Production potential of the Mallik field reservoir

D. Khairkhah¹, M. Pooladi-Darvish¹, P.R. Bishnoi¹, T.S. Collett², and S.R. Dallimore³

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Abstract: Immense volumes of naturally occurring gas hydrate in different parts of the world, onshore and offshore, have encouraged the belief that gas hydrate in the next century may become a viable energy resource. Various issues need to be resolved to convert gas hydrate from an energy resource to an energy reserve of real commercial value. The production capability of a gas hydrate reservoir and the gas production technique that could be utilized should be addressed through geological and petrophysical studies, well-production tests and reservoir simulation. To make the simulation of practical value, the controlling mechanisms of fluid flow, kinetics, and heat transfer should be incorporated in the model.

The Mallik gas hydrate accumulation in the Mackenzie Delta has exhibited promising potential to be considered a gas reserve through the assessments made of the Mallik L-38 and 2L-38 wells. The data available from both wells and the results of production tests in JAPEX/JNOC/GSC Mallik L-38 gas hydrate research well accommodate basic requirements for comprehensive modelling of the reservoir and production of gas from the in situ gas hydrate through various methods.

Résumé : L'immense volume d'hydrates de gaz naturels présent sur terre et au large dans diverses parties du globe conforte les affirmations selon lesquelles les hydrates de gaz pourraient devenir une source d'énergie rentable au XXI^e siècle. Divers problèmes devront être résolus pour faire en sorte que les hydrates de gaz deviennent une source d'énergie à valeur commerciale réelle. La capacité de production des réservoirs d'hydrates de gaz et les techniques de production de gaz susceptibles d'être utilisées devront être définies essentiellement par des études géologiques et pétrophysiques, des essais de production et une simulation des réservoirs. Pour que la simulation soit utilisable dans la pratique, les mécanismes contrôlant l'écoulement des fluides, la cinétique et le transfert de chaleur devront tous être incorporés au modèle.

Dans le delta du Mackenzie, les estimations effectuées dans les puits Mallik L-38 et 2L-38 ont révélé que l'accumulation d'hydrates de gaz de Mallik montre un potentiel prometteur de devenir une réserve de gaz. Les données recueillies aux deux puits et les résultats des essais de production effectuées au puits de recherche sur les hydrates de gaz JAPEX/JNOC/GSC Mallik L-38 constituent une base suffisante pour la modélisation globale du réservoir et la production de gaz à partir des hydrates de gaz en place en faisant appel à diverses méthodes.

¹ University of Calgary, 2500 University Drive N.W., Calgary, Alberta, Canada T2N 1N4

² United States Geological Survey, Denver Federal Center, Box 25046, MS-939, Denver, Colorado 80225, U.S.A.

³ Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario, Canada K1A 0E8

INTRODUCTION

Gas hydrate deposits are crystalline solids, consisting of natural gas and water, which, if under suitable pressure conditions, are stable at temperatures above and below the freezing point of water (Fig. 1). Gas-to-solid volumetric ratio for gas hydrate can be as large as 170 (Katz et al., 1959) demonstrating that gas-hydrate-bearing reservoirs can have gas reserves several times more than if the same reservoir contained only free gas.

In most cases, only two structures for gas hydrate are known to exist in nature. Gas hydrate in most reservoirs is likely to be of Structure I if only methane exists. Structure II may exist if other gas constituents like propane are present. The amount of gas contained in the clathrate crystal does not generally depend on the structure type. In both Structure I and II gas hydrate forms, if all cavities are occupied, the maximum gas concentration of about 15% by mole will occur in the gas hydrate phase. It should be noted that the presence of Structure II gas hydrate lowers the dissociation pressure which enhances the stability of gas hydrate and accommodates a wider spectrum of reservoir conditions for the existence of gas hydrate.

Typical gas hydrate pressure-temperature phase diagrams for various gas compositions are presented in Figures 1 and 2. They show that depending on pressure and temperature of the reservoir, different combinations of gas hydrate, free gas, ice, and water can occur and the composition of the gas within the clathrate structure has a pronounced effect on the conditions of gas hydrate formation. Gas composition, permafrost depth, geothermal gradient, and pore-water salinity have definite effects on the stability of gas hydrate in onshore permafrost areas (Collett, 1993). Increase in pore-water salinity lowers the temperature of gas hydrate formation by about 0.06°C for each part per thousand (ppt) of salt, which results in reduction of thickness of the gas hydrate stability zone.

Due to the complex nature of gas hydrate formation in porous media, it is expected that numerous geological, petrophysical, and physical parameters play their respective roles in the formation of gas hydrate in nature. Moisture saturation, gas-water contact area, and capillary radii of the pores are known to influence gas hydrate formation (Makogon, 1981). For example, increases in gas hydrate formation pressures are observed due to capillary effects in porous media (Clarke et al., in press).

As previously indicated, gas hydrate occurs in sedimentary basins under conditions of pressure and temperature present in permafrost regions and beneath the sea in outer continental margins (Collett, 1998). Because gas hydrate deposits are widespread in permafrost regions and in offshore marine sediments, they may be a potential energy resource. The role that gas hydrate deposits will play in contributing to the world's energy requirements will depend ultimately on the availability of sufficient gas hydrate resources and the cost to extract them. Yet considerable uncertainty and disagreement prevails concerning the world's gas hydrate resources. Even with the confirmation that gas hydrate may exist in considerable volumes, significant technical issues need to be resolved before gas hydrate can be considered a viable energy reserve. Even though gas hydrate deposits are known to occur in numerous marine and Arctic settings, little is known about the technology necessary to produce gas from gas hydrate.

With the drilling of the JAPEX/JNOC/GSC Mallik 2L-38 gas hydrate research well, the Mallik gas hydrate accumulation in the Mackenzie Delta of northern Canada has become one of the most studied gas hydrate occurrences in the world.



Figure 1. Methane hydrate phase diagram (modified from Katz et al., 1959).



