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ENVIRONMENTAL SAFETY DURING TRANSMISSION OF DIFFERENT TYPES OF GAS: PIPELINE, LIQUEFIED, COMPRESSED AND HYDRATED

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ABSTRACT

The paper is devoted to results of assessment of environmental safety during transmission of different types of gas using both domestic and foreign experience. It describes contemporary methodological approaches, including assessment of environmental impact, ecological and geoecological risks, life cycle of transported products, specific emission indicators at different stages of the life cycle with account of advanced standard specifications.

Since in JSC Gazprom the environmental impact is primarily associated with pipeline gas transmission, the paper presents both dynamic statistics on atmospheric industrial pollutant emissions, and data on environmental impact analysis of trunkline gas transmission processes, including gas treatment in new gas production regions exemplified by gas transportation from Bovanenkovo gas condensate field via Yamal-Ukhta gas pipeline, onshore section of the Nord Stream pipeline. The authors also implemented analysis of environmental risks for different stages of gas production on the Bovanenkovo field.

Analysis of the impact of liquefied (LNG) and compressed (CNG) natural gas transmission processes, including gas treatment for transmission and regasification were also carried out to show the environmental aspects.

Although today there are only pilot projects on transmission of hydrated natural gas (HNG), the authors analyzed environmental impact of HNG transmission, including its treatment and further regasification. It should be noted that first of all reserves of natural gas hydrates are spread across large permafrost polar and subpolar territories of Russia, and secondly experimental studies performed at Gazprom VNIIGAZ LLC and international companies prove technical possibility to transmit gas in hydrated form. Transmission process itself, as experiments show, will exert minimum impact on the environment (greenhouse gas emissions). However gas hydrating will require large volumes of water.

Methodology of assessment of the product life cycle takes into account emission standards for greenhouse gases and nitrogen oxides. Used specific emission parameters reveal the environmental impact from equipment manufacturing process and transmission means, namely production of pipes of different diameters and construction of gas transportation vessels.

CONTENTS

INTRODUCTION

Natural gas is transported by four main ways: by trunk pipelines, in liquefied, compressed and hydrated forms. Harmful substances are discharged and have an impact on the environment at different stages of gas chain or during the whole life cycle of the product.

During the life cycle natural gas produces significantly less harmful substances than other fuels, but such compounds as CO_2 (carbon dioxide), CH_4 (methane) and NO_x (nitrogen oxides) are always there. Together they are called greenhouse gases (GHG). If methane emission is mainly caused by process blow-downs during natural gas production, processing, transmission and distribution as well as process equipment leaks, carbon dioxide is the dominant emission at combustion of all types of fuels in the gas industry. Every year about 80-85 BCM of methane or ~ 3% of global production are lost worldwide. Apart form that, both during pipeline transmission and under alternative variants sulphur and nitrogen oxides are emitted, which has an acidifying and eutrophing effect on ecosystems.

Thus, the environmental safety of gas transmission is connected with such concepts as: environment contamination, greenhouse effect, global warming, water eutrophication, sea and soil acidification, etc.

The paper is aimed at improvement of the environmental safety at different modes of gas transmission.

1. ANALYSIS OF ENVIRONMENTAL IMPACT CAUSED BY TRUNK GAS TRUNSMISSION PROCESSES, INCLUDING TREATMENT FOR TRANSMISSION AND TRANSMISSION IN NEW GAS-PRODUCING REGIONS

1.1 Dynamics of contaminant emissions in JSC Gazprom

The impact on the atmospheric air is the most important environmental aspect in gas transmission in particular and in assessment of the impact of other subsectors of Gazprom Group's production activity. The impact on other environment components is created via interaction in the system "atmosphere – plants – soil – natural waters". We will study the component composition and dynamics of these emissions [1].

In 2009 the gross emission of contaminants to atmospheric air from stationary sources of Gazprom Group's facilities amounted to 3391,14 thous.t., including: carbon oxide – 645,79 thous.t., nitrogen oxides –335,29 thous.t., hydrocarbons - 1859,75 thous.t., including methane –1831,2 thous.t.

96,4% of these contaminants belong to the main contaminants of gas industry, among them methane (70,8 %), carbon oxide (19,5 %), and nitrogen oxides (6,1 %).

Thus, the provided data show that pipeline gas transmission causes significant emission of contaminants – methane, nitrogen oxides and carbon oxide.

Gas transmission via pipelines accounts for over 99% of natural gas transmission in Gazprom, which has a significant impact on the environment. Taking into account that a large number of trunk gas pipelines are running through not only the territory of Russia, but also foreign countries, it is necessary to use contemporary methods, accepted at the international level, for assessment of this impact.

1.2 Critical loads as an indicator of environmentally acceptable levels of impact of atmospheric pollutants on natural ecosystems

Scientific and methodical approaches developed within the frames of the *Critical Load Methodology* acknowledged at the international level is of the most practical interest for analysis of the environmental impact and substantiation of acceptable emission of atmospheric pollutants from gas industry facilities. Basic provisions of the Critical Load Methodology are formulated in materials and publications related to the scientific support of the international Convention on Long-Range Transboundary Air Pollution in Europe [2]. This methodology is based on the differentiated nature of different ecosystems response to man-caused impact.

The *critical load* concept (or CL value), according to the definition [2], means the maximum level of pollutants in the ecosystem that does not lead to irreversible changes in the biota, ecosystem structure and its long-term productivity – up to 100 years and more. Thus, CL assessment comprises identification of the threshold of contaminants emission into ecosystems: its exceedence can lead to negative consequences for living organisms and ecosystem on the whole, whereas below this level there are no negative effects or violations. As distinct from traditional for Russia and the majority of other countries "environmental" indicators that regulate pollutant concentrations in individual environments, CL value is an *ecosystem indicator.*

CL assessment is aimed at establishing quantitative connections between the impact of specific contaminants and environmental consequences caused by this impact, which is especially important for environmental and economic substantiation of management decisions. Qualitative values that determine acceptable level of man-caused impacts of certain contaminants on specific ecosystems can be identified by experimental and monitoring studies. These are the so called *empirical critical loads.* However, regional investigations of territories with high natural diversity more often employ quantitative methods of CL assessment based on mathematical calculations using modern well logging technologies.

Quantitative methods of CL calculation are based on simple chemical models of element mass-balance [3]. Critical load assessment can account for certain nature protection priorities determined by selection of recipients (preservation of specific natural sites) and corresponding biogeochemical indicators.

1.3 Analysis of environmental risks of transmission of different gas types

As it is mentioned above, all types of gas transmission are characterized by potential man-caused impact on the environment. The following criteria should be used for estimating man-caused impact on ecosystems and emerging respective risks:

- scale of spreading – local, territorial, regional, transboundary and global;
- duration – one-time, periodical, continuous, short-, mid- and long-term;

- type – reversibility or irreversibility;
- intensity – absolute and relative;
- probability – high, mean or low;
- uncertainty – high, mid or low.

It should be noted that due to structural and functional complexity of ecosystems the forecast of their changes has high degree of uncertainty. It is caused by inevitable simplification of various environmental processes for modeling, lack of initial data for forecast calculation and insufficient reliability or scientific substantiation of used algorithms.

The most detailed studies on environmental risks assessment incorporate the analysis of environment contamination consequences. The quantitative pollutant emission environmental risks assessment is provided in papers [3, 4].

1.4 Environmental risks of gas production and transmission regions

It should be mentioned that the main environmental impact is made by operation of gas turbine drives on compressor stations (CS), since fuel gas accounts for 80% of all consumed gas for in-house process needs. The CS efficiency is determined by transported gas/total gas consumption for in-house needs ratio. During CS operation under established process scheme gas is combusted on compressor stations with emission of harmful substances, such as nitrogen oxides and other (carbon oxides, sulphur oxides, heavy metal compounds, volatile organic compounds, etc.) in discrete points of gas pipeline. The composition of emitted contaminants depends on the natural gas composition, which is another component of geoecological risks.

In this connection it is reasonable to study methods for assessment of pollutant critical load on the environment in more detail in order to control geoecological risks. [3]. Quantitative risk assessment can be based on the critical load concept.

1.5 Assessment of environmental risks of gas transmission from new fields: impact zone of NO_x emission from the Bovanenkovo gas condensate field.

The relevance and importance of environment protection during development of natural resources of the High North of Russia, which ecosystems are less resistant to external man-caused impacts, are generally acknowledged today. The Bovanenkovo field group (BGCF) located in the western part of the Yamal Peninsula with large natural gas and condensate reserves is one of the priority areas for development. The assessment of environmental risks for ecosystems in the zone of BGCF emissions is performed under standard algorithm [4].

<u>Stage 1 Identification of hazards</u>

According to BGCF development plans, field development will be done by stages, with subsequent commissioning of process facilities, which will influence the dynamics of pollutant discharge rate. Methane, carbon oxide and nitrogen oxides prevail in the atmospheric emission. The most important hazard factor for the regional ecology of western Yamal will be an increase of man-caused emission of nitrogen compounds, which excess can cause, apart from direct toxicity risks for biota due to NO_x high concentrations in the air, indirect (secondary) environmental eutrophication and acidification risks.

Phytocenosis species diversity in the impact zone of the Bovanenkovo field is determined by the complexity of tracheophytes species, moss and lichens. Graminaceous species, sedge, pink, buttercup, cruciferous willow species prevail; there is wide diversity of moss species. Lichenobiota is composed of mainly Epigaea species (84%), but there are no favourable conditions for their wide spreading due to considerable waterlogging, and continuous deer grazing in recent years resulted in the substitution of feed lichens by poorly eaten species and crustaceous and scablike lichens. The food ration of deer mainly consists of graminaceous species, sedge, suffruticous willows and moss. Overgrazing in the studied area led to thinned or considerably disturbed vegetation cover, which reduces productive phytomass. Potential recipients of nitrogen oxide emissions will be surface lichen waters, mosses, main tracheophytes (including registered in the Red Book of YNAD (1997) [6]), as well as soil algal flora which is the main biological atmospheric nitrogen fixation pool in tundra soils.

Stage 2 Assessment of “dose-response” ratio (CL calculation)

According to the proposed algorithm of environmental risks assessment, acceptable (reference) doses of nitrogen oxide impact on phytocenoses in the impact zone of the Bovanenkovo GCF emissions were calculated using probabilistic methods of CL calculation in terms of eutrophication and acidification effects ($CL(N)_{nut}$ and $CL(S)_{max}$). CL calculations were done with 1x1km spatial resolution. Variable parameters of mass-balance equations were: supply of cations and ions with atmospheric fallouts; fixation of nitrogen and cations in surface phytomass; immobilization of nitrogen in organic matter of tundra and tundra-bog soils. For every ecosystem random sampling from 1000 possible CL values was calculated by Monte Carlo method. The further examination showed that such big number of “runs” ensures high replication of results. Then, 50 %, 75 % and 95 % level values (Figure 1) (corresponding maps-schemes were generated for these values in ArcView (Figures 2-3)) were taken from obtained cumulative distributions of CL probabilistic values.

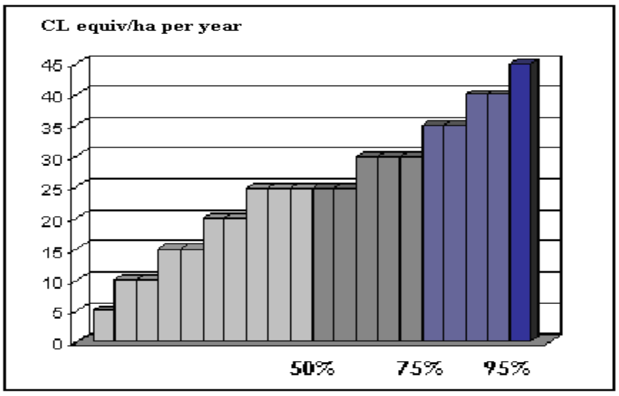

Figure 1 – Example of the CL possible distribution cumulative curve for the specific ecosystem

Depending on phytocenosis type and edificatory species, nitrogen CL calculated values in relation to eutrophication effects amount to (Figure 2):

- for 50 % of $CL(N)_{nut}$ level – 210-350 g-equiv./ha per year;
- for 75 % – 210-700 g-equiv./ha per year;
- for 95 % – 210-840 g-equiv./ha per year.

Obtained values correspond to the acceptable fallout of from 3-5 to 10-12 kg N/ha per year, which is higher than current atmospheric nitrogen fallout indicators.

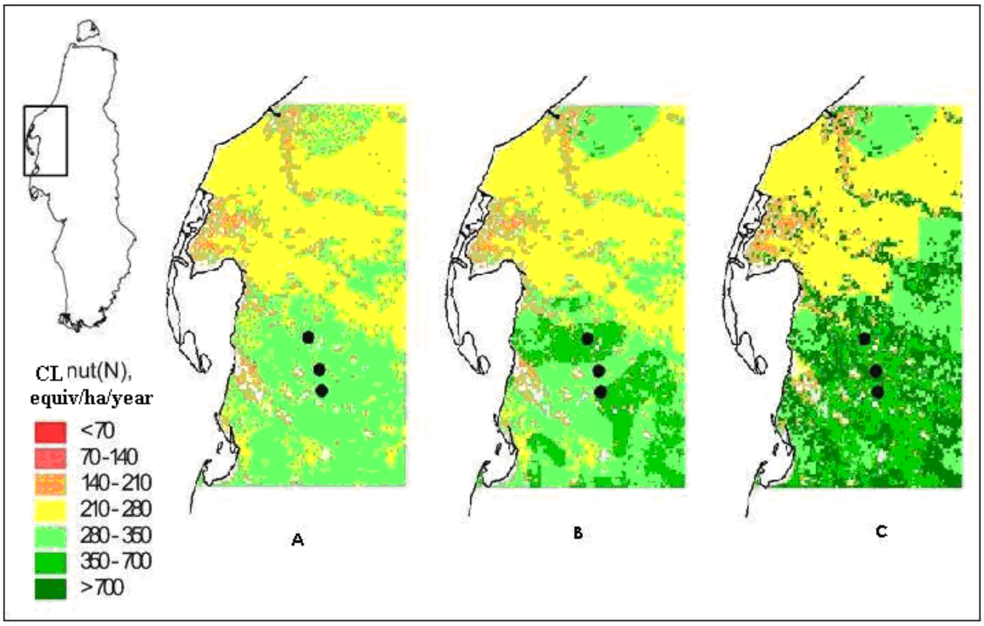

Figure 2 – Probabilistic nitrogen CL distribution in relation to eutrophication effects (A – 50 % , B – 75 %, C – 95 %)

Obtained $CL(S)_{max}$ values reflect the low potential concerning resistance to acid compound of atmospheric fallouts, which is typical for tundra ecosystem. According to minimum assessments (50 % level of probabilistic values), calculated $CL(S)_{max}$ in 30 km zone from BGCF facilities correspond to the acceptable fallout of acidifying compounds - 50-100 g-equiv./ha per year. CL of 75 % and 95 % levels are higher but do not exceed 280 g-equiv./ha per year, which can be compared with the fallout of about 3,5-4 kg of sulphur and/or nitrogen and is in accordance with current cumulative fallouts of these elements.

Stage 3 Exposure assessment

Scenarios of nitrogen oxide emission by process units of BGCF correspond to their stage-by-stage commissioning under field development schedule. Spatial modeling detail level – 1x1 km sites, which corresponds to CL model calculation sites. Obtained results are provided on Figure 4.

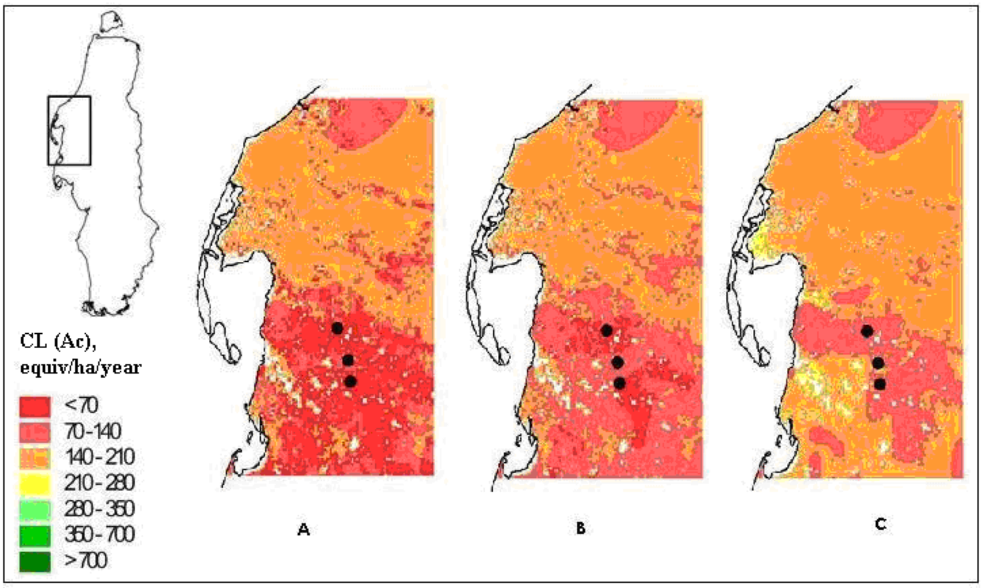

Figure 3 – Probabilistic acidifying compounds CL distribution (A – 50 %, B – 75 %, C – 95 %)

The modeling data shows that after stage-by-stage commissioning of BGCF process facilities the regional background of nitrogen compounds atmospheric fallouts increases. Major effect will be in the 30 km zone. In first years after commissioning of 1 and 2 GPU the level of additional nitrogen fallout for this zone is estimated at 35-140 g-equiv./ha per year, which corresponds to annual fallout of 0,5-2 kg N/ha per year. In future when 3 GPU are commissioned, nitrogen oxide emissions will grow and the maximum impact may amount to over 2000-2500 g-equiv./ha (or 30-35 kg N/ha) per year, which can be compared with fallout levels of industrial and urbanized territories. But even in case of maximum nitrogen discharges, its man-caused fallouts at the boundaries of considered 30 km zone will amount to 2-5 kg N/ha per year.

