OPTIMUM TRANSPORTATION OF NATURAL GAS UNDER ARCTIC CONDITIONS

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ABSTRACT

Moving large volumes of natural gas through areas with permafrost presents unusual problems. Current practice in Siberia already incorporates the use of large diameter pipelines operating at high pressures. Large diameter buried pipelines do not reach equilibrium with ground temperatures under normal compressor station spacing. Earlier studies have suggested that the use of refrigerated gas, buried pipelines and low temperature alloys will reduce the impact on the environment, the corrosion of the pipeline, and the cost of moving large volumes of natural gas. Lowering the flowing temperature of the natural gas will increase the capacity of the pipeline by reducing its volumetric flow rate not only by thermal contraction of the gas but also by enhancing the effectiveness of increasing pressure. This non-ideal behavior of the gas is shown by low values of the compressibility factor.

INTRODUCTION

During the 1960's, the discovery of large natural gas deposits in Northern Alaska and the MacKenzie Delta of Canada generated interest in and stimulated research efforts on the economical movement of natural gas under arctic conditions. These activities resulted in a number of significant papers that defined suitable conditions for transporting natural gas in North America at that time.

After extensive environmental protests, which resulted in long delays, the Alaska Pipeline was finally completed from Prudhoe Bay to Valdez, Alaska in June of 1977. Many of the design changes made to mitigate the environmental concerns resulted in massive cost increases over the originally projected costs. These large cost overruns may be one reason that there has been very little interest expressed in constructing arctic gas lines in North America during the ensuing years.

During the 1970's and 1980's, the demand for natural gas in Europe initiated the development of one of the longest pipeline systems in the world to bring gas from Siberia to Europe. The Soviet designs of this period emphasized large diameter pipelines. The Northern Lights Pipeline, a northern part of the system, with sections of 1,420 mm OD. diameter pipe is one of the largest in the world as described by Carson and Stram (1993). During much of the time that these systems were being built, the availability of compressors and pipe was severely restricted by political circumstances. Recent construction of new pipelines in Northern Siberia does not seem to reflect the results from earlier Canadian and American research with respect to buried and refrigerated pipelines.

SCOPE

The exploitation of natural gas deposits under arctic conditions imposes a number of unique problems. In general there are no significant local markets and, except for unusual situations such as those near Norilsk, the need for small or medium sized projects will be very limited. Therefore only very large deposits can be developed and the gas must be moved over long distances. Thus only large systems requiring massive investments will be economically practical.

Extensive engineering and design efforts are justified for projects of this magnitude. Complex processing of the natural gas to eliminate impurities to ensure that it is suitable for long distance transmission is appropriate.

Masaru Hirata, Chairman of the National Pipeline Research Society of Japan has recently proposed the construction of an international trunk pipeline network linking natural gas fields in Central Asia, Southeast Asia, Siberia, and North America with the main markets of Asia, primarily Japan, Korea and China as discussed by Haggin (1994). Although it is only a small part of Mr. Hirata's vast proposal, the line from North America across the Bering Strait, through Eastern Siberia and Sakhalin Island to Japan would be the longest pipeline in the world to be constructed through permafrost conditions.

The design codes in the former Soviet Union and the United States are not the same as described by Aynbinder et al (1994) and Dalton et. al (1994). While the codes produce similar results, for a project of the size proposed by Mr. Hirata involving at least three or four countries, the efforts necessary to reach mutual agreements on specifications would be justified. The usual pressure limit of 7.5 MPa for major gas-transmission lines in the former Soviet Union would need to be waived to achieve optimum pipeline performance.

This particular line from Canada to Japan would have its maximum impact on Northern Alaska and Magadan Oblast. It is approximately 1000 km from Prudhoe Bay to the Bering Strait and at least another 3000 km to Sakhalin Island. The construction of the haul road, communication systems and other necessary facilities to build a major pipeline would aid the development of these sparsely populated areas. Magadan seems to be an ideal location to discuss the design of such a high capacity, long distance pipeline system for service under arctic conditions.

