

Perspectives for the development of gas-hydrate deposits

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Large reserves of natural gases in the hydrate state are concentrated in the cryolite section of the earth's crust and on the sea-floor. Gas in such deposits is combined with water in a solid state. These deposits require unconventional methods of development. The presence of hydrate formation conditions on the sea-floor and on land have, to a large extent, helped to conserve and concentrate the hydrocarbon fuel on our planet.

The tremendous gas reserves in the hydrate phase, which amount to tens of trillions of cubic metres on land and tens of thousands of trillions of cubic metres beneath the oceans, require thorough multidisciplinary investigations and the development of effective means of detection. The question of prospecting and development of free hydrocarbons concentrated in the region between the arctic shelf and the exposed continents, and beneath the hydrated impermeable cover which extends along the whole arctic coast, is of particular importance.

De vastes réserves de gaz naturel sont concentrées sous forme d'hydrates dans la partie gelée de la croûte terrestre et sur le fond marin. Dans ces gîtes, les gaz se combinent à l'eau sous une forme solide. Le développement de ces gîtes exige des méthodes non conventionnelles. L'existence de conditions favorables à la formation d'hydrates sur le fond marin et sur les continents a, dans une certaine mesure, favorisé la conservation et la concentration des hydrocarbures sur notre planète.

Pour explorer les immenses réserves de gaz conservées sous les océans sous forme d'hydrates, et constituant des dizaines de trillions de mètres cubes, il faudra effectuer des investigations pluridisciplinaires détaillées, et mettre au point des moyens efficaces de détection. On cherche surtout à savoir comment prospector et exploiter les gîtes d'hydrocarbures libres concentrés dans la région entre la plate-forme arctique et les continents exposés, et au-dessous de la couverture imperméable hydratée qui s'étend tout au long de la côte arctique.

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Introduction

At the present stage of development of human society, one of the factors defining any country's progress is its energy supplies and the state of its supply and consumption of fuel. The world energy consumption for the last eighty years has increased tenfold and, by the beginning of the next century, it will have doubled again, while the specific biological energy consumption practically has not changed.

The world consumption dynamics are derived from several different energy sources (Figure 1). A hundred years ago people used coal, wood, and other vegetable fuels as the sources of energy. The second half of this century is characterized by preferential use of oil and natural gas in the world energy balance, especially in the industrial countries. In 1900, the oil and natural gas portion in the world energy balance did not exceed 3 per cent, by 1950 it was 40 per cent, and by 1960 it was 65 per cent.

It is interesting to follow the change in energy sources used in the world. In 1800, the main source of heat was wood and agricultural waste material. At that time, the coal portion in the world energy balance was only 5 per cent; however, by 1888 it was already 50 per cent, and, by 1925, it reached its maximum (74 per cent), after which oil and natural gas began to take over from coal in the energy picture.

The oil portion at present has reached its maxi-

imum, and in spite of a continued increase in absolute oil production, the oil portion in the energy balance will decrease while the natural gas portion will increase during the next several decades until, by the year 2000, it will exceed 50 per cent (oil portion will be 30 per cent). At the same time, the total energy produced from natural gas by the year 2050 will be roughly twice that produced from oil.

Currently, parallel with the production of raw energy minerals, some countries are studying effective

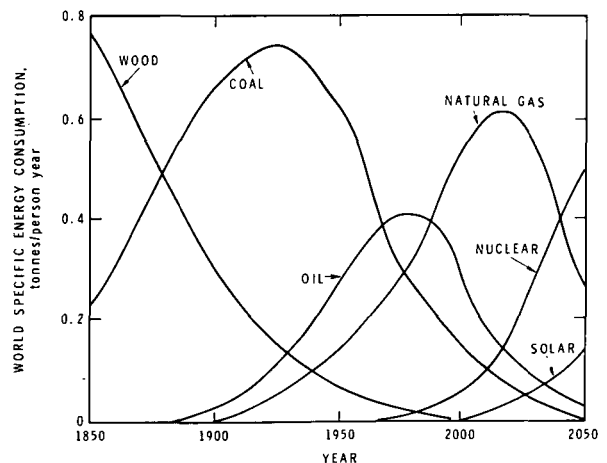


FIGURE 1. Specific world consumption of different energy reserves.

methods of production and utilization of new natural sources based on nuclear, solar, and other kinds of energy. At the same time, oil and natural gas will remain as the main energy consumption sources in this decade.

In the last decade, the increased rate of energy production has been considerably higher than the rate of increase of new proven hydrocarbon resources, resulting in a serious energy crisis in some countries.

For this reason, one property of natural gases, discovered by the Soviet scientists (Makogon 1965, 1966; Vasil'ev *et al.* 1970), of combining with water to form the gas-hydrate deposits in the earth's crust under specific thermodynamic conditions, has received widespread public attention.

The hydrates are formed by practically all known gases (except hydrogen, helium, and neon). Equilibrium conditions of hydrate formation of some gases are shown in Figures 2 and 3. The hydrates are formed in the earth's crust under corresponding conditions.

Hydrate Formation Zones

The hydrate formation zone (HFZ) is a zone of sedimentary rock saturated with water and gas in

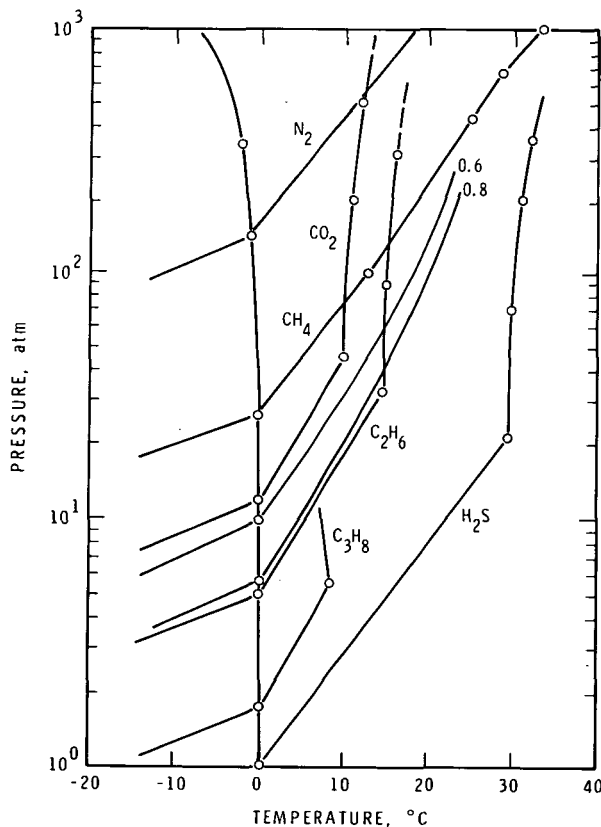


FIGURE 2. Equilibrium curves of gas-hydrate formation.

