CHALLENGES TO RELIABILITY IN CONSTRUCTION AND OPERATION OF HIGH-PRESSURE PIPELINES

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1. INTRODUCTION

As is known per the Energy Strategy of Russia up to 2020, the major statements of which were reviewed and approved at the session of the Government of the Russian Federation [1], it is anticipated to increase the annual gas production up to \(6.55 \times 10^{11} \text{ m}^3\) by 2010 and \(7.0 \times 10^{11} \text{ m}^3\) by 2020. At present the major source of natural gas are the basic fields of West Siberia which are already depleted to significant extent. By 2020 more than 76% of natural gas production has to be obtained at the new fields. Major reserve fund of explored fields consists of unique in terms of reserves fields of the Yamal peninsula and Pre-Yamal shelf, less huge and condensate containing deposits of deep burial in Nadym-Pur-Tazov region. Explored are the major fields on the shelf of the Barents, Okhotsk and Kara seas. In East Siberia and in the Far East has been explored more than \(2.7 \times 10^{12} \text{ m}^3\) of gas reserves, from which is developed only 7.4%.

Starting from 2006-2007 for compensation of gas production reduction and production growth it will be necessary to put into operation the fields in water areas of the Ob and Tazov bays, the Yamal peninsula and consequently Pre-Yamal shelf and Stockmann field on the Shelf of the Barents sea. The other major center of gas production in the second half of the considered period can become Kovyktin field in Irkutsk region.

Thus we can conclude that the nearest prospects for Russian gas industry development are related with development of the fields of the Far North. The new feedstock sources are significantly far off both from the gas consuming regions and existing gas transport trunk lines. At the same time for arranging the gas deliveries to the consumers and providing the transit will be required significant development of the Unite Gas Supply System and construction of gas transmission systems on the Far North, East Siberia and Far North. Among the major project of the new main gas pipelines shall be mentioned Yamal-Torzhok (length of the route 2465 km, including in the new corridor 1074 km), Urengoi-Surgut-Ulan-Bator-Beijing (6020 km, including on the Russian – 4300 km) and Kovyktin-Irkutsk-Ulan-Bator-Beijing-the port of Zhijao (3400 km, on the Russian territory – 300 km). In the further prospect on the basis of gas pipelines Urengoi-China and Kovyktin-China can be created the Far East gas transmission system which besides Kovyktin, Novo-Urengoi and East-Urengoi fields could unite the fields of Vilui and Botuobinsk regions of Saha-Yakutia. Absence of the developed infrastructure along the new corridors, complicated natural-climatic and geo-cryological conditions along the new corridors lead to significant growth of capital investments. In such situation of tremendous importance is the task of increasing the efficiency of long-distance gas transmission.

2. GAS TRANSMISSION TRUNK LINES

In Russia today for the onshore trunk transmission lines the technology, established during 60-70s, is used with working pressure of 5.4-7.4 MPa. The modern level of the industry development allows to switch to using the higher working pressure. In some cases the use of extremely high pressure in the onshore gas pipelines has evident economic advantages. As an example one can mention the offshore pipeline systems with branch lines to the shore, where the working pressure will be defined by the pressure in the offshore trunk line, or gas pipelines for the long-distance gas transmission including big length offshore and onshore sections. In such cases the inlet pressure can be much higher than the ordinary working pressure in the onshore pipelines. If onshore are not used high pressure gas pipelines there will arise necessity of pressure reduction at the shore terminals with further gas transportation per the conventional technology. Further along the route of the gas pipeline can be needed compressor stations increasing the working pressure.

Use of super-high pressure can be beneficial also for the onshore pipeline systems. Presence in the trunk lines of big amount of branch lines to the existing gas distribution lines can restrict the possibility of increasing the working pressure. However the new onshore gas pipelines of super-high working pressure can be used as trunk pipelines, transmitting major volumes of gas to great distances from the low-populated regions to the main gas consumers. In such case the super high pressure systems will be probably more efficient than the conventional ones. It shall be emphasized that one of the prerequisites of new generation of pipelines implementation is development of high strength steels.
manufacturing, which provide for greater calculated pressure at the same wall thickness, i.e. without significant increase in the expenditures for materials and construction.

