and the method allows the detection of local concentrations of mechanical stress caused by the metal defects. This is a fundamental advantage over other technologies, especially relevant for offshore pipelines.

One of the "headaches" on offshore pipelines is the free spanning. In a free-span zone of a pipeline, the stress in the pipe metal increases significantly. Therefore, even a minor defect can be critical, since the overall stress level in the pipe can be in just a step away from the breakdown stress (often denoted as the specified minimum yield strength, or SMYS).

In case of free spanning, even on the pipelines equipped for the in-line inspection, it is not always possible to make a correct assessment of the danger degree of a defect, since it is impossible to take into account all the existing forces acting on the pipeline. And here the magnetic tomography method provides a direct answer to the question posed: yes, the magnetic tomography method is capable of estimating the stresses that arise in the pipeline during its operation in actual conditions.

This is what can be called the Risk-Based Inspection methodology, i.e. obtaining information about the pipeline based on all forces acting on it during operation. The stress in the pipe metal, calculated as a result of the magnetic tomography method, arising from defects, external impacts and/or stress-deformed state (SDS), reflects the actual technical condition of the pipeline, and the accuracy of this stress calculation was confirmed at the test site provided by Petronas, the largest oil and gas company in Malaysia, during the mock-up test while developing the AQUA-MTM technology.

While MTM technology shows locations on ground surface (in longitudinal, along the pipeline axis, and absolute geographical coordinates) and danger degrees of pipeline sections that have defects of
metal, the Aqua Magnetic Tomography Method, the underwater MTM implementation, is a technology for assessing underwater pipelines technical condition.

Additional advantages of the magnetic tomography method and AQUA MTM that are especially beneficial for offshore pipelines are the following aspects:
- There is no need to connect any special equipment to the pipeline; magnetic field recording is performed remotely. The maximum distance from the axis of the pipeline to the magnetometer moving above the pipe should not exceed 15 diameters of the pipeline being examined;
- AQUA MTM inspection using ROV can be carried out in the free fly mode, it is only important to maintain the position of the ROV over the pipeline axis and maintain a vertical distance;
- As a result of the inspection, the pipeline operator receives a report reflecting the actual technical condition of the tested object based on the actual stresses in the pipe metal.

In the report, a pipeline operator receives, among all, the data on the effective stresses in each identified anomaly, and also the period of the incident-free operation - $T_{safe}$, the safe working pressure - $P_{safe}$ and the estimated repair factor - ERF.

Based on the inspection data, at the request of the customer, a digital twin of the inspected pipeline can be created, or a risk map for the pipeline, indicating the most dangerous sections and forecasting the development of the situation over time, i.e. predictive and proactive functions. For subsea pipelines, the main criterion for the risk of transition to the critical state is the excess of local stresses with the possibility of local loss of stability due to an abrupt unpredicted increase in loads. This situation is reliably controlled by the magnetic tomography method.

Pipeline Integrity Services and Risk management of offshore pipelines at depths up to 200 m include:
- Control of metal pipelines with any type of insulation coating throughout the facility - remotely, without preparation for inspection;
- Registration of local mechanical stresses;
- Compliance with NACE ICDA – the standard of internal corrosion direct assessment (ICDA) of National Association of Corrosion Engineers and monitoring of metal defects of any nature (corrosion, stress-corrosion cracking, fatigue cracks);
- Identification of free spanning, general and local stability loss areas in the zone of inspection, or in seismically active zones;
- Report includes the data on safety parameters, including for the difficult & non-pigable pipelines: $P_{safe}$, $T_{safe}$, $S_i$, SCF, ERF;
- Removes restrictions on the minimum possible operation of the ROV - up to the shoreline.

![Figure 5. AQUA-MTM operation system.](image-url)
The AQUA-MTM system operates as shown in Figure 5. Vessel (2) locates its position on the GPS-navigation system (1). By «ROV Navigation and tracking equipment» (4) the system locates the relative position of ROV (with «Aqua SKIF Underwater Unit»), (3). Control Container (6) with the Vessel survey system calculates absolute coordinates of ROV in real-time “on-line” or “off-line” on the base of data of items 1,2. In “on-line mode” Control Container transmits absolute coordinates of ROV in real-time to Aqua SKIF Control Unit or - in “off-line mode” - Aqua SKIF Control Unit shall receive the absolute coordinates of ROV by Flash Drive. Matching of the navigation data and SKIF magnetometers data in “off-line mode” shall be realized with the time stamps Aqua SKIF Control Unit receives from GPS Time Receiver. “Aqua SKIF Control Unit” (7) transmits the signal “Turn on” to “Aqua SKIF Underwater Unit” through interfaces: “Interface Control Container - Aqua SKIF Control Unit” (8), “Interface ROV-Control Container” (5). “Aqua SKIF Control Unit” (7) receives the absolute coordinates of ROV from Control Container.