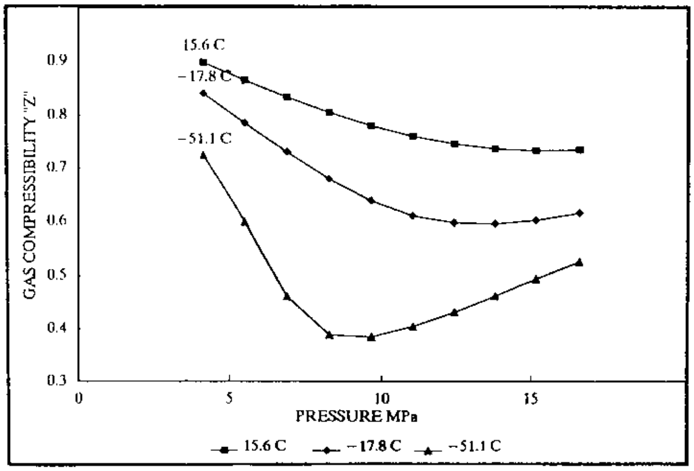
METHODS

After teaching the design of natural gas pipelines for over twenty years using the "Handbook of Natural Gas Engineering" by Katz et. al. (1958), I found that the Coates (1970) article on "Optimum Economic Design of Pipeline Facilities" presented the most easily followed discussion of the design process. A short while later, Walker and Stuchly (1973) presented "Design Problems of Flowing Gas Pipeline Temperature in Permafrost". This paper suggested that refrigeration should be used to keep the natural gas below 0° C in regions with permafrost. Katz and King (1973) showed the physical properties of natural gas that produce significant savings in transportation costs. These papers were presented over twenty years ago. During these intervening years, there has not been any change in the physical behavior of pipelines but there have been important changes in the availability of pipe and compressors. This study will use a single gas composition to evaluate the effects of line size, temperature and pressure on the cost of moving natural gas.

For large capacity pipelines under arctic conditions King (1977) showed that the gas arriving at the next compressor station could arrive at a temperature less than it had entered the pipeline even if its flowing temperature was below ambient conditions. Good insulation would increase this effect. Controlled tests on the large Russian pipelines would be valuable to confirm this behavior.

GAS COMPOSITION

The natural gas used for this study was a 0.6 specific gravity gas composed of 90.9 mol percent methane and 9.1 mol percent ethane. The compressibility factors used in these calculations were calculated using the Hewlett-Packard (1980?) Petroleum Fluids Pak and are shown on Fig. 1.



Compressibility of 0.6 gravity methane ethane mixture. By Hewlett - Packard Petroleum Fluids Pac.

Gas of this composition would not have a two phase region at temperatures above -56° C or at pressures above 6.2 MPa. Using the higher line pressures such as 11 to 8 MPa, richer gases containing more ethane and propane could be moved in single phase conditions but determining the physical properties would be subject to more uncertainty. In fact, it would probably be more economical to move such gases at -51° C than to move the gas used in this study at that temperature. Such gases would have lower compressibility factors. Additional experimental data are required to define the physical properties of these gases at the conditions of interest.

SURFACE PIPELINES

One of the common methods of building pipelines through areas of permafrost has been to construct them on piles to prevent thawing of unstable soils. With suitable overpasses to permit wildlife to pass under the pipeline, such lines have been operated successfully for many years.

The first cases considered will evaluate surface pipelines. An uninsulated natural gas pipeline operated under arctic conditions presents a number of problems. If no refrigeration is used to reduce the temperature of the compressed gas, bare pipe or protective coverings with a high thermal conductivity are desirable to permit the flowing gas to approach air temperatures. Calculations indicate that under still air conditions, a bare 1520 mm diameter pipeline, carrying 127 Mm^3/d of gas 22° C above ambient air temperature, would reach the next compressor station, 50 km away, at approximately 8° C above the ambient air temperatures. Because a pipeline is exposed to wide temperature changes, measures such as expansion joints must be used to reduce the stresses caused by these changes.

The transition temperature for pipe and other metallurgical components that will be installed above ground is controlled by the lowest possible ambient temperature. A value of -62° C was assumed by Walker and Suchly (1973) for Northern Canada (Table 1). Even lower transition temperatures may be justified in parts of Eastern Siberia. Under shut-down conditions with an exposed, pipeline even the gas used in this study would have liquid condensation under such temperatures.

Table 1. Temperature in Permafrost, AIChE Annual Meeting, New Orleans, 1973.