Figure 2. Hydrate phase diagram for various gas chemistries (modified from Katz et al., 1959).

The Mallik gas hydrate accumulation exhibits numerous geological characteristics that are believed to be important for the successful production of gas hydrate. For example, the Mallik gas hydrate accumulation contains a relatively thick, highly concentrated gas-hydrate-bearing sedimentary section (Collett et al., 1999b). The Mallik gas hydrate accumulation has also been determined to be underlain by free gas, which may be critical to the future energy resource potential of this hydrocarbon accumulation.

Because of the historical gas hydrate research focus on the Mallik area, a wealth of scientific and engineering data has been compiled regarding the Mallik gas hydrate accumulation. Of particular interest are the results of the formation production tests conducted in the Mallik L-38 well drilled in 1972 by Imperial Oil Limited (Bily and Dick, 1974; Collett and Dallimore, 1998). The combination of the recently acquired geological and engineering data from the Mallik 2L-38 gas hydrate research well and the industry-acquired gas hydrate production test data from the Mallik L-38 well provide us with the unprecedented opportunity to evaluate the potential production.

The primary objectives of this paper are to review the production technology needed to extract gas hydrate, to conduct a preliminary assessment of the available geological and engineering data from the Mallik area which pertain to the resource potential of the Mallik gas hydrate accumulation, and to present general aspects of gas production simulation for gas hydrate reservoirs. The paper begins with a historical review of proposed gas hydrate production technology and an analysis of the production history of the Messoyakha gas hydrate field in northern Russia. The next section of the paper contains an assessment of the available geological and engineering data from the Mallik L-38 and 2L-38 wells. The last two sections of the paper deal with an overview of the kinetic, thermodynamic, and flow equations that govern gas hydrate dissociation in porous media. The paper concludes with a review of the information needed to assess the production potential of the Mallik gas hydrate accumulation.

GAS PRODUCTION FROM GAS HYDRATE RESERVOIRS

Information from numerous international gas hydrate studies indicate that the volume of gas in the gas hydrate accumulations of the world are so immense that they can be considered a new potential source of energy, likely exceeding the volume of known conventional natural gas reserves of the world (Collett, 1998). Most of the existing gas hydrate resource assessments do not address the problem of gas hydrate recoverability. In general, proposed methods of gas recovery from gas hydrate (Fig. 3) commonly deal with dissociating or 'melting' in situ gas hydrate by heating the reservoir beyond hydrate formation temperatures, by decreasing the reservoir pressure below gas hydrate equilibrium, or by injecting an inhibitor, such as methanol or glycol, into the reservoir to decrease gas hydrate stability conditions. In the following section of this report we review some of the methods that have been proposed to extract gas from gas hydrate.



Figure 3. Schematic of proposed gas hydrate extraction methods.

Production methods

Gas hydrate deposits are solid crystalline substances, which must be converted to free gas before they can be extracted. This conversion of the solid methane hydrate to free gas and water can take place as:

$$(CH_4 \cdot 6H_2O)_{solid} \rightarrow (CH_4)_{gas} + 6(H_2O)$$
(1)

The above phase change requires 10–20 kcal of heat energy for each mole of methane gas produced (Holder and Angert, 1982). Although the energy required for gas hydrate dissociation is about 10% of its heating value, the severe environmental conditions of gas hydrate reservoirs and the production method employed might cause high energy losses to the surrounding formation, resulting in low energy efficiency. The production techniques that have been considered for gas-hydrate-bearing reservoirs have been schematically presented in Figure 3: 1) thermal stimulation, 2) pressure reduction, and 3) inhibitor injection.

Thermal stimulation

Thermal stimulation can be performed either through surface heating (injection of hot fluids including water, brine, and/or steam from the ground surface) or downhole in situ heating (Kamath, 1998). First-order thermal stimulation computer models (incorporating heat and mass balance) have been developed to evaluate gas hydrate production from hot water and steam floods, which have shown that gas can be produced from gas hydrate at sufficient rates to make it a technically recoverable resource. However, the economic cost associated with these types of enhanced gas recovery techniques would be prohibitive. For example, heavy-oil-related hot water injection projects often require the ability to handle very large volumes of injected and coproduced fluids. In addition, gas hydrate production methods that rely on the injection of hot fluids from the surface may be hampered by substantial downhole heat loss into the formation overlying the targeted gas-hydrate-bearing formation. Thermal injection stimulation requires the establishment of reliable flow paths within the formation to allow the injection of fluids into the gashydrate-bearing sediments. Fracture stimulation may be required to establish the required flow paths in gas-hydratebearing formations, however, the sedimentary rocks that host many of the known gas hydrate accumulations may not have the mechanical strength to allow the generation of significant flow paths. During the initial phases of production from highly concentrated gas hydrate accumulations, heat transfer into the formation is controlled by only conductive processes, but after some amount of gas hydrate dissociation and increased fluid flow, heat transfer into the formation will be enhanced by convective processes. Laboratory studies and computer simulations have shown that hot-brine injection, relative to simple hot-water injection, is characterized by more favourable results. In addition to the thermal effect of the heated brine, the brine acts as a gas hydrate inhibitor, reducing gas hydrate dissociation temperatures. Gas hydrate brine stimulation would also be characterized by less heat loss and better thermal efficiency (Kamath, 1998). It has also been shown that cyclic water or brine injection is favoured more at the start of production, but when flow paths between injecting and producing wells are established, continuous injection might be more promising. It should also be noted that water loading in wells might significantly hinder the flow of gas to the surface.

In downhole heating methods, the techniques that might be employed include downhole in situ combustion, radio frequency–electromagnetic heating, downhole electrical heating, and microwave heating. Our current assessments of these methods are mostly conceptual and speculative, although they may be viable. Comprehensive modelling and experimental work is needed for better appreciation and assessment of these techniques.