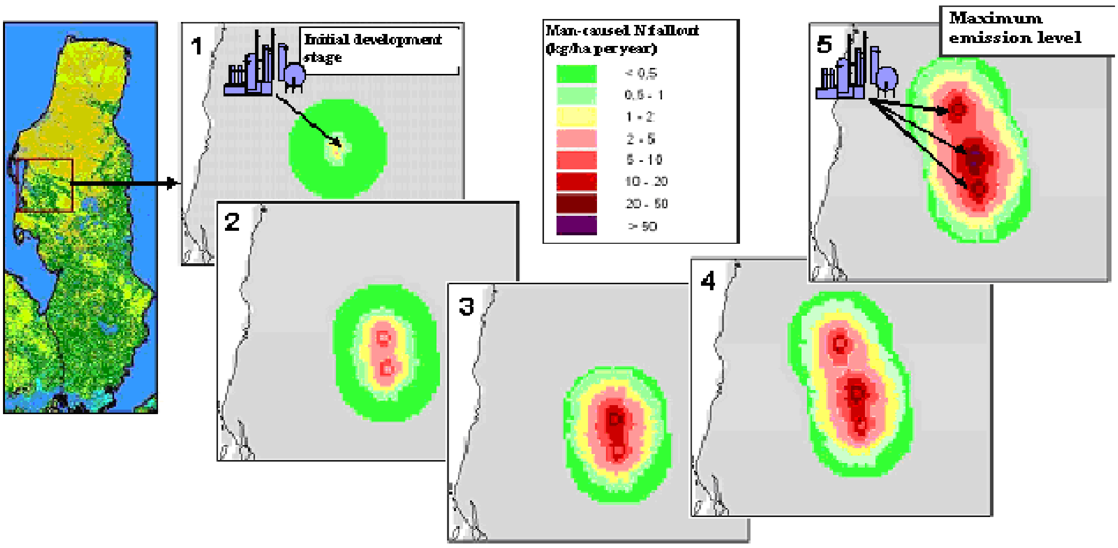

Figure 4 – Level of nitrogen fallout to land ecosystems at different stages of BGCF development in the impact zone in case of stage-by-stage commissioning of process units (%)

Stage 4: Risks

Results of calculations of eutrophication risks for all land ecosystems are presented in Figure 5. At all stages the large part of considered territory has no violations of CL $(N)_{nut}$, which are calculated for the most sensible to nitrogen contamination oligotroph species – lichens and mosses. High eutrophication risks are forecasted for ecosystems close to BGCF after commissioning of booster compression stations.

Under maximum emission level nearly all 30 km impact zone will experience $CL(N)_{nut}$ violation that will cause changes in the vegetation cover of this territory due to death of lichens and mosses as well as certain oligotroph tracheophytes. The most probable eutrophication effect for ecosystems at this territory will be the increase of sedges and graminaceous species and total phytocenoses productivity, which may result in changes of thermal properties of soil-plant layer. Other environmental effect of increased atmospheric nitrogen compounds fallouts can be the growth of ground and surface waters acidity. Taking into account that the majority of atmospheric nitrogen fallouts at this territory are deposited in snow cover, it is possible to forecast the carry-over of part of "excess" nitrogen from land ecosystems to local water bodies by melt waters. Thus, ecosystems exposure to BGCF emissions will result in "relevant" nitrogen loads amounting to about 50% of model fallout values.

