Collett, T.S., and Dallimore, S.R., 2002, Detailed Analysis of Gas Hydrate Induced Drilling and Production Hazards, Proceedings of the Fourth International Conference on Gas Hydrates, Yokohama, Japan, May 19-23, 2002, p. 47-52.

Detailed Analysis of Gas Hydrate Induced Drilling and Production Hazards

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Gas hydrates pose significant hazards to drilling and production operations in both deep marine and onshore Arctic environments. Specific case histories of gas-hydrate-related problems are better documented for onshore Arctic regions, and thus they may serve as useful analogs for some marine gas hydrate settings. Operators involved in Arctic exploration and development activities have described numerous problems associated with gas hydrates, including uncontrolled gas releases during drilling (including blowouts), collapsed casings, and gas leakage to the surface outside of the casing. When the drill bit penetrates a gas hydrate accumulation, under normal Arctic or marine drilling conditions, the drilling mud can become highly gasified as the in-situ hydrate decomposes. The hydrate adjacent to the wellbore will continue to decompose and gasify the drilling mud as long as drilling introduces heat into the formation. Recent drilling in the Russian Yamburg field, in the Cirque area near the Kuparuk River field on the North Slope of Alaska, and in a near shore marine well in the Mackenzie Delta of Canada have all shown the potential severity of hydrate-induced drilling problems, which included “gas kicks”, blowouts, and, in one case, a severe fire. The production of hot fluids from depth through shallower gas-hydrate-bearing intervals can also raise formation temperatures, resulting in further hydrate decomposition. If the dissociated free-gas becomes trapped behind the casing, reservoir pressures may substantially increase and cause casing strain, or the free-gas can leak to the surface outside of the casing. Remediation of hydrate-related drilling and production problems has generally followed two courses of action: (1) prevention of hydrate dissociation or (2) promotion of hydrate dissociation. Both approaches involve regulating mud weights, utilizing mud additives, and adjusting mud temperatures to control the dissociation of in-situ gas hydrates.

1 Introduction

Gas hydrates are crystalline substances composed of water and gas, in which solid lattices of water molecules trap gas molecules in a cage-like structure, or clathrate. Gas hydrates are widespread in permafrost regions and beneath the sea in sediment of outer continental margins. While methane, propane, and other gases can be included in the clathrate structure, methane hydrates appear to be the most common in nature (Kvenvolden, 1988). Gas hydrates represent a significant hazard to drilling and production operations. Russian, Canadian, and American researchers have described numerous problems associated with gas hydrates, including uncontrolled gas releases during drilling (gas kicks), stuck drill-pipe, blowouts, fires, catastrophic well-site subsidence, gas flows disrupting casing cementing operations, gas leakage to the surface outside of the casing, and casing failures (Bily and Dick, 1974; Goodman, 1978; Franklin, 1980, 1981; Makogon, 1981; Yakushev et al., 1989; Yakushev and Collett, 1992). Even though gas hydrates represent a significant hazard, the documentation of actual problems is surprisingly limited. The primary objectives of this paper are (1) to document drilling and production problems that have been attributed the presence of gas hydrates and (2) to review the techniques and procedures used to remediate gas hydrate induced problems.

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2 Permafrost-Associated Gas Hydrate

Gas hydrate in onshore arctic environments is typically closely associated with permafrost. It is generally believed that thermal conditions conducive to the formation of permafrost and gas hydrate have persisted in the Arctic since the end of the Pliocene (about 1.88 Ma). Maps of present day permafrost reveal that about 20 percent of the land area of the northern hemisphere is underlain by permafrost (Figure 1). Geologic studies (Mackay, 1972; Lewellen, 1973) and thermal modeling of subsea conditions also indicate that permafrost and gas hydrate may exist within the continental shelf of the Arctic Ocean. Subaerial emergence of portions of the Arctic continental shelf to current water depths of 120 m (Bard and Fairbanks, 1990) during repeated Pleistocene glaciations, subjected the exposed shelf to temperature conditions favorable for the formation of permafrost and gas hydrate. Thus, it is speculated that "relic" permafrost and gas hydrate may exist on the continental shelves of the Arctic Ocean to present water depths of up to 120 m. In practical terms, onshore and near shore gas hydrate can only exist in close association with permafrost, therefore, the map in Figure

1 that depicts the distribution of onshore continuous permafrost and the potential extent of "relic" sub-sea permafrost also depicts the potential limit of onshore and near shore gas hydrate.