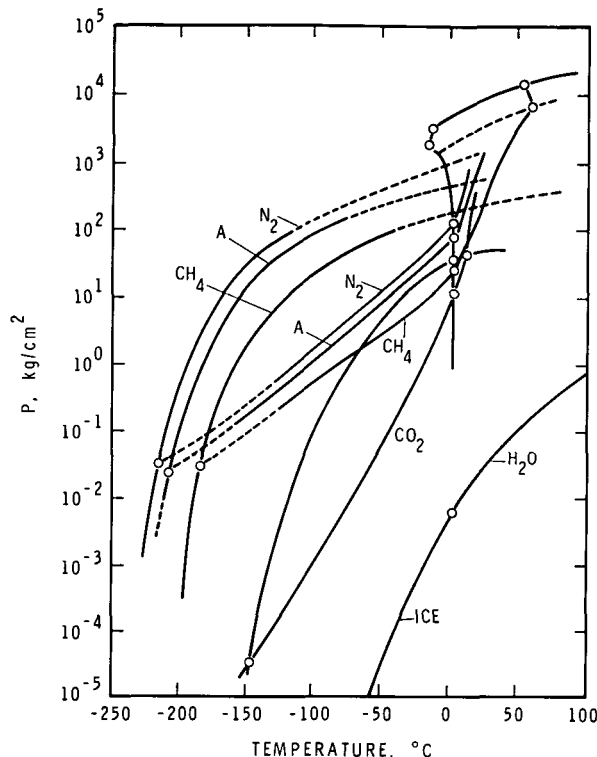


FIGURE 3. Vapour pressure and equilibrium curves of hydrate formation of individual gases.

which thermodynamic conditions are suitable for hydrate formation. The HFZ thickness is determined by pressure, temperature, gas composition, and mineralization of reservoir waters.

Different zones of formation at average temperatures on our planet are outlined (Figure 4). An average annual temperature over the planet surface of above 15°C would be accompanied by the destruction of all glaciers and cryogenic zones on the planet. A temperature decrease from 15°C would lead to the intensive formation of glaciers and permafrost zones on the continents while a temperature decrease below 12°C would lead to the progressive formation of thick ice in the oceans.

The average annual temperatures on the Earth's surface have fluctuated considerably for the period of its existence (Figure 5). The first glaciers on the present continents were found to occur in the Lower Proterozoic, 2.3 to 2.5 × 10⁹ years ago. Then, a fall of temperature was repeated cyclically several times. The last large glacier formation began 2 × 10⁶ years ago.

The hydrate formation process significantly affected the concentration and conservation of hydrocarbons in the sedimentary cover of the earth's crust and contributed, to a large extent, to the accumula-

tion and conservation of the present natural gas and oil reserves (Makogan 1972, 1974).

The present thermodynamic characteristics of the sedimentary cover of the earth's crust (25 per cent of land territory and about 90 per cent of the world oceans) fit the accumulation and conservation conditions of natural gases in the solid hydrated state (Makogan 1972, 1974; Trofimuk *et al.* 1975).

HFZ thicknesses on land are 700 to 1500 m or more, and beneath the ocean floor are 100 to 400 m. The maximum thickness of the continental HFZ is related to the most cooled section of the sedimentary cover of the earth's crust characterized by the fresh-water reservoirs.

Solutions to problems of hydrate formation in sediments and the definition of the degree of this process must lead to considerable revision of our ideas about natural gas resources on our planet and

the mechanisms of hydrocarbon accumulation both within the ocean floor and the continental shelf.

The most sedimentation on the ocean floor, depths from some tens to some thousands of metres, falls within the HFZ. In the tropical seas, the HFZ begins at depths from 250 to 500 m and beneath the polar seas from 100 to 250 m. A diagram illustrating the top and bottom of the zone can be illustrated as a function of pressure and temperature (Figure 6). The upper boundary of the HFZ in the oceans is usually in the water layer and is defined by the intersection of the hydrate formation equilibrium curve and the curve of water temperature change. The lower boundary of the HFZ is in the bottom sediments and is found by the intersection of the curve of the geothermal gradient in the sediments and the hydrate formation equilibrium curve.

For the conditions (see Figure 6) where the ocean depth reaches 1600 m, the upper boundaries of HFZ are defined for natural gas with relative density of 0.6 to be 170 m, carbon dioxide to be 200 m, methane to be 350 m, and argon to be 1050 m. The lower boundaries are, respectively, 2100, 2020, 1900, and 1800 m. HFZ thickness in the sediments for the given conditions and gases may reach 400, 320, 200, and 100 m. In the marine environment, the maximum HFZ thickness falls within the zone of the continental shelf and slope which is characterized by moderate values of geothermal gradient, maximum thickness of sediments, and intensive hydrocarbon generation.