Compressibility Factor			H-P 0.6 Methane Ethane Mixture	
Pressure	15.6° C	-17.8° C	-51.1° C	0.006895
600	0.8979	0.8411	0.724	4.136854
800	0.8651	0.7851	0.599	5.515806
1000	0.8339	0.7298	0.4615	6.894757
1200	0.8052	0.6789	0.3888	8.273708
1400	0.7803	0.6378	0.385	9.65266
1600	0.7601	0.6105	0.405	11.03161
1800	0.7454	0.5973	0.4324	12.41056
2000	0.7363	0.5955	0.4628	13.78951
2200	0.7326	0.6022	0.4945	15.16847
2400	0.7336	0.6148	0.526	16.54742

The effects of wide ambient temperature changes on line capacity would be extreme. The capacity of a 1178 mm internal diameter pipeline would increase 57%, assuming constant compressor power, as the air temperature is reduced from +15.6 to -51.1° C. These two situations are shown in Table 2 as cases 1 and 2. Case 1 was compared with the values shown on the graphs given by Coates (1970) and indicated a reasonable check. This calculation ignores the increase in available power exhibited by a gas combustion turbine with such a reduction in ambient air temperature.

BURIED PIPELINES

All of the buried pipelines considered in cases 3 through 11 are refrigerated. In order to bury pipelines in unstable permafrost, the pipeline must either be extremely well insulated or operated at temperatures below the freezing point of water. In either case natural gas must be cooled after it is compressed, before it is returned to the pipeline. Walker and Stuchly (1973) limited their flowing gas temperatures to -17.8° C because of a limited pipe transition temperature. This is certainly a serious issue. An accident in 1944 at Cleveland, Ohio caused by low temperature brittle failure of the steel in a storage vessel was one of the most serious accidents ever experienced by the natural gas industry as reported by Elliott et. al. Recent advances in metallurgy have enabled manufacturers to reduce transition temperatures at lower costs. Recent estimates from a major pipe supplier indicate that reducing the transition temperature of steel for large orders of 1220 mm pipe from -17.8 to -51.1°C would increase its cost by approximately 3.2%.

This estimate suggests that lower operational costs at lower temperatures might justify the slight additional cost of the pipe designed for lower temperature service. It has been suggested that the availability of suitable valves and fittings for such low temperature service may be more limiting than the cost of suitable line pipe.

The additional cost for insulating the pipeline would also be required at a temperature of -51.1° C to reduce the refrigeration costs associated with heat flowing into the pipeline from the ground. Additional depth of burial, as suggested by Walker and Stuchly (1973) would not be necessary to reduce heat gain in such cases. The rate of change of temperature under shut-down conditions would be much less for an insulated pipeline.

Table 2. Pipeline flow according to Katz equation 7-29 (1) and power of compression according to Katz equation 7-73 (2)

(1) `Q = 0.0011462*To/Po(((P1^2-P2^2)*D^5)/(G*T*L*F*Z))^0.5` (1)

Case	P1	P2	D	T	L	Z	Q	Ratio	Cases
Surface Pipelines									
1	6.895	5.6951	1178	300.0	50	0.88	75,807		
2	6.895	5.5198	1178	233.3	50	0.52	118,894	1.57	2/1
Buried Pipelines									
3	6.895	5.6951	1178	255.6	50	0.74	89,570		
4	6.895	5.6951	1178	222.0	50	0.51	115,657	1.29	4/3
5	6.895	5.6951	1178	288.9	50	0.86	78,151		
6	6.895	5.6951	1489	288.9	50	0.86	140,474	1.80	6/5
7	11.03	8.8867	1178	288.9	50	0.78	138,458	1.77	7/5
8	6.895	5.6951	1489	222.0	50	0.51	208,093	1.80	8/4
9	11.03	8.4892	1178	222.0	50	0.39	239,976	2.07	9/4
10	6.895	5.6951	1178	222.0	52.3	0.51	113,129		
11	11.03	8.1526	1178	222.0	250.4	0.39	113,129		

(2) `HP = Q*0.0000856*(k/k-1)*T*((P2/P1)^(Z*(k - 1)/k) - 1)` (1)

Case	P1	P2	k	T	Z	Q	HP	Act. HP
Surface Pipelines								
1	5.661	6.9288	1.28	296.8	0.87	75,807	18107	22634
2	5.486	6.929	1.33	230.0	0.62	118,894	18107	22634
Buried Pipelines								
3	5.661	6.929	1.31	255.6	0.77	89,570	16299	20374
4	5.661	6.929	1.33	222.0	0.59	115,657	13955	17444
5	5.661	6.929	1.31	288.9	0.86	78,151	17992	22490
6	5.661	6.929	1.28	288.9	0.86	140,474	32289	40361
7	8.853	11.066	1.28	288.9	0.79	138,458	32289	40361
8	5.661	6.929	1.33	222.0	0.59	208,093	25109	31386
9	8.455	11.066	1.33	222.0	0.39	239,976	25109	31387
10	5.661	6.929	1.33	222.0	0.59	113,129	13650	17063
11	8.119	11.066	1.33	222.0	0.39	113,129	13650	17063
Composition of Methane Ethane Mixture								
	0.909	0.555	0.504	0.09	1.046	0.1	0.599681	

(1) equations are written for Lotus 123 program.