Drilling problems attributed to the presence of permafrost-associated gas hydrates have been noted within numerous sedimentary basins throughout the circumarctic, including those in northern Alaska, the Mackenzie Delta-Beaufort Sea region, Sverdrup Basin of Canada; and in the West Siberian Basin. The occurrence of gas hydrates in these Arctic sedimentary basins is further discussed in the following section.

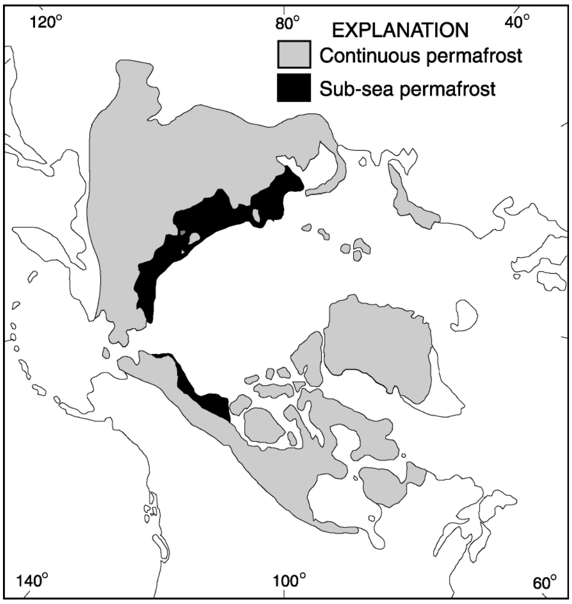

Fig. 1 Distribution of permafrost in the Northern Hemisphere (modified from Pewe, 1983).

2.1 Northern Alaska, United States. The only direct confirmation of gas hydrate on the North Slope was obtained in 1972 when a core containing gas hydrate was recovered from a well in the Prudhoe Bay area (Collett, 1993). Well-log data from an additional 445 North Slope wells were examined for possible gas-hydrate occurrences. This review of all available data revealed that gas hydrate occurs in 50 of the surveyed wells. Many of these wells have multiple gas-hydrate-bearing units, with the thicknesses of individual occurrences ranging from 3 to 31 m. The well-log inferred gas hydrate occurs in six laterally continuous sandstone and conglomerate units geographically restricted to the east end of the Kuparuk River production unit and the "Westend" of the Prudhoe Bay production unit. Open-hole logs from wells in the Westend of the Prudhoe Bay field also indicate the presence of a large free-gas accumulation trapped stratigraphically downdip below four of the log-inferred gas-hydrate-bearing units (Collett, 1993).

2.2 Mackenzie Delta – Beaufort Sea Region, Canada. Assessment of gas hydrate occurrences in the Mackenzie Delta-Beaufort Sea area have been made mainly on the basis of data obtained during the course of hydrocarbon exploration conducted over the past three decades. In addition, two dedicated scientific drilling programs (Dallimore and Collett, 1995; Dallimore et al., 1999) have included the collection of gas-hydrate-bearing core samples.

Prior to a recently completed gas hydrate research drilling program, the most extensively studied gas hydrate occurrences in the Mackenzie Delta-Beaufort Sea region were those drilled in the onshore Mallik L-38 and Ivik J-26 wells (Bily and Dick, 1974) and those in the offshore Nerlerk M-98, Koakoak O-22, Ukalerk C-50, and Kopanoar M-13 wells (Weaver and Stewart, 1982). On the bases of open-hole well log evaluation, it is estimated that Mallik L-38 encountered about 100 m of gas-hydrate-bearing sandstone, and Ivik J-26 penetrated about 25 m of gas hydrate. The well-log inferred gas-hydrate-bearing sandstone units in the Mallik L-38 well occur within the depth interval from 820 to 1,103 m, while in Ivik J-26, gas hydrate occupies a series of fine-grained sandstone and conglomeratic rock units within the depth interval from 980 to 1,020 meters. Analyses (Weaver and Stewart, 1982) of open-hole well logs and mud-gas logs, indicate that the offshore Nerlerk M-98 well penetrated about 170 m of gas-hydrate-bearing sediments, while the Koakoak O-22, Ukalerk C-50, and Kopanoar M-13 wells drilled approximately 40 m, 100 m, and 250 m of gas hydrate respectively. In all four cases, the well-log inferred gas hydrate occurs in fine-grained sandstone rock units.