Pressure reduction

In gas hydrate depressurization methods, the sensible heat of rock matrix, gas hydrate, and excess water or gas provides the energy required for dissociation. Consequently, a temperature gradient is established between the gas-hydrate-bearing sediments and the surrounding media which accommodates the flow of heat to the gas-hydrate-bearing sediments. Continuous gas production from gas hydrate reservoirs, accompanied by reduction in reservoir pressure, will maintain the heat flow and the required temperature gradient. Depressurization has been used in the Messoyakha free-gas–gas-hydrate reservoir since 1969 (discussed in more detail later in this paper). Gas hydrate deposits have contributed to the total gas production from this reservoir but the volume of gas produced from the gas hydrate in the Messoyakha field is uncertain (Collett and Ginsburg, 1998).

Among the various techniques for production of natural gas from in situ gas hydrate, the most economically promising method is considered to be the depressurization scheme. However, extraction of methane by depressurization may be hampered by the formation of ice and/or the reformation of gas hydrate due to the endothermic nature of gas hydrate dissociation; establishing reliable flow paths within the formation may also require fracture stimulation. It also appears that the presence of free gas, in conjunction with gas hydrate, is essential for establishing and maintaining extraction by depressurization production. Similar to other proposed gas hydrate extraction schemes, large volumes of water will probably be produced which will require facilities for surface-water handling and also artificial lifting of wells if natural gas flow cannot be sustained.

Inhibitor injection

Inhibitor injection causes the decomposition of gas hydrate by shifting its thermodynamic equilibrium. Inhibitors reduce the temperature of gas hydrate decomposition, increase temperature gradient, and produce higher energy efficiency ratios (Kamath, 1998). However, their application is limited to small volumes due to the high cost of inhibitors.

It should be noted that combinations of the above methods might prove advantageous based on the characteristics of a given gas hydrate accumulation. In the Messoyakha reservoir, gas hydrate inhibitors (methanol and calcium chloride) were circulated in the wells while depressurization methods were applied to the reservoir. The inhibitor prevented plugging of flow channels and caused the gas production rates to be increased by a factor of one to six (Kamath, 1998).

Messoyakha gas hydrate reservoir

In the 1960s, gas hydrate deposits gained importance when they were discovered in the West Siberian Basin of the former Soviet Union (Makogon, 1981). It is generally accepted that the first practical gas production from a gas hydrate accumulation was in the West Siberian Messoyakha field in the 1970s. In subsequent years, an increasing number of direct

Table 1. Geological	and	reservoir	engineering	data
from the Messoyakha	field	in the We	est Siberian B	asin.

Thickness of permafrost	450 m		
Pay-zone area	12.5 km x 19 km		
Total thickness of the pay zone	84 m		
Effective thickness	25 m		
Hydrate Saturation	40% at the top of hydrate zone 20% at the bottom of hydrate zone		
Porosity	16–38% (average 25%)		
Permeability	10–1000 mD (average 125 mD)		
Depth of pay zone	730 m		
Depth of initial water contact (for gas hydrate and free gas)	850 m		
Residual water saturation	29–50%		
Water salt content	Up to 1.5%		
Initial pressure	7.8 MPa		
Initial gas composition	$\begin{array}{c} CO_2 \\ N_2 \\ C_1 \\ C_2 \\ C_3^+ \end{array}$	0.5% 0.7% 98.6% 0.1% 0.1%	
Lithology	Mainly shale and sandstone		
Initial temperature	 8°C at the top of the formation 12°C at the bottom of the formation 10°C at the boundary between gas hydrate and free gas 		

and indirect observations of the presence and role of gas hydrate in the Messoyakha field were compiled (Collett and Ginsburg, 1998).

The Messoyakha field is the only gas hydrate reservoir with actual sustained gas production inferred to be directly from gas hydrate. The field is located in the permafrost region of the Yenisei-Khatung Trough in northeastern part of western Siberia, some 250 km west of Noril'sk. Production data and other pertinent geological information (Table 1) have been used to document the presence of gas hydrate within the upper part of the Messoyakha field (Makogon, 1981). It has also been suggested that the production history of the Messoyakha field demonstrates that gas hydrate deposits are an immediate producible source of natural gas and that production can be started and maintained by conventional methods. Long-term production from the gas hydrate part of the Messoyakha field is presumed to have been achieved by the simple depressurization scheme (Fig. 4). As production began from the lower free-gas portion of the Messoyakha field in 1969, the measured reservoir pressures followed predicted decline relations; however, by 1971 the reservoir pressures began to deviate from expected values. This deviation has been attributed to the liberation of free gas from dissociating gas hydrate.



Figure 4. Production history of the Messoyakha field in the West Siberian Basin (modified from Makogon, 1997).

The seventeen-year production history of the Messoyakha field has been divided into five stages (Fig. 4). During stage A, from 1969 to 1971, the reservoir pressure did not fall below gas hydrate stability conditions and gas production was only from the deeper free-gas part of the field. During stage B, from 1971 to 1975, the actual reservoir pressures exceeded predicted reservoir pressures. This departure marked the start of gas hydrate dissociation and gas production from the gas hydrate part of the field. From 1976 to 1977, designated here 'stage C', the volume of gas withdrawn from the reservoir was equal to the amount of gas liberated from the dissociating gas hydrate. During stage D. from 1978 to 1981. production from the Messoyakha field was slowed and eventually terminated. The reservoir pressures began to rise as the gas hydrate continued to dissociate. Since 1982, stage E, there has only been modest production from the Messoyakha field. During this period the amount of gas liberated from the gas hydrate has been equal to the amount of gas produced.

Throughout the production history of the Messoyakha field it is estimated that about 36% (about $5x10^9 \text{ m}^3$) of the gas withdrawn from the field has come from the gas hydrate (Makogon, 1981). Recently, however, several studies suggest that gas hydrate may not be significantly contributing to gas production in the Messoyakha field (Collett and Ginsburg, 1998).