Of particular interest is the zone of the arctic continental shelf, most of which is underlain by a thick layer of permafrost. In the coastal regions of land the thickness of the cryolite zone decreases from the influence of the ocean. The thickness of the HFZ also decreases. On the other hand, the thermodynamic regime of the Arctic Ocean corresponds almost

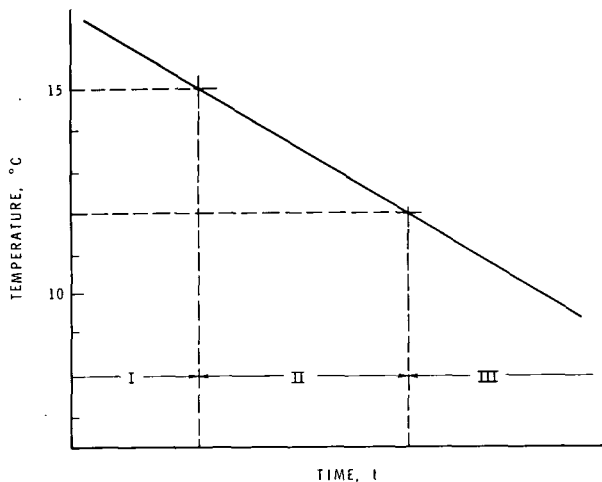


FIGURE 4. Diagram of gas-hydrate formation.

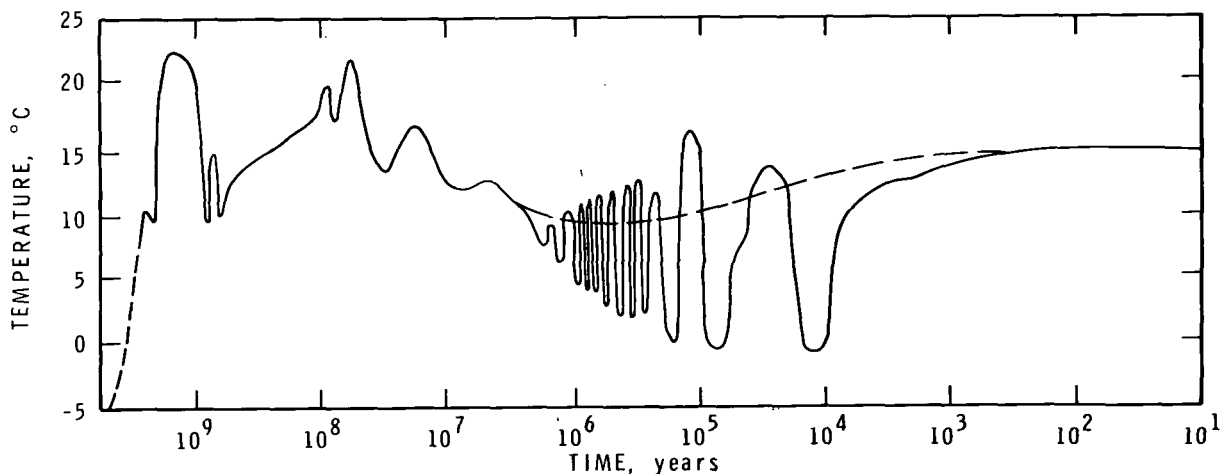


FIGURE 5. Average temperature change on the Earth's surface.

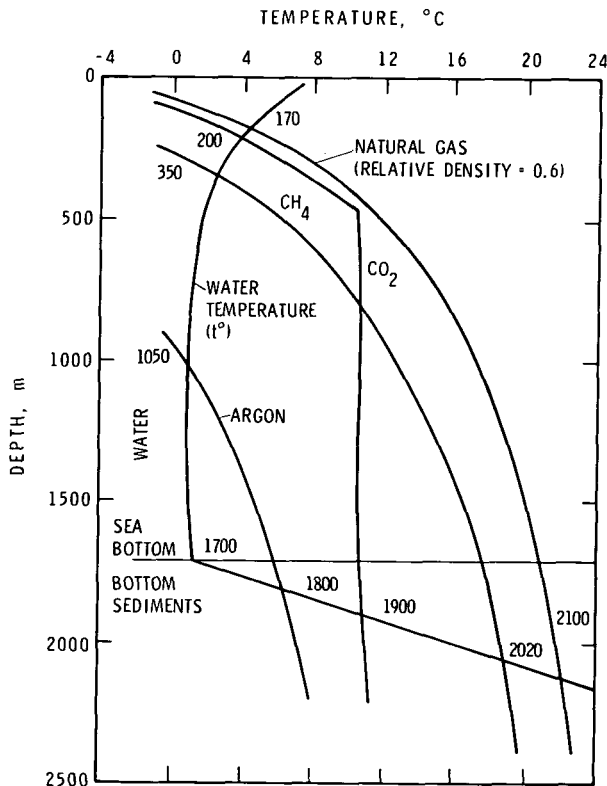


FIGURE 6. Diagram of dependence of gas-hydrate formation depth in the ocean and bottom sediments.

everywhere to hydrate formation. The lower boundary of the HFZ deepens with greater ocean depths.

At the coast-line, the zones of hydrate formation on land and in the bottom of the ocean join together to form a thick dome-shaped screen. This screen extends along the coast and is a reliable trap for free hydrocarbons. Generated and migrating gases form thick accumulations of hydrocarbons beneath this cover independently of the presence of lithological traps.

In the profile of the cryolite zone (Figure 7), its thickness on the continent reaches 800 m. The lower boundary of the HFZ forms an impermeable roof of a unique reservoir extending along the coast of the Arctic Ocean possibly accumulating thick deposits of hydrocarbons.

Mineralization of reservoir waters in the HFZ section is practically the same in any part of the ocean and shifts the equilibrium curve of the HFZ by 1 to 2°C, whereas, on the continent, variable mineralization of reservoir waters may considerably effect the HFZ thickness.

In the profile (see Figure 7), based on thermodynamic conditions in the Yakut Autonomous Soviet Republic, the influence of reservoir water mineraliza-

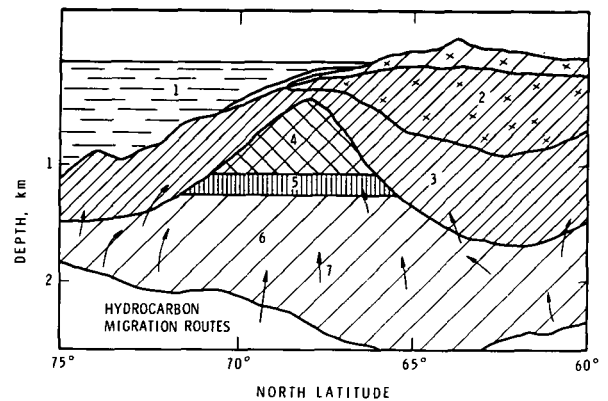


FIGURE 7. Relation between the Arctic Ocean and cryolite zone: 1) ocean; 2) cryolite zone; 3) hydrate formation zone; 4) and 5) free hydrocarbon deposits; 6) hydrocarbon generation zone.

tion and gas composition on a decreasing HFZ thickness is evident.

An oceanic bed characterized by a small thickness of sedimentary cover, high geothermal gradient, and weak generation of hydrocarbons shows little prospect for the discovery of large deposits of gas hydrates (probably with few exceptions).

Classification of Gas-Hydrate Deposits

Generated in, and migrating through, the earth's crust, gases form hydrates under specific thermodynamic conditions. Accumulation of hydrates leads to the formation of gas-hydrate deposits (GHD). These GHD contain gas partially or completely in the hydrated phase according to thermodynamic conditions and their stage of formation.

Three types of continental gas-hydrate deposits are recognized (Figure 8). From below, GHD may be in contact with reservoirs, bottom or side water, free gas, gas condensates, and oil deposits; from above, GHD may be in contact with free gas deposits and gas-tight beds; and within the ocean, with free water.

The mechanism of GHD formation differs significantly from that of the formation of free gas deposits because of low diffusion permeability of hydrate, low concentration of gas in reservoir water in contact with the GHD, and low gas-hydrate pressure.

Accumulation of separate components of natural gas in the solid phase may begin during the first stages of conversion of organic matter by biochemical transformation if such transformation occurs in the hydrate formation zones. Free gases entering an HFZ from deep in the earth where temperature is higher than that of hydrate formation also convert into hydrates.

GHD existing in the present thermodynamic condi-

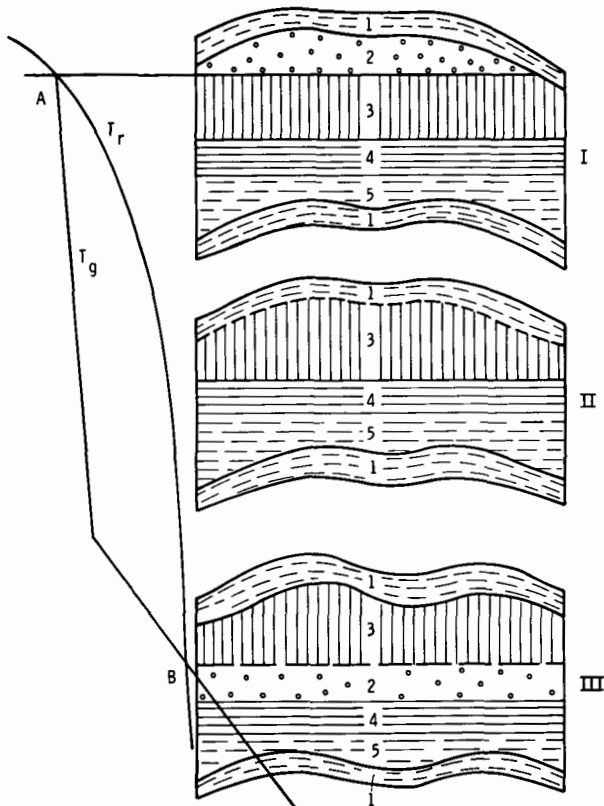


FIGURE 8. Scheme of gas-hydrate deposit bedding: 1) impermeable layer; 2) gas deposit; 3) gas-hydrate deposit; 4) oil deposit; 5) bottom water.

tions of sedimentary cover of the earth's crust can be primary or secondary deposits. The primary GHD are those which, after formation, were not subjected to cyclic changes of thermodynamic conditions accompanied by phase transition of gas and water into hydrate deposits. Usually such GHD are found on the ocean floor and can be without lithological cover. The period of existence of the primary GHD is equal to that of its formation and coincides with the period of the last great fall of temperature on the earth.

The primary GHD are characterized by three factors: First, generated hydrocarbons do not diffuse into bottom water, as previously assumed, but accumulate in the form of hydrate in the immediate vicinity of the sea-floor; secondly, GHD accumulate from the waters undersaturated with gas; and thirdly, lithological covers are not needed for GHD conservation (Makogon 1974).

The secondary GHD are formed from the free gas deposits by a change of their thermodynamic conditions. Usually they lie under an impermeable lithological cover. The age of the secondary GHD is de-

finied by the duration of the period of the stable conditions for hydrate formation in the deposit.

Gas-Hydrate Reserves

The estimation of the world gas-hydrate reserves is no less difficult a question than the development of an effective means for their recovery.

The estimation of the present world gas-hydrate reserves requires both regional and global knowledge of present and paleo-temperatures, sediment thickness, concentration of organic compounds in sediments, rate of its conversion, and degree of conservation under cyclic change of thermodynamic parameters of sedimentary cover.