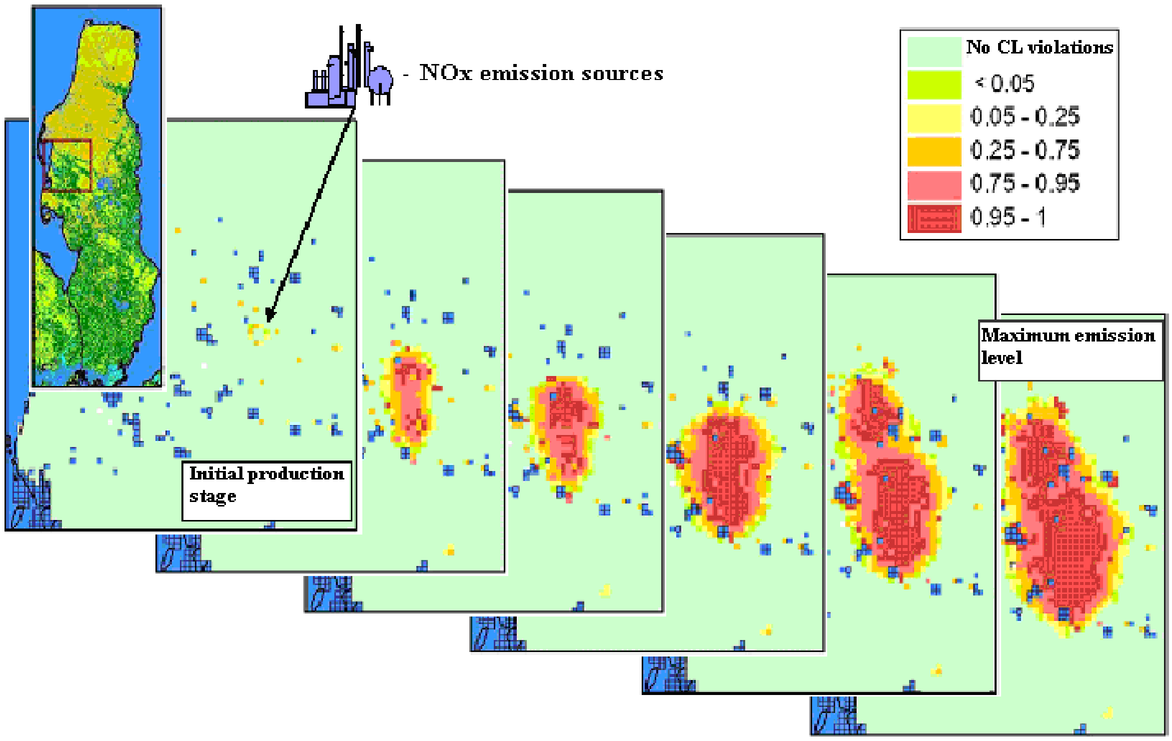

Figure 5 - Results of calculations of eutrophication risks for ecosystems

When modeling fallouts, we did not account for the part (relatively small) of nitrogen oxide emissions involved in global air dispersion processes, which increases general regional background of nitrogen fallouts at the Yamal territory. The calculated data shows that the increase of atmospheric nitrogen fallouts conditioned by emissions from Bovanenkovo GCF in the regional scale should not exceed 1-1,5 kg N/ha per year and it will not lead to significant growth of eutrophication risks.

2 ANALYSIS OF THE IMPACT OF LIQUEFIED (LNG) AND COMPRESSED (CNG) NATURAL GAS TRANSMISSION PROCESSES, INCLUDING GAS TREATMENT FOR TRANSMISSION AND REGASIFICATION

Gas is transmitted by sea in compressed or liquefied forms.

Compressed natural gas is transported by sea for comparatively small distances (to 1000-1500 km) and at present its transportation to international markets is limited. Such type of gas is more readily used on motor vehicle filling stations. This issue, however, is not the focus of the present paper.

Today it is LNG transmission that accounts for significant share of total natural gas transmission to markets; in 2010 LNG transmission amounted to 283 BCM or ~28% of total transmission. Main LNG producers are Qatar, Indonesia, Malaysia, Algeria, Egypt, Nigeria, Trinidad and Tobago. In Russia LNG plant was constructed in 2009, but production volumes are small. Gazprom’s share in “Sakhalin-2” amounts to 50%, which ensures approximately 4,5 BCM per year. It accounts for about 3% of total natural gas export.

2.1 Environmental risks of liquefied natural gas transmission

Taking into account that the prospect of onshore hydrocarbon feedstock and other mineral resources depletion determines the orientation of mineral resources exploration and production to the continental shelf and farther to the World Ocean, organization of gas transmission by sea becomes an important issue.

Transmission by vessels becomes a solution of many problems arising from complicated fields development in remote areas and on the shelf. Pipeline construction in such projects can be not cost-effective, environmentally hazardous or have negative impact on field commissioning schedule.

Lack of infrastructure at the first stage of remote field development as well as large distances to gas consumers determine the development strategy based on organization of marine transmission and construction of floating units and subsea facilities. This approach is as usual economically justified since it allows to considerably reduce capital expenditures and development schedule for remote fields.

At present the intensive development of LNG market is accompanied by development of corresponding production, transmission and marketing infrastructure [8]. When considering life cycle of LNG projects and respective environmental risks, the following factors related to environmental impact and risks should be accounted for:

- selection of locations for liquefied natural gas production plants;
- construction of plants and gas-filling terminals;
- LNG marine transmission;
- Construction of LNG regasification terminals.