To confirm the presence of gas hydrate within the upper part of the Messoyakha field, a series of gas hydrate inhibitor injection tests were conducted (Collett and Ginsburg, 1998). During these tests, substances, such as methanol and calcium chloride, which destabilize and prevent the formation of gas hydrate, were injected into the suspected gas-hydrate-bearing portion of the Messoyakha field. Most of these tests resulted in dramatic increases in production rates, which was attributed to the dissociation of the in situ gas hydrate. Table 2
 Table 2. Effect of methanol injection on gas production rates (Makogon, 1981).

WELL A		WELL B		
<i>Q_ь</i> (1000 m³/day)	Q_a / Q_b	<i>Q_ь</i> (1000 m³/day)	Q _a / Q _b	
25 50 100 150 200	2 2 1.5 1.3 1.25	5 10 25 50	10 10 5 4	
Q_{b} : gas flow rate before methanol injection Q_{a} : gas flow rate after methanol injection				

shows the results of methanol injection on gas hydrate decomposition and gas flow from two wells in the Messoyakha field. It has been interpreted that the injection of methanol prevented plugging of flow channels due to reformation of gas hydrate and ice, which had a dramatic effect on the gas production from these wells.

MALLIK GAS HYDRATE ACCUMULATION

As described in Collett et al. (1999a), the Mallik gas hydrate accumulation is located on Richards Island, in the outer portion of the Mackenzie Delta of Canada. The Mallik gas hydrate accumulation appears to be laterally continuous and is estimated to cover an area of 51 km². Seismic mapping and analysis of log data from the Mallik L-38 and 2L-38 wells, reveals that gas hydrate is highly concentrated along the crest

of the Mallik anticline. Well-log data suggest that the Mallik L-38 well, drilled by Imperial Oil Limited, appears to have penetrated numerous gas-hydrate-bearing layers in the crest of the Mallik anticline and several closed-chamber production tests confirm the presence of gas-hydrate-bearing and free-gas-bearing zones in the Mallik L-38 well (Bily and Dick, 1974; Collett and Dallimore, 1998). In 1998, the JNOC/JAPEX/GSC Mallik 2L-38 research well drilled and cored the Mallik gas hydrate accumulation. Extensive research coring and geophysical well logging were conducted in Mallik 2L-38. The extensive body of scientific and engineering data collected from both Mallik wells, along with the closed-chamber production tests conducted in the Mallik L-38 well, offers the opportunity to assess the potential production characteristics of the Mallik gas hydrate accumulation. In the following section of this paper, we have reviewed the scientific and engineering data from the Mallik L-38 and 2L-38 wells needed to assess the Mallik gas hydrate accumulation.

Mallik L-38 well

The Mallik L-38 well was drilled by Imperial Oil Limited in 1972 to a total depth of 2524 m. The Mallik L-38 well is believed to have encountered at least ten significant gashydrate-bearing stratigraphic units (Fig. 5) (Dallimore and Collett, 1998). Bily and Dick (1974) concluded that the gashydrate-bearing units in the Mallik L-38 well contained significant volumes of gas hydrate. However, no attempt was made to quantify the amount of gas hydrate or associated free gas that may have been trapped within the log-inferred gas hydrate occurrences. Analysis of downhole logs and the results of formation production testing by Collett and Dallimore (1998) has confirmed the occurrence of at least ten gashydrate-bearing stratigraphic units in the Mallik L-38 well. Downhole log data and formation production tests also infer but do not prove the occurrence of a free-gas-bearing unit at the predicted base of the gas hydrate stability zone in the Mallik L-38 well. Collett and Dallimore (1998) used the available downhole density-log data from the Mallik L-38 well to calculate accurate sediment porosity in the well-log-inferred gas-hydrate-bearing reservoirs. The corrected densitylog-derived sediment porosity for the gas-hydrate-bearing units in the Mallik L-38 well average 35%. Collett and Dallimore (1998) also determined that the gas hydrate saturations within the gas-hydrate-bearing units of the Mallik L-38 well, calculated from the standard Archie relation, average 67%. They determined that if the gas hydrate deposit at Mallik was laterally continuous within a 1 km² area surrounding the Mallik L-38 well, the gas-hydrate-bearing stratigraphic units would cumulatively contain $4284 \times 10^6 \text{ m}^3$ of gas.

The possibility of free gas in contact with gas hydrate occurrences is an important consideration in terms of designing possible extraction scenarios and also in terms of assessing drilling hazards. Bily and Dick (1974) originally interpreted the presence of free gas in contact with gas hydrate on the basis of spontaneous-potential (from the DIL (dual induction-laterolog)) well-log responses within several intervals. They also speculated that rapid pressure responses during a production test (production test 1: 1104–1107 m; all depths were measured from the kelly bushing: 8.99 m) within a suspected free-gas unit are evidence of highly permeable free-gas-bearing sediments. Collett and Dallimore (1998) were not able to confirm the occurrence of the free-gasbearing units delineated by Bily and Dick (1974) because of insufficient data. However, the analyses of log data from the Mallik 2L-38 well have confirmed the occurrence of a



Figure 5. Well display of the Mallik L-38 and Mallik 2L-38 wells, showing the distribution of gas hydrate, free gas, and the depths of the completed formation production tests in the Mallik L-38 well.

Table 3. Results of flow test, test 1 (1104–1107 m).

		Well head pressure	Bottom hole pressure at 1086 m		
Test	Duration	(final)	(initial)	(final)	
1 st flow 2 nd flow	5 min 5 min	4.9 MPa (710 psi) 6.7 MPa (975 psi)	8.8 MPa (1276 psi) 9.3 MPa (1347 psi)	9.1 MPa (1319 psi) 9.4 MPa (1360 psi)	

Table 4. Results of flow test, test 2 (924–927 m).

		Well head pressure	Bottom hole pressure at 920 m (3019 ft.)		
Test Duration		(final)	(initial)	(final)	
1 st flow 2 nd flow	5 min 31 min	0.34 MPa (50 psi) 0.41 MPa (60 psi)	1.3 MPa (191 psi) 1.8 MPa (260 psi)	1.6 MPa (231 psi) 1.85 MPa (268 psi)	

relatively thin free-gas zone (1108.4–1109.8 m) at the base of the deepest downhole-log-inferred gas hydrate at the Mallik drill site (Collett et al., 1999b).

Mallik L-38 formation production tests

Two closed-chamber formation production tests were conducted within the log-inferred gas-hydrate-bearing and freegas-bearing interval (819.1–1111.3 m) of the Mallik L-38 well. This type of test is different from conventional openhole drill-stem tests (DST) in that in the closed-chamber test, the well is closed at the surface when flowing, and open at the surface only when shut in at the formation (Alexander, 1977). In closed-chamber testing the rate of fluid influx from the formation can be estimated by analyzing the variation of wellhead pressures during different phases of the test. The various rates of flow that can be measured make this method of testing similar to that of a multi-flow-rate well test. Reviewed below are the main features of the closed-chamber test (CCT) conducted in the Mallik L-38 well.

Test 1

The test interval was 1104–1107 m (perforated interval). Based on downhole log analysis, Bily and Dick (1974) interpreted this interval to contain a free-gas zone 'sandwiched' between a gas hydrate layer above and water layer below.

Observations

This test consisted of two flow periods (Table 3). During flow 1 and flow 2, gas flowed into the drill stem causing a rapid buildup of pressure at the surface in 5 min. Also noted was a rapid downhole pressure increase during the final shut-in period, reaching 11.1 MPa (1607 psi) in 367 min. On blow-down of the drill pipe, methane gas was recovered (195 m of gassy mud was recovered).

Conclusion

Based on the above observations, Bily and Dick (1974) concluded that the test interval contained a permeable free-gasbearing zone, with the potential of significant gas production rates. Imperial Oil Limited (IOL) engineers calculated a gas flow rate from this interval of about 93 000 m³/day of gas. However, since these observations are mainly concerned with the initial flow rate of the well, we believe the full extent of the reservoir and practical potential of the well needs to be evaluated through production tests of longer duration.

Test 2

The test interval was 924–927 m (perforated interval). Based on downhole log analysis, Bily and Dick (1974) interpreted this interval to contain gas hydrate.

Observations

The test consisted of two flow periods (Table 4). During the first flow period, the pressure at the surface reached 0.34 MPa (50 psi) at the end of a 5 min initial flow period. During the second flow period of 30 min, the surface pressure increased slightly to 0.41 MPa (60 psi). On blowdown of the drill pipe, methane gas was recovered along with 91 m of mud in the drill pipe.

Conclusion

Based on the above observations, Bily and Dick (1974) concluded that this tested interval exhibited very low permeabilities that may be an indication of gas hydrate filling the pore spaces of the host sediment. Imperial Oil Limited engineers calculated a gas flow rate from this interval of about 7000 m³/day of gas.

Mallik 2L-38 well

In late March of 1998, the JAPEX/JNOC/GSC Mallik 2L-38 gas hydrate research well was completed in the Mackenzie Delta (Dallimore et al., 1999). The Mallik 2L-38 gas hydrate research well was drilled near the site of the existing Mallik L-38 well. Downhole electrical resistivity and acoustic transit-time (both compressional and shear-wave) logs from the Mallik 2L-38 well confirm the occurrence of in situ gas hydrate at the Mallik drill site within the subsurface depth interval between 897.3 m and 1108.4 m (Fig. 5) (all depths were measured from kelly bushing [8.31 m above sea level]). Downhole log data also confirm the occurrence of a relatively thin free-gas zone (1108.4-1109.8 m) at the base of the deepest downhole-log-inferred gas hydrate in the Mallik 2L-38 well. Collett et al. (1999b) used a three component densityporosity equation to calculate accurate downhole-logderived porosities from the Mallik 2L-38 well. The corrected density-log-derived sediment porosities for the gas-hydratebearing units in the Mallik 2L-38 well average 34%. Gas hydrate saturations within the gas-hydrate-bearing units of the Mallik 2L-38 well, calculated from the standard Archie relation, average 64%. Collett et al. (1999b) also determined that if the gas hydrate deposit at Mallik was laterally continuous within a 1 km² area surrounding the Mallik 2L-38 well, the gas-hydrate-bearing stratigraphic units would cumulatively contain 4150 x 10^6 m³ of gas, which is similar to the amount calculated for the Mallik L-38 well. No production test was conducted in the Mallik 2L-38 well.

GAS HYDRATE PRODUCTION MODELLING

Mathematical modelling of gas production from gashydrate-bearing reservoirs started mainly on the basis of the depressurization scheme (Holder and Angert, 1982) and heat balance for thermal stimulation process (Kamath and Godbole, 1985; Bayles et al., 1986). Subsequent models included convection and conduction in the heat balance equation (Selim and Sloan, 1990) and single-phase Darcy law for gas flow. More recent models (Yousif et al., 1991; Masuda, 1996) have incorporated the Kim-Bishnoi kinetic equation (Kim et al., 1987) in the simulation of dissociation process of gas hydrate.

A comprehensive 'three-mechanism' mathematical model for gas production from gas hydrate needs to include the three mechanisms discussed below.