Note: To = temperature base K = 288.15; Po = pressure base kPa = 101.325; P1 = initial pressure, MPa; P2 = final pressure, MPa; D = internal diameter, mm; G = gas gravity (air = 1) = 0.6 ; T = flowing temperature in K; L = line length in km; Z = average compressibility; F = moody friction factor = 0.008; HP = power in Kw; Actual power = 1.25 (calculated); k = Ratio of heat capacities Cp/Cv

Cases 3 and 4 consider the change in capacity resulting from lowering the operating temperature. Case 3 in Table 2 is for buried 1220 mm pipeline operating at -17.8° C. Its capacity would increase 29% as its operating temperature is reduced from -17.8 to -51.1° C as shown for case 4. The required compressor power in case 4 would be reduced 13% while handling the larger volume of gas. The added power needed for the lower temperature refrigeration in case 4 would roughly be balanced by the savings in compression.

Cases 5, 6 and 7 compare the results of increasing the size of the pipe or increasing its operating pressure at 15.8° C. Cases 5 versus 6 shows that increasing the outside diameter of the pipe to 1524 mm increases the pipeline's capacity by approximately 80%. Case . uses the same amount of steel to increase the operating pressure of the line from 6.9 to 11 MPa. Using the same compressor power the capacity of the high pressure line is 77% higher than the lower pressure line of case 5.

Cases 4, 8 and 9 compare the same situation at - 51.1° C. Cases 4 versus 8 show the same 80 % increase in pipeline capacity by increasing the diameter of the line. However, increasing the operating pressure of the line to 11 MPa results in an increase in the line capacity of over 107% at the same compressor power as shown for cases 4 versus 9.

When the line capacity is already 113.1 Mm^3/d, an increase in the spacing between compressor stations may be of more interest than just increasing the capacity of the pipeline. For the 1220 mm pipeline operating at -51.1°C with an inlet pressure of 6.895 MPa and a discharge pressure of 5.6951 MPa, a compressor station spacing of 52.3 km is required to handle 113.1 Mm^3/d as shown for case 10. Keeping the compressor power fixed and increasing the operating line pressure to 11 MPa will increase the compressor station spacing to 250.4 km as shown for case 11. This increase in station spacing will reduce the installed compressor power by 79 %. Preliminary estimates indicate that this saving in compressors would almost be enough to pay for the increased cost of the higher pressure pipeline. The 79% reduction in compressor fuel is almost enough to pay for the increased cost of the pipeline as well. These combined saving more than justify increasing the operating pressure of the pipeline at -51.1°C. The capacity of such a pipeline could easily be increased by adding additional compressor stations.

Calculations for case 11 show that the power required to operate the refrigeration equipment to cool the compressed gas and to remove the heat flowing into a well insulated pipeline would be approximately 80% of the power required for the compression of the gas.

CONCLUSIONS

Significant increase in the capacity of large high volume pipelines can be achieved by lowering the operating temperature from -17.8 to -51.1° C.

Increasing the pipe diameter is the more effective use of steel at 15.6° C, while increasing the operating pressure on the line is the more effective use of steel at -51.1° C. This effect is a result of the much steeper rate of change in the compressibility of the natural gas as a function of pressure at -51.1° C. This change in slope with temperature can be seen on Figure 1. Although the temperatures are still above the critical temperature of the system, the compressed gas is beginning to exhibit liquid like behavior.

The use of low temperatures and higher than normal transmission pressures appears to be economically attractive under permafrost conditions.

The smaller diameter pipeline will expose a smaller area to corrosion, reduce the heat gain by the pipe, reduce the buoyancy of the line and reduce the stress on the line caused by soil movements. Even in areas with extensive permafrost there are areas under permanent streams and lakes where all the soil is not frozen. In such areas the placement of a large diameter refrigerated pipeline in non-frozen soil could cause frost heave. The use of more insulation in such areas may be required.

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