

## **BEHAVIOUR OF GAS PRODUCTION FROM TYPE III HYDRATE RESERVOIRS**

**Mehran Pooladi-Darvish\***  
**Department of Chemical and Petroleum Engineering**  
**University of Calgary**  
**2500 University Drive NW, Calgary, AB, T2N 1N4, and**  
**Fekete Associates Inc.**  
**Suite 2000, 540 – 5<sup>th</sup> Ave SW**  
**Calgary, AB, T2P 0M2**  
**CANADA**

**Olga Zatsepina**  
**Department of Chemical & Petroleum Engineering**  
**University of Calgary**  
**2500 University Drive NW, Calgary, AB, T2N 1N4**  
**CANADA**

**Huifang Hong**  
**Fekete Associates Inc.**  
**Suite 2000, 540 – 5<sup>th</sup> Ave SW**  
**Calgary, AB, T2P 0M2**  
**CANADA**

### **ABSTRACT**

A large number of studies are underway to evaluate the possible role of gas hydrates as a potential energy resource. One class of such studies involves development and use of mathematical models (i) to estimate the rate of gas production from hydrate reservoirs under different operating conditions and (ii) to better understand the role of different parameters on hydrate decomposition. A number of researchers<sup>1-4</sup> have already studied gas production from those hydrate reservoirs that have an underlying free-gas phase (Type I). However the study of gas production from those hydrate-reservoirs that totally lie within the hydrate stability zone and are sandwiched by impermeable layers on top and bottom (Type III) have received less attention. Furthermore, while gas production rates from Type I hydrate reservoirs have been found to be significant, the results for Type III gas hydrate reservoirs are less promising.

In this study, a gas hydrate reservoir simulator is used to study gas production from Type III hydrate reservoirs. A large number of mechanistic and sensitivity studies have been conducted to better understand the factors controlling rate of gas production. It is shown that the ability to decompose hydrate at a significant rate not only depends on the rate of heat transfer (as in Type I reservoirs) but also on the ability of the formation to allow fluid flow. (This is a much less important factor for Type I reservoirs). In this work, the interaction between fluid flow and heat transfer is explored, and conditions that would allow significant gas production rate are illustrated. The challenges in numerical modeling of Type III hydrate reservoirs have also been described.

*Keywords:* hydrate reservoir, modeling, hydrate decomposition

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\* Corresponding author: Phone: +1 403 213 4429 Fax +1 403 284 4852 E-mail: pooladi@ucalgary.ca

## INTRODUCTION

Over the past decade much research has been devoted to evaluating producibility of natural gas hydrates. Gas hydrates occur in different settings with different characteristics affecting their producibility. Among these, hydrates may occur in disseminated form in fine-sediments (clays and silts) with little permeability and weak mechanical strength; they may occur in concentrated form along faults and seepage paths that allow upwards movement of gas from deeper formations; and they may occur in coarse sediments (e.g. sands) filling part of the pore space<sup>5,6</sup>. This last form, which may be found in offshore and on-shore environments, is closest to conventional hydrocarbon reservoirs. Here we focus on a sub-set of these reservoirs, that are at temperatures above the freezing temperature of water (i.e. marine and below permafrost) and have a cap-rock. Moridis and Collette have further categorized these hydrate reservoirs into three types: Type I with underlying free-gas, Type II with underlying free water and Type III that is sandwiched by impermeable formations.

It is reported that the only case of long-term production from natural gas hydrates is from the Messoyakha field in Siberia with an underlying free gas<sup>7</sup> (Type I). However, scarcity of data about this reservoir limits what can be learnt about production behavior of natural-gas hydrate reservoirs. In the absence of any other field experience, our understanding of producibility of gas hydrates is primarily based on laboratory experiments, short-term production tests from natural settings (e.g. Mallik 5L and Mt. Elbert 01 production tests<sup>8</sup>) and results of mathematical models calibrated against such measurements. A number of investigators have studied producibility of Type I reservoirs under depressurization. Production from a well completed in the free gas zone of a Type I hydrate reservoir leads to pressure reduction. The hydrates above the free gas that are at or close to equilibrium conditions are destabilized and decompose. The generated gas acts as a pressure support mechanism. This has been modeled as an additional compressibility, not unlike total compressibility defined for coal-bed reservoirs<sup>9</sup>. The rate of gas generation is strongly affected by the heat available for decomposition<sup>10</sup>, which is partly provided by the sensible heat of the

