

## **TECHNICAL LIMITS FOR DEVELOPMENT OF NATURAL GAS HYDRATE DEPOSITS**

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### **ABSTRACT**

In this work we have formulated the set criteria for cost-effective selection of technologies for industrial production of gas from a hydrate deposit, which rely on the properties of hydrate-bearing rock and the geologic properties of the gas hydrate deposit. For over forty years the world's energy industry has been trying to effectively master vast unconventional resources of natural gas – the natural gas hydrates [1;3;4]. Specialists have accumulated during this period of time a great deal of knowledge about gas hydrates [8;10]. They established the conditions of hydrate formation in sedimentary rock and the conditions of formation and disappearance of gas hydrate deposits, and offered several classification methods for gas hydrate deposits. Specialists have proposed several methods to locate the gas hydrate accumulations on land and offshore and determined the probable areas where gas hydrate deposits may exist. More than 220 gas hydrate deposits were found to-date, and methods to calculate the amount of gas in a hydrate deposit were developed [1;12]. The principles of gas production from a hydrate deposit were formulated and real experience of commercial natural gas production from a hydrate deposit was gained. However, until now there were no set economic criteria for selection of effective technologies for industrial development of gas hydrate deposits. This results in periodic development of various models not applicable to specific geologic conditions.

*Keywords:* gas hydrates, development, technical limits

### **NOMENCLATURE**

$C_{ph}$  hydrate heat capacity [ $\text{kJ}/\text{m}^3/\text{K}$ ]  
 $C_{pr}$  heat capacity of the hydrate bearing rock [ $\text{kJ}/\text{m}^3/\text{K}$ ]  
 $dH_f$  heat of dissociation (fusion) of hydrate [ $\text{kJ}/\text{m}^3$ ]  
 $dT$  hydrate deposit supercooling [K]  
 $E_h$  energy to dissociate hydrate [kJ]  
 $F_h$  potential energy of hydrate deposit [kJ]  
 $H_h$  total thickness of hydrate bearing layers [m]  
 $Q_c$  heating value of gas [ $\text{kJ}/\text{m}^3$ ]  
 $Q_h$  content of gas in hydrate, [ $\text{m}^3/\text{m}^3$ ]

$Q_{hd}$  energy to heat hydrate to dissociation, [kJ]  
 $Q_p$  energy to heat rock to hydrate dissociation [kJ]  
 $S_h$  area of hydrate deposit, [ $\text{m}^2$ ]  
 $V_h$  volume of hydrate in 1  $\text{m}^3$  of hydrate deposit [ $\text{m}^3$ ]  
 $V_{hp}$  total volume of hydrated gas [ $\text{m}^3$ ]  
 $V_p$  volume of the hydrate bearing rock [ $\text{m}^3$ ]  
 $\lambda$  hydrate saturation coefficient  
 $\phi$  porosity of hydrate saturated rock

### **INTRODUCTION**

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Over nine thousand research papers were published on gas hydrates. More than two thirds of those deal with gas hydrates in nature. A tremendous knowledge was accumulated on the hydrate deposits formation, stability and dissociation, as well as effective methods of finding a gas hydrate deposit and estimating its size were developed. A number of technologies were proposed for hydrate deposit development. However, these technologies are of particular scope and are designed for development of specific hydrate deposits with defined geologic and thermodynamic parameters [8;9;11].

Clear criteria are unavailable for the selection of commercial hydrate deposit development technique depending on geologic, rock type, saturation and thermodynamic properties of gas hydrate deposits. Gas hydrate accumulations are also not categorized.

One must convert hydrate to gas with subsequent production by conventional means, which is the key characteristic of a gas hydrate deposit development. Conversion of hydrate to gas may be accomplished by a number of ways: pressure drawdown below dissociation pressure, temperature increase above dissociation temperature, equilibrium shift by injection of chemical hydrate inhibitors [4].

## CRITERIA

Gas hydrate deposits in-situ exist at different pressure and temperature. Fig.1 indicates average parameters for several discovered hydrate deposits [10].