Besides, it can be economically viable to use the transport systems of super high pressure for gas supply to relatively small populated settlements by means of small diameter branch lines using high pressure. And pipeline diameter can be significantly reduced which will cut construction costs and at the same time will provide for greater flexibility in route selection and drastic decrease in technogenic impact upon environment.

To demonstrate efficiency of high pressure systems for further gas transport we will show here some comparative rough assessments for conventional gas pipeline with commercial productivity $6 \cdot 10^{10} \text{ m}^3/\text{year}$

- (I) two-lines pipeline with outer diameter $D = 1420 \text{ mm}$ and working pressure $p = 7.5 \text{ MPa}$;
- (II) one-line pipeline at $D = 1420 \text{ mm}$ and $p = 14 \text{ Mpa}$;
- (III) two-line pipeline at $D = 1420 \text{ mm}$ and $p = 14 \text{ Mpa}$;
- (IV) two-line pipeline at $D = 1220 \text{ mm}$ and $p = 14 \text{ Mpa}$.

First option corresponds to the conventional technology of trunk pipeline of gas in Russia. For definitive and concrete character of comparison we will presume natural-climatic conditions characteristic of Far North of Russia. Degree of compression at compressor stations (CS) for all the options we will take equal to -1.4. Pipe material - steel of strength grade X80. Shutting valves at the linear part for each of the options we will locate after each 30 km.

While obtaining the values of technical characteristics higher than the shown schemes of far transport of gas we will use the existing presently in Russia normative base. On fig. 1 are shown some calculation results.

As is seen from the diagram depicted on Fig.1 if the pumping pressure is increased and switch on to the one-line pipeline has been made (scenario II), somewhat increased is the required amount of intermediate CS and summary consumed capacity for gas transport (for 5.5% and 6.8%, respectively). For 6.7% will increase the summary fuel gas flow rate. At the same time for almost 8% is cut total metal consumption for linear pipeline portions. While increasing the pumping pressure and maintaining the two-line scheme of gas transport (scenario III) metal consumption for linear pipeline portions will increase almost 2 times but simultaneously 5 times as little becomes the necessary number of intermediate CS. Respectively the summary consumed capacity for transport and consumption of fuel gas as per scenario III will amount to 20.1% and 20.8% from the conventional option. Option of gas transmission by two-lines pipeline with $D = 1220 \text{ mm}$ and $p = 14 \text{ MPA}$ occupies here intermediate position between scenario III and basic scenario.

The particularities of gas pipeline construction designed for higher than conventional pressure are related with increase of thickness and weight of pipes. Scope of preparatory and land works will practically not be changed, some increase is possible on the curved sections. Increase of pipes mass and hardness will result in larger required working effort during assembly, the built-up metal volume will grow and welding works will become more effort consuming. There will be needed some certain increase in ballast mass at the convex sections. Also will be necessary modernization of welding units and pipes cutting and bending equipment. Besides, increase in pipes mass will draw to use of heavier pipelayers, cranes and pipe-carriers.
The increase in wall thickness and thus in weight of pipes that was related to the increase in operating pressure has required new approaches to the construction of gas pipelines. The volume of preliminary and excavation works has not practically changed, though at some curved pipeline sections a slight increase is possible. The increase in pipe weight and rigidity makes the construction works more labor-intensive with increasing added metal volume. Convex sections will require some increase in ballast weight. Besides, upgrading of welding machines and cutting and bending equipment will be also required. The increase in pipe weight may necessitate the use of heavier pipelayers, cranes and pipe trucks.

When estimating Capex of different gas transmission systems, expenses on pipe steel, cranes, valves, fittings, packing materials, welding, bending, pipeline laying, handling, shipment, inspection and control, wages and catering are assumed to increase with pipe weight. At the same time cost per unit of pipeline coating, cathodic protection, service and administrative rooms, communication, monitoring equipment, and pig launching and receiving stations will remain unchanged. A number of pig launching and receiving stations will depend on a number of intermediate compressor stations.

