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PRELIMINARY ASSESSMENT OF THE TECHNICAL CONSEQUENCES OF THE INCIDENTS ON THE NORD STREAM 1 AND 2 GAS PIPELINES. POSSIBLE WAYS OF SOLVING THE PROBLEMS

Abstract: *The incident on the Nord Stream pipeline system at the bottom of the Baltic Sea in 2022 caused a significant release of natural gas into the atmosphere and made it impossible to transport gas further through three of the four pipelines. Before the pipeline system was inspected and the results of the technical commission were available, a preliminary assessment of the volume of natural gas released was carried out, the possible technical consequences of the incident were evaluated and a preliminary assessment of the possibility of carrying out repair and restoration work was carried out. The existing technical solutions and alternative technologies to restore the pipeline system integrity have been analyzed. The feasibility of applying the technologies taking into account the specific conditions of the Baltic Sea has been evaluated. A preliminary assessment of the scope of repair works has been carried out and repair technologies have been considered.*

Keywords: *Offshore Pipeline, Calculation of Gas Leakage Volume, Offshore Pipeline Repair, Offshore Pipeline Incident, Baltic Sea Oil and Gas Infrastructure*

1. Introduction

The Nord Stream pipelines are complex technical facilities designed and built in 2006-2012 and 2014-2021. They are the longest uncompressed gas pipelines in Europe. The length of these pipelines is about 1,224 km of each of the strings. The internal diameter is Ø 1,153 mm. Each of the four pipelines previously had an annual capacity of 27.5 billion cubic meters of gas. The design pressure varied from 220 bar at the Russian onshore compressor station exit to 106 bar at the Greifswald onshore exit in Germany: Kostianoy et al. (2008). The September 2022 accident resulted in the shutdown of natural gas from Russia to Europe via the Nord Stream pipeline system. Pipeline ruptures resulted in complete depressurization of the system, loss of a number of pipeline fragments as a result of explosions, destruction of the base and backfill of the pipeline sections. The works to establish the causes of the accident and assess the technical condition of the pipeline system will continue for an indefinite period of time. At the same time the technical specialists face a number of nontrivial problems which require additional research, analysis, discussion and development of the concept of repair-rehabilitation work at these objects. Such works and actions are rare in

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the world practice and are of significant interest both in terms of offshore oil and gas technologies, engineering, mechanics, and in terms of ecology, economics, and organization of technological processes in general.

The raised problems are extremely extensive and surely will be widely discussed in scientific journals in the nearest future, especially taking into account new data and results of researches. The uncertainty of available information, the difficulty of organizing pipeline inspection processes, analyzing the data obtained and the importance of developing the concept of equipment rehabilitation, made the authors to summarize the technical data on the gas transportation systems of Nord Stream as of the beginning of 2023, as well as the task of assessing the possible consequences of the emergency situation and, as a result, developing recommendations for the maintenance of these pipeline systems. It should be noted that, in fact, each realized project of offshore hydrocarbon transportation system is individual, because it is necessary to take into account not only specifics of equipment materials, but also depths, winds, currents and characteristics of the bottom of the water area (Rosicki & Rosicki, 2012). Therefore, the experience of emergency situations, their consequences and peculiarities of the approaches related to offshore pipeline systems repair can be used only partially. Among the most remarkable incidents of this kind are pipeline ruptures in the North Sea at the Dutch and British gas fields in the 1980s (Mitchell et al., 1990), gas pipeline ruptures in the Kara Sea (Bovanenkovo-Ukhta in 2018), gas pipeline ruptures in the Gulf of Mexico (the latest case in 2021 with the inflammation of gas released from the destroyed offshore pipeline of Petróleos Mexicanos). In the scientific and technical literature, the incident rate of the offshore oil and gas pipelines varies depending on the pipeline diameter and operating conditions in the range of $1*10^{-5}$ to $1*10^{-3}$ (events/year) /km.

In order to conduct a detailed analysis of the technical condition of the pipeline system after the incident and assess the repair options, we first consider the characteristics of the pipes and coatings used in the project, the specifics of the technology used during the construction of laying and placement of pipelines on the seabed, which will give a clearer picture of the original technical and hydrological characteristics of the strings of Nord Stream 1 and 2 gas pipelines.

2. Linear part of the Nord Stream pipeline system. Technical characteristics and breakdown points

When designing the Nord Stream pipeline route, a number of parameters were taken into account. They include not only the minimum distances along the pipeline route, but also the depths of the sea in the area of the pipeline route, the underwater relief, the presence of debris, shells, chemical weapons dumped since World War II, benthic communities, etc. (Värk et al., 2011). To improve safety and reliability of the system before design and construction, we collected geotechnical, environmental, bathymetric, and other baseline data with the participation of the Shirshov Institute of Oceanology of the Russian Academy of Sciences (IO RAS) and the Russian Federal Research Institute of Fisheries and Oceanography. The environmental feasibility study, risk assessment and quality management were carried out with the participation of Marin Mätteknik, Rambøll, DoF, PeterGaz, ERM, DNV, etc.

The bottom of the Baltic Sea is composed of different types of rock, it has prominent ridges, hollows, crevices, quicksands and muds and it is not always possible to lower the pipeline directly onto these soils. Technically, if there is a big sag of the gas pipeline string between two natural supports, its construction can collapse over time (Dadonov, 2008). That is why after the route was finally chosen the bottom relief in the laying zone was corrected artificially, by means of creating stable foundations preventing sagging, rolling and siltation of pipes. During the construction of each of the pipeline strings, a special vessel loaded with gravel and small stones, using a pipe, the lower end of which was equipped with nozzles, filled the bottom cavities, giving it a more suitable profile (Dantsevich, Kosolap, Cherkasov, 2021). Sometimes concrete slabs were lowered down instead of stones, to strengthen the base of the pipeline. In a number of sections, the buried location of the pipeline strings was preferred. Thus, along the entire route the bottom structure was checked and strengthening works were carried out. Different layouts were used depending on the type of seabed. In the northern part of the pipelines (Gulf of Finland area), due to the rocky ground, the pipelines were placed through bunding on the seabed as well as via a bunding scheme with a reinforced block base; in the central area of the Baltic Sea, a simple bottom placement with an additional weight coating was used more frequently as well as bunding in some places. In areas with heavy shipping traffic, on fairways and main port traverses (where soils allowed), the buried pipeline option was used. Considering the damage points of the gas pipeline strings, we can state that the emergency situation is localized in the areas where the laying was carried out in areas where the pipeline was simply placed on the bottom with an additional weighting coating. Special pipes with an outside diameter of 1220 mm and an inside diameter of up to 1153 mm were used in the linear part of the Nord Stream pipeline. The pipe wall thickness varied depending on the depth of the pipeline installation and the pressure of the pumped gas. The pipe was designed to withstand a pressure of 220 bar in the first 300 km, 200 bar in the next 500 km, and 170 bar thereafter. On each of these sections the pipeline wall thickness varies from 34 to 27 millimeters.

Table 1. Key data on pipe manufacturers used in the Nord Stream 1A, B and Nord Stream 2A projects

Gas pipeline	Nord Stream 1 A	Nord Stream 1 B	Nord Stream 2 A
Pipe manufacturers	Europipe - 75% Vyksa Steel Works - 25%	Europipe - 65% OMK - 25% Sumitomo - 10%	Europipe - 40 % OMK - 33 %, CHTPZ - 27 %.
Manufacturers of related materials - coating, cement, reinforcement	Saipem; Allseas; Van Oord; Boskalis Tideway; Rohde Nielsen		

This segmentation made it possible to save on the production costs of the pipes while maintaining their reliability. The maximum sea depth at the pipeline strings was 210 meters. The pipelaying was carried out in accordance with DNV OS-F-101 Submarine pipeline systems. The materials (steel pipes) used for construction of the pipelines were made by a number of companies (Table 1) in accordance with the international standard - ISO3183-3 Petroleum and natural gas industries - Steel for pipelines. The grade of steel used for main pipelines - SAWL 485 I FD - has three-layer external and internal antifriction coating (thickness from 90 to 150 microns), pipe length 12.2m with minimum yield strength of 485 MPa, submerged arc welding with one longitudinal seam capable of bearing a load of 570-605 MPa was carried out. The steel used in pipe production is unique, and during its manufacture special importance is given to metal desulfurization process, which is carried out in three stages, which allows to

obtain a material having very low sulfur content (not more than 0, 0015%), the content of other impurities is also within narrow limits (Dantsevich I. M. et al., 2021).
The outer surface of the pipes has an anti-corrosion component consisting of a three-layer polyethylene coating (3LPE) including epoxy resin (inner layer), adhesive layer and high-density polyethylene (outer layer), then there is a concrete coating over the anti-corrosion coating on the main pipes, whose task is to weight the pipeline for a stable position on the seabed (Lohmann, 2019) (Figure 1).

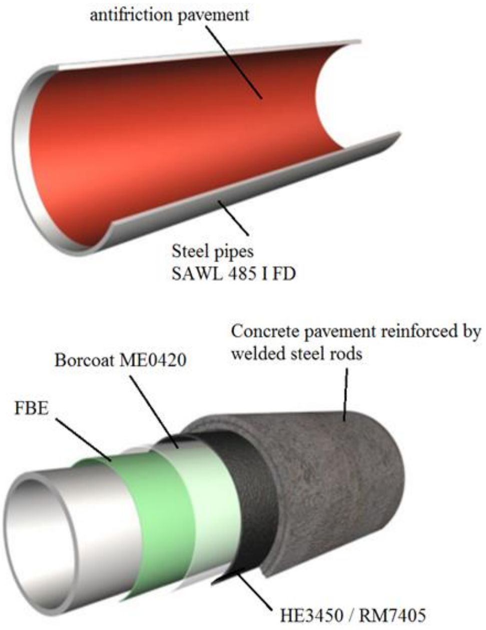

Figure 1. Structure of internal and external pipe coating of the Nord Stream pipeline system.
Source: North Stream AG

In addition to cement, water and standard aggregates (gravel, crushed stone, sand), aggregate containing iron ore is added to the concrete mixture to increase its density; the concrete coating is also reinforced by a framework having welded steel rods (the minimum diameter of the rod is 6 mm). After welding the concrete coated pipes, the joints are protected with a heat shrink sleeve and highdensity polyethylene, then, as a frame, a sheet of carbon steel or polyethylene formwork is installed around the joints; after installing the frame, the voids formed between the heat shrink sleeve and the frame are filled with two-component polyurethane foam, which has a density of 160 kg/m3 after hardening.

The chosen system combines a base layer of fusion-bonded epoxy coating (FBE) 0.15-0.30 mm thick, which is slightly less than the thickness of a standard base layer of three layers of polyethylene. A 0.2-0.4 mm thick Borcoat ME0420 (a binder made of polyethylene modified with maleic anhydride) from Borealis and an outer layer of Borcoat HE3450 (black, bimodal, co-polymer high density polyethylene), also from Borealis, was applied over the base layer. RM7405 (so called coarse coating) of black polyethylene from Borealis was used as a cover layer. This coarse polyethylene layer, applied on the still hot outer layer, is designed to increase the adhesion to the subsequent concrete layer with a thickness of 60-110 mm.

The total thickness of the polymer coating is about 4.2 mm.

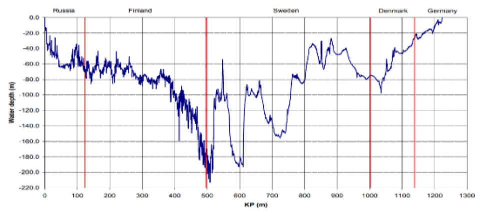

Figure 2. Depth of Nord Stream 1A and 1B.
Source: North Stream AG

The pipeline sections passing in the deepest areas are equipped with bend protectors, so-called deformation dampers, directly welded into the pipe and made of the same alloy, steel as the main pipes, but with a thicker wall and more delicate machining at the ends in order to match the main pipes.

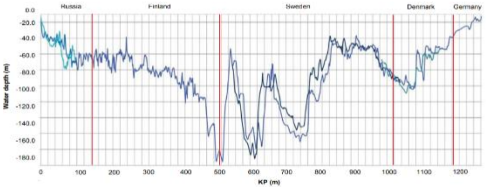

Figure 3. Depth of Nord Stream 2A.
Source: North Stream AG

Let's consider the bathymetric characteristics of the position of the Nord Stream 1 and 2 pipes (Figures 2 - 4). The total thickness of the polymer coating is about 4.2 mm. The pipeline sections passing in the deepest areas are equipped with bend protectors, so-called deformation dampers, directly welded into the pipe and made of the same alloy, steel as the main pipes, but with a thicker wall and more delicate machining at the ends in order to match the main pipes. Let's consider the bathymetric characteristics of the position of the Nord Stream 1 and 2 pipes (Figures 2 - 4). Given the coordinates of the incident points, we can say that in the case of the North Stream 1 string A, the pipeline failure occurred at a depth of -85 m. In the case of string B, the pipeline rupture occurred at a depth of -84 m. In the case of Nord Stream 2 A, the pipeline breakdown occurred at a depth of -87 m and -73 m.

As for the peculiarities of Nord Stream pipeline design, it should be noted that apart from primary corrosion protection, it has secondary protection, which is provided by anodes made of galvanic material (Chen et al., 2022). This protection represents a separate (independent) system, the effect of which is aimed at pipeline protection in case of damage of external pipe coating.

Anode alloys for preserving pipeline integrity for the calculated operation time have been determined by tests, the results of which showed that zinc alloy is appropriate for the sections with low and medium mineralization, for the remaining sections the use of indium-activated aluminum has been declared (Aulia et al., 2021).

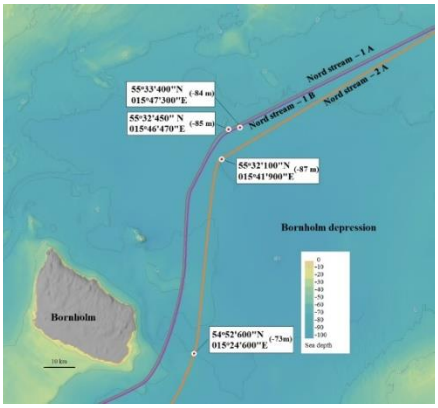

Figure 4. Breakdown points on gas pipelines and depths
Source: Authors

Taking into account the technical characteristics of the Nord Stream pipeline system, as well as the location of failure points, sea depths, peculiarities of the location of pipelines on the bottom, we will make two types of calculations. First, we preliminarily estimate the volume of natural gas release from each of the pipeline strings, and second, we consider the issue of repair and restoration work volumes by calculating the lengths of destroyed and flooded sections.

3. Preliminary assessment of the consequences of the gas pipeline system destruction

To make the calculations, we consolidate the materials on the technical parameters of the pipeline and the external environment in all damaged sections. Then we calculate the leakage volume from section to section and make a preliminary assessment of the length of flooding of each of the pipeline strings - both by sections from the gas supply point and by sections adjacent to the receiving point (Maksimov & Polovinka, 2015; Podvalny et al., 2021), (Figure 5).

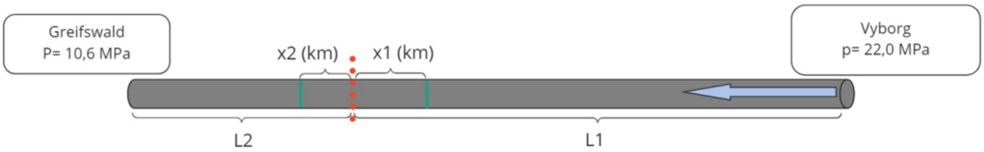

Figure. 5. Example of the location of sections of the Nord Stream-1A pipeline, in relation to the incident point.
Source: Authors

The distance from the place of the gas pipeline rupture to the nearest emergency valves is marked x1 and x2. L1 and L2 are distances from the place of rupture to compressor stations.

At the first stage let us determine the initial critical gas flow rate (STO Gazprom 2-3.5-051-2006; Kóczy et al., 2022) (1):

$$G_0 = \frac{P_0 \cdot \pi \cdot d_0^2 \cdot \sqrt{k}}{4 \cdot \sqrt{R \cdot Z_k \cdot T_0^m}} \cdot \left[\frac{2}{k+1}\right]^{\frac{k+1}{2\cdot(k-1)}}, \#(1)$$

Where: P_0 - pressure at the moment of the incident at the point of gas pipeline rupture (Pa); d_0^2 - pipe inner diameter (m); k - gas adiabatic index (b/r); R - gas constant (J/(kg·K); Z_k - gas compressibility factor in the critical section; T_0^m - average temperature (K).

Thus, the gas flow rate for the first damaged section with the length L_1 will be determined by the expression:

$$G_1(t \le t_l) = \frac{M_n}{\eta_L^2 \cdot \varepsilon_L} \cdot exp\left[-\frac{1}{\eta_L^2 \cdot \varepsilon_L}\right] + \frac{[M_g - M_n]}{\varepsilon_L} \cdot exp\left[-\frac{t}{\varepsilon_L}\right], \#(2)$$

Where: t_l we assume more than 0.1s; M_n - mass of gas flowing in adiabatic mode (kg);

M_g - mass of gas in the damaged section of the pipeline (kg).

The value of η_L is determined according to the expression (3):

$$\eta_L = \frac{2 \cdot M_g}{\varepsilon_L \cdot G_0}, \#(3)$$

Where: ε_L - time constant, s.

In this case, depending on the section, it is determined by the following ratio:

$$\varepsilon_L = \frac{2}{2} \cdot \frac{L_1}{a_0} \cdot \sqrt{\frac{k \cdot \lambda \cdot L_1}{d_0}}, \#(4)$$

Where: a_0 - speed of sound in the gas before the incident; λ - hydraulic resistance coefficient.

Figure 6. Destruction of the Nord Stream-1 pipeline section, initial inspection results
Source: Nord Stream AG

Further in the calculation it is necessary to take into account the mass of gas at the point before the incident (kg):

$$M_g = \frac{L_1 \cdot \pi \cdot d_0^2 \cdot P_1^m}{4 \cdot R \cdot Z_0^m \cdot T_1^m} \pm M_{ks}, \#(5)$$

Where: Z_0^m – the compressibility factor of the gas before the incident at the parameters P_1^m and T_1^m; M_{ks} – mass of gas (kg) pumped into the first section of the pipeline by the compressor station until the cut-off of the damaged section, kg. The sign "+" is used in calculations for the first damaged section, the sign "-" in calculations for the second damaged section.

$$M_{ks} = G_{ks} \cdot t_i, \#(6)$$

Where: G_{ks} – the pipeline capacity in normal operating mode (kg/s); t_i – time from the moment of the incident till the stationary emergency valve is completely closed (s).

Then using formula (7) it is necessary to determine the mass of gas flowing in adiabatic mode:

$$M_n = \frac{2 \cdot M_g \cdot d_0}{\lambda \cdot L_1 \cdot \sqrt{k}} \cdot \left\{ \begin{array}{c} \left[\frac{1}{k} \cdot \left(\frac{k+1}{2}\right)^{\frac{k+1}{k-1}} + \frac{\lambda \cdot L_1}{d_0} \right]^{\frac{1}{2}} \\ - \left[\frac{1}{k} \cdot \left(\frac{k+1}{2}\right)^{\frac{k+1}{k-1}} \right]^{\frac{1}{2}} \end{array} \right\}, \#(7)$$

To determine the mass of gas at the gas release from the first section until the line valve is closed, we use the expression (8):

$$M_{11} = M_n \cdot \left(1 - exp\left(-\frac{t_l}{\eta_L^2 - \varepsilon_L}\right)\right) + \left(M_g - M_n\right) \cdot \left(1 - exp\left(-\frac{t_l}{\varepsilon_L}\right)\right), \#(8)$$

Next, to determine the total volume of gas leakage it is necessary to establish the value of its flow at the time of closing the damaged section, which can be done by the following formula (9):

$$G_1(t_l) = \frac{M_n}{\eta_L^2 \cdot \varepsilon_L} \cdot exp\left(-\frac{t_l}{\eta_L^2 \cdot \varepsilon_L}\right) + \frac{\left(M_g - M_n\right)}{\varepsilon_L} \cdot exp\left(-\frac{t_l}{\varepsilon_L}\right), \#(9)$$

Since the emergency shutdown system is triggered when the gas pipeline is damaged, it is necessary to calculate the gas flow rate for the damaged section 1 after closing the valve:

$$G_1(t > t_l) = G_1(t_l) \cdot exp\left(-\frac{t - t_l}{\varepsilon_x}\right), \#(10)$$

Where: ε_x – time constant

$$\varepsilon_x = \frac{2 \cdot x_1}{3 \cdot a_x} \cdot \sqrt{\frac{k \cdot \lambda \cdot x_1}{d_0}}, \#(11)$$

Where: a_x – sound velocity in the cut-off section at the time t_{ij}:

$$a_x = \sqrt{k \cdot R \cdot Z_0^m \cdot T_{ch}^m}, \#(12)$$

Where: T_{ch}^m – average temperature in the cut-off section after closing the line valve (K).

The mass of gas in the second phase of the flow after closing the line valve is calculated by the formula (13):

$$M_{12} = \varepsilon_x \cdot G_1(t_l), \#(13)$$

Total mass of gas on the first incident section (14):

$$M_1 = M_{11} + M_{12}, \#(14)$$

For the second cutoff section, we perform the same calculation. The intensity of gas outflow in each of the strings during the incidents on the North Stream 1 and 2 are shown in the graphs (Figures 7 - 9). We assume that the time passed from the moment of the incident to the moment of complete closure of the line valves at both sections of the pipeline is 40 sec. For the second section of length x2 the calculations are made in the same way (Lurie et al., 2020).

Certainly, it should be noted that the indicated volumes based on the results of calculations are based on open data and were obtained considering the above-mentioned calculation methodology.

Results may differ significantly in case of other technical characteristics or other methods (STO Gazprom 2-3.5-051-2006).

The final results will be obtained by visual inspection and inspection. Data obtained using the above mentioned, methodology for natural gas leakage volumes and the length of pipeline strings flooding were summarized in the following table (Table 2).

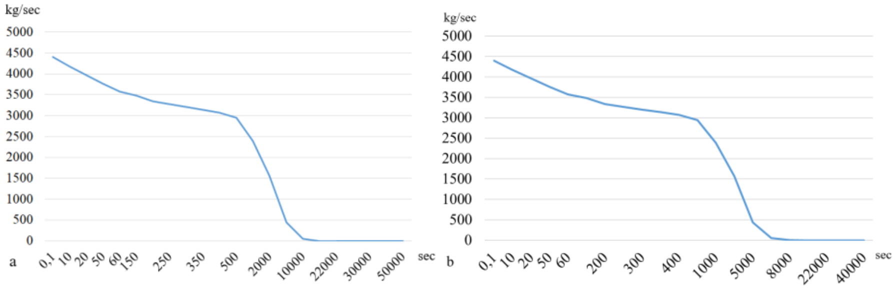

Figure 7. Graphs of natural gas leakages from the damaged segments of the Nord Stream 1A pipeline: a - section of the pipeline from the gas compressor station in Russia to the rupture place; b - section from the rupture place to Greifswald. Source: Authors

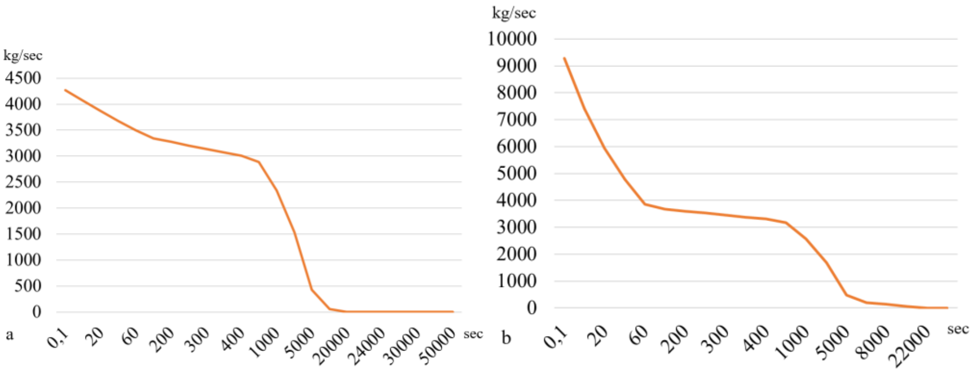

Figure 8. Graphs of natural gas leakages from the damaged pipeline segments of Nord Stream 1B: a - section of the pipeline from the gas compressor station in Russia to the rupture point; b - section from the rupture point to Greifswald). Source: Authors

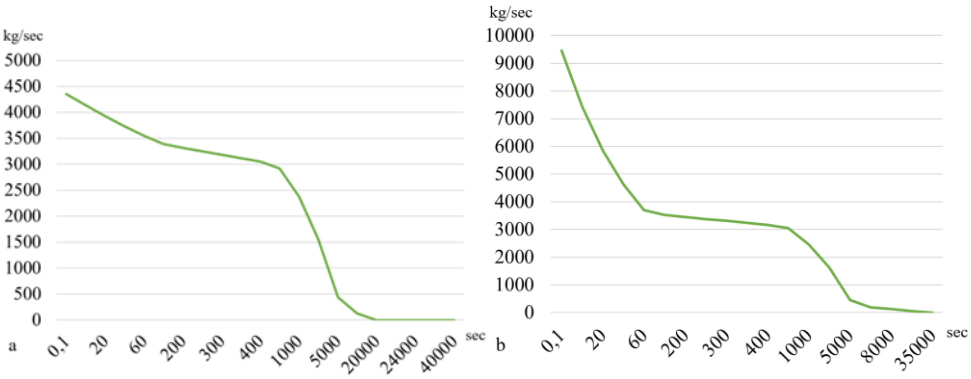

Figure 9. Diagrams of natural gas leakages from the damaged pipeline segments of Nord Stream-2A: a - section of the pipeline from the gas pumping station in Russia to the rupture point; b - section from the rupture point to Greifswald). Source: Authors

Table 2. Preliminary volume of natural gas leakage from damaged strings of the Nord Stream system. Estimated volume of repair and rehabilitation work.

Pipeline string	**NS-1A**	**NS-1B**	**NS-2A**
mass of the gas during the total time of outflow (in mega tons)	0,018217	0,017851	0,044246
mass of the gas during the total outflow time (in mega tons)	0,0803		

Using the results of calculations we can preliminarily assert that the volume of methane emission caused by all incidents was about 0,0803 mega tons, emissions of different intensity took place over a period of 4-6 days. At the same time, no more than 10% of the gases dissolved in the sea water, and the main mass was released into the atmosphere.

In general, the total volume of leakages corresponds to the volumes of emissions assumed by different expert organizations (Mehrafrooz et al., 2019). Thus, according to the calculations made by: Stéphane Orjollet in his publication dated October 5, 2022 "Nord Stream leaked less methane than feared: atmospheric monitoring" - the leakage volume in all pipeline sections was about 0.07 meg tons; according to the article "Improved estimates of Nord Stream leaks" by Christine Forsetlund Solbakken dated October 12, 2022: the leakage volume from all damaged sections was 0.056 - 0.155 meg tons. Interested results of gas leakage was shown by Katharine Sanderson, they are also confirming presented calculations (Sanderson, 2022).

4. Analysis of the application of different methods for gas pipeline restoration on the bottom of the Baltic Sea

The investigated emergency situations require decision-making on carrying out repair-rehabilitation works on the gas pipelines of the Nord Stream system. At the same time we can state that after direct visual inspection of pipelines, their sonar sounding, metal sampling and establishing the actual length of flooded sections, a number of obligatory operations will be required at the transition stage before repair works:

1. Restoration of at least 100-150 meters of embankments under pipeline strings in emergency areas;
2. Dismantling of destroyed and flooded sections of pipelines;
3. Preparation of pipeline sections for repair works;
4. Carrying out works on connection of broken sections (installation of new section of pipes instead of lost ones);
5. Carrying out of external and internal diagnostics of gas pipeline strings, testing;
6. Obtaining of the special permission documents for putting into operation after the execution of the repair-restoration works and registration of the insurance.

It should be noted that, in fact, each of these stages requires a separate investigation, as it is connected with the solution of a large number of technical, technological, organizational, managerial and political problems. Nevertheless, the technical and technological aspect of the problem results in choosing the optimal method of repairing the damaged pipeline strings. At the same time it is obvious that the repair works on the Nord Stream-2A pipeline is unreasonable due to the high length of the flooded section (over 105 km), as well as the absence of permits for putting the pipeline into operation (insurance). In the case of Nord Stream-1A, B pipelines the repair is possible by applying such technologies as Heier & Mellem, 2007:

1. Underwater welding operations with cut-in points and hyperbaric chambers (e.g. application of PRSI - Pipeline Repair and Subsea Intervention or Eni/Saipem SiRCoS - Sistema Riparazione Condotte Sottomarine)
2. Lifting and welding of the pipeline strings on the surface, with subsequent laying

Now let's analyze the application of these methods, their strong and weak points, as well as the risks associated with the repair process of the gas transportation system. We should note that some of the presented technologies have already been used during the pipeline construction.

For example, hyperbaric welding was performed at three points along the route of each of the pipeline strings. The welding works were remotely monitored by the Skandi Arctic, while divers performed the monitoring and control of the welding of the sections themselves. These cases (for any of the pipeline strings) allow this type of work to be carried out because the depth of the incident does not exceed 180 m. (depth limitation for divers, according to DNV-RP-F113 Pipeline subsea repair).

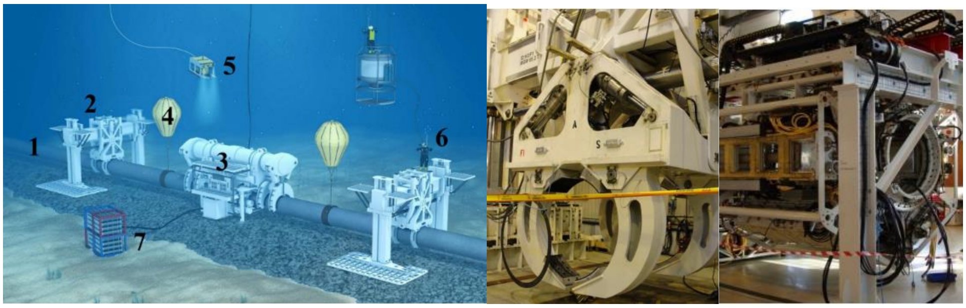

Figure 10. a - North stream pipeline bracing by hyperbaric welding; b - PHF; c - PRS. 1 - Pipeline string; 2 - Supporting mechanisms (PHF); 3 - Hyperbaric welding chamber (PRS); 4 - Inflatable diving lifting bag; 5 - Underwater inspection apparatus; 6 - Diver; 7 - Gas cylinders. Source: a- Nord Stream AG, b, c – Authors

In technological terms, the process is as follows. A specialized welding equipment is lowered on the sea floor, to the area containing the retained section, which has been cleaned and prepared by the divers; this is where the old section and the new section lowered from the ship can be welded (Amaechi et al., 2023).

The specialized dry-welding system used during construction of the Nord Stream pipelines was previously supplied by Statoil. It is a dry zone (PRS), where divers work without diving equipment to set up the automatic welding machine. At the same time, the welding process is fully controlled from the support vessel. At the same time, two specialized supporting mechanisms (PHFs) are lowered onto the same seabed area, which provide support and alignment of the welded pipeline strings (this is necessary to ensure the quality of the welded joint).

There are different modifications of such technological scheme of repair performed by companies. Thus, the repair can be carried out with or without the use of divers - for example, with the use of special robots, with the involvement of various support and alignment systems and with special telemetry systems. In general, we can distinguish three large groups of companies that provide such technologies - Norwegian, Italian and American companies. Whether it is possible to carry out such repair and restoration work under current conditions with the involvement of partners from these countries is an open-ended question.

Another method of repairing damaged sections of gas pipelines is surface repair, using specialized vessels (Sharifi et al., 2022). Considering the process of welding area preparation, welding operations and subsequent flaw detection, as well as pipeline coating operations - this method allows to achieve higher quality and reliability and fully meets the requirements of DNV-OS-F101: Submarine Pipeline Systems. However, we should mention some specific aspects that may complicate this technological process. Initially, after inspection, clearing and elimination of the damaged pipeline section, cleaning and fastening of the repaired pipeline to the hoists is performed (Figure 11 a).

During this operation, the integrity of the lifted pipe string, the uniformity of fastening and distribution of loads during the lifting of the pipeline section are of great importance. Then, additional pipes are delivered to extend the pipeline (Figure 11 b).

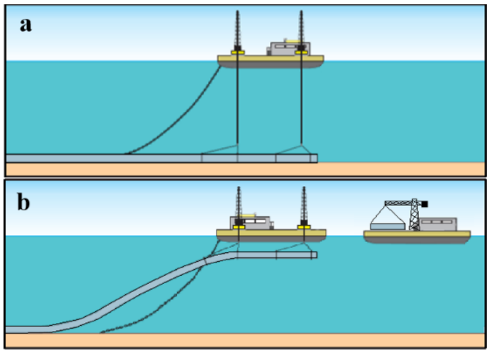

Figure 11. a. Lifting the flooded pipeline from the seabed; b. Bringing in additional pipes for welding on the surface
Source: Authors

At the same time the lifted pipe section is gradually filled with gas to be lifted aboard the ship. Next step is onboard inspection and inspection of the welded-on string, removal of protective coating on the end section, and subsequent onboard welding and joint assembling of the sections on the ship (Figure 12 a). This ensures their alignment, quality of edge stripping, quality of welded joints and protective coating.

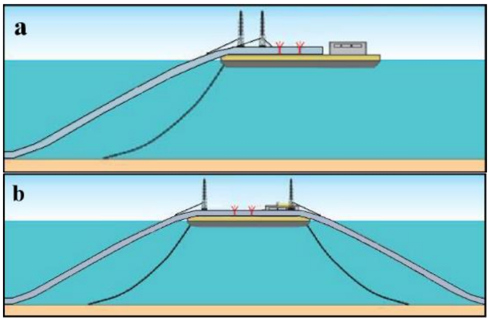

Figure 12. a. Emptying of the pipeline, inspection, preparation for welding, welding of new sections; b. Connection of the expanded section and the second end of the gas pipeline
Source: Authors

At the final stage, welding is performed with the opposite old section, which is also lifted from the bottom, with the performance of the whole complex of measures for its examination and preparation for joining (Figure 12 b). After that, the final welding, weld quality control, coating with external protective coatings, lowering and laying on the bottom, with subsequent tests take place.In fact, this work was already performed during the construction of the Nord Stream pipeline, involving specialized vessels: Castoro Sei, Far Samson, Allseas' Solitaire, as well as many other tugs, supply vessels, and soil preparation vessels. Of course, arrangement of works using this technology will also require consolidation of efforts at the international level. At the moment, unfortunately, the Russian Federation doesn't have a fleet capable of handling the whole range of operations. However, there are plenty of contractors (as compared to underwater hyperbaric welding) in this case - a number of firms and companies in East Asia, South America and, of course, in Europe.

In this regard, it is more rational to repair and restore the damaged sections of the Nord Stream pipeline by repairing it on the surface (due to the complexity of contracting, organization of the technological process, and the quality of the work itself).

A preliminary analysis of the scope of work shows the necessity of forming a group of vessels to provide not only lifting and welding of the strings, but also clearing and strengthening the bottom in the emergency areas (for the strings of Nord Stream 1, this will be about 2 km). Strengthening and restoration of the embankment - about 120 km, with clearing of flooded pipes. In addition, material support is required - production and delivery of the proper amount of pipes, fittings, concrete, gravel and electrodes. So, according to preliminary assessment (excluding a direct underwater inspection), the restoration of both strings of Nord Stream-1 will require at least 9837 pipes

5. Conclusion

Initial analysis suggests that about 0,0803 meg tons of natural gas was released into the atmosphere as a result of the incident on the three strings of the Nord Stream pipelines. Preliminary modeling shows that gas release from the breakdown points continued for up to 6 days. If the valves in the pipeline sections had operated normally, after the shutdown the volume of flooding was about 60 km in the pipeline sections Nord Stream 1A and B, and about 110 km in the pipeline section Nord Stream 2A. (taking into account the pipe section between the two incident points).

If the pipeline valves were not closed, the gas release could last longer and be larger in volume, and the flooding process of the pipeline strings took place up to the hydrostatic pressure level - between the sea water and the gas remaining in the system. Considering the relatively shallowness of the seabed in the area of the Bornholm basin - based on data from bathymetric maps, it is impossible to establish these hydrostatic pressure levels in an analytical way. More precise results can only be obtained by direct underwater inspection of the pipeline strings.

Taking into account the complexity and high cost of repair and restoration of pipelines, it seems rational to repair only the Nord Stream-1A and B gas pipeline strings. In this case, the most affordable and at the same time controllable and qualitative way of repair will be lifting of flooded strings on a ship, its inspection, repair, extension, welding and lowering onto a prepared ground. To perform these works a wide range of contractors can be involved. It should also be noted that application of this technology will provide a full range of tests of the system after welding works in accordance with the requirements of DNV-RP-F113 Pipeline subsea repair.

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