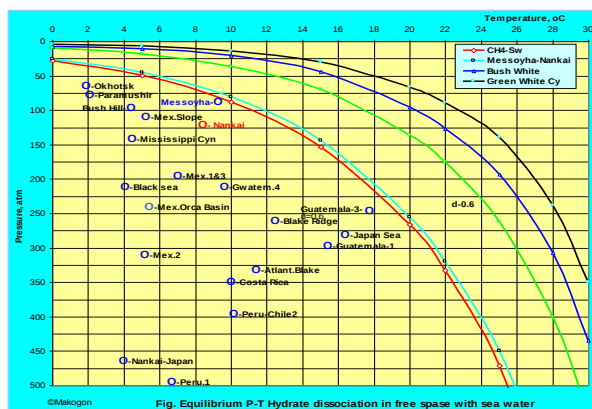


Fig. 1 Pressure (depth) and temperature for several gas hydrate deposits [2,6,7]

From these data one may see that pressure drawdown of up to several hundred atmospheres may be needed to dissociate gas hydrate in certain deposits. With the use of thermal technique temperature must be increased by several degrees to several tens of degrees C.

Selecting an effective technique for gas hydrate deposit development does not always depend on economic factors. Hydrate properties and geology of the hydrate-bearing matrix rock are the critical factors for selection of development method in specified conditions.

The most available and economic method for gas extraction from a gas hydrate deposit is reservoir pressure drawdown. This method has been used successfully during the Messoyakha gas hydrate deposit development [6]. However, this technique has its limitations both in the strength of the matrix rock and water coning. Hydrate dissociation in weakly consolidated rock may cause increased sand production, while water coning increases water cut of the produced fluids. Besides these effects, under certain conditions an intensive dissociation of hydrate with pressure drawdown may result in ice formation in rock pores, which sharply reduces permeability. Formed ice can't be dissociated by pressure decrease.

Pressure drawdown method applicability is very limited in highly supercooled gas hydrate deposits, particularly in deepwater ones. For example in order to dissociate gas hydrate in two of the most promising layers of the Blake Ridge deposit drawdown of 125 and 165 atm are needed (Fig.2), which is not possible in reservoir conditions.

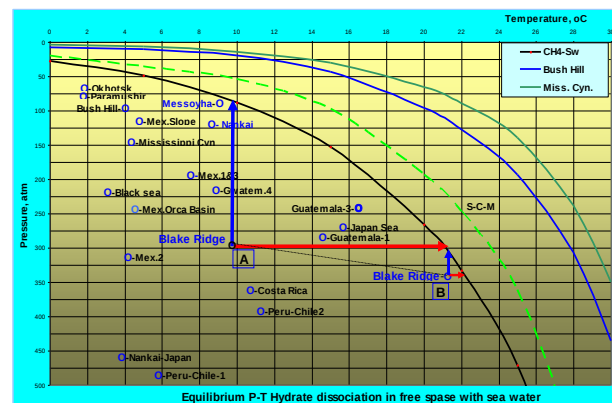


Fig. 2 Hydrate dissociation equilibria for gas compositions in different gas hydrate deposits.

Blake Ridge GHD [1;2;12] has 9 hydrated layers (Fig. 3) with different thickness of hydrated layers and screens, different hydrate saturation, pressure and temperature. Gas recovery may range from 17% to 51% of original reserve depending on position of hydrated layers.

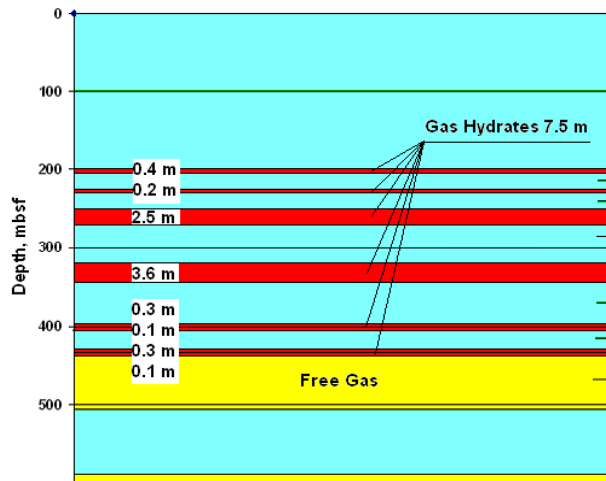


Fig.3 Cross-section of the Blake Ridge gas hydrate deposit [5].

The main factor in setting the maximum reservoir drawdown is the rock strength gradient and rock solids production from well completion with pressure drawdown. Based on Messoyakha experience a 2-4 atm maximum drawdown is allowed in weakly consolidated sand. Drawdown limits for sandstone are 10-20 atm, for carbonate and shale rock it is up to 10 atm.

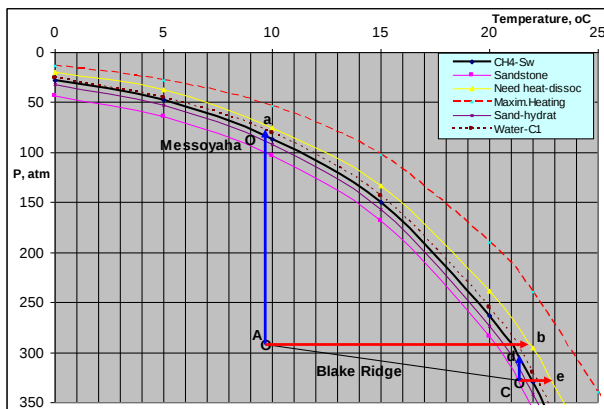


Fig. 4 Hydrate deposit drawdown and heating limits. A - for layers at the deposit top; B - for layers at deposit bottom.

Fig. 4 above shows the maximum allowable drawdown depending on rock strength, as well as

the necessary and allowable limits of heating gas hydrate deposit during its development. We review just two deposits, which contain methane hydrate. Each requires a special design project to account for real geologic characteristics.

Thermal technique effectiveness for gas production from hydrate deposits depends on geologic, rock type and heat capacity, hydrate supercooling, saturation and thermal conductivity properties, especially offshore. Heat loss from a heating fluid circulated in a well to warm up a gas hydrate deposit must also be taken into account, which is a subject of a separate computation. With a heating technique using external heat sources the limit of their effectiveness is at equality of the price of heating value of gas in the hydrate deposit and the price of development and fuel required to heat all hydrate-bearing rock to hydrate dissociation temperature. In order to compare effectiveness of gas extraction from hydrate deposits one may compare just the amounts of energy needed to be supplied to each deposit to dissociate hydrate and produce gas.

The set of source data are required for evaluation of gas production from a hydrate deposit:

- water depth above the deposit,
- bottom temperature,
- pressure and temperature depth profiles,
- hydrate stability interval,
- depth and thickness of all hydrate saturated layers,
- rock porosity,
- hydrate saturation in all hydrate saturated layers,
- composition and heating value of gas,
- heat of dissociation of gas hydrate,
- heat capacity of hydrate saturated rock.

Some supporting information is also needed:

- presence of impermeable screens over hydrate saturated layers and their stability to pressure drawdown,
- presence of free gas below hydrate deposits,
- gas saturation of water in neighboring layers,
- thermal conductivity and permeability of hydrate bearing and neighboring layers,
- permeability of underlying rock at gas-water contact depth.

Potential energy in hydrate is determined by composition and heating value of gas in hydrate.

For example, one cubic meter of methane hydrate at 283 K contains up to 164 m<sup>3</sup> of gas. Heating value of methane (Q<sub>c</sub>) equals 38\*10<sup>3</sup> kJ/m<sup>3</sup>. Thus each cubic meter of methane hydrate contains 164 \* 38\*10<sup>3</sup> = 6.23\*10<sup>6</sup> kJ/m<sup>3</sup> of energy. Heat of methane hydrate dissociation at 283 K is 54.2 kJ/mole. One mol of methane hydrate with density of 0.91 g/cm<sup>3</sup> equals 124 grams. One m<sup>3</sup> of methane hydrate contains 7339 mols. It would take 3.98\*10<sup>5</sup> kJ/m<sup>3</sup> to dissociate gas hydrate, which is 6.4% of the energy contained in 1 m<sup>3</sup> of hydrate. However such comparison is valid only for deposits, which contain 100% pure hydrate at equilibrium pressure and temperature. Such perfect deposits seldom exist in nature.

For real deposits one must take into account deposit geology and stratigraphic structure and thickness of screen layers between hydrate-saturated layers, rock porosity and saturation with gas hydrate, fraction of hydrate crystal lattice cavities filled with gas molecules, degree of hydrate supercooling, heat capacity of hydrate bearing rock.

We present two examples of energy balance of development of two real offshore gas hydrate deposits.

Total volume of hydrate in 1 m<sup>3</sup> of a hydrate deposit is:

$$V_h = H_h * \varphi * \lambda * S_h \quad (1)$$

Total volume of hydrated gas, V<sub>hp</sub> is:

$$V_{hp} = H_h * \varphi * \lambda * Q_h * S_h \quad (2)$$

(for methane hydrate at 100 atm and 286 K, Q<sub>h</sub>=164 m<sup>3</sup>/m<sup>3</sup>)

Potential energy of a gas hydrate deposit is:

$$F_h = V_{hp} * Q_c \quad (3)$$

(for methane Q<sub>c</sub> = 38\*10<sup>3</sup> kJ/m<sup>3</sup>)

Part of the gas hydrate deposit potential energy is spent to:

a) heat the hydrate to dissociation:

$$Q_{hd} = V_h * C_{ph} * dT \quad (4)$$

b) dissociate hydrate:

$$E_h = V_h * dH_f \quad (5)$$

(dH<sub>f</sub> is approx. 3.98\*10<sup>5</sup> kJ/m<sup>3</sup> for methane hydrate)

c) heat the rock:

$$Q_p = V_p * C_{pP} * dT \quad (6)$$

It is very important to properly determine thickness of rock saturated with hydrate, heating of which would take up part of the energy contained in hydrate gas. For the example the gas hydrate deposit we review (505 m thick) has three hydrate saturated layers with 17 m total thickness, which is 3.4% of the total deposit thickness. Top of the uppermost hydrate layer is at 1141 m depth. Bottom of the lowest hydrate layer is at 1210 m depth. Thickness of the layers to be heated, with account for heating of a part of the surrounding rock is 93 m.

Energy required for heating the gas hydrate deposit rock on a 1 km<sup>2</sup> area by 14°C (see Fig.3 above), with account for rock heat capacity (2.5\*10<sup>3</sup> kJ/m<sup>3</sup>/K), is:

$$Q_p = V_p * C_{pP} * dT = 93 * 10^6 * 2.5 * 10^3 * 14 = 3.25 * 10^{12} \text{ kJ}$$

If the hydrate heat capacity equals that of the rock then the energy required to heat hydrate deposit rock does not depend on rock saturation with hydrate; otherwise both heat capacities of hydrate and rock must be taken into account.

Thus the total energy recovered during gas hydrate deposit development is defined as the difference between the potential heating value of gas contained in the deposit (F<sub>h</sub>) and the energy required to recover hydrated gas (heating hydrate Q<sub>h</sub>), heating rock (Q<sub>p</sub>), and dissociating hydrate (E<sub>h</sub>).

If the quantity F<sub>h</sub> exceeds cumulative energy spend E<sub>h</sub> + Q<sub>h</sub> + Q<sub>p</sub>

$$F_h > E_h + Q_h + Q_p \quad (7)$$

then a project may be started to determine technology for thermal development of this gas hydrate deposit. Otherwise, other gas recovery techniques should be sought.

When chemicals are used, their concentration at hydrate surface must be up to 15-25 wt%, as seen in Fig.5.

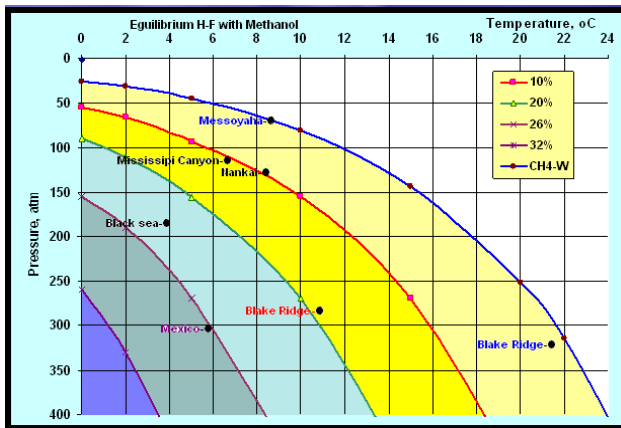


Fig. 5 Concentration of methanol needed to dissociate gas hydrate in reservoir

Injection of chemicals for hydrate dissociation (Fig. 5) into the hydrate deposit is controlled by diffusion of injected fluid to the hydrate dissociation surface, their cost and environmental safety. One should keep in mind that addition of chemicals may remove hydrates from cementing rock and contribute to further destabilizing it thus causing increased sand production.

One of the limiting factors is the allowable pressure upon hydrate dissociation inside the gas hydrate deposit. Figure 6 presents the dependence of pressure after methane hydrate dissociation in a constant volume. High permeability of hydrate bearing rock mitigates the risk of gas hydrate deposit explosion caused by an active flow of gas released from hydrate [8].

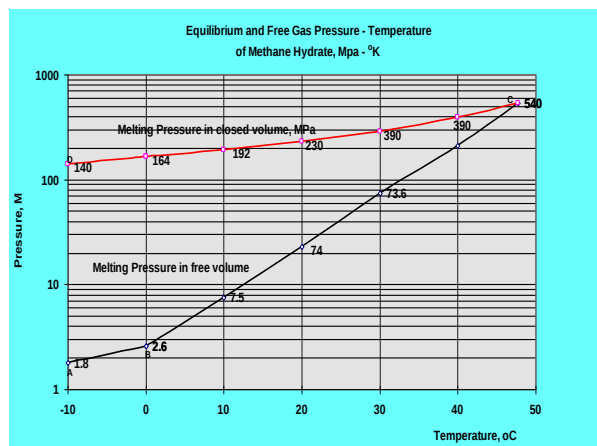


Fig.6 Pressure after methane hydrate dissociation in a constant volume

Injection of chemicals for hydrate dissociation (Fig. 5) into the hydrate deposit is controlled by diffusion of injected fluid to the hydrate dissociation surface, their cost and environmental safety. One should keep in mind that addition of chemicals may remove water from cementing rock and contribute to further destabilizing it thus causing increased sand production.

When several techniques are used simultaneously, it is important to control the processes of hydrate dissociation *in situ* and recovery of free gas from the deposit. A gas hydrate deposit drawn too hard may easily explode along with all engineering and environmental consequences.

Novel hydrate deposit development techniques may include ones that use the properties of hydrate itself. This would be the most profitable way to commercial mastering the gas hydrate resources.

## CONCLUSION

Energy industry specialists from the whole world have successfully proven, at a relatively low cost of about one billion dollars, that gas hydrate deposits as unconventional potential sources of energy are widespread in nature. A large operations experience was accumulated with the Messoyakha gas hydrate deposit. Over two hundred new hydrate deposits were found. A number of these could be placed economically today into commercial development. Both onshore and offshore deposits to 2000-2500 m water depth can be developed effectively. Effectiveness of a gas hydrate deposit development is determined by the size of the deposit, hydrate saturation of rock, deposit stratigraphy, properties of hydrate and of matrix rock. A gas hydrate deposit has a more favorable economics if development with a thicker deposit, higher porosity, higher hydrate saturation of rock, and smaller supercooling.

Any possible method of commercial hydrate deposit development has its limitations, determined by the properties of hydrate and by regional geologic factors. Technical deployment of any method requires close monitoring and managing the reservoir and bottomhole pressure. Absence of such management may result in a loss of containment of the hydrate deposit and serious environmental consequences. With a knowledgeable selection and deployment of a gas

hydrate deposit development technique, the lifting cost of gas production from a hydrate deposit may be lower than the regional lifting cost of gas production from a conventional deposit.

The criteria discussed in this paper should be evaluated in the following order:

1. Supercooling
2. Rock consolidation
3. Safety and Deposit strength
4. Stratigraphy and impermeable screens
5. Mass transfer
6. Heat transfer
7. Economics

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