Two-phase flow through porous media

Dissociation of gas hydrate results in water and methane, which flow toward the well bore (Fig. 6). Darcy's equations for gas and water and the equations of continuity for each phase describe the flow of this two-phase mixture:

$$\rho_w \boldsymbol{u}_w = -\frac{\rho_w K k_{rw}}{\mu_w} \nabla P_w \tag{2}$$



Figure 6. Schematic diagram of two-phase flow, pressure profile, and fluid production from the dissociation of gas hydrate in porous media by the depressurization scheme. T_s =decomposing surface temperature; p^* = interface pressure; u_g =Darcy velocity of gas; q_g =flow of gas; u_w =Darcy velocity of water; q_w =flow of water; S_g =saturation of gas; S_w =saturation of water; S_h =saturation of gas hydrate; P_{wf} =well flowing bottom hole pressure; P=resevoir pressure; P_e =equilibrium pressure.

where ρ_w is density of water (kg/m³), \boldsymbol{u}_w is Darcy velocity of water (m/s), K is absolute permeability (m²), k_{rw} is relative permeability to water, μ_w is viscosity of water (Pa·s), and P_w is pressure of water.

$$\rho_g \boldsymbol{u}_g = -\frac{\rho_g \, K k_{rg}}{\mu_g} \, \nabla P_g \tag{3}$$

where ρ_g is density of gas (kg/m³), \boldsymbol{u}_g is Darcy velocity of gas (m/s), k_{rg} is relative permeability to gas, μ_g is viscosity of gas (Pa·s), and P_g is pressure of gas (Pa).

$$-\nabla \cdot (\rho_w \boldsymbol{u}_w) + \dot{\boldsymbol{m}}_w - \rho_w q_w = \phi \frac{\partial}{\partial t} (\rho_w S_w)$$
⁽⁴⁾

where \dot{m}_w is generation rate of water (kg/s) per unit volume of a porous medium, q_w is flow rate of water (m³/s) per unit volume of porous media, ϕ is original porosity (fraction), and S_w is saturation of water.

$$-\nabla \cdot (\rho_g \boldsymbol{u}_g) + \dot{\boldsymbol{m}}_g - \rho_g \boldsymbol{q}_g = \phi \frac{\partial}{\partial t} (\rho_g \boldsymbol{S}_g) \qquad (5)$$

where \dot{m}_g is generation rate of gas (kg/s) per unit volume of a porous medium, q_g is flow rate of gas (m³/s) per unit volume of porous media, \hat{S}_g is saturation of gas, and t is time (s).

$$S_g + S_w + S_h = 1 \tag{6}$$

where S_{g} is gas saturation, and S_{h} is saturation of gas hydrate.

The capillary pressure (P_c) curve (or equation) should be used to determine the pressure difference between gas and water:

$$P_c = P_g - P_w = \sigma_{wg} \cdot \cos\theta_c \cdot J(S^*) \sqrt{\frac{\phi_{wg}}{K}}$$
(7)

where σ_{wg} is interfacial tension between gas and water (N/m), θ_c is the contact angle, J is the normalizing function, S^{*} is normalized water saturation, \emptyset_{wg} is effective porosity to the flow of gas and water (fraction) where:

$$S^* = \frac{\left(\frac{S_w}{I - S_h}\right) - S_{iw}}{I - S_{gr} - S_{iw}} \tag{8}$$

and where S_{iw} is irreducible water saturation (dimensionless) and S_{gr} is residual gas saturation (dimensionless).

Kinetics of gas hydrate dissociation

Based on the kinetic model of Kim et al. (1987), the generation rates of gas and water per unit volume of gas-hydratebearing porous media are:

$$\dot{m}_{g} = \phi S_{h} \overline{K} M_{g} A_{h} \left(f_{h} f_{g} \right) \tag{9}$$

where K is a decomposition-rate constant (mol/m²·Pa·s), M_g is molecular weight of gas (kg/mol), A_h is area of gas hydrate (m²), f_h is fugacity of methane at T_s and P_h (equilibrium decomposition pressure of gas hydrate in Pa), and f_g is fugacity (N/m²) of methane at T_s and p^* (p^* is interface pressure in Pa).

$$\dot{m}_w = N_h \, \frac{M_w}{M_g} \dot{m}_g \tag{10}$$

where N_h is hydrate number and M_w is molecular weight of water (kg/mol) and where:

$$\overline{K} = K_o \rho_h e^{-\frac{E}{RT_s}} \tag{11}$$

where K_o is a constant (m/MPas), ρ_h density of gas hydrate (kg/m³), *E* is activation energy (J/mol CH₄), *R* is universal gas constant (J/mol·K), and T_s is decomposing surface temperature (K).

The decrease in gas-hydrate saturation with gas hydrate decomposition is expressed (Masuda, 1996) as:

$$\dot{m}_{h} = \frac{M_{h}}{M_{g}} \dot{m}_{g} = \rho_{h} \phi \frac{\partial S_{h}}{\partial t}$$
(12)

where \dot{m}_h is generation rate of gas hydrate (kg/s) per unit volume of a porous medium and M_h is molecular weight of gas hydrate (kg/mol).

Heat transfer rates

For gas hydrate to decompose, heat needs to flow towards the decomposition front. Both conduction and convection play a role in this heat transfer. The governing differential equation for conductive heat transfer rate, where a dissociation front is considered, and the initial and boundary conditions are:

Heat balance:

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial \gamma^2} \tag{13}$$

where α is thermal diffusivity of gas hydrate (m²/s), T is temperature (K), and χ is a spatial position (m).

Initial condition:

$$T(,0) = T_i \tag{14}$$

where T_i is initial temperature (K).

Boundary conditions:

$$\frac{\partial T}{\partial \chi} = 0 \quad (a) \quad \chi = 0, t > 0 \tag{15}$$

$$q_s = \mathring{K} \left(\frac{\partial T}{\partial \chi} \right) @ \chi = S(t), 0 < t < t_{in}$$
⁽¹⁶⁾

where q_s is specified heat flux at the decomposition surface (W/m^2) , *K* is thermal conductivity of gas hydrate (W/(mK)), *S*(*t*) is position of the decomposing interface (m), *t* is time (s), and t_{in} is initial time for decomposition.

$$q_{s} = \overset{\circ}{K} \left(\frac{\partial T}{\partial \chi} \right) - \rho_{h} M_{h} \lambda \frac{\partial s}{\partial t} @ \chi = S(t), t > t_{in}$$
⁽¹⁷⁾

where λ is heat of dissociation of gas hydrate (J/kg).

A rigorous approach to this subject, when both conduction and convection are included, can be expressed by:

$$\nabla (k_{eff} \nabla T) - \nabla (\rho_w h_w u_w + \rho_g h_g u_g) =$$
(18)
$$\frac{\partial}{\partial t} (\phi S_h \rho_h h_h + \phi S_w \rho_w h_w + \phi_g S_g \rho_g h_g + (1 - \phi) \rho_r h_r)$$

where k_{eff} is thermal conductivity of formation (W/mK), ρ_r is density of the rock (kg/m³), and *h* is enthalpy (Ws/kg) and where the left hand side of the equation accounts for heat transfer, and the right-hand side of the equation accounts for the change in the enthalpy of the constituents due to temperature and phase change.

The above liquid flow, heat transfer, and kinetic equations need to be solved with the appropriate initial and boundary conditions. Figure 6 shows the typical change in pressure profile of a gas hydrate zone due to depressurization and gas hydrate decomposition. The above system of partial differential equations, coupled with correlations depicting permeability and porosity variations with gas hydrate dissociation, can be solved by appropriate numerical techniques to produce pressure distribution, temperature distribution, gas hydrate saturation, and rate of gas (and water) generation due to gas hydrate decomposition.

For performance prediction of gas production from hydrate reservoirs, using the mathematical models described above, a comprehensive set of rock and fluid data is needed. The list of input data required for gas hydrate modelling are presented in Table 5.

The available data for the Mallik gas hydrate accumulation are presented in the appropriate columns of Table 5.

MALLIK GAS HYDRATE ACCUMULATION EXTRACTION METHODS

The geological and engineering characteristics of the Mallik gas hydrate accumulation has been studied through various tests and field measurements carried out in the Mallik L-38 and 2L-38 wells. Production tests and well-log responses were analyzed in the Mallik L-38 well. In Mallik 2L-38 the focus of the research efforts subsequent to the fieldwork have been on the analysis of the recovered gas-hydrate-bearing cores and downhole well-log measurements. These results provided the following observations pertinent to the production potential of the Mallik gas hydrate accumulation.

Mallik L-38 well

- About 110 m of gas-hydrate-bearing strata occurs with the depth interval from 819 m to 1111 m.
- Regional formation temperature of the gas-hydratebearing interval ranges from about 4°C to 12°C.
- Average porosity is 35%.
- Average gas hydrate concentration is 67%.

 Free gas occurs (1104–1111 m) at the base of the deepest gas hydrate.

Mallik 2L-38 well

- Regional formation temperature of the gas-hydratebearing interval ranges from about 7°C to 14°C.
- Gas hydrate has been noted between 897 m to 1108 m, based on electrical resistivity and acoustic transit-time well-log responses.
- Average porosity is 34%.
- Average gas hydrate concentration is 64%.
- Compressional wave-to-shear wave velocity ratios (below 1.8) indicate occurrence of free-gas-bearing strata (1108.4–1109.8 m) at the base of the deepest gas hydrate.

The two closed-chamber production tests conducted in Mallik L-38 provide basic understanding of the short-term gas production capabilities of the Mallik gas hydrate accumulation. However, for a complete evaluation of practical capability of gas production from the gas-hydrate-bearing reservoir at Mallik, there are many other issues that should receive considerable consideration. Some of these issues have been addressed in literature, while others are rather speculative, requiring directed testing and research. To achieve better appreciation of this subject, a review of the basic features of gas hydrate production methods and the inherent problems associated with gas hydrate production (McGuire, 1982) are presented in the following section. This discussion can be considered a general guideline to designing the most feasible production procedure for any gas hydrate accumulation.

The first major problem is low reservoir permeability due to plugging of pores by solid gas hydrate. This is mostly evident from typically poor pressure responses observed during flow and build up periods in drill-stem tests, which in turn may make reservoir fracturing an imperative component of a successful gas hydrate production scheme. The second issue is the large amount of heat energy required for gas hydrate dissociation. In the case of methane hydrate, approximately 500 kJ/kg are required for the decomposition of gas hydrate to methane gas and water. The third major issue to be addressed is freezing of water released from gas hydrate dissociation, which may cause plugging of pore spaces and may prevent the flow of gas. This problem might be solved by the use of inhibitors, as was the case in Messoyakha field. Presently, the most promising techniques for the production of gas from gas hydrate reservoirs seem to be thermal stimulation and pressure reduction, which have been reviewed below in greater detail.

Thermal methods

In thermal stimulation methods, heat for gas hydrate dissociation may be supplied by hot water or brine injected into the gas-hydrate-bearing reservoir. The low permeability of gashydrate-bearing sediments may prevent the development of the required high injection rates needed for effective

Table 5. Input data for gas hydrate production model.

			Mallik	
Data	Source	Typical value	L-38	2L-38
GRID				
Reservoir boundaries in x-y direction Reservoir boundaries in vertical direction (thickness)	*		110 mª	113 mª
ROCK				
Absolute permeability, k Relative permeability curve for gas Relative permeability curve for water Original porosity, ϕ Change of k with hydrate saturation Change of ϕ with hydrate saturation Thermal conductivity Heat capacity	* * * * * *		33–44%	25–35% ^b
Effective rock compressibility Heat transfer coefficient Irreducible water saturation Residual gas saturation Density of rock matrix Capillary pressure curve	* * * *			
WATER				
Salinity, ppm Thermal conductivity, W/m·K Density, kg/m ³ Specific heat, kJ/kg·K Viscosity, Pa·s	* L L L	25 000 (Collett et al., 1999b) 0.6 (Masuda et al., 1998) 1013 (Frick et al., 1962, chap. 22, p. 24) 4.1 (Perry and Chilton, 1973, chap. 3, p. 135) 0.0014 (Frick et al., 1962, chap. 22, p. 24)		
GAS	1			1
Composition Enthalpy Density Viscosity, Pa-s Thermal conductivity, W/m·K Fugacity Phase equilibria properties	* L L L L	Methane (Lorenson et al., 1999) Computational evaluation [®] Computational evaluation [®] 10.6 x 10 ⁻⁶ (Vargaftik, 1975, p. 222) 0.0325 (Vargaftik, 1975, p. 224) Computational evaluation [®] Computational evaluation [®]		Methane
GAS HYDRATE	1			
Thermal conductivity, W/m·K Specific Heat, kJ/kmole·K Density, kg/m ³ Heat of dissociation, kJ/kmole Hydrate number Decomposition constant, K ₀ , m/MPa·s Activation energy, kJ/kmole	L* L* L* L* L* L* L*	0.5 (Sloan, 1998, p. 60) 279 (Makogon, 1997, p. 112) 917 (Makogon, 1997, p. 95) 54 000 (Makogon, 1997, p. 109) 5.7–7.4 (Sloan, 1998, p. 223) 1.564 x 10 ⁷ (Kim et al., 1987) 78 152 (Kim et al., 1987)		
INITIAL AND BOUNDARY CONDITION	IS			1
Hydrate saturation Water saturation Reservoir temperature Reservoir pressure	* * *		67%	47%° 53%° 10°Cª
 Parameters should be evaluated throug a: Dallimore et al., 1999 b: Uchida et al., 1999 c: Collett et al., 1999b The data that can be obtained from litera the reservoir. 'L*' indicates that approxim data are obtained from the reservoir of in 	gh an equ ature are r ate values	ation-of-state or other computational procedure. narked 'L', whereas '*' designates the data that s s for the data can be obtained from literature, bu	hould be obt	ained from

uata are optained from the reservoir of interest. The values obtained from the literature with the appropriate references are given under 'Typical values'. These are reported for methane-hydrate-brine system at approximate conditions of 10°C, 10 MPa, and 25 000 ppm salinity. flooding. This drawback can be countered by the use of hydraulic fracturing. Recombination of produced gas and water (from gas hydrate dissociation) into new gas hydrate crystals and freezing of water released from gas hydrate can pose other major practical problems in gas production. All of the proposed thermal methods require significant investment in fluid injection and fluid handling equipment, which contribute to high operating and maintenance costs. In McGuire (1982), both hot water frontal sweeps and hot water fracture injection (between injection and producing wells) methods revealed the following observations relative to gas hydrate production:

- The gas production rate becomes high for temperatures below 120°C in frontal sweep gas hydrate production models.
- Steam with temperatures higher than 200°C cannot act as an efficient injection fluid.
- Frontal sweep methods require the thickness of the gas hydrate layer and sediment porosity to be more than 5 m and 15%, respectively.
- In fracture-flow production, a very complicated heattransfer system develops and heat-transfer efficiency decreases with time.
- Best performance is achieved from frontal sweep and the worst efficiency is from fracture-flow stimulation methods.

Subsequent studies and simulations by other investigators including Holder and Angert (1982), Collett (1998), and Selim and Sloan (1990) have brought further insights into this subject.

Pressure reduction

In pressure reduction methods the producing well may require hydraulic fracturing and bottom-hole pressures should be drawn down to the lowest possible pressures (McGuire, 1982; Holder and Angert, 1982; Collett, 1998; Larsen et al., 1998). The main features of this method are listed below.

- The equipment required is rugged, field-proven, and suitable for harsh Arctic operations. This is in complete contrast with the thermal methods, which need complex equipment to handle the high volume of injected and coproduced water.
- Gas production is strongly dependent on the permeability of the gas-hydrate-bearing reservoir. In most gas hydrate reservoirs, the portions of the reservoir in which gas hydrate dissociates are expected to be much more permeable because gas hydrate exhibits a volume decrease of about 13% when dissociation takes place.
- The bottom hole pressure should be kept as low as practical to ensure acceptable gas flow from the producing wells. Fluid removal provisions should be employed to prevent liquid accumulation in the production well.

- Among the various methods for production of gas from gas hydrate reservoirs, the depressurization scheme is considered to be the most economically promising method.

The Mallik gas hydrate accumulation, with significant gas hydrate concentrations and promising reservoir characteristics presents itself as a definite candidate for potential production. Thermal stimulation, inhibitor injection, and/or pressure reduction can be used in this reservoir. However, assessment of these techniques indicates that pressure reduction should prove to be the most economical method for production of gas from the Mallik gas hydrate accumulation. For the practical development of this reservoir, however, a few important tasks should to be considered. An extensive production simulation of the gas hydrate zone, involving all three governing mechanisms (fluid flow, kinetic, and heat transfer) is needed. Analysis of data (from cores, logs, and production tests) and complementary experimental works are major issues that have to be addressed as requisite tasks for the comprehensive evaluation of the Mallik gas hydrate accumulation. In addition, new drilling and completion technologies should be considered. For example, horizontal wells may prove to be advantageous to production by the pressure reduction method, because of the increased surface area exposed to gas hydrate dissociation.

CONCLUSIONS

Relative to the general aspects of gas hydrate production and specific findings dealing with the Mallik gas hydrate accumulation, we have made the following conclusions:

- Gas hydrate represents a promising potential source of energy.
- Pressure reduction methods appear to yield favorable rates of gas hydrate dissociation and volumes of produced gas.
- The Mallik gas hydrate reservoir with its favourable physical characteristics meets the major requirements of a promising gas hydrate accumulation for the production of gas by pressure reduction methods.
- Further data is needed for the practical assessment of the production potential of free-gas zones beneath the gas hydrate in the Mallik accumulation.
- A comprehensive 'three-mechanism' simulation is needed to predict the production characteristics of the Mallik gas hydrate accumulation.

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