Gas reserves in the continental GHD are estimated by the author as $57 \times 10^{12} \text{ m}^3$. McIver (1979) gave the figure of GHD for land as $31.1 \times 10^{12} \text{ m}^3$, of which $5.4 \times 10^{12} \text{ m}^3$ are concentrated in Canada.

The gas reserves concentrated in the hydrated phase within the shelf and continental slope are estimated by the author to be in the range of $(5 - 25) \times 10^{15} \text{ m}^3$.

Methods of GHD Prospecting

For GHD prospecting the following properties of hydrates, found in the porous medium, are used: Low electric conductivity and permeability; increased velocity of acoustic waves passing through sedimentary rock saturated with gas hydrates; anomalous values of diffusion gas flows over GHD; the deposit temperature decreasing during its recovery; gas composition change; reservoir water freshening during GHD recovery, etc.

Regional GHD prospecting both on land and under the ocean can be performed using seismo-acoustic prospecting in the frequency range 0.1 to 10 KHz together with gas thermometry. These methods allow an estimate of the area, thickness, and depth of the GHD top and bottom and an evaluation of hydrate and gas saturation of pay zones.

Improvements in GHD parameters should be done using combined geophysical methods and core testing of the GHD interval.

The large hydrate fields along the north-west coast of the USA, the north coast of Canada, and the east coast of Africa were revealed with the help of seismo-acoustic prospecting of the sedimentary cover. (Davidson *et al.* 1979; McIver 1979).

Estimation of Gas Reserves in GHD

Estimation of gas reserves in GHD was considered by the author (Makogon 1974). Gas reserves in GHD lying at depths up to 1500 m always exceed the re-

serves of deposits of free gas identical by volume. In deeper GHD, free gas concentration per unit volume of deposit exceeds that for gas hydrate. For example, at pressure of 80 kgf/cm² in a cubic metre there is 100 m³ of free gas and about 160 m³ of gas hydrate, and at a pressure of 200 kgf/cm² in the same volume there is 250 m³ of free gas and only 165 m³ of gas hydrate.

Conclusions

In principle, GHD development is possible and methods are known. However, thermodynamic parameters of the hydrate degradation process in GHD require radical and more-effective methods of GHD development, both on land and, especially, in deep-water parts of the oceans.

One general principle is the basis of the continental GHD development, i.e. conversion of hydrates in a GHD into free gas directly in the deposit, followed by the traditional methods of recovery. Conversion of hydrates into free gas can be accomplished by pressure reduction relative to hydrate degradation pressure in the pay zone, and by thermochemical and electro-acoustical simulation.

On drilling into, and in developing, GHD it is necessary to take into account some specific properties of hydrate, such as the sharp increase of gas volume as gas converts from hydrate into the free phase, reservoir pressure constancy corresponding to the definite isotherm of GHD development, release of large volumes of free water during hydrate degradation, etc.

Marine GHD development has some distinctive features compared to development on land, namely:

1. The absence of an impermeable lithological cover on the GHD.
2. Small depth to pay zone from the sea-floor, i.e. from a fraction of a metre to some hundreds of metres.
3. Relatively low mechanical strength of overlying and hydrate-containing uncemented deposits.
4. Large spatial area of GHD pay zones.
5. The main cementing component within GHD in bottom sediments is the hydrate itself.
6. The presence of thick water cover over the GHD surface in the ocean.
7. GHD development is carried out during the whole period of gas withdrawal at constant hydraulic pressure independent of hydrate degradation.
8. The degree of supercooling in GHD depth is variable and is determined by the depth of the upper boundary of the HFZ in ocean, the GHD thickness, and the geothermal gradient in the interval of GHD section.

9. GHD are the impermeable covers for underlying free gas and oil deposits.

10. If there is free gas or oil beneath gas-hydrate deposits, it is necessary, first to withdraw the oil and free gas, and then to develop the gas hydrate.

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