The JAPEX/JNOC/GSC Mallik 2L-38 gas hydrate research well, drilled in 1998 near the site of the Mallik L-38 well, included extensive scientific studies designed to investigate the occurrence of in-situ natural gas hydrate in the Mallik field area (Dallimore et al., 1999). Approximately 37 m of core was recovered from the gas hydrate interval (878-944 m) in the Mallik 2L-38 well. Pore-space gas hydrate and several forms of visible gas hydrate were observed in a variety unconsolidated sands and gravels interbedded with non-hydrate bearing silts. The cored and downhole logged gas hydrate occurrences in the Mallik 2L-38 well exhibit both high electrical resistivities and rapid acoustic velocities. In total, the gas hydrate-bearing strata was approximately 150 m thick within the depth interval from 889 to 1,101 m.

During a permafrost-coring program in the Taglu area on Richards Island in the outer Mackenzie Delta, ice-bearing cores containing visible gas hydrate and possible pore-space gas hydrate were recovered (Dallimore and Collett, 1995). The visible gas hydrate occurred at a depth of about 330 to 335 m and appeared as thin ice-like layers that released methane upon recovery. Gas yield calculations suggest that other ice-bearing cores from a corehole in the Niglintgak field area on Richards Island also contained non-visible pore-space gas hydrate (reviewed by Dallimore and Collett, 1995).

2.3 Sverdrup Basin, Canada. A study of downhole logs from 138 onshore exploratory wells in the Sverdrup Basin indicate that about 71% of the surveyed wells may have encountered gas hydrate, while about 17 of 30 offshore wells may have penetrated gas hydrate. Most studies dealing with the occurrence of gas hydrate in the Sverdrup Basin have been concerned with gas hydrate induced drilling hazards (Franklin, 1980, 1981). The review of limited information obtained from reports on drilling in the Sverdrup Basin infer the possible occurrence of gas hydrate on or near King Christian, Ellef Ringnes, and Mellville Islands. In 1971, during drilling of the King Christian Island N-06 well, gas leaked into the rig cellar around the outside of the surface casing, which was set at 160 m. A well drilled on Ellef Ringnes Island also experienced significant gas flow from behind casing (405 m) while drilling at 2,560 m. Similar gas leaks have been reported throughout the basin, which may be the result of drilling activity thermally disturbing by-passed gas hydrate occurrences. Drilling on Mellville Island has also revealed the possible occurrence of gas hydrate. For example, while drilling a well at Hearne Point several significant gas flows where encountered, one at a depth of 356 m and a second at 895 m. Hydrocarbon production test of both zones yielded classical gas hydrate test results, with low gas flow rates and shut-in pressures that slowly increased beyond hydrostatic during testing. While drilling the Jackson G-16 well off the southwestern coast of Ellef Ringnes Island (approximately 60 m water depth) gas was detected at a depth of 453 m and again at 567 m, indicating possible gas hydrate occurrences. Based on drilling reports, it appears that gas hydrates likely exist in the Sverdrup Basin; however, no direct evidence of gas hydrates has been obtained.

2.4 West Siberian Basin, Russia. Production data and other pertinent geologic information have been used to document the presence of gas hydrate in the Messoyakha field, located in the northeastern corner of the West Siberian Basin (Makogon, 1981, Cherskiy et al., 1985). The Messoyakha gas accumulation is confined to the Dolgan Formation of the Pokur "suite," and production has been established from the depth interval between 720 and 820 m. The upper part (about 40 m) of the Messoyakha field lies within the zone of predicted methane-hydrate stability; thus, separating the Messoyakha field into an upper gas-hydrate accumulation and a lower free-gas accumulation.

The presence of in-situ methane hydrates is usually limited to the zone of predicted methane hydrate stability, which in most Arctic settings occurs from a subsurface depth of 130 m to a maximum depth of over 2,000 m. But laboratory experiments (Yakushev, 1988) and field investigations (Porokhniak, 1988) have shown the presence of "self-preserved" gas hydrates at depths above the predicted methane hydrate stability zone (less than 130 m). "Self-preserved" gas hydrates are believed to be unstable relicts of ancient gas hydrates, which formed, in the geologic past when either formation temperature and/or pressure conditions were more favorable for gas hydrate formation. A relict, "self-preserved", gas hydrate was encountered in the Yamburg Gas Field of western Siberia. Here several frozen permafrost cores (cored interval from 20 to 150 m) were determined to contain gas hydrates (Yakushev et al., 1989).

3 Gas Hydrate Induced Drilling and Production Problems

The review of published papers and drilling reports filed with government regulatory agencies in various countries have documented two general categories of problems associated with the occurrence of gas hydrates (Figure 2): (1) uncontrolled gas releases during drilling (including blowouts) and (2) well casing deployment and damage problems (including gas leakage to the surface outside of the casing). In this section of the paper we have described several of the best-documented examples of these problems.

3.1 Gas Release During Drilling. When a gas hydrate is mechanically and thermally disturbed during drilling, a large amount of gas can enter the well bore. The severity of this problem is controlled by many factors, including, but not limited to, the volume of gas hydrates, the temperature and weight of the drilling-mud, circulation and penetration rates, and the size of the borehole. For example, during drilling, cementing, and gas production activity in the Russian Yamburg field, severe gas flows are often encountered in the shallow permafrost sequence (reviewed by Yakushev and Collett, 1992). Some of these gas flows have resulted in fires. Similar gas flows from suspected gas hydrates have been observed in other western Siberia gas fields; including Bovanenkovskoe, Kharasaveiskoe, Youzhno-Tambejskoe, Bystritskinskoe, Parusovoe, Yourkharovskoe, Ourengojskoe, Tazovskoe, and Goubkinskoe (Agalakov, 1989; Yakushev and Collett, 1992). In the Bovanenkovskoe field some blowouts occurred at very shallow depths (60-80m) with flow rates reaching 14,000 m^3/d (Chuvillin et al, in press; Dallimore et al., 2001). While under normal conditions these gas flows would be too shallow to be considered gas hydrates it is possible that local geopressure anomalies caused by shallow intrapermafrost gas hydrates may have been a factor.

In February of 1992, while drilling the Cirque-1 well near the western edge of the Kuparuk River Oil Field on the North Slope of Alaska, a shallow gas zone (depth of about 710 m) was encountered which subsequently blew out the well (Alaska Oil and Gas Conservation Commission, 1992). It was later determined that this shallow free-gas zone is overlain by a thick gas-hydrate-bearing interval (depth interval of about 250-350 m) which also contributed to the gas flow problem in the Cirque-1 well. The blowout in the Cirque-1 well occurred while pulling the drill-string out of the hole to run surface casing. While tripping the drill

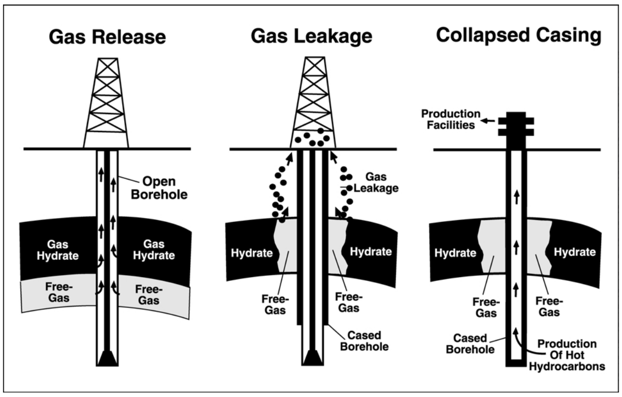

Fig. 2 Drilling and well completion hazards associated with the occurrence of gas hydrates.

string, the well "kicked hard" and unloaded large amounts of mud and debris on the rig floor, the well was put on the diverter. To gain control of the well the mud pumps were used to pump more than 35 barrels of mud down the annulus at a maximum pressure of 27,600 kPa; however, one of the diverter valve bodies was cracked and gas began to flow into the cellar of the rig. The primary cause for the blowout was attributed to excessive trip speeds, which swabbed gas into the well from the free-gas zone at a depth of 710 m. However, it appears that the shallower gas hydrate interval also contributed to the Cirque-1 blowout. The mud used in the initial attempt to "kill" the well was a CaCl based brine. After pumping the brine based kill mud, the gas flow rates from the well actually increased. This response characteristic is one piece of evidence that gas hydrate contributed to the gas flow in the Cirque-1 well since a CaCl brine should affect the stability of the in-situ gas hydrates causing them to dissociate. The well operator also reported that after the blowout the gas flow continued in episodic manner. Several authors have suggested that this behavior is indicative of a gas hydrate blowout (reviewed by Franklin, 1980)

The Immiugak exploratory well was drilled in 32 m of water using a floating drilling unit in the Beaufort Sea north of Tuktoyaktuk, N.W.T. This area of the Beaufort Sea is underlain by a thick permafrost sequence with local occurrences of shallow gas. While making a connection at 397 m, the Immiugak well flowed gas to the surface. Despite "weighting-up" the well several times with chilled, 1500 kg/m^3, kill mud the well continued to flow and eventually the drill was evacuated. Gas hydrate was speculated as a possible cause (Canada Oil and Gas Lands Administration, 1989) and the cyclic gas flow observed is perhaps characteristic of a gas hydrate flow response. However, a more realistic cause may the combination of overpressured free-gas perhaps in contact with a gas hydrate occurrence.

3.2 Well Casing Installation and Damage. Within wells drilled in the Arctic, the shallow permafrost and gas-hydrate-bearing intervals are often cased before drilling to greater depths. After casing, the continuation of drilling may thermally disturb the in-situ gas hydrates behind the casing. The gas from the dissociated hydrates may leak to the surface outside of the surface casing. For example, while drilling on the 1C production pad in the Kuparuk River Oil Filed, gas was detected "bubbling" into the rig cellar around the outside of the conductor and surface casing. This leakage problem was documented in four wells drilled from the Kuparuk River Unit 1C production pad (Alaska Oil and Gas Conservation Commission, 1981). The drilling-rig operators concluded that the source of the gas was a series of gas-hydrate-bearing sandstone units (depth interval 350 to 430 m) that had been thermally and mechanically disturbed by drilling and casing operations. The disassociated hydrate gas migrated to the surface along thawed channel within the permafrost sequence behind the casing (Figure 2).

Within a well completed through a gas-hydrate-bearing interval, the production of the underlying hot oil and formation fluids will destabilize the in-situ gas hydrates. If this thermal disturbance persists, the gas hydrates will continue to dissociate and the resultant formation pressures will rise. If these pooled gases and high pressures are not dissipated, the well-bore casing may be damaged (Figure 2). Franklin's (1981) review of drilling reports from wells drilled in the Arctic Islands revealed numerous casing problems attribute to the presence of gas hydrates. For example, the drilling records from a well drilled in Helicopter Bay on Ellef Ringes Island indicated that while drilling below (about 2,400 m) two casing strings, one string landed at 400 m and the second at 1,800 m, a significant gas flow from between the inner casing and outer casing was observed. In this instance an accidental fire resulted due to this gas flow. It was speculated that the gas was from thermally disturbed in-situ gas hydrate.

Another drilling problem attributed to gas hydrates in Alaska, which was only indirectly related to the well bore casings, dealt with a casing installation problem. In May of 1990, while drilling the Prudhoe Bay Unit Z-7 development well in the "Westend" of the Prudhoe Bay Oil Field, two significant gas shows were observed at a depth of 628 m and 683 m, which were correlated with two regional extensive gas-hydrate-bearing stratigraphic units. After drilling to a depth of 756 m the bit was tripped to the surface in preparation to run the permafrost casing. Upon running casing into the hole, it was discovered that the gas-hydrate-bearing intervals has sloughed into the borehole. Subsequently, the casing had to be removed and the previously drilled section from 620m to 756 m had to be redrilled requiring more than a day of drilling-rig time.

4 Remediation of Gas Hydrate Related Drilling and Production Problems

The permafrost sequence in most Arctic wells is drilled as quickly as possible utilizing heavy drilling-muds at normal mud-pit temperatures (+5 to +20 degrees C) (Goodman, 1978). No attempt is usually made to cool the drilling-muds because of the high cost of mud refrigeration equipment. After the permafrost sequence is drilled, casing is usually set before drilling deeper. The cements used to set the casing in the permafrost sequence are specially formulated to provide high strength, good bond, short curing times, and low heat of hydration. Both Franklin (written communication, 1989, L.J. Franklin, Panarctic Oils Limited of Canada, Calgary, Alberta, Canada) and Yakushev et al (1989) have documented that these standard drilling and completion techniques are inadequate when dealing with thick gas-hydrate accumulations.

Laboratory and field investigations have shown that oil and gas wells can be safely drilled and completed within gas-hydrate-bearing rock sequences (reviewed by Yakushev et al., 1989). Remediation of gas-hydrate related drilling and production problems have generally followed on of two courses of action: (1) prevention of gas hydrate dissociation, or (2) promotion of gas hydrate dissociation.

4.1 Prevention of Gas Hydrate Dissociation. Canadian (written communication, 1989, L.J. Franklin, Panarctic Oils Limited, Calgary, Alberta, Canada) and Russian (Yakushev et al., 1989) researchers have described specialized drilling and completion techniques which prevent gas hydrate dissociation, which in-turn has significantly reduced the number of gas hydrate related problems. These specialized techniques are employed at each stage of well operations (i.e., drilling, completion, and production). During drilling muds are cooled, to a temperature between 0 and 5 ^{o}C, to reduce gas hydrate dissociation. Sometimes the permafrost sequence is drilled without muds, but with forced cold air (air drilled). When completing the well through a gas-hydrate-bearing sequence, a cement with low heat of hydration is used. Yakushev et al (1989) concluded that to maintain conventional oil and/or gas production in a well completed through a gas-hydrate-bearing interval the well casing should be cooled by an external refrigeration system. It is also recommended that the gas hydrate zones should be cased with a high-collapse-strength casing (Goodman, 1978). In general, the mechanical well-site operations used to prevent gas hydrate dissociation are very costly and in many cases are not feasible.

In Alaska, numerous techniques have been used to control the affects of pressure and temperature fluctuations on in-situ gas hydrate stability. For example, cold makeup waters, reduced circulating times, and the use of smaller downhole motors have all been used to keep mud temperatures down. Increased pressures also stabilize gas hydrates, leading to the use of higher mud weights (860-900 kg/m^3). In some cases, very high mud weights have been used to control gas hydrate stability (mud weights as high as 1,100-1,150 kg/m^3), fighting the balance between gas hydrate control and lost circulation. However, some researchers have questioned the effectiveness of increasing mud weights to control in-situ gas hydrate stability conditions (reviewed by Roadifer et al., 1987). To help with this problem, drilling engineers in Alaska and Canada have started to use chemical mud additives to stabilize gas hydrates in the borehole. A surfactant named lecithin has proved to be a useful "gas hydrate stabilizer" (Downhole Talk, 1993). In normal filed operations, lecithin (Baroid's product name DRILTREAT) is used to change the water-wetting characteristics of drilling solids, to coat shale surfaces and to act as a secondary emulsifier. Some believe that lecithin actually slows gas hydrate dissociation, but in reality lecithin most likely slows the exchange of fluids between the gas hydrate in the borehole and the drilling muds, thus preserving the in-situ gas hydrate.

One of the best studies on effect of drilling mud temperatures and the use of lecithin on gas hydrate stability was conducted in 1998 during the drilling of the JAPEX/JNOC/GSC Mallik 2L-38 gas hydrate research well in northern Canada (Dallimore et al., 1999). Prior to coring and drilling the gas hydrate section in the Mallik 2L-38 well, 6 liters per cubic meter of lecithin were added to the mud system. The mud weights were gradually increased from 1,070 kg/m^3 to 1,190 kg/m^3. The mud coolers effectively held the mud temperatures between 1 and 3 degrees Celsius throughout this phase of the program; which is about 5 to 10 degrees colder than the actual in-situ formation temperatures. Subsequent caliper logging of the Mallik well revealed an almost perfect well, with a near gauge hole throughout the gas hydrate interval.

4.2 Promotion of Gas Hydrate Dissociation. To improve the efficiency of well drilling and completion in the presence of in-situ gas hydrates, Panarctic Oils Limited of Canada (Franklin, 1980) used a unique operating procedure that promoted gas hydrate dissociation. Franklin (1980) indicates that by increasing the temperature of the drilling muds and by decreasing the mud weights it is possible to promote gas hydrate dissociation. With a properly managed drilling program it is possible to safely control and vent the flow of dissociated hydrate gas. Franklin (1980) notes that the long-term objective of this procedure is not to accelerate gas hydrate dissociation, but to concentrate the gas production into periods when the gas can be handled safely. However, this controlled dissociation of in-situ gas hydrates may require long periods of time to complete.

5 Summary

Oil and gas drilling operations in the West Siberian Basin, on the North Slope of Alaska, and within the Canadian Arctic are often hampered by gas hydrate related problems. The most severe problems have included uncontrolled gas flows during drilling, gas leakage to the surface outside of the wellbore casing, and wellbore casing damage.

The most important factor to be considered when assessing a potential gas-hydrate hazard within a given region is understanding the geologic controls on the occurrence and formation of a gas hydrate accumulation in nature. Information on gas hydrate distribution, gas hydrate volume, reservoir temperatures, formation pore-pressures, rock porosities and permeabilities are needed for safe drilling and completion operations in the presence of in-situ gas hydrates.

Even though documented problems attributed to the presence of gas hydrates have been relatively few, the frequency of gas-hydrate-related problems will increase as exploration and development activity moves farther offshore into deeper (greater than 300 m) water and to higher latitudes in the Arctic.

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