Fig. 2 illustrates a comparative estimate of capital investment for the scenarios considered. Feasibility study of the Bovanenkovo-Vorkuta pipeline carried out by Gulf Interstate Engineering Company was taken as a basis for estimating expenses:
As follows from the diagrams of Fig. 2, the transition to one-string gas transmission scenario with a simultaneous increase in operating pressure allows to cut capital investment by 5.9 %. All the other scenarios assume the increase of total costs. However, the efficiency estimate may be quite different if we calculate total costs for 30-year period of pipeline operation. From the Hand-book for gas/oil pipeline designers [2] capital investment in linear pipeline portions amounts to, on average, 4.1 % of a total costs. Capital investment in compressor stations can be found by the equation:

$$W_{CS} = 0.12C_{CS} + C_g$$  \hspace{1cm} (1)

where $C_{CS}$ is the capital investment in CS and $C_g$ is the cost of fuel gas. Assuming that $C_g$ is equal to $70 per 1000 m^3$, one can find that the increase in operating pressure will lead to total costs reduction, Fig. 3. The third and fourth scenarios are more effective, with the latter being, in our opinion, the most effective. The fourth diameter includes 2 strings of $D = 1220 \text{ mm}$ and $p = 14 \text{ MPa}$. A less diameter and wall thickness as compared with the other high-pressure scenarios will provide better flexibility in choosing route and pipe and fitting suppliers.
However, all this is very relative as the presence of the more or less developed infrastructure and more favorable climatic conditions can sufficiently redistribute the structure of expenses. At the same time, the above sample for a conditional gas pipeline says about favorable prospects for the transition of gas transmission to high-pressure scenarios.

The experts who prepared feasibility study of new promising projects have proved the efficiency of increasing operating pressure in gas mains. For example, for the Shtokmanov field an optimal value of operating pressure accounts, in different experts’ opinion, for 12 MPa. However, the transition to a new technology of gas transportation by gas mains is retarded by the tendency to economy of Capex on gas mains construction at the conditions of insufficient own investment potential of gas and oil producing companies. There is the opinion that the problems of safety, reliability and risk are also a barrier to the construction of land high-pressure gas pipelines.

It should be noted that transportation of gas at 9.8 MPa in Russia requires the development of appropriate domestic standards on designing and operating high-pressure gas mains. Special attention should be paid to the problems related to safety, individual and environmental risk at a stage of operation of super high-pressure compressor stations and dangerous linear pipeline sections.

3. METHODOLOGY OF GAS PIPELINE RELIABILITY ESTIMATION

Generally speaking the problems of reliability evaluation and related to this evaluation the problems of risk are sufficiently new in Russia. The source of these problems lies in the practice of design that was formed long ago but is still existing at the present time [3]. In spite of some influence of pipeline category factor that includes the purpose, operating conditions and regional distinctive features there is no sufficient differentiation by reliability, safety and service life indicators in the process of design.

As a rule, the design ideology is based only on proof loads and operating conditions while a final conclusion about the order and serviceability of facility results from a positive result of hydraulic and pneumatic pre-operational tests. A new design ideology is based on two levels of evaluation:

- 1st level is a base and includes preliminary estimates of regional and route features obtained by the existing building regulations
- 2nd level is a probabilistic analysis of safety based on possible realizations of undersigned loads and effects, occurrence and missing of defects in the process of intelligent pigging, tests and operation.

The 2nd level requires confirmatory calculation of service life of the facility. A general scheme is presented in Fig. 4.

To compare the above scenarios of a conditional gas pipeline from the viewpoint of technological risk let us calculate gas losses during gas pipeline rapture. According to Ref. [4,5], an approximate value of the total gas losses, M, during gas pipeline rapture at a distance of x from a head CS is defined as a sum of mass of gas M1 between cutoff valves at a moment of rapture and mass of gas M2 flowed through cutoff valves till their complete closing:

\[
M = S(\rho_1t_1 + \rho_2t_2) + (K_1(x)t_1 + K_2(x)t_2)Q
\]  

(2)
where $Q$ is the stationary mass flow, $K_1(x)$ and $K_2(x)$ are coefficients related to the law of valve closing, $S$ is the cross-section area, $l_1$ and $l_2$ are the distances from a point of rapture to the appropriate cutoff valves, $\rho_1$ and $\rho_2$ are average density of transported gas at the sections $l_1$ and $l_2$ at the moment of rapture. $t_1$ and $t_2$ from the moment of rapture till the complete closing of the cutoff valves can be find by the following equation:

$$t_i = \sqrt[3]{\frac{\rho_1}{\rho_0} / \gamma P_0}$$

where $\rho_1$, $\rho_0$ are the density and pressure of gas at a point of rapture respectively; $\tau$ is time of cutoff valve closing ($\tau$ is assumed to be 60 s); $\gamma$ is the index of adiabat.

Fig. 5 illustrates the calculation results for the first 600 km of a conditional gas pipeline. According the graph of Fig. 5, gas losses at a critical accident will increase by approx. 93 % (almost twice) as compared with a traditional technology during the transition from base scenario to one-string scheme of gas transportation at $p = 14$ MPa and $D = 1420$ mm (scenario II), and by 70-90 % and 20-35 % respectively during the transition to 2-string scenario III ($p = 14$ MPa and $D = 1429$ mm) and scenario IV ($p = 14$ MPa and $D = 1220$ mm). These figures necessitate toughening of requirements to reliability indicators for high-pressure systems.

The required values of reliability indicators for each scenarios can be evaluated with the help of the concept of equivalent technological risk $T(L,t)$ during the operation of linear portion of gas pipelines.
Fig. 4. Chart of designing gas mains based on the requirements for reliability, safety and service life

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1st level design

- Design preliminary data on route and region
  - Site category
- Design options
  - Safety factor
  - Functional requirements

Engineering (design) parameters of pipeline (D, t, p, technical requirements for pipes and coating; pipe geometry, etc.)

2nd level design

- Regional background risks evaluation and specification of project indicators of risks at construction stages and
- Probabilistic analysis of initial events leading to critical failures and emergency situations
  - Prediction and modeling of processes of failure accumulation and initiation and development of defects
  - Analysis of stress-deformed condition at accidental effects based on degradation mechanism

- Evaluation of failure probability (analysis of emergency sequences)
- Evaluation of damage
- Confirmatory analysis of operating risks based on a predicted service life
Fig. 5. Overall gas losses with the conditional gas pipeline being broken

\[ T(L, t) = n_k \int_{0}^{L} q_k(x, \tau) M_k(x) d\tau dx \leq [T]. \]  

Here \( t \) – operation time, \( L \) is length of gas pipeline route, \( n_k \) is number of lines, \( q_k(x, \tau) \) is probability of critical failure, \( M_k(x) \) is pipeline breaking gas losses, \([T]\) is allowable level of technological risk. Subscript \( k \) corresponds to each case under consideration.

Assume that the allowable level of technological risk is that applied to the existing pipelines. Then, relationships (2)-(4) can give the following failure rate critical values for high-pressure systems: 0.31 failure per 1000 km per year for second case; 0.16 and 0.23 failure per 1000 km per year for third and fourth cases, respectfully (Fig. 7).

Thus, it is obvious that breakdown gas losses owing to increased number of shut-off valves and adjusting interline ties must be cut down and new type trunk gas pipeline reliability during operation should be enhanced in order to introduce high forward pressure gas transmission technologies in Russia. The pipeline reliability enhancement could be achieved through improved quality and timely diagnostic and repair and renewal operations, corrosion protection system development, toughened quality control for the suppliers, more stringent operating rules control, as well as by employing novel engineering solutions aimed at assuring the gas pipeline design position.
4. CONSTRUCTION OF ARCTIC GAS PIPELINES

In conclusion we shall dwell at greater length on the gas transport projects to move gas from the Yamal peninsula, which lately became particularly urgent. The Ukhta-Torzhok gas pipeline system has been considered as top-priority option to carry gas from the Yamal peninsula. In this case two alternatives are under consideration - pipeline built across and bypassing the Baidaratskaya bay. Besides, construction of an additional section of the Yamal-Yamburg gas pipeline (corridor) is being studied.