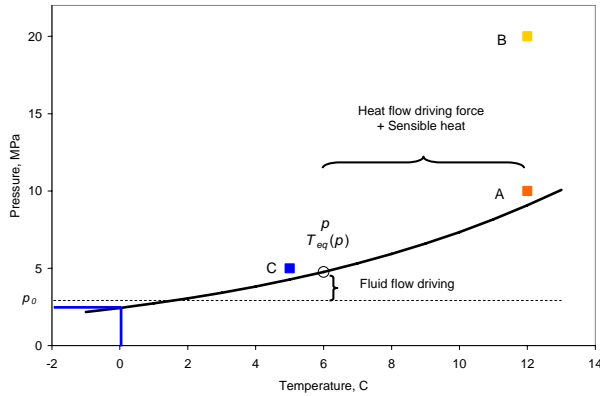
hydrate-bearing formation and partly by conduction from the surrounding formations. In Type I hydrate reservoirs, a large surface area between the free-gas zone and the hydrates above allows a large rate of heat transfer. Production rates of a few MMSCF/day (from the hydrates alone) have been reported. Based on this understanding, reservoir engineering models analogous to those for conventional hydrocarbon reservoirs (i.e. material balance and well-testing models<sup>9,11,12</sup>). These have been validated against numerical simulators – the final usefulness of these models need be tested when actual field data becomes available.

As compared to Type I reservoirs, producibility of Type III reservoirs is restricted due to a number of factors including the low permeability of the porous medium with hydrates within. The low permeability limits the volume of the hydrates that are destabilized (by pressure reduction), affecting the surface area for heat transfer (as it will be shown later in this paper). Furthermore, unlike Type I reservoirs where the free-gas hydrate interface is at equilibrium conditions, Type III hydrate reservoirs could occur at pressure-temperature (p/T) conditions that are significantly stable.

The objective of this paper is to present a number of numerical simulation studies of gas production from Type III hydrate reservoirs in 1-D and 2-D geometries for improved understanding of hydrate decomposition by depressurization. Some of the questions that we will answer include (i) is 1-D modeling of Type III hydrate reservoirs a reasonable approximation? (ii) When does gas rate increase/decrease with time? (iii) What reservoir characteristics are important in determining rate of gas production, (iv) how does competition between fluid and heat flow affect hydrate decomposition. In the following, the relation and interaction between the heat and fluid flow mechanisms in depressurization of Type III hydrate reservoirs is described. This is followed by results of a number of 1-D and 2-D numerical simulation, and analyses of these results. All of the results are generated using the STARS simulator of the Computer Modeling Group (CMG). Use of this simulator for modeling gas hydrate reservoirs has been previously demonstrated<sup>13,14</sup>.

## HEAT AND FLUID FLOW EFFECTS

Figure 1 shows a typical three-phase hydrate equilibrium curve. Consider a reservoir (designated by letter A) with an approximate initial pressure and temperature of 10 MPa and 12 C as shown in Figure 1. (For a horizontal reservoir of say 10 m thickness, variations in the hydrostatic pressure and temperature along depth would be approximately 0.1 MPa and 0.3 C, which in Figure 1 may be represented by the location of letter A in Figure 1.)



**Figure 1:** Schematic representation of heat and fluid flow driving forces in decomposition of reservoir A.

Let us consider a depressurization scheme where the wellbore pressure ( $p_0=2.8$  MPa) is kept at a pressure that is shown by the dashed line. This pressure is chosen to be close but above 2.6 MPa (i.e. equilibrium pressure corresponding to freezing temperature of water in Figure 1), so that the formation of ice that could plug the pores may be avoided. This lower pressure (as compared with the reservoir pressure) initiates fluid flow, which in turn leads to reduction of pressure within the reservoir. We shall refer to this effect as diffusion of a reduced-pressure pulse, as it may be represented by the multi-phase diffusivity equation. Where (and when) the pressure surrounding the hydrate particles in the porous medium is sufficiently reduced, the hydrate would decompose. The endothermic heat of decomposition may be provided by the sensible heat of the hydrate-bearing formation and its constituents (rock, hydrate and fluids) and by conduction from farther away. The p/T conditions of the hydrates (at this location and time) are represented by the open circle in Figure 1, and are determined by the balance between heat flow and fluid flow. When fluid flow

is restricted (say because of low permeability) the open circle would move further up the equilibrium curve to provide the necessary driving force for fluid flow. This in turn would reduce the heat availability and reduce decomposition rate. Another condition that may lead to the open circle appearing further up the equilibrium curve is if more heat is available (say because of lower porosity leading to increased sensible heat).

One may consider a total driving force for decomposition that may be represented by either  $T_i - T_{eq}(p_0)$  or  $p_{eq}(T_i) - p_0$ , which may be divided among the heat flow and fluid flow mechanisms<sup>1</sup>. As the above simplified description suggests the rate of the gas production is strongly affected by (i) how much the formation pressure may be reduced, (ii) how far into the reservoir pressure can be reduced and (iii) how much (sensible) heat is available and (iv) how fast the heat may be conducted. These factors are related to reservoir properties, initial p/T conditions and the operating conditions. In the following we will explore the effect of permeability and initial pressure/temperature conditions on the balance between heat and fluid flow and how this affects the rate of gas generation. First however, the effect of hydrate saturation on permeability is reviewed.

## PERMEABILITY IN THE PRESENCE OF HYDRATES

It is well understood that the presence of hydrates in porous medium leads to a reduction in ease of fluid flow (i.e. permeability). However, the relation between permeability of a porous medium and hydrates saturation is not known. In one set of models, the permeability at the initial hydrate saturation depends on the intrinsic permeability and hydrate saturation. In another set of models,

<sup>1</sup> A similar analysis of decomposition, which also addresses the driving force for the intrinsic kinetics of hydrate decomposition, has been previously presented. A number of simulation studies have shown that the intrinsic kinetics of decomposition is so fast that its driving force is negligible as compared with the other driving forces; i.e. equilibrium decomposition may be assumed. The simulation studies reported in this work account for the intrinsic kinetics of decomposition; however analysis of the results will be based on equilibrium assumption. Other simplifications in the above description include ignoring the effect of convective heat transfer.

geological drivers control the hydrate saturation, such that permeability at initial hydrate saturation is independent of (initial) hydrate saturation.

The measurements at Mallik indicate permeability values in the range of 0.001 to 0.1 mD at initial hydrate saturation. At Mt. Elbert, where an open-hole MDT test was conducted above at equilibrium p/T conditions such that hydrates were stable, permeability to flow of (single-flowing phase) water was estimated to be between 0.1 and 0.2 mD<sup>14</sup>. Research for quantification of permeability of porous media in the presence of hydrates continues. In the numerical simulation studies below, a change in permeability at the initial hydrate saturation is allowed to study the effects of fluid flow on decomposition. This is incorporated through the use of a model, where relative permeability to water is a function of water saturation alone,

$$k_{rw} = \left( \frac{S_w - S_{wirr}}{1 - S_{wirr}} \right)^{n_w}. \text{ This model is similar to that}$$

used in the comparative simulation studies reported in this conference<sup>13</sup>. Other properties used in the simulation studies are given in Table 1.

**Table 1: Parameters used in simulation runs**

Porosity	0.3
Permeability (md)	1000
$S_{wi}$	0.3
$S_{Hi}$	0.7
$S_{gi}$	0
Initial pressure (kPa)	10000
Temperature (°C)	12 °C
$E_H$ (std m <sup>3</sup> /m <sup>3</sup> )	178
$\lambda$ (dimensionless)	39.04
$\beta$ (K)	8533.80
Density (kg/m <sup>3</sup> ):	
Rock	2750
Hydrate	919.7
Water	1000
Heat capacity (J/kg·K):	
Rock	1000
Hydrate	2134
Water	4180
Thermal conductivity (W/m·K):	
Rock	2
Hydrate	0.393
Water	0.6
Heat of decomposition (J/kg)	477,000

## SIMULATION RESULTS

The results are divided into two parts, 1-D and 2-D. In the 1-D section below, effect of permeability and initial p/T conditions on hydrate decomposition rate is investigated.

### 1-D Results

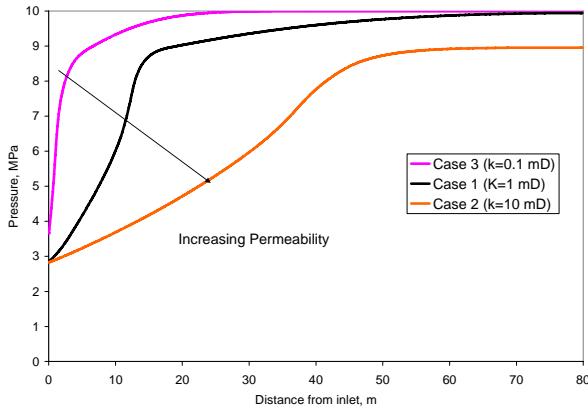
The 1-D simulation studies consider a linear reservoir of 80 m length, 1 m width and 1 m thickness (modeled using 800 grid blocks). Porosity and permeability (in the absence of hydrates) are 0.3 and 1 Darcy. The initial hydrate (and water) saturation values are 0.7 (and 0.3). Five simulation runs are conducted to investigate effect of permeability (Cases 1 to 3) and initial conditions (Case 1, 4, 5). These are listed in Table 2, where highlighted parameters identify a change from Case 1.

**Table 2: 1-D Cases studied**

	$k(S_{Hi})$ , mD	$p_i$ , MPa	$T_i$ , C
Case 1	<b>1</b>	<b>10</b>	<b>12</b>
Case 2	<b>10</b>	10	12
Case 3	<b>0.1</b>	10	12
Case 4	1	<b>20</b>	12
Case 5	1	<b>5</b>	<b>5</b>

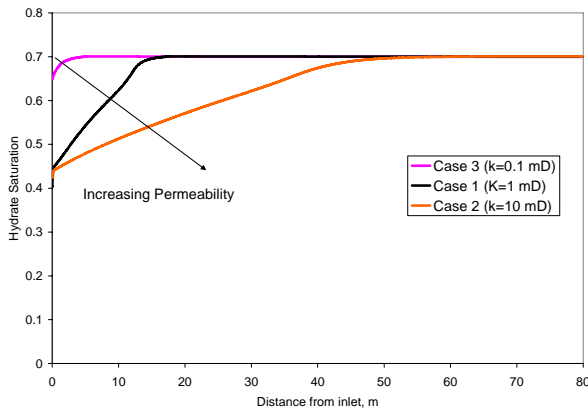
### Effect of Permeability

The exponent of water relative permeability in the relative-permeability model was varied to represent permeability to (single-flowing phase) water at the initial hydrate saturation of 1, 0.1 and 10 mD. Figure 2 below shows the variation of pressure vs. distance from the inlet at one day for Cases 1 to 3. As results in Figure 2 show, the pressure reduces deeper into the reservoir when permeability is more. In reservoir engineering a radius of investigation  $r_i = 2\sqrt{\eta t}$  is defined that represents how deep the reduced pressure has diffused. In the above relation  $\eta = k / \phi \mu c_r$  is hydraulic diffusivity and represent the diffusive velocity of the reduced-pressure pulse. The use of the above equation for multi-phase flow, particularly when hydrate decomposes and permeability increases is not valid. Nevertheless, the above equation demonstrates that a higher permeability leads to a deeper radius of pressure reduction, consistent with what is seen in Figure 2.



**Figure 2:** Effect of permeability on pressure in the porous medium (time = 1 day)

Figure 3 shows hydrate saturation for the same three cases. Results in Figure 3 show that when permeability is larger, a larger depth of decomposition is achieved, leading to a larger rate of gas production as demonstrated in Figure 4. Note that the equilibrium pressure for decomposition at the initial temperature is about 9 MPa. This is why Figure 2 indicates pressure reduction (to about 9 MPa) at large distances for the highest permeability case, without any reduction in hydrate saturation.



**Figure 3:** Effect of permeability on hydrate saturation in the porous medium (time = 1 day)

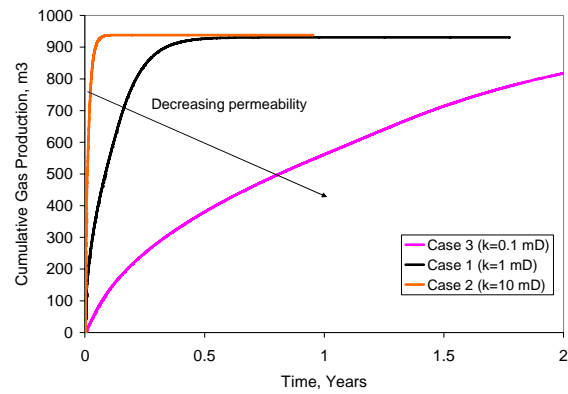
Figure 3 indicates that hydrate saturation at the inlet for two of the cases is 0.45. Results not shown here indicate that this value of hydrate saturation remains constant even at later times (for all three cases). This suggests that a hydrate saturation of about 0.45 is left at the end of decomposition, leading to a recovery of about 35%. This value could be

approximately predicted before any simulations are conducted by noting that in this system, most of the heat of decomposition is provided by the sensible heat of the system (i.e. heat conduction plays a small role). For a system where sensible heat is the only source of heat, hydrate recovery is given by the Stefan number, which is the ratio of sensible heat to

heat of dissociation;  $Ste = \frac{\rho c_p \Delta T}{\rho_H S_H \phi \Delta H}$ , where

$\Delta T = T_i - T_{eq}(p_0)$ . Using values given in the

Appendix, Stefan number is 0.32.



**Figure 4:** Effect of permeability on gas production (time = 1 day)

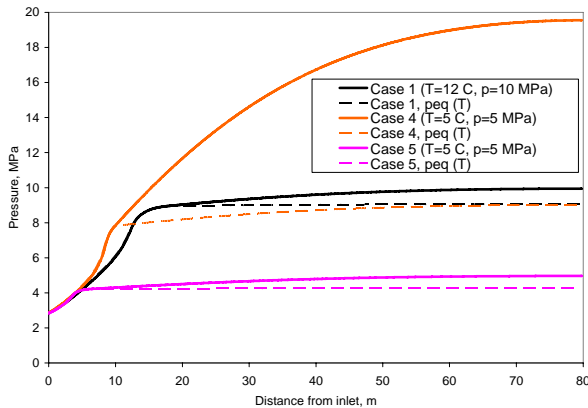
Unlike the 1-D simulation model, in an actual Type III hydrate reservoir, heat can flow towards the decomposition zone from above and below. In this case, when permeability is increased, not only the affected reservoir volume increases, but also the surface area for heat transfer is increased. 2-D simulation studies reported later in this paper will demonstrate how this effect can lead to an *increase* in rate of gas production with time. Furthermore, hydrate recovery for such a case will be more than that given by the Stefan Number.

### Effect of Initial Conditions

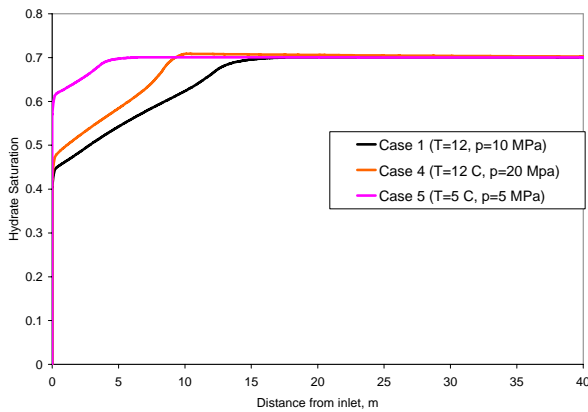
Effect of initial conditions on hydrate decomposition could be explained with the help of Figure 1. Case 1, 5 and 6 are represented by letters A, B and C, respectively. The results of the simulation studies are shown in Figures 5 to 7.

In Case 5, the initial pressure of the hydrate reservoir is more than that of Case 1. When both are produced at a constant bottomhole pressure,

reservoir pressure will stay higher than that in Case 1 (orange vs. black lines in Figure 5). This higher pressure leads to a larger remaining hydrate saturation and less gas production, as shown in Figures 6 and 7, respectively. Note that Case 5 (as a result of high pressures), demonstrates hydrate reformation ahead of the decomposition front (exhibited by hydrate saturations slightly larger than 0.7).

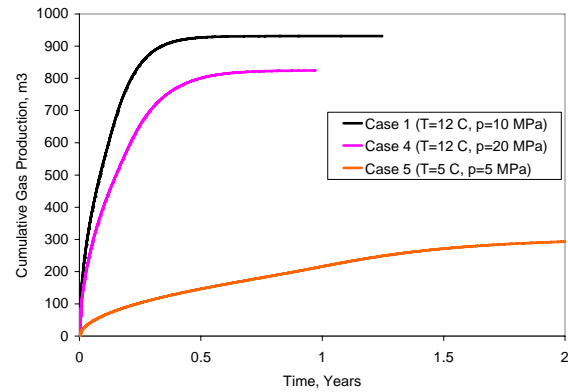


**Figure 5:** Effect of initial p/T conditions on pressure in the porous medium (time = 1 day)



**Figure 6:** Effect of initial p/T conditions on hydrate saturation in the porous medium (time = 1 day)

Case 6 represents a much colder reservoir. The pressure is chosen to be close to the equilibrium pressure to allow immediate decomposition. However, because of the lower initial temperature, the total driving force for hydrate decomposition (conduction and sensible heat) is much smaller than Case 1, resulting in significantly less hydrate decomposition and gas generation, as shown in Figures 6 and 7, respectively.

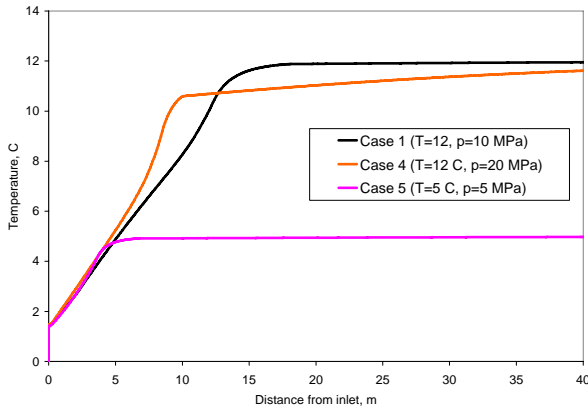


**Figure 7:** Effect of initial p/T conditions on gas production

Figure 6, exhibits a hydrate saturation of 0.62 at the inlet for Case 6. This corresponds to a hydrate recovery of 11%, which once agrees well with the value of Stefan Number = 0.11 and the maximum value of cumulative gas produced (orange line in Figure 7).

A complicating factor that has been observed in some simulation runs of Type III hydrate reservoirs is a competition between heat flow and fluid flow. In the depressurization, pressure reduction diffuses to ahead of the decomposition region such that the pressure there may reduce to below equilibrium pressure at the initial conditions. However, in some cases, temperature there may have already been reduced by conduction towards the decomposition region. When this situation occurs, the hydrate may remain stable and the decomposition region would be narrow.

One of such cases can be observed by comparing Cases 1 and 4. Figure 5 suggests that Case 4 exhibits a pressure equal to the equilibrium pressure (of about 9 MPa) at about 13 m from the inlet. However, the decomposition zone extends to a distance of 10 m from the inlet (as seen in Figure 6). The stability of hydrates between 10 and 13 m can be explained using Figure 8 below, which shows a significant reduction in temperature of Case 4 between 10 and 13 m from the inlet (orange vs. black lines).



**Figure 8:** Effect of initial p/T conditions on temperature inside the porous medium

This can be further demonstrated by comparing the equilibrium pressure at the local temperature  $p_{eq}(T)$ , with the local pressure (see Figure 5). For Case 4, at about 10 m distance from the inlet, the local pressure (solid orange) exceeds the equilibrium pressure at the local temperature (dashed orange), negating the condition for hydrate decomposition.

## 2D Results

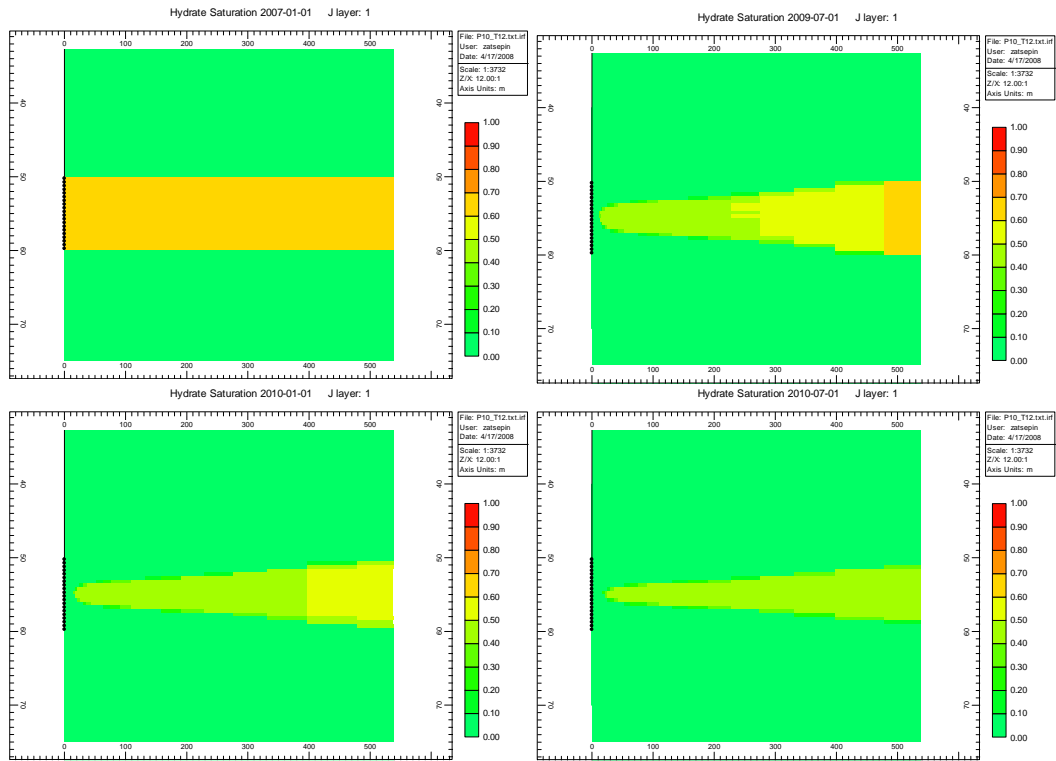
As pointed out earlier, heat flow in a Type III reservoir is not 1-D. In this section, we present simulation results to demonstrate how such 2D effects change the behavior of hydrate decomposition. It will be shown that sometimes a thin layer of hydrate decomposes along the top and bottom of the hydrate interval (where heat conduction from the surrounding strata arrives). This thin decomposition zone might propagate far distances into the reservoir, before it widens. Appearance of this thin layer of decomposition and the vertical heat flow has implications on selection of grid-blocks in the vertical direction. Moridis and Reagan<sup>5</sup> have shown that the rate of gas production in Type III hydrate reservoirs may increase with time. We will demonstrate results that suggest rate of gas production increases so long as this thin decomposition layer has not arrived at the outer reservoir boundary (and the surface area of heat transfer is increasