Seafloor drilling of the hydrate economic zone for exploration and production of methane

J.J. Kollé and M.D. Max

Abstract

The economic production of natural gas from oceanic hydrate deposits will not occur using conventional offshore drilling systems. By definition, hydrated formations will produce wet gas at low pressure and low production rates. The low production rate requires low-cost drilling methods to ensure economic viability. Fortunately hydrates are located relatively close to the seafloor when compared to conventional gas reservoirs. Large numbers of low-cost wells could produce enough gas to recover costs. A concept for a workboat-based drilling system that includes an integrated gas production capability is described.

Introduction

Drilling capabilities developed for conventional deepwater hydrocarbon exploration and production are presently sufficient for drilling and completing production in hydrate and associated gas deposits. But the direct application of this expensive, deep-water capability equipment in the field of methane recovery from oceanic hydrates may not be necessary. Hydrate system deposits are always to be found relatively close to the seafloor (within 1 km and usually much less). Both biogenic and thermogenic hydrates are associated with rapid sedimentation of organic source material. Except where carbonate crusts have formed, the shallow, hydrated sediments should be relatively unconsolidated and easy to drill. Therefore, a substantially less expensive drilling approach should be pursued.

Hydrated sediments are expected in water depths of between 500 and 2000 m. Semi-submersible drilling systems with this depth capacity is currently available, however costs are extremely high (Brandt et al. 1998). These systems are capable of deep drilling for oil and gas with multi-lateral completions into reservoir compartments. A marine riser is used for safety reasons; for recovery of expensive drilling fluids; and to allow re-entry to set multiple casing strings. The cost of this equipment can be recovered only for large reservoirs of high-grade oil. Gas production is often avoided because of the cost of transport.

For the foreseeable future, natural gas will be produced primarily from onshore and shallow offshore fields with pipeline connections. Natural gas is steadily displacing oil as a primary energy source. As onshore resources are depleted, there will be a long-term need to access deepwater marine gas hydrates. Efforts to explore the development of gas hydrate resources are already underway in energy resource poor countries such as Japan and India. In order to maintain reasonable gas costs, new technologies for recovery and transport are required.

Current research on cost reduction for deepwater offshore has focused on riserless drilling and hazard reduction (shallow water flows and abnormally pressurized formations) for conventional drill rigs. Concepts for seafloor-based drilling systems are also under consideration. Low-cost seafloor based systems for sensor implantation are currently available (Kolle 1996). A significant obstacle to the use of seafloor-based systems is the high-cost and lower power of submersible, remote controlled equipment. An alternative approach involves riserless drilling of small diameter holes using lightweight, composite tubing that avoids the weight and cost of conventional oil and gas drilling equipment (Kolle 1994). Techniques for integrating the drilling, completion and production operation would greatly reduce the cost of gas recovery from hydrated sediments.

Oceanic methane hydrate

Gas hydrates are ice-like materials formed from a framework of water molecules containing large intra-lattice voids that can be occupied by gas (mainly methane) and, in some cases, a fluid with light hydrocarbon molecules (Sloan 1997). Hydrocarbons thermodynamically stabilize the water molecule lattice by hydrogen bonding. In appearance, hydrates take the form of inter-grown, transparent to translucent white to gray crystals, having poorly defined crystal form. Gas hydrates are a secondary or diagenetic phenomenon in marine sediment. They are commonly observed on the seafloor where their presence can influence seafloor stability.

Hydrate formation draws methane molecules into closely packed lattice sites, effectively concentrating the methane. Methane hydrate is non-stoichiometric in that the crystal structure of the hydrate can be established without all the lattice sites being occupied. One cubic meter of fully saturated methane hydrate contains about 164 m^3 of methane (at STP) and 0.87 m^3 of water (Sloan 1997). In a normal oceanic hydrate, perhaps 150 m^3 of gas may be released from 1 m^3 of hydrate because of naturally occurring under-saturation of the available guest lattice sites[1]. Some of the molecular sites available for methane in the hydrate lattice may be filled with small amounts of other gas molecules, such as ethane.

Temperature increases downward from the seafloor through the sediments according to the local geothermal gradient. Pressure also increases with depth from both hydrostatic (water depth) and, to a minor extent, lithostatic (depth of burial) effects. The increasing pressure makes the gas hydrate more stable with depth but the rising temperature eventually becomes too high for the hydrate to exist (Figure 1). This defines the base of the Hydrate Stability Zone (HSZ). Because the thermal gradient is fairly constant over an area of seafloor, this stability limit remains at approximately the same depth beneath the seabed and creates a fairly uniform thickness for the HSZ, commonly hundreds of meters in water deeper than 2,000 m. As the HSZ exists to a common depth below the seabed for a constant geothermal gradient, it will rise and fall with the seabed bathymetry. The base of the HSZ is commonly seen in seismic reflection data as a Bottom Simulating Reflector (BSR), that follows the bottom depth contour at a constant thickness.

Methane hydrate occurs in marine sediments in water depths greater than about 450 meters on continental margins of open oceans (Figure 2). Below this, the temperature - pressure conditions in the sediment are appropriate for hydrate formation (Miles, 1995). However, gas hydrates do not exist where methane flux is too low, regardless of ambient thermodynamic conditions. Gas hydrates exist within seafloor sediments because sufficient gas and water are available to form hydrate in intergranular pore spaces. Oceanic hydrate system deposits occur mainly along continental slopes.

---

[1] By way of comparison there can be as much as 150 m^3 of gas associated with 1 m^3 of crude oil.

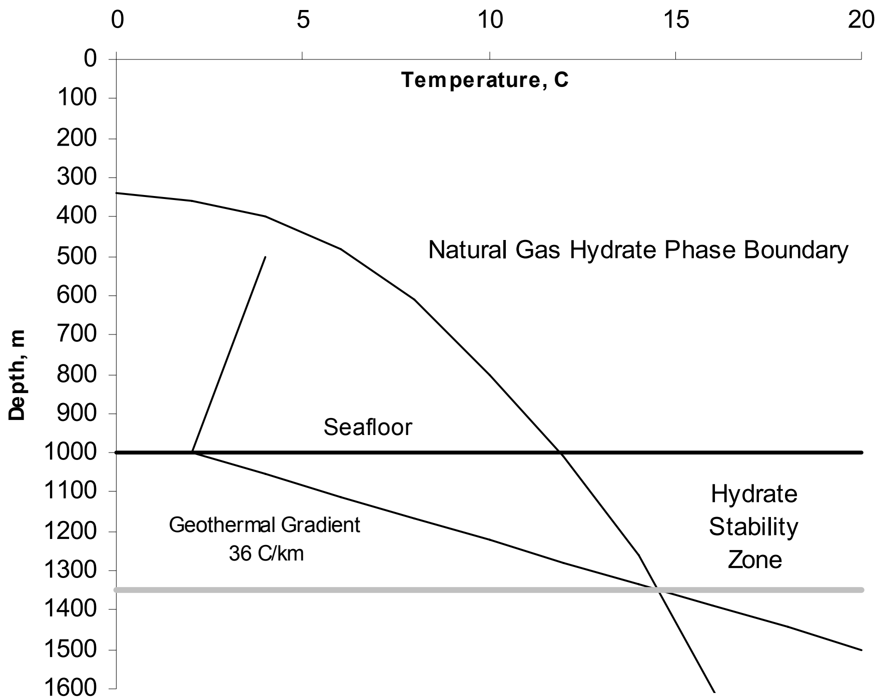

Figure 1. Position of the hydrate stability zone in the upper sediment (Kvenvolden 1993). Geothermal heat rising from below establishes the base of Hydrate Stability Zone (HSZ) as phase boundary limit. Representative hydrothermal and geothermal temperatures shown.

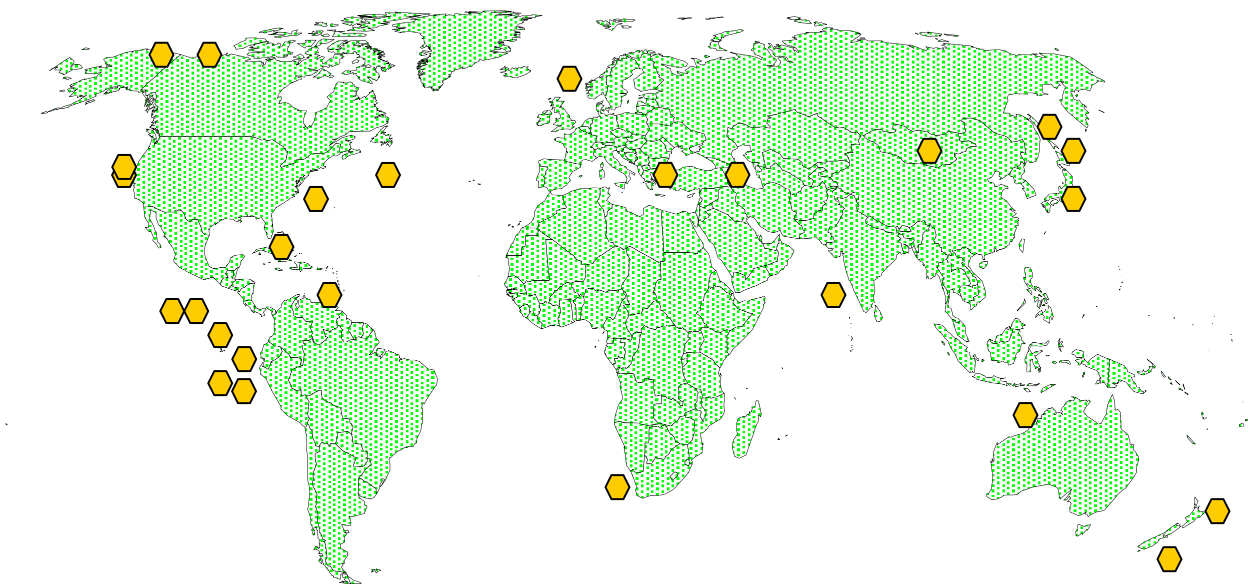

Figure 2. Known and inferred marine gas hydrate occurrences (after Kvenvolden 1988)

Methane in hydrates is derived from both within the HSZ and more importantly from the great thickness of sediments below. Both shallow, biogenic gas derived mainly from bacteriological decay of organic matter buried along with the sediment, and deeper sourced, thermogenic gas produced by thermal cracking of higher density hydrocarbons, have been found within hydrate deposits. Biogenic methane is usually dominant (Kvenvolden 1995). The requirement for sediments rich in organic carbon explains the suitability of continental margin sediments. Methane formed from either biogenic (Parkes et al. 1994) or thermogenic activity will tend to migrate upwards, and be trapped as hydrate within the HSZ or as free gas beneath it. Once trapped as hydrate, the methane will tend to stay concentrated in the HSZ (Paull et al. 1994a, Max and Lowrie 1996, Max and Dillon, 1998). Oceanic methane hydrate and associated gas deposits could not have formed without gas flow in the sediments, and the development of a gas-fluid interface. Otherwise the methane would be dispersed near its source of production and there would be no significant concentrations of either gas or hydrate.

The Hydrate Economic Zone (HEZ) is the combined hydrate, gas, and subjacent sediment zone for which it is important to characterize methane and the geotechnical properties that bear on the gas recovery (Max and Chandra 1998). It includes the HSZ and subjacent gas and pore fluid zones that are gas rich. This is because the gas flux and transport to the HEZ, as well as methane interchange between hydrate and gas phase, affects sediment properties and stability. In an area where sedimentation has continued over a long period of time, hydrate at the base of the HSZ may become unstable and dissociate because of rising geotherms. Where this happens, the hydrate conservation cycle, which is a steady state, long-term process, conserves and concentrates the methane (Max and Lowrie 1996). Gas produced in or below sediment from dissociated hydrate will rise through buoyancy into the HSZ and tend to again form gas hydrate. It is presently estimated that this economic zone is no more than 1.5 to 2 times the thickness of the HSZ. Below this zone, where sediment compaction and geotechnical properties are more predictable and only gas generation occurs.

Deep-concentrated and shallow-dispersed hydrate

There are two distinct types of hydrate deposits, and they constitute two different research and exploration issues. Both types of occurrence are important, especially from the point of view of an industry that must establish considerable engineering plant within and on the seafloor in order to recover hydrocarbons. The possibility of extracting methane from oceanic hydrate system deposits is presently driving the active hydrate interest in India and Japan, and to a large extent in the United States, which has outlined a broader hydrate research program (DOE 1998). Production issues are the primary industrial concern.

The first, and most obvious type of hydrate formation, is concentrated hydrate. It constitutes a primary economic target. Concentrated hydrate is fortuitously imaged on reflection seismic records that were taken for other reasons. Most attention at present is focused on concentrations of hydrate in the lower part of the HSZ that may offer the greatest energy resource potential (Max and Lowrie 1997, Max and Chandra 1998).

Knowledge about the strength of the marine sediment 'soils', in which these concentrated hydrate deposits are likely to occur, is vital to their eventual economic exploitation. The high porosity fine-grained sediments that host variable amounts of hydrate throughout the HSZ are nowhere as strong as conventional geological traps and reservoirs. Geotechnical studies have established that the strength and elastic properties of hydrates are similar to ice, while the morphology and strength of hydrated sediments are similar to those of permafrost (Wittebolle and Sego 1985). Hydrates found near the seafloor are commonly associated with authigenetic carbonates that result from the oxidation of methane. Authigenetic carbonate should be less common in deeper hydrated sediments. Drilling carbonate layers will be substantially more difficult than drilling in unconsolidated sediment or permafrost.

The second type of hydrate occurrence is dispersed in low concentrations. Little is known about dispersed hydrate. Its effect on reflection seismics is uncertain. Dispersed hydrate may occur throughout the HSZ, but it is most important when it occurs near or at the seafloor in the upper part of the HSZ. Hydrate in such locations is very important to seafloor stability and safety, as well as to global carbon flux. Entrapment of methane in hydrate is often transitory, depending on local water temperature. The hydrate can apparently form and dissociate quickly (Brewer 1998). Rapidly dissociating hydrate near the sediment surface can cause seafloor collapse. It can produce thixotropic sediments, which could cause a seabed ocean engineering plant to fracture and slide irregularly. Short-term seafloor stability and environmental risk to engineering structures may also be affected by rapid dissociation of more massive hydrate concentrations. Engineering site studies that take into account the destabilizing potential of dispersed hydrate, and modeling of the effect of rapid dissociation, should be important industrial concerns.

Where gas flux is very high, such as in a number of sites in the Gulf of Mexico, solid hydrate knolls can form on the seafloor in direct contact with sea water. In addition, the carbon flux cycle is one of the primary controls of global climate response. Hydrate near the seafloor participates through an open system within the carbon flux cycle. Greater knowledge of methane flux is crucial to our understanding of the controls and prediction of global climate change. The role of hydrates, both capturing and withholding methane from the ocean-atmosphere system or causing it to flood the system in a positive feedback mode, are of fundamental importance.

Drilling strategy and concerns

Mapping suggests that gas trapping beneath the hydrate-bearing layer may cause near-seafloor structural failure. The resulting mass sediment flows would result in catastrophic releases of natural gas (Dillon et al. 1993). Even with no attempted extraction, these hydrate-gas reservoirs may be metastable, at least with respect to the 10,000-to-100,000 year timescale of the glacial-interglacial cycle. Hydrate engineering must focus on developing different, and probably more closely monitored and controlled exploration and extraction practices, than are used in dealing with conventional hydrocarbon deposits. The dangers of massive blow-out or, less catastrophic but still very significant seafloor motion must be addressed.

In the case of a hydrate-culmination gas deposit, drilling strategy can be either direct or indirect. In the first case, the gas reservoir is drilled directly through the hydrate in the second case, the gas is drilled and tapped from the side, or possibly from below the gas closure, through the use of horizontal drilling techniques. Direct drilling into a normally pressurized gas trap does not usually result in undue safety or blow-out problems because of the physical strength of the reservoir. The U.S. Department of Energy considers that drilling directly through hydrate could be made safe, with insulated and/or refrigeration techniques (Malone, DoE, pers. comm). In a study carried out for the Ocean Drilling Program, Claypool (1991) suggests that severe blowout from a geopressurized hydrate-associated gas pocket is unlikely. The HSZ is relatively shallow, greatly limiting potential overpressures. In addition, over-pressurization will enhance the hydrate stability field leading to the formation of a thicker hydrate section.

Recent advances in drilling technology, which allow for considerable lateral and possible upward return drilling, might be used to avoid problems associated with direct drilling. Avoiding technical problems associated with drilling directly down through the hydrate layer may be preferable to attempting to compensate for them. Indirect drilling, for instance, would penetrate the HSZ to the side of a bathymetric culmination gas trap, minimizing likelyhood of blow-out. There is an additional advantage in having a long lateral hole in a gas reservoir – draw-down of gas would take place over a broad area through the reservoir rather than being localized near a vertical hole exposed to a shorter gas section. A larger draw-down intersection may make it easier to maintain reservoir pressure and hydrate cap stability, as well as compensating for low or variable porosity and permeability.

Currently available drill string lengths are up to 8-10 kms. In deep water, and to a lesser extent on continental slopes where terrigenous marine sediments are more common, sediment lithologies are generally fine-grained silts and clays. As a result, the theoretical maximum drill string lengths may be realized in practice. Because the maximum water depths that drilling could take place in are no more than 5 km, the excess string length, could be applied to curved and horizontal runs to indirectly tap hydrate-trapped gas.

Because the hydrate layer will almost certainly have variable concentrations of hydrate, its mechanical structure is likely to be variable and the strength of the cap may be very difficult to characterize. This is very different from a classical reservoir where cap strength is usually not an important consideration because of overwhelming geological strength. Methane can normally penetrate the HSZ along faults (Dillon et al. 1997) and natural blow-outs of considerable volumes of methane have taken place (Dillon et al. 1998).

Hydrate Seafloor Drilling Capability

The exploration and recovery of natural gas from the HEZ requires the development of low-cost drilling and well completion techniques. The value of a gas well is determined by the value of the gas and the rate of production. Gas hydrates must be dissociated for gas production. Even in the case of production from a gas pocket, the recharge mechanism requires dissociation of the overlying gas by geothermal heat flow (McGuire 1982). Other options for providing heat or agents such as methanol that will promote gas dissociation will be more complex and costly. Since production rates will likely be low, all aspects of drilling and completion must be simple and low cost for an economic return on investment.

Deepwater drillships and platforms that are capable of operations in the 2 km water depths where the HEZ occurs are highly complex, extremely high cost systems. These systems are economic – when oil prices are high – for oil production but are not used for gas production because of the lower value of natural gas and because of the high cost of transporting the gas to shore from a deepwater site that may be hundreds of kilometers offshore. Recent developments in gas-to-liquids conversion will enhance the economic potential of gas hydrates. Compact, exothermic reactors are becoming available for the production of process gas (CO and H_2) and the subsequent production of liquid fuels based on the Fisher-Tropsch process (Agee et al. 1999). Clean, liquid fuel has a much higher value than crude oil and could be stored and transported in tankers.

Drilling within the HEZ, which extends no more than about 1-1.25 km below the seafloor mudline, can be carried out differently from conventional drilling. Ordinary drilling must penetrate much deeper below the seafloor and is likely to encounter a much wider variety of drilling conditions, including rock-like materials and substantially higher temperatures. Initial development of hydrate concentrations by forced dissociation (Max and Dillon 1998, 1999) in shallower water, where increased gas pressures and porosity filled by gas are likely, will yield HEZ drilling targets on the order of 0.5 km at maximum.

A less costly drilling capability, which could be implemented specifically for studying, sampling, and drilling hydrate localities, can be envisaged. A much smaller vessel, on the order of a 250-300 foot mudboat, could be outfitted with a moderate sized drill. On the other hand, a vessel of this type could also be used to control special seafloor-mounted drilling capability. These vessels are available at orders of magnitude lower cost than conventional deepwater systems. Dynamic positioning using the Global Positioning Satellite system now makes it possible for these vessels to hold position within a 100 m circle anywhere on the ocean. A low cost drill rig deployed from such a vessel would allow the drilling of a large number of low-cost, shallow wells into the HEZ. By gathering production from a large number of wells, the gas rates required to justify the investment of drilling could be achieved.

An analysis carried out for the U.S. Department of Energy (Kolle 1994) shows that a low-power, hose drilling system could drill relatively shallow (<1 km) holes for hydrate system exploration and production. This system would be mounted on a mud supply boat. A high-pressure hose is used to power a low-thrust, low-torque drill on the seafloor. The hose provides the flexibility required for heave compensation. This system was equipped with 1500 m of 25-mm diameter, 17 MPa hose capable of supplying 10 kW hydraulic power to a positive displacement drill motor (PDM). A small-diameter (45-mm) PDM provides 2 kW mechanical power. The remaining hydraulic power drives hydraulic jets that are capable of eroding consolidated sediments. Low thrust, low torque drilling is possible in shallow sediments with jet-assist. Near-surface hydrate deposits may be associated with authigenetic carbonate deposits, which result from the oxidation of methane by organisms in the water and near surface layers of sediment. Reliable drilling of carbonates will require a hard rock capability. The hose drilling system operates at a jet pressure of 17 MPa and includes a mechanical drill capable of penetrating carbonate formations.

Another option under consideration is the adaptation of coiled tubing (CT) drilling to the seafloor environment. This technique uses a continuous length of mild steel tubing with a diameter of 25 mm to 100 mm or more that is coiled onto a reel. The tubing can be injected into a producing oil or gas well through the production wellhead. CT is commonly used to place production tubing or to carry out workover operations. More recently, this technology has been used to drill small diameter holes from an existing wellbore (Fultz and Pittard 1990). Following a rapidly growing trend, approximately 600 wells were drilled with CT rigs in 1997 (Leising and Walton 1998). CT drilling replaces a conventional rotary drill rig that uses jointed tubing greatly simplifying the drilling process and allowing drilling into a pressurized wellbore. CT drilling is currently under consideration for deepwater offshore oil and gas exploration because of its operational simplicity. Composite CT is attractive for offshore applications because of its light weight, and flexibility. A composite CT could be suspended from the surface ship to power a drill. CT provides much higher load capacity than hose but is less flexible. Flexible hose provides heave compensation in deep water since the hose can stretch. A combination of hose and CT may provide a deepwater drilling capability.

A recent study of microborehole drilling (CTES 1996) shows that a 75 kW hydraulic system would easily power a small (25 mm tubing diameter) coiled tubing rig using seawater as the drilling fluid. Such systems are currently in use on land for shallow drilling. The primary issues in powering a system such as this are the limited torque and thrust capacity of small diameter tubing. The addition of high-pressure jets would significantly add to the penetration capabilities of these systems. Such a system would need to incorporate automated casing installation tools. As discussed previously, horizontal penetration of gas pockets beneath a gas hydrate accumulation would provide greater gas production while eliminating the need to penetrate the hydrate cap directly. The hose and coiled tubing drilling systems described above have been used primarily for vertical well drilling. The simplest and most effective directional drilling systems are deployed from rotary drill rigs. In this approach a bent-housing drill motor is oriented by rotating the drill string. Once the bent-housing orientation is known, the hole is drilled without further drillstring rotation; resulting in a curved hole. Typically this technique is used to build hole angle from an initial vertical orientation. Angle building is followed by periods in which the drill string is rotated in order to drill a straight hole. This technique is not possible with CT since the drill string cannot be rotated. More sophisticated downhole motors with adjustable stabilizers and bend angles can be used to drill directional holes from CT (Anon. 1998), however the cost for these tools is quite high. Passive angle-build and hold assemblies are less accurate but have the advantages of simplicity and low-cost.

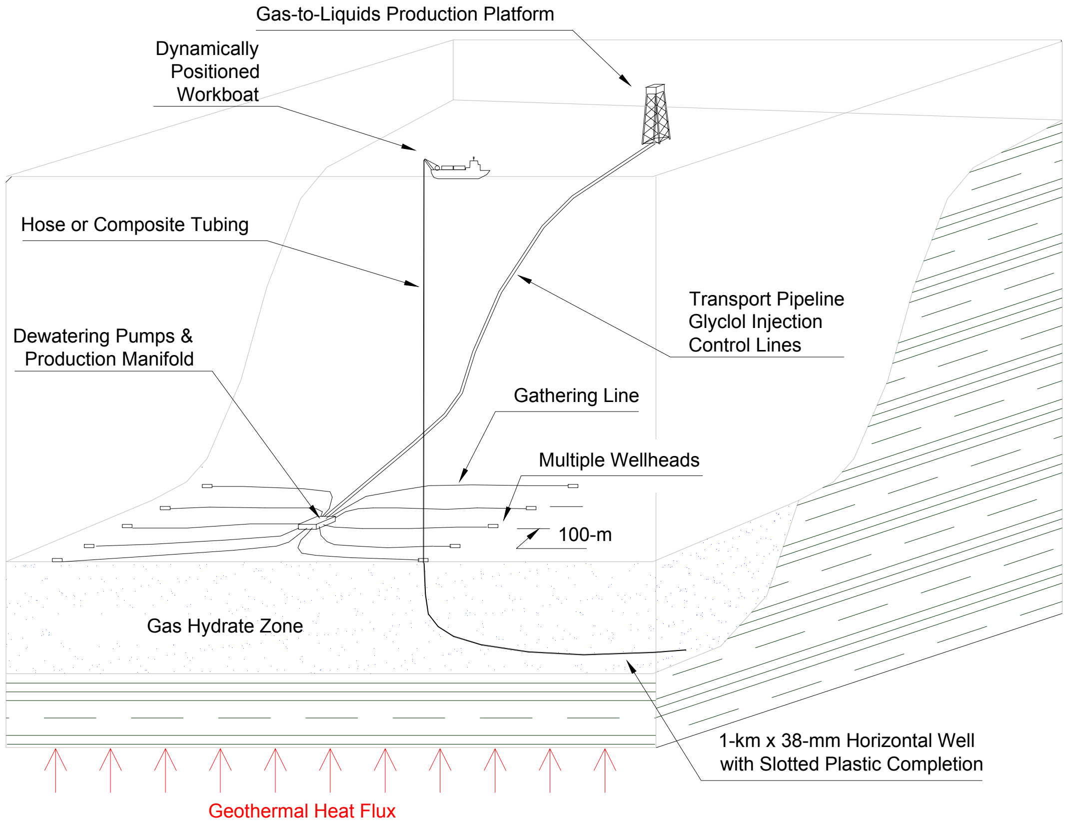

Figure 3. Riserless drilling and production system for gas hydrates.

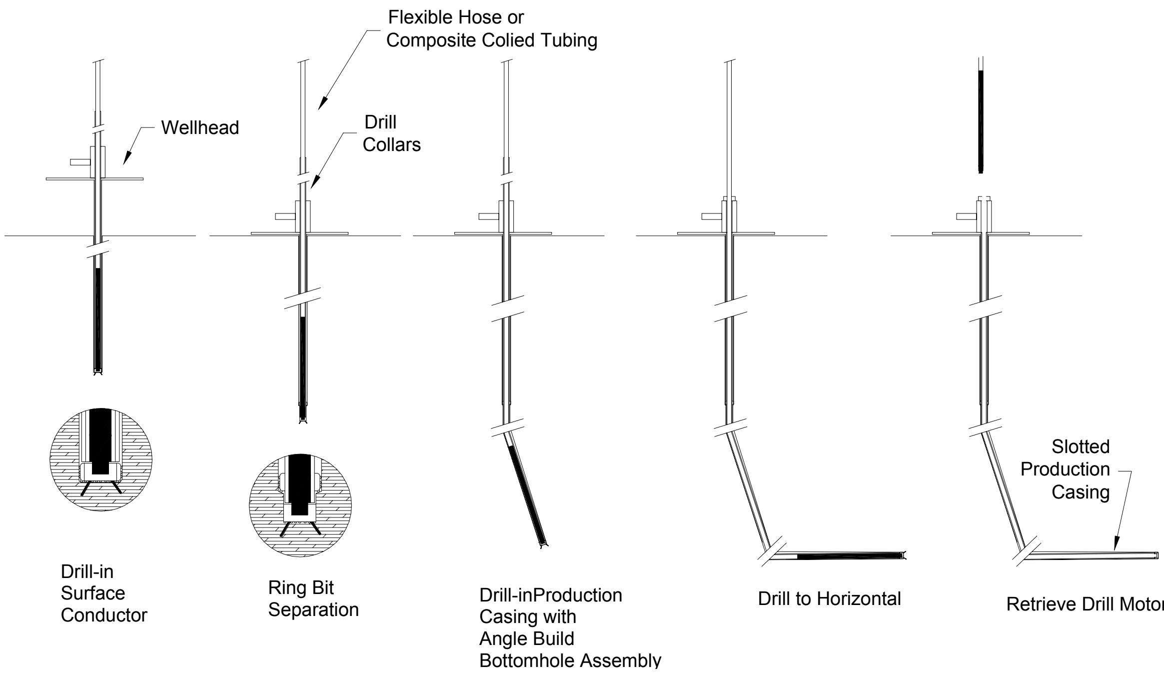

Figure 4. Detail of horizontal well placement using drill-in casing techniques with coiled tubing.

A critical issue facing such a system is well stability in unconsolidated sediments. The presence of hydrates in the surface sediments would stabilize the borehole and there may be an advantage to drilling directly through the hydrate zone. We propose a riserless hose or composite CT drilling drilling system as shown in Figure 3. Seawater/polymer drilling fluid would be pumped through the hose to a section of drill collars mounted above a positive displacement drill motor. The drilling fluid would be cooled to the ambient seawater temperature on the bottom as it approaches the seafloor. During drilling, mud in the hose and annulus would be at a lower temperature than the sediment, ensuring that the borehole will remain stable.

In order to reduce the cost of completing the wells, a drill-in, telescopic casing system technique would be employed. The system would employ drilling casing techniques with ring bits as shown in Figure 4. The drill motor would engage ring cutters on the casing to allow placement of surface conductor and production casing during drilling. Drilling would commence with the wellhead, surface conductor and production casing in place on the drillstring. The initial casing section could be drilled with freshwater drilling fluid to promote hydrate stability around the surface conductor. The surface conductor would insulate and protect the upper hole to ensure a seal during drilling and production. Once the surface conductor penetrates, the wellhead will land on the seafloor. Drilling will continue with the production casing. The casing and drill tubing would be sized to allow drill returns to circulate inside the production casing, thereby preventing drilled returns from contacting the surface conductor. Cuttings would be dumped on the seafloor. A passive, angle-build stabilizer assembly would be employed to cause the borehole to deviate to a horizontal direction beneath the surface conductor. When the well is complete, the drill hose, collars and drill motor would be recovered, leaving the production casing in place. The production casing would be perforated and screened to allow immediate production. The entire hole will need to be cased in order to prevent collapse in the event of hydrate disassociation. Each well would be drilled relatively quickly. Penetration rates of 50 m/hr are easily reached in soft sediments and a 1 km well would require about a day of drilling.

The wells would be drilled to target high porosity, high permeability formations at the base of the HSZ . Since gas reservoir drive pressures are limited by relatively shallow depth and by hydrate formation, production rates from a single well will be relatively low. Hundreds of production wells would be drilled on a relatively tight spacing to recover the gas. Each well would be pre-connected to a gathering line, and wellhead controls consisting of a choke valve and pressure and temperature sensors. The gathering lines would meet at a subsea manifold for tieback to a fixed production platform. Production of gas from hydrates will be accompanied by significant water production. Transport of gas on the seafloor is currently used on the deepwater Mensa platform in the Gulf of Mexico. Satellite production wells are as much as 100 km from the fixed platform. Glycol injection is used required to prevent hydrate formation in the gas flow lines.

A lightweight, composite drill rig could be deployed from a dynamically-positioned workboat at a cost of around $10Kper day. We assume that one boat could drill and complete one well per day. Costs for drilling and production of a single gathering well as follows

Dynamically positioned offshore workboat in the Gulf of Mexico	$10,000
Drilling equipment, supplies and manpower	$10,000
Gathering lines	$10,000
Total	$30,000

The estimated cost per km of gathering well for a simple, coiled tubing drilling system would be on the order of $30,000. In order to recoup the interest (assume 10%) and principal over 3 years for such a well it would have to produce about $13,000 worth of gas per year.

The primary constraint on production of gas from the HEZ is the relatively low value of natural gas. We assume that the gas can be processed into liquids offshore and has a value of $0.1/m^3 ($2.83/Mscf) at the wellhead. Low-cost production would not allow for systems to inject heated water or agents such as methanol to drive the dissociation process. Passive gas production requires dissociation of hydrates by the geothermal heat flux. The heat flux on the continental shelf averages about .07 J/m^2s (Stacey 1965); while the latent heat of dissociating a typical natural gas composition is about 2 MJ/m^3 of gas (Sloan 1990). The steady-state gas production rate would be 3.5×10^{-8} m^3/m^2s. If we further assume a 1 km horizontal well section draining a 100-m wide area, the production would be 300 m^3/day or 100,000 m^3 per year. The value of the gas would be on the order of $10,000 per well per year. This value could justify a low-cost horizontal drilling program.

Conclusions

The development of new, lower cost technologies and approaches is required for economic recovery of gas from offshore hydrates. Low-cost production from gas hydrates will be limited by the rate of gas dissociation. Geothermal dissociation of gas hydrates provides the simplest, and lowest-cost, production technique. This approach will be viable only if the cost of each individual well is extremely low. A workboat-based, riserless coiled tubing drilling system is proposed for this application. Composite coiled tubing would be used to drill-in horizontal production casing a few hundred meters beneath the seafloor. Large numbers of these low cost wells could be tied together to support an offshore production facility and pipeline transport to shore.

Acknowledgements

MDM was supported by the Federal Energy Technology Center (FETC), Morgantown WV (U.S. Department of Energy), funding element DE-AT26-97FT34344, and the Office of Naval Research, Program Element No 0601153N.

References

Adamson, J.E. and J.J. Kolle (1996) "Development of a waterjetting cable burial system for a broad range of soils in up to 2500 meters of seawater," presentation at *Underwater Intervention '96*, Marine Technology Society.

Anonymous, "Coiled Tubing Drilling System" February (1998), *J. Pet Tech*., 50 (2) p. 83.

Brandt, W., Dang, A.S., Magne, E., Crowley, D., Houston, K., Rennie, A,. Hodder, M., Stringer, R., Juiniti, R., Ohara, S., Rushton, S. (1998) "Deepening the search for offshore hydrocarbons," *Oilfield Review*, Spring, pp. 2-21.

Booth, J. S., Rowe, M. M., and Fischer, K. M., (1996) *Offshore Gas Hydrate Sample Database: U. S. Geological Survey Open-File Report 96-272*, 38pp.

Brewer, P.G., Orr, F.M., Jr., Friederich, G., Kvenvolden, K..A. & Orange, D.L. (1998) "Gas hydrate formation in the deep sea: In situ experiments with controlled release of methane, natural gas, and carbon dioxide," *American Chemical Society. Energy & Fuels,* Vol. 12. Pp. 183-188.

Bryan, G.M. & Markl, R.G. (1966) "Microtopography of the Blake-Bahama Region," Columbia University, Lamont Geological Observatory Technical Report No. 8 (*CU-8-66 NOpBSR 85077*), 26pp, 16 figures.

Dillon, W.P., Holbrook, W.S., Drury, R., Gettrust, J., Hutchinson, D., Booth, J. & Taylor, M. (1997) "Faulting of gas- hydrate-bearing marine sediments - contribution to permeability," *Paper # 8296*, Offshore Technology Conference Houston, Texas, 5-8 May 1997, 201-209.

Claypool, G. (1991) Presentation at Gas Hydrates and Ocean Drilling Workshop, Texas A&M University, College Station Texas, March 5-6.

CTES (1996) “Micro Borehole Drilling Platform Study,” *LA-UR 96-4632*, Los Alamos Scientific Laboratory, Los Alamos, New Mexico.

Dillon, w.P., Danforth, W.W., Hutchinson, D.R., Drury, R.M., Taylor, M.H., & Booth, J.S. (1999) *Evidence for faulting related to dissociation of gas hydrate and release of methane off the southeastern United States*, *Geological Society of London, Special Paper*, (11 pp. 10 fig. in press).

DOE. (1998) A strategy for methane hydrates research & development. U.S. Department of Energy, Office of Fossil EnergyReport DOE/FE-0378, 54pp.

Fultz, J.D. and F.J. Pittard (1990) “Openhole drilling using coiled tubing and a positive displacement motor,” *SPE 20459, presented at 65th Annual Technical Conference and Exhibition, New Orleans September 23-26*, Society of Petroleum Engineers, Richardson Texas.

Leising, L.J. and I.C. Walton (1998) Cuttings transport problems and solutions in coiled tubing drilling,” *IADC/SPE 39300, paper presented at IADC/SPE Drilling Conference*, Dallas TX 3-6 March 1998.

Kolle, J.J. (1994) Low-cost drilling system for characterizing marine gas hydrate accumulations. *Proceedings of the fourth (1994) International Offshore and Polar Engineering Conference, Osaka, Japan, April 10-15, 1994*, pp. 333-336.

Kolle, J.J. & Bibee, L.D. (1996) “Deep ocean sensor implantation system,” *Int J. of Offshore and Polar Eng.*, Vol. 6, No. 4, pp. 255-260.

Kvenvolden, K.A. (1993) “A primer on gas hydrate,” in *Howell, D.G. et al. (eds). The Future of Energy Gases*, U.S. Geological Survey Professional Paper 1570, pp. 279-291.

Max, M.D. & Chandra, K. (1998) “The dynamic oceanic hydrate system: Production constraints and strategies” in *Proceedings of the Offshore Technology Conference, 4-7 May 1998, Houston Texas*, 217-226.

Max, M.D. & Lowrie, A. (1997) “Oceanic methane hydrate development: Reservoir character and extraction,” *Proceedings Offshore Technology Conference 5-8 May, Houston Texas*, pp. 235-240.

McGuire, P.L. (1982) “Recovery of gas from hydrate deposits using conventional technology,” SPE/DOE 10832, *Proc. Unconventional Natural Gas Recovery Symposium Pittsburgh PA*, pp. 373-387, Society of Petroleum Engineers, Richardson Texas.

Millan, S.M., G. Cammaert, L. Spracklin and P. van Meurs (1998*) Natural Gas Utilization Study: Offshore Newfoundland*, Newfoundland Ocean Industries Association/ACOA, St. John’s Newfoundland.

Rojey, A. and C. Jaffret (1996) *Natural Gas: Production, Processing and Transport*, Editions Technip, Paris.

SOD (1999) Spearhead Online Directories OCEANSPACE ISSUE 104. Thursday 14 January 1999 <christine.rose@spearhead.co.uk> Information supplied by: <mike.hamilton@gbvgi.mail.abb.com>

Sloan, E.D. (1999) *Clathrate Hydrates of Natural Gas*, Marcel Dekker, New York.

Stacey F.D. (1969) *Physics of the Earth*, p. 240, John Wiley & Sons Inc., New York

Stoll, R.D., Ewing, J., and Bryan, G.M. (1971) “Anomalous wave velocities in sediments containing gas hydrates,” *J. Geophys. Res.* , Vol 76, pp. 2090-2094.

WitteBolle, R.J. and S.C. Sego (1985) “A laboratory facility for testing sediments containing gas hydrates,” Proc. Int. Offshore Mech. and Arctic Eng. Symp., Vol II, ASME, New York, pp. 52-58.