The Yamal peninsula gas-condensate fields development needs the gas mains being laid under complicated environmental-and climatic and geocryological conditions. The pipeline sections in question must be laid strictly in one winter season. Special and expensive engineering solutions - gas cooling, complicated interaction with frozen and thawing soils, slope pipeline stability, prevention of pipeline trench washouts, artificial waterways, ravine formation, estimation of a complex of natural and man-caused factors, which are hard to predict, and so on are to be used to ensure stable operation of linear pipeline portion and compressor stations (shops, processing lines, equipment). Special solutions will also be required to minimize negative man-caused ecological effects on local ecological systems.

It is essential that high forward pressure used to move gas from the Yamal peninsula enables not to build intermediate gas compressor stations on section, for instance, Bovanenkovo-Yamburg with resulting substantial decrease in the region’s man-caused load. It should be noted that should a decision to build an aboveground pipeline on the Yamal territory be taken, it might be a possible way to tackle the problem of minimizing the negative man-caused ecological effect. From this viewpoint, the results of ground investigations conducted on the research section built in 1987 in the Northern Solensinsky field area are of particular interest [6]. The research section area has a little more severe climate than the Bovanenkovo field: winter is longer, average annual air temperature being somewhat lower with January-February average temperature being minus 30°C (in Yamal minus 20 - 25°C) and much the same windy and blanket of snow conditions. Comparisons of frozen ground - geological conditions were made based on the geological sections of the research section and one of the field gas pipeline routes at Bovanenkovo. The comparisons showed that these routes are practically the same as regards the soil composition, frozen earth nature and their thermal and mechanical parameters.

Four types of laying gas pipeline were provided for the research section: aboveground pipeline on piles (1.68 km), beam-supported ground-surface pipeline (0.79 km), buried pipeline (1.60 km) and banked pipeline (0.79 km). In this case new engineering solutions were implemented in each section. So, the aboveground section was characterized by being laid as close as possible to earth, low friction coefficient movable supports with heightwise-adjustable girders; anti-heave piles and trapezoidal heat expansion loops with axial load angle optimization. The ground-surface section has one symmetrical double trapezoidal heat expansion loop on surface supports with material "komponor" used to make them. The following engineering solutions were employed to lay the ground-surface section: anti-heave cuts to prevent heaving and floating up, frozen earth belts, anchor support, anchor boards, thermal shields; concrete stream crossing ditch, trench plugs, special drainage systems, etc. for waterway and on slopes.
Some results of the investigations in the course of the research section operation are given below.

The ditch backfilling integrity and prevention of pipeline floating are challenges to laying buried pipelines in frozen ground. These challenges could not be met on the research pipeline section despite some technical improvements aimed at preventing the undesirable processes, posing threat to normal structure operation (erosion, thermokarst, heaving, swamping, etc.). Two years after the pipeline completion it was exposed throughout its entire underground length, here and there being floated up with inter-soil flows of water from melted snow being developed along the pipeline. Special concrete stone bridge plugs and concrete water passage troughs could not prevent trench flows formation.

Construction of the water passages for gas pipelines laid in the permafrost soils turned out to be rather a complicated task.

No direct effect on frozen soils and non-top soils was envisaged by the banked surface-ground pipeline construction technology.

Man-caused loads had no detrimental effect on landscape as regard the gas pipeline from the viewpoint of ecological problems along the entire research section length. It has been found that the aboveground pipeline on special anti-heave piles practically does not respond to soil dynamic processes.

On the whole, the comprehensive investigations performed on the research section demonstrated that the aboveground pipeline laying option is the most reliable one of all engineering solutions considered with the least detrimental effects on the environment.

A detailed comparative assessment of engineering solutions applied to Arctic gas pipelines is necessary.

5. CONCLUSIONS

So, the conclusions may be as follows:

Russia's gas producing industry should develop new fields located primarily in Arctic regions difficult of access and far away from main gas consumers to make up for gas production drop and to boost gas production to the level projected by Russia's energy strategy until 2020. Construction of new gas pipelines needs substantial increase in capital investments and consequently gas transmission intensification becomes particularly urgent.

Application of higher working pressure and aboveground pipeline laying method in Yamal will enable to minimize detrimental man-caused effect on the environment.

The enhanced gas transmission system reliability is a foreground task when passing to a higher working pressure. The task is to be performed by using a new design methodology including two calculation levels. In this case the second calculation level includes the probabilistic safety analysis.

REFERENCES