The values of internal strain obtained using MTM technology were compared to stress values calculated according to other technologies of stress evaluation. Average relative accuracy is given in table 2.

| MTM-Strain Gauges | MTM - ASME B31.G | MTM - DNV RP F101 Part A | MTM - API RP 579 | MTM-FEM |
|-------------------|------------------|--------------------------|-----------------|---------|
| 74%±10%*         | 97%±1%*          | 88%±2%*                  | 91%±2%*         | 84%±3%* |
| MTM-Strain Gauges | ASME B31.G       | DNV RP F101 Part A       | API RP 579      | MTM-FEM |

Note: *Confidence intervals are given for confidence level 95%.

The probability of detection (POD) of defects was proved by 86±11%. Probability of Interpretation (POIn) of defects was calculated from MTM and FEM (finite elements model) comparison. The comparison results are as follows:
1. POIn for Corrosion defects: POI=83.3%±10.5%;
2. POIn for Dents: POIn=100%-10.5%;
3. POIn for Scratches: POIn=50%±RAs;
4. Gouges defects were identified as metal loss defects.

During correlation of MTM data on stresses with results of strength calculations by International codes, the following parameters of assessment were determined: all corrosion defects (100%) with ERF>0.98 was found; correlations of anomalies danger on stresses in accordance with ERF is ±14.52% with confidence level 95%.

The primary result of the huge Petronas-inspired test was the confirmation that AQUA-MTM technology is capable of high accuracy calculation of safety parameters of sub-sea pipelines, and it may serve as a basis for repair schedule. Consequently, Petronas became one of the largest end clients for MTM (Aqua MTM) inspection in the region.

To date, a number of projects that involved inspection of unpiggable pipelines by means of MTM technology in Arctic conditions have been carried out: 2018 year – Rosneft, Sakhalin, offshore oil pipeline, Nevelsky Strait - 18 km; 2017 year - water passages across rivers of the main gas pipeline of OJSC ALROSA-Gas, Republic of Sakha-Yakutia [16] (figure 6); 2017, 2016 and 2014, Statoil pipelines, Norway.
Figure 6. Non-contact FLY MTM diagnostics using a UAV of a water passage across the Bolshaya Batuobiya river of the main gas pipeline of OJSC ALROSA-Gas, Republic of Sakha-Yakutia, October 3, 2017 [16].

Other non-Arctic inspection projects involving offshore unpiggable pipelines (shelf depth of up to 200 m) applying the AQUA MTM technology include works for Petronas (Malaysia), offshore Oil pipelines from Platform oilfield (SKO, SBO, PMO); Chevron Pacific (Indonesia) offshore oil pipelines from Balikpapan, ADMA OPCO (UAE); offshore oil pipelines, and others. The total length of the inspected offshore pipelines by AQUA MTM totals to about 1,500 km.

3. Conclusion

To summarize, a convenient, reliable tool has been created to ensure the integrity of the underwater pipelines in the Arctic regions. This tool is particularly useful in view of the risks imposed by harsh climatic conditions.

The AQUA MTM inspection advantages are:

- Remote measurements up to 15 diameters away from the pipeline axis;
- The pipeline operation mode change or stop is not required;
- The pipeline is not affected in any way;
- No prior preparation of the pipeline for inspection is necessary;
- Detection of pipe sags, strains, and twists is possible;

As a result of inspection, the following information is provided:

- Location (longitudinal, GPS coordinates) of all defective (anomaly) zones;
- An assessment of danger degree (deviation of a pipe material stress-deformed state for each defective area is reported, the period of incident-free operation is estimated, safe working pressure for each anomaly area in the pipeline is determined);
- The absolute value of local stress in pipe material.

The MTM (Magnetic Tomography Method) Technology developed by R&D Center “Transkor-K” (Russia) and AQUA MTM, developed in a joint effort with Petronas (Malaysia) are both intended for metal stress-deformed state assessment of offshore steel pipelines of any purpose. The core method is based on remote registration of surrounding magnetic field of a pipeline using a subsea Remote Operated Vehicle (ROV). The technology allows inspecting the entire length of a pipeline with high probability of detection of stress-deformed state anomalies: POD >75%.

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