



SUBMARINE METHANE HYDRATES- POTENTIAL FUEL RESOURCE OF THE 21ST CENTURY

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Natural methane hydrates have a potential of being an alternate fuel resource. They occur worldwide in the sediments of continental margins and in polar regions in association with permafrost. Methane hydrates are ice-like crystalline solids, composed of water and gas molecules and *are* thermodynamically stable within a limited range of pressure and temperature. The global amount of carbon stored in methane hydrates is conservatively estimated to be about 10,000 Gigatons, which is nearly double the amount of carbon stored in all known fossil fuel deposits. The presence of methane hydrates within the sediments can largely be detected through geophysical techniques and by non-geophysical proxies. Though harvesting of methane hydrates has not been initiated to date, some interesting ideas have been conceived for the production of methane from hydrates and its transportation to shore. Apart from being an abundant fuel resource, methane hydrates are also a matter of concern, as destabilization of sub-seabed methane hydrates can cause geological hazards and/or release of methane - a powerful green house gas - to the atmosphere. Research on the methane hydrate system may also lead to the development of useful downstream technologies, such as desalination of seawater and sequestering of exhaust-generated carbon dioxide in the deep seabed.

Introduction

The industrial and social changes that engaged mankind during the 20th century, resulted in a rapidly increasing demand for hydrocarbon-based fuels. This increasing demand has been met by increasing the tempo of exploration and exploitation of the vast resources *of* conventional oil and gas. These resources however are neither renewable nor inexhaustible, and we should expect to encounter severe depletion in the not-too-distant future. In this scenario natural gas hydrates appear to be an exciting alternative and, if approached holistically, may become the main and bountiful source of fuel for an energy hungry world.

India is not self sufficient in primary resources with its import dependence for oil increasing with time. In 1985 India produced 70% of her requirements, and though production has gone up since then it is static at about 35 MMT since 1990, which is about 35% of the country's needs. Commercial energy available as on April 1999, showed that India had recoverable crude oil reserves of 660 MMT. Estimated reserves of natural gas are of the order of 648 BCM. Known crude reserves, and natural gas are expected to last for next 22 and 23.6 years respectively at the current rate of production.

However, India also possesses potential of around 850 BCM of coal bed methane, 600 MMT of oil shale and 6,156 TCM of gas hydrates. If these estimates are confirmed by detailed exploration, there will be a major improvement with regard to availability of energy sources for the development of our country.

What are Gas Hydrates?

Sir Humphry Davy discovered in 1811, that gas could be hydrated, when he observed that under certain conditions, water and chlorine form a crystalline substance - chlorine hydrate. However, until the beginning of the 1930's, gas hydrates were looked upon solely as a scientific curiosity, for which there appeared to be no practical use. Gas hydrates caught the attention of industry in 1930's when it was realized that the long distance oil and gas transmission pipelines in the USA were being clogged by formation of gas hydrates within the pipelines. This was the beginning of an experience that changed gas hydrates from a bane to a possible future boon.

Gas hydrates are ice-like crystalline accumulations formed from natural gas and water. The building block of this crystalline solid is a cage like structure [clathrates] in which water molecules form the rigid lattice and the void is occupied by a guest gas molecule. Many gases have molecular sizes suitable to form hydrates, including such naturally occurring gases as carbon dioxide, hydrogen sulfide and several low-carbon-number hydrocarbons. However the most common gas hydrates in nature are methane hydrates. Because of the arrangements of the gas molecules within this framework, gas hydrates can store a large percentage of gas per unit volume. Gas hydrate is thus a gas concentrator; the break down of one unit volume of gas hydrate at standard temperature and pressure produces about 164 units of gas (Kvenvolden, 1993).

In appearance, hydrates are inter-grown, transparent-to-translucent, white-to-grey and yellow crystals, with poorly defined crystal form. Hydrates may cement sediments in which they occur, or they may occur in pore spaces in uncemented sediment grains. Hydrates can occupy a significant percentage of pore space in high-porosity sediments, and can occur in large, contiguous deposits.

Methane hydrates are thermodynamically stable within a limited range of pressure and temperature [P-T] conditions. They exist where suitable P-T conditions and sufficient quantities of gas and water are available in the pore spaces of sediments. Worldwide these sediments are found in polar regions in association with permafrost, and in the deep-water sedimentary basins. Gas hydrates are concentrated at the depocenters of continental margins where both organic detritus [from which bacteria generate methane] and sediments [which protect detritus from oxidation] accumulate rapidly. The worldwide locations of known and inferred gas hydrates are around 48.

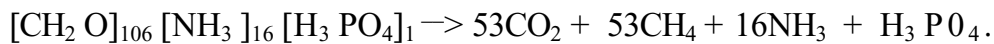
In addition to serving as a kind of reservoir for methane, gas hydrates are also impermeable to free gas so that within the sediments a layer of gas hydrate can trap free gas beneath it. Thus, there are two ways in which hydrates can create deposits of energy gases: (i) by binding gas into hydrates within the sediments and (ii) by creating a trap, using hydrate-cemented sediments as a seal.

The present mapping of worldwide distribution of methane hydrate zones is far from adequate and the technique for proper quantification of the volume of methane

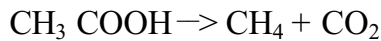
in these zones is yet to be developed. However, it is considered that about 10,000 Gigatons is a reasonable estimate of carbon stored in methane hydrates. This quantum of organic carbon in gas hydrates is twice that in all known fossil-fuel deposits. *Even if a small percentage is recoverable, it will constitute a major stock of energy.*

Formation of Methane Hydrate in Sediments

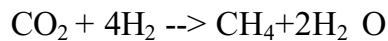
Sub-seabed methane within the continental margin sediments is produced primarily by microbial or thermogenic processes. In the microbial process organic debris are decomposed by a complex sequence (methanogenesis) into methane, by bacteria in an anoxic environment. Organic matter is composed of carbon, hydrogen and phosphorus in the ratio of 106:16:1, and decomposition results in production of methane,



Acetate fermentation, a stage in the decomposition process, also produces methane



Further reduction of carbon dioxide also produces methane



In the thermogenic process, thermal cracking of organically derived materials form petroleum hydrocarbons [including methane]. This generally occurs at considerable depth [$> 2\text{km}$] in sedimentary basins where temperatures exceed 100°C . Thermogenic methane may also be derived by thermal degradation of oil at even greater depths, and by the maturation of coal.

Gas Hydrate Stability Zone: The occurrence of gas hydrates in nature is controlled by an interrelation between temperature, pressure and composition, and thus there exists a minimum depth below which hydrates will be stable. This minimum depth is about 300 m for colder Arctic waters, and about 600 m for warmer sub-tropical regions.

In deep-sea sediments, temperature normally increases with depth and eventually reaches a point at which hydrate is unstable, despite the continued increase of pressure with depth. Thus a zone within the sediments exists in which gas hydrate is potentially stable from the seafloor down to a depth, commonly from a few hundred to a thousand meters below the seafloor. The thickness from the seafloor down to the base of the gas hydrate stability is considered to be the theoretical thickness of the gas hydrate stability zone [GHSZ], where hydrate will form if methane saturation exists within this zone.

It has been assumed that the structure of the gas hydrate layer is simple - that its thickness should gradually increase on moving to deeper water because gas hydrate becomes stable at higher pressure - temperature conditions. This assumes that pressure is a simple function of total depth [water and sediment], and the chemistry of pore waters and the thermal gradient are fairly uniform.

Formation of Methane Hydrates: After generation, methane in sediment can be transported through the movement of pore-water containing dissolved gas, free gas flow, and/or molecular diffusion. When ascending, methane molecules reach favorable conditions when hydrate will form within the pore spaces of sediments in the presence

of water molecules. Thus biogenic methane formation may take place both in situ [within the hydrate stability zone] and beneath it, whilst thermogenic methane must be formed below the HSZ, and move up into it. Geo-chemical and isotopic techniques are used to identify the biogenic or thermogenic origin of the methane. Hydrate progressively fills and cements the sediment pore-spaces and fractures, giving rise to massive and vein type hydrate deposits.

The temperature and pressure conditions for hydrate stability depends on the composition of the gas and on the presence of salts and other components in seawater. It is generally believed that pore water has to be fully saturated with methane before natural hydrate can form. This condition can be met by (i) supply of sufficiently large amounts of organic matter in the sediments to generate enhanced methanogenic decomposition, or (ii) large upward methane fluxes, mostly related to fault zones, or other conduits such as diapirs, mud volcanism etc.

Free gas below hydrates: Free gas is often mentioned in the context of methane hydrate deposits. This free gas refers to methane molecules that exist as gas, which are neither bound to other molecules [as in complex hydrocarbons] nor trapped within a hydrate. More commonly, free methane in a geologic formation exists within the pores of low-density rocks. Any hydrate layer may trap free methane as long as the layer forms a seal through which gas cannot migrate. The free methane may be thermogenic gas that has migrated upwards from the earth's crust, or it may be biogenic gas that was previously a hydrate layer but has now melted.

Indicators of Gas Hydrates in Sediments

The presence of gas hydrates, within sediments, manifest in various ways, most commonly through acoustically derived geophysical data. Non-geophysical proxies can also provide some indication on the occurrences of gas hydrates.

Geophysical indicators

The presence of gas hydrates, over large areas, can be efficiently detected through seismic reflection profiles (Dillon et al, 1993,) most commonly through the presence of an anomalous acoustic signature known as Bottom Simulating Reflection [BSR]. The Carolina Rise, over the Blake Ridge, was the area where gas hydrate was first identified (Markl et al, 1970) on the basis of a BSR. Two other manifestations in seismic profiles that are more unique to hydrates are amplitude blanking, and velocity inversion.

Bottom Simulating Reflections [BSR]: Bottom simulating reflection is the anomalous reflection seen on marine seismic records indicating the position, in the sediment column, of the base of the zone of gas hydrate stability. Solan (1990) observed that sediments impregnated with gas hydrates produce a high velocity section [approximately 3.3 km/sec, about twice that of sea floor sediments], whilst if water saturated, they have lower velocities [water velocity is about 1.5 km/sec.]. The velocity is further lowered even with a small percentage of trapped gas. As the phase boundary sets a distinct limit to hydrate occurrence, the base of the hydrate-cemented zone is expected to produce a very strong reflection. Since the base of the GHSZ occurs at approximately uniform sub-bottom depths over a small area, the reflection from its base appears roughly parallel the sea floor.

Other criteria used to characterize inferred BSRs are (i) reversed polarity of the seismic wavelet relative to the reflection from the sea floor [equivalent to a negative reflection coefficient] at the BSR, and (ii) frequent crosscutting by the BSR of the seismic reflections from bedding planes, indicating that it is not a bedding plane reflection.

Not all BSR-like reflections necessarily arise from gas hydrate formations. In some cases, these acoustic features may also result from temperature-controlled diagenetic effects. As an example, samples from the Deep Sea Drilling site 185 indicated the presence of only methane in the sediment with no evidence of gas hydrates, even though BSR-like features were detected. This anomaly was attributed (Kvenvolden, 1987) to a lithologic transition from hemipelagic diatom ooze to indurated claystone. Since a BSR represents an acoustic velocity contrast in the sediment, it is not necessary that all BSRs reflect the existence of hydrates. Similarly a BSR may not always be discernible when a hydrate is present. Nonetheless, coincidence in depth of the BSR with theoretical conditions, coupled with in situ sampling of hydrate above the BSR, gives confidence that this seismic indication of hydrates is dependable.

Amplitude blanking: The amplitudes of seismic reflections from within the GHSZ are generally much lower in the area of an observed BSR. Such reduction of the amplitude of seismic reflections caused by hydrate cementation of the sediment is known as blanking. Reflection amplitudes below the BSR are higher than above the BSR. This phenomenon consistently appears in sediments containing gas hydrates, making amplitude blanking a useful seismic attribute in hydrate location (Lee et al, 1993).

Velocity inversion: A third characteristic of gas hydrates is the abrupt decrease in acoustic velocity across the boundary between hydrate-cemented sediments above the BSR, and non-cemented sediments below that may be water gas-filled. This downward velocity decrease, known as an inversion, is detectable with some seismic techniques. The BSR and velocity inversion are related only to the bottom boundary of the hydrate zone, whereas the top of the hydrate zone [within sediments] does not produce a sharp reflection as it has no such precisely defined boundary.

Non-geophysical proxies

Apart from the acoustic geo-physical signatures, several geological and biological parameters may be useful tools for reconnaissance.

Chlorinity anomalies in pore water: During gas-hydrate formation process, salt ions are excluded from the crystal structure, and only water molecules crystallize into a cubic lattice structure. This excluded salt increases the pore-water chlorinity in the host sediments initially (Kvenvolden, 1998). With time, this high salinity pore water diffuses back to ambient levels. When the hydrate is decomposed, the freshwater released from the lattice dilutes the salt content of the pore-water causing the chlorinity to decrease drastically. Though the chlorinity anomalies of the pore-water can be an useful indicator of hydrate presence, they also can be generated by fluid flows. Nevertheless, such fluid flows generally induce hydrate formation.

Sediment grain size parameter. In many of the deep-water ODP and DSDP bore well hydrate records, the occurrences of the gas-hydrates were generally associated

with coarse textured sediment. Thus, grain-size parameters of the sediment may be useful to qualify the likelihood of hydrate deposit.

Benthic biomass: The melting of hydrate at depth generates methane, small amounts of hydrogen sulfide and ammonia, and fresh water. These gases oxidise to form carbon dioxide, sulfates and nitrates - rich nutrients for chemosynthetic bacteria such as methanotrophs. These bacteria are harboured within a group of deep-sea organisms known as pogonophorans, and form the base of the benthic food web in these conditions. The occurrence of vestimentifera, tubes or calm colonies on an otherwise sparse sea-floor are therefore visible clues of buried hydrates at depths when methane is either oxidised or reduced. Both the oxidation and reduction of methane release CO₂ which reacts with the calcium in sea-water, precipitating carbonate slabs and nodules that are usually enriched in the light carbon isotope.

Gas escape features on the sea floor: In many parts of the world's ocean, high resolution acoustic investigations of the sea floor have indicated the presence of exposed and buried pock marks. Most of these pock marks are considered to have been caused by escaping gas. Some of these gas-escape features are related to the release of methane from hydrate dissociation during a perturbation in the pressure / temperature regime. These features could be used as additional exploration indicators.

Other features such as mud diapirs, bacterial mats and methane-derived carbonates were also reported on the sea-bed in hydrocarbon rich sedimentary basins in numerous parts of the world. These features are considered as evidence of gas seepage activity, and as additional exploration indicators in hydrate rich regions.

Some Techniques for Exploration of Methane Hydrates

Indirect geophysical approach

The objectives of methane hydrates exploration are to locate zones of hydrates and any underlying free gas, and to quantify the prospect. The indicators described earlier, seen on conventional near-normal seismic reflection records, can satisfy velocity models for average structures. Data enhancement and analysis techniques have focussed on more precisely determining the nature of the sub-surface methane, and quantifying the prospect. The emphasis of these techniques is on precise velocity determination from the different methane hydrate and gas bearing structures.

Data enhancement and analysis techniques: Acoustic impedance is the product of velocity and density, and reflection strength at an interface is proportional to the change of impedance across the interface. Bulk sediment density changes only marginally whether impregnated with water, or cemented by hydrates or containing interstitial gas. We therefore need to look at how velocity changes with sediment constitution.

The increase or decrease of velocity in sediments depends upon the degree of saturation of the sediment pore spaces by hydrate or free gas respectively. Information about the seismic velocity across the BSR therefore provides indication about the hydrate and gas concentration. Estimation of the amount of hydrate can be done in two steps. Firstly, the increase in velocity in the hydrate bearing sediments is determined with respect to a reference velocity-depth profile. This is then converted to hydrate concentration using a theoretical or laboratory based relation between velocity increase

and hydrate concentration. Seismic data enhancement and analysis techniques for hydrate research, focuses on deciphering the high-resolution velocity anomalies and other elastic properties above and below BSR.

AVO analysis: Early velocity models were based on the assumption that BSRs arose from the impedance contrast between partially hydrated sediments and partially gas saturated sediments. It is now accepted that there are several other combinations of this model, including well hydrated sediments with little or no free gas below; or little hydrate with considerable free gas below; or even a combination of both. In order to distinguish between the different possible combinations, researchers have used the amplitude versus offset [AVO] analysis.

The characteristics of the reflection AVO can be an important indicator of the sediment physical properties, since AVO depends on the variation of the S-wave as well as the P-wave velocities across the reflection interface. The major controlling elastic parameter for the AVO analysis is the Poisson's ratio of the medium (Lee et al., 19%). Theoretical AVO analysis suggests that (i) even small amounts of free gas in sediments cause substantial reduction in the P-wave velocity as well as in the Poisson's ratio, such that the BSR reflection amplitudes increase with increasing reflection angle or offset and, (ii) the Poisson's ratio of the hydrated sediments decreases as the hydrate concentration increases and porosity decreases.

Since Poisson's ratio is a function of the hydrate concentration, different types of AVO anomalies can exist for a BSR reflection. Amplitude decreases with increasing angle of incidence [negative AVO] for high hydrate concentration, and increases with increasing angle of incidence [positive AVO] for low hydrate concentration.

AVO analysis of the BSR amplitude can be used for estimating the hydrate concentration in sediment and to provide indication of the presence of underlying free gas zone. AVO analysis alone can not uniquely define the different structure models across the BSR, nor can the AVO technique define the upper and lower boundaries of the free gas zone. For this, the technique of wave form inversion is used.

Wave-form inversion: Waveform inversion of reflection data is an iterative modelling methodology by which reflected data is simulated through different velocity models until it matches the real data at the BSR over all offsets. Waveform inversion can be used to distinguish the models and provide tighter constraints on the thickness of a gaseous zone beneath the BSR.

Non-geophysical proxies

It is not always possible to observe natural gas hydrates directly in tropical conditions, because they may decompose during recovery of samples from the seafloor. Methane however can also occur as dissolved gas in sediment pore fluids and adsorbed on particulate matter. Thus proper thermal and mechanical handling and storage of the sample is essential not to alter the gas content of a sediment sample. Methane analyses techniques have to consider these influences.

There are three proxies that provide more or less reliable evidence of hydrates in cores, if these can be collected and stored under in situ conditions for later analyses.

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Proxies: Pore water chemistry is studied at various intervals of the core. The entire core can also be studied for textural parameters and microbial signatures. Water samples should also be tested for methane proxies.

Recently, carbonate crusts have been found on the continental margin seafloor in association with methane-bearing cold water seepages and are suspected to be related to dissociation of gas hydrates. Carbonate lenses encountered within the sedimentary sequences may indicate methane seepage to the seafloor in response to massive decomposition of gas hydrates.

Total bacterial numbers and bacterial activity rates also need study since bacteria plays a dominant role in the degradation of organic matter within the sediments, driving chemical changes and early diagenesis.

Harvesting Methane Hydrates - Some Ideas

Recovering methane and economically transporting it, pose a challenge to technologists and scientists. Ideas have been conceptualized and research mounted to address these challenges.

Production and recovery of methane: The key problem in the production of methane from the hydrate layer will be dissociation of in situ hydrates. Tapping the free methane below the gas hydrate zone is another possible source. Three processes have been proposed for dissociation of methane hydrates: thermal stimulation, depressurization, and inhibitor injection.

In the thermal stimulation process, heat energy can be released into the methane hydrate strata to dissociate the gas. This process has a favourable net energy balance, as the heat energy required for dissociation is about 6% of the energy contained in the liberated gas. In simple terms steam or hot water can be pumped down a drill hole to dissociate the hydrate and release methane. The released methane could then be pumped to the surface of the seafloor through another drill hole.

In the depressurization process, the hydrates are exposed to a low-pressure environment where they are unstable and decompose to methane and water. The heat energy for the process comes from the earth's interior [geothermal heat flow]. The released methane can then be recovered by conventional technology. The depressurization method as envisaged involves horizontal drilling in the underlying free gas zone. As the free gas is removed, the overlying hydrate depressurizes and decomposes into free gas. Continuous removal of gas is expected to sustain this pressure-induced dissociation of hydrate zone at its base. This method appears to be most suited to those deposits where widespread gas occurs in a closure below the hydrate cap (Max and Cruikshank, 1999).

In the inhibitor injection process, an inhibitor such as methanol is injected into the gas hydrate zone. Chemical inhibitors shift the pressure-temperature equilibrium so that the hydrates are no longer stable at *in situ* pressure-temperature condition, and hydrate dissociates in the contacted surface.

Of these three production methodologies, the depressurization combined with the thermal stimulation process appears to be the most practical for zones where free gas is trapped beneath the methane hydrates.

Transportation of gas to shore: Transporting methane from the production site to the shore could be through submarine pipelines as is done for long distance transportation of natural gas. However, submarine pipelines are expensive and the geological hazards of the continental slope [avalanches] make this option difficult. Other alternatives such as liquifying the gas on ship or drilling platform can also be considered. One procedure involves burning part of the methane to get hydrogen and carbon monoxide, which can then be catalytically converted to liquid hydrocarbon. However, 35% of energy is lost in this process. Another method involves reacting the methane with water on the seafloor to obtain hydrate free from sediment. This pure hydrate then can be stored in zeppelin shaped storage tanks and towed to shallow water infrastructure where they can be safely decomposed into water and gas in a controlled environment.

Methane hydrate will be commercially exploited only when the price of petroleum oil and conventional gas rises substantially. The apparent abundance of conventional hydrocarbon deposits and their relatively low prices are inhibiting research into various aspects of gas hydrate. Research and development activities in this field need to be sustained. Hydrate recovery will in all probability involve forced dissociation, which will involve significant demand for heat. Supplying and managing this heat and maintaining an artificial thermodynamic balance that allow the controlled dissociation of hydrate and the safe recovery of methane will probably prove the key to commercialization.

Gas Hydrate R & D : Possible by-products

Apart from using methane hydrate as a source of fuel energy, research in the methane hydrate system may also catalyse several other direct and indirect uses of the methane hydrate or the process by which hydrates form.

Desalination of sea-water. It was suggested that if sea-water is combined with a hydrate former [for e.g. methane] in a suitable pressure temperature controlled vessel, then hydrate will form. The brine can be separated from the hydrate and the hydrate then be allowed to disintegrate. This hydrate disintegration will yield fresh water and hydrate former. The hydrate former can again be returned to the system for continuing hydrate formation with sea-water.

Storage of CO₂: Carbon dioxide from the environment can be converted into hydrate in deep-sea environmental condition and stored there till dissociation back in terms of CO₂ in geological time scale. This subject is the basis of much debate and speculation.

Separation of gaseous mixtures: In this programme, the process of hydrate formation was considered for separating gaseous mixtures. It was demonstrated that using the differing tendencies of gases towards hydrate formation, good separation factors can be obtained by allowing the gaseous mixtures to form hydrates.

Electricity generation from flowing gas: One interesting possibility has also been conceived for energy generation while transporting methane from deep sourced hydrates to shore through pipelines. A pipeline to a land based terminal will have a large pressure gradient that could conveniently be dealt with by stage decompression. The gas/fluid in the pipeline can be used for driving turbines for electricity generation. This would accomplish the dual objectives, reducing flow velocity through the transfer of kinetic energy and producing electrical current.

Methane Hydrates - Some Aspects of Concern

The significance of methane hydrates lies mainly in its tremendous resource potential. Even a small percentage of the estimated global resource, if exploited, can meet the requirement of the world's energy demands for centuries. Methane hydrates are located in the shallow submarine geo-sphere, which is a finely balanced system in equilibrium with all its components such as sediment, pore-water, fluid flows, pressure, temperature, overlying water, hydrate etc. *Removal of any one component of this equilibrium may destabilize the whole system leading to irreparable damage.* The destabilizing factors may be either natural perturbations or perturbations associated with exploitation. Studies have indicated that methane hydrates have the potential to affect global climate and the geological environment at a catastrophic scale. Some of the perceived impacts of this destabilization are described below.

Impact on global climate : The earth's atmosphere has a large number of sources and sinks for methane including gas hydrates which exist in metastable equilibrium with the environment. This equilibrium is affected by natural changes in pressure and temperature. The amount of methane that is trapped in gas hydrates is perhaps 3000 times the amount in the atmosphere and this enormous quantity of methane is available for release with catastrophic consequences for global climate. Some of the postulated ways by which this methane could have been released from these reserves to the atmosphere in the past are : (i) escape from gas hydrate zones as a result of thermal decomposition caused by climatic warming, (ii) escape from gas hydrate zones due to the upward shift of the base of the hydrate stability caused by pressure decrease related with lower sea level during glaciatioh; and (iii) large-scale catastrophic release in association with widespread slope instability.

Gas hydrates have been linked with environmental problems mainly because methane is a potent greenhouse gas with a potential about 10 times that of carbon dioxide. These figures underline the potential role which hydrates could play in amplifying or damping temperature changes.

It has been postulated that the Pleistocene global climate changes may have caused methane released from gas hydrate deposits, but the opposite may have been true, i.e. methane released from gas hydrates might in turn have caused changes in global climate. The study of ice core records of the past 200 Ka suggests that atmospheric carbon dioxide and methane decreased gradually at the initiation of glaciation, but increased rapidly with deglaciation. It is interesting to note that, the rapid climate change in the past from the glacial to interglacial is indeed attributed to the huge release of methane from gas hydrates. Some of the models (Kenett et al, 2000, Blunier, 2000) linked these observations with climatic change caused by hydrate decomposition

or vice versa. Accordingly, glaciation and/or sea level fall will reduce hydrostatic pressure on the sediments of shelf and slope at mid-latitudes, thereby destabilizing hydrates and consequently releasing methane into the atmosphere. The methane so released will cause rapid warming which will lead to dissociation of hydrates in the permafrost regions and shallow continental margins of the high latitude regions, a positive feed back causing further warming. Consequently ice in the higher latitude will melt thereby increasing sea level. This rise in sea level will in turn increase the hydrostatic pressure on the sediments of shelf and slope at mid-latitudes, initiating a negative feed back that inhibit further release of methane from hydrates.

The potential connection, between the gas hydrate reservoir and the earth's climate is little understood and the quantitative contribution of different elements in this complex loop need to be established through further research. It may not be amiss to mention here that this lack of understanding between gas hydrate reservoir and the earth's climate could be an even bigger inhibitor on hydrate exploration than present low oil prices and lack of funding support for hydrate research. The balance may lie between mounting intensive campaigns on climate research and safety procedures on the extraction and use of gas hydrates.

Impact on geological environment: Submarine sediment slumping or sliding occurs when huge piles of unstable sediments build up. In some cases movement of these sediment slumps or slides can possibly be caused by the decomposition of gas hydrates and the resulting expansion or release of gas. In the continental slope area, continued sedimentation may lead to burial of hydrated sediment to such a depth, that the hydrates are no longer stable and dissociate into liquid-gas-water mixture. The dissociated hydrates create a zone of weakness in the sediment where slope failure could be triggered by further *gravitational loading* or earthquakes. Similar slope failures may also occur because of changes of pressure and temperature resulting from fluctuations in sea level or bottom water temperatures, such as those which took place during the Pleistocene epoch. These changes, though of long duration, may have caused solid sediment to become gas-cut mud and resulted in mud diapirs, mud volcanoes, mud slides or turbidite flows, depending on sediment composition and bottom topography.

Hazards of drilling : Drilling for recovery of methane from the hydrate is a challenging task because of the characteristics of the hydrates especially, its unstable nature with change in pressure temperature conditions. Hydrates may dissociate during the process of drilling and initiate a process of uncontrolled gas release and site subsidence.

Baseline data and monitoring: The possible short and long term impacts of large-scale hydrate exploitation on the geological environment and global climate need to be studied to develop safe standardized procedures for exploration and production before attempting to exploit this resource. It is also necessary to systematically collect base line information on related environmental indicators and continuously monitor short and long term effects on them. Perturbations associated with exploiting methane hydrates need to be analyzed by careful modeling and techniques have to be developed to avoid or mitigate them.

Realising Gas Hydrates - Some Consequences

Economic factors: Most methane hydrate deposit locations were discovered serendipitously when scientists looked anew at existing seismic data. These initial efforts did not require much expenditure. As the number of finds increased, knowledge about various aspects of oceanic hydrates also increased and scientists began realising its immense potential as a fuel resource. The challenges of its exploration and production and its probable impact on global climate and the geological environment became clearer. Policy makers are gradually recognising the long term potential of marine methane hydrates as well. It appears however that the complexities and challenges for exploration and production of methane hydrates from the hostile and difficult marine environment require considerable focused R & D effort in various fields, for which adequate financial support is lacking. This is perhaps due to the perception that methane hydrate exploitation will be economically viable only when the price of conventional hydrocarbon and other fuels rises substantially.

On the other hand, many hydrate deposits are located on continental slopes not far from major markets in industrialised countries. Countries that have strong economic bases, or are witnessing high industrial growth rates, but have low energy resource potential, could potentially become energy independent, an event that would affect international affairs, foreign policy and other interrelations. The repercussions would extend to world trade, regional power equations, and foreign currency balance of existing major importers, when gas hydrate begins to be exploited. The realisation that such a situation could come about has lately generated some interest in the field of gas hydrate research in many countries recently. It is expected that the prospect of energy self reliance will catalyse some of these countries to initiate harvesting methane hydrates as soon as scientists and technologists come forward with dependable, safe and cost effective mechanisms to explore and exploit this resource.

Technological factors : Lack of suitable production technology was a major impediment in exploitation of this resource. However the past five years has witnessed a dramatic improvement in drilling technologies for oil and gas in deep water areas, where hydrate deposits occur. There has also been a distinct reduction in deep-water development costs. All these are positive factors for hydrate exploration and development. Much of the engineering required to exploit these deposits can be achieved by suitably adopting proven technology currently used in connection with exploitation of deep-water oil and gas reserves. However as exploitation is not expected in the near future, the corporate sector is not willing to venture into this field. At present, whatever research is ongoing is mostly supported by governmental sources. The industry view is that when hydrate development is required, challenges will be met, just as industry has mastered other difficult environments in energy resource development.

One interesting outcome of R & D in gas hydrates has been the identification of several possible uses of gas hydrates other than as fuel. Since the benefits from those uses are quite significant, the importance of gas hydrate is increasing. If continued research can find an increasing number of such alternate uses, the economics of exploiting methane hydrates will improve and such activities will gain momentum.

Prospects of *gas hydrate research* : The first National U.S. Gas Hydrate Workshop in 1991 brought together government, industry, and academic research interests and proposed that research into hydrates should take place as a broad, integrated research program. Presidential consent was given to the Methane Hydrate Research and Development Act of 1999, with \$5 million in research funding (Lowrie and Max, 1999) for the Year 2000 and about \$46 million until Year 2004.

The government of Japan established a national hydrate research program, and in 1998 the Japan National Oil Corporation [JNOC] sponsored test drilling of known hydrate deposits, and drilled test wells in two locations in 1999. Commercial production is targeted for 2010, barely 10 years away. Only one tenth of Japan's estimated reserve would suffice it for 100 years. The Japanese New Energy and Industrial Technology Development Organisation is expected to develop methane recovery engineering.

India, in 1996, was the second nation to establish a gas hydrate research program. The Oil Industry Development Board of India, as part of its plan to boost natural gas resources, is funding a program of methane hydrate research. The early research was carried out under funding of the Gas Authority of India Limited [GAIL]. Later several others such as the Oil and Natural Gas Commission [ONGC], Directorate General of Hydrocarbons [DGH], in collaboration with research institutes - National Institute of Oceanography [NIO], and National Geophysical Research Institute [NGRI] have begun a systematic appraisal of the Indian continental margin for methane hydrates. Several promising locales have been identified for intensive exploration.

Other nations are also conducting assessment of deep-water hydrocarbons, including hydrates. Canada is revitalising its program, and the European Union has allocated funds for development of methane sensors, specialised hydrate coring apparatus, and marine research to identify hydrate and quantify methane prospects in European North Atlantic waters.

The NIO has recently declared its intention to start a Centre for Hydrate Research, with a committed funding of Rs 1 crore for 3 years. The Centre will have a formal structure for identifying topics of interest, and a review mechanism. Recently, the NIO along with its sister laboratory NGRI, presented the case for an unified national effort in this direction. There is now a realisation at the decision makers level that research on hydrates needs to be a parallel activity along with preliminary ground truth collection. The aspects of climate concern are also realised. Most important is an appreciation for the need to focus in one area, as a sort of reference site, the way the Blake Ridge has been studied.

Conclusion

An enormous amount of methane is sequestered in the shallow geosphere, even a small percentage of which could meet the energy requirement of the world for centuries. Gas hydrate research has opened a new frontier in ocean and earth sciences that crosses many disciplinary boundaries.

Scientists believe many other hydrate deposits, which cannot be detected with available exploration techniques, are bound to exist. Improved techniques for detection

of hydrates and an assessment of its abundance could influence the hydrocarbon industry to take an interest in exploration and exploitation of this resource.

Methane hydrates will most likely constitute an important environmental and geological hazard. It is required to determine their geographical distribution, quantify their abundance in subsurface environments and fully understand their response to environmental perturbations.

It may be the right time to consider some global regulatory mechanism for exploration and exploitation of this complex energy resource, by various nations and organizations. Incorporated in the proposed regulations, among other things, should be descriptions of possible hazards and their impact on the marine environment, measures for the prevention, reduction and control of such eventualities, program of oceanographic and environmental data collection and monitoring and mandate for dissemination of relevant information and sharing of experience with the world scientific community.

Insight about many aspects of methane hydrate system perhaps can be obtained through laboratory experiments or computer simulation modelling. Such studies should also be carried out in parallel with data collected through field investigations. Neural network based modelling of the geological environment and processes may have to be developed as a viable exploration aid.

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