For all these facilities corresponding procedures connected with Environmental Impact Assessment (EIA) and formalized by the legislation in countries that had similar projects before have been developed.

Apart from environmental risks caused by standard process operations, there are specific risks that are typical for LNG projects in particular. These include the following risks:

- possible LNG leaks in case of damage of LNG-tankers in offshore area;
- possible LNG leaks in case of damage of LNG-tankers in ports;
- possible LNG leaks during regasification.

Moreover, social and environmental risks related to the presence of protest population groups in LNG facilities locations must be also taken into account.

The analysis of available information does not allow to ignore the environmental risks theory, which requires development of corresponding regulations for strictly quantitative assessment of environmental risks as an independent risk group. The approaches based on integrated analysis of LNG subindustry in the gas industry should be the methodical foundation of such developments. These developments are relevant both for companies with experience in LNG projects and Gazprom that only enters into the market.

For major projects environmental risks associated with changes in ambient environment during construction of process facilities and possible man-caused impact during development are significant and considered independently.

Environmental risks of gas transmission projects are analyzed by parameters with account of noise, atmospheric discharges, water quality and contamination from planned activity [8]. The results of the analysis are used for:

- selection of locations for liquefied natural gas recovery, production and shipment within the frames of EIA;
- design and construction - EIA;
- tanker transmission organization – EIA and environmental risk assessment;
- construction of LNG regasification terminals – EIA and environmental risk assessment.

Specific risks related to LNG leaks and dispersion can occur:

- in case of damages and accidents at LNG plant, vessel or off-loading terminal,
- in case of incidents at sea: collisions or taking the ground.

According to studies of DNV and Knutsen shipping company, the risk of gas carrier collision is relatively low – 2,62 e^{-04} and has little impact on the total risk level [8].

When analyzing the strategy of environmental risk management at LNG shipping, all measures can be divided into two groups: measures for hazardous consequences prevention and measures for hazardous consequences mitigation. The first group includes, first of all, protection of LNG carriers from reasons of collisions, including keeping distance, barriers, do not enter zones and shutdown of operations in case of environmental risk. There are also engineering capacities due to process free spaces in the tanker hull filled with inert gas. Prevention of hazardous consequences is also achieved by the growth of mobility (for example, use of tow boats). Considerable attention should be paid to the armed escort of LNG-tankers (airplanes, vessels, on-board escort), monitoring using sonars, underwater swimmers, coast guard, surveillance (onshore, air, subsea, on-board), control over crew on-board and programs controlling access to the tanker. Storm warnings and the program for avoidance of storm zones also play an important role in prevention of environmental risks.

Mitigation of emergency situations related to environmental risks comprises the following measures: rehabilitation operations, current and emergency plans, presence of equipment and personnel, trainings of tanker crew and population in areas of possible impact under the evacuation plan.

Fire fighting means, including spill sensors, flooding systems, radial barriers, on-board fire fighting means are necessary as well.

Offshore offloading of LNG is the best for mitigation of environmental risk consequences.

Thus, the integrated system of measures for prevention and mitigation of environmental risks at liquefied natural gas transmission has been developed.

3 ASSESSMENT OF ENVIRONMENTAL IMPACT OF HYDRATED NATURAL GAS PRODUCTION AND TRANSMISSION

At present the assessment of the impact of hydrated natural gas production and transmission is mainly confined to greenhouse gas assessment.

HNG transmission leads to reduction of greenhouse gas discharges: in the process of production and 3000 km transmission of 0,4 MTPA of hydrated gas, 1900 t/a of CO_2 is discharged to the atmosphere (LNG – 2200 t/a (by 14 % more).

Moreover, if HNG vessels are conversed to gas fuel, it results in further reduction of not only natural gas discharges, but also sulphur oxides, nitrogen and carbon.

4 IMPACT OF EQUIPMENT AND TRANSMISSION MEANS PRODUCTION

4.1 Greenhouse gas discharges at pipeline construction: study of the whole production cycle

This section is aimed at study and understanding of the environmental impact of pipeline construction in the form of greenhouse gas discharges. The whole production cycle is subject to the study. This approach seams to be convenient and gives reliable results for short time compared to the service life assessment.

400mm (16’’), 500 mm (20’’), 605 mm (24’’), 907 mm (36’’) and 1210 mm (48’’) and 1420 mm (56’’) pipelines, which are most often used in construction projects both in Russia and abroad, were used for the study. Discharges were calculated for 1 km of constructed pipeline. The calculations accounted for discharges from the maximum complete chain, including pipe production, pipe and equipment transmission, fuel consumption by equipment, other works, for example, insulation coating application and welding and non-production activity: energy consumption in offices, for business flights and personnel transportation.

It has been shown that for 1 km of 1210mm (48") pipeline under construction discharges amount to 1,260 tons of CO_2, the majority of these discharges occurs during steel pipe production.

Table 1 summarizes all the results and shows the total CO_2 discharges from laying of 1 km pipeline of different diameters.

Table 1 - Total CO_2 discharges at pipeline laying (on the basis of NACAP assessment of greenhouse gas specific discharges at pipeline construction)

Diameter (mm/inch)	CO_2 discharges (t/km of pipe)					Total
	Steel production and pipe drawing	Transport (1000 km)	Equipment fuel consumption	Insulation coating & welding	Non-production activity	
400/16	133,7	9,85	49,2	6,9	40,7	240,4
500/20	206,4	15,96	53,4	8,6	56,9	341,2
605/24	258,6	22,28	84,0	10,4	75,1	450,4
907/36	543,0	48,75	119,7	15,8	145,5	872,8
1210/48	973,7	85,59	138,6	21,5	243,9	1463,3
1420/56	1098,7	110,14	159,9	25,4	278,8	1672,9

It can be seen that the major source of CO_2 discharges is pipe production. These discharges can be reduced by using the stronger steel, which will allow to decrease the pipe thickness.

4.2 Environmental impact of vessel construction: assessment of the whole production cycle

According to ISO 14000 [7], main sources of environmental impact at vessel (tankers-gas carriers) construction are also connected with the use of steel and fuel consumption.

Steel is the main material since vessel (tankers-gas carriers) hulls are made of steel. Environmental impact of the steel life cycle is made at the stage of steel production, installation of steel plates, build-up of steel plates by welding, grinding, sand blasting, painting and transmission of steel components and sections.

During tanker operation the impact is made by discharges of pollutants: sulphur, nitrogen and carbon oxides. Specific discharge volume depends on the fuel type (vessel fuel oil, LNG) and its consumption.

Figure 6 shows the comparative environmental impact in the form of eco-points (specific values that allow to parameterize the impact of different contaminants - CO_2, NO_x, VOC).

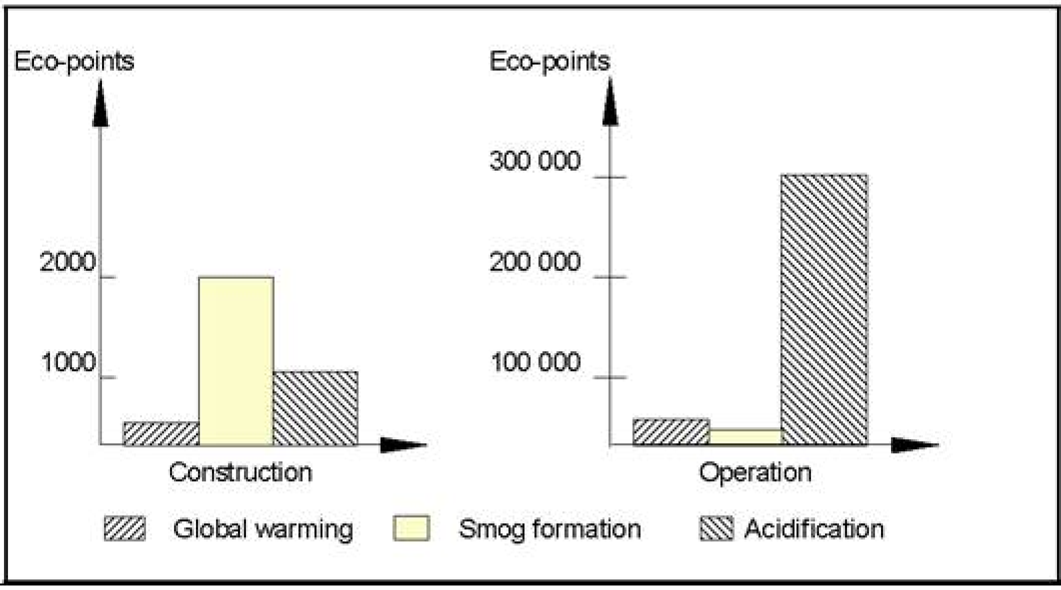

Figure 6 – Discharges of contaminants during vessel construction and operation **[7]**

It can be seen that at the construction stage the dominant contaminants are VOC (volatile organic compounds) generating smog and at the operation stage - sulphur and nitrogen oxides that cause acidification of water ecosystems. Greenhouse gas discharges (carbon oxides and dioxides) that cause global climate change are nearly similar at construction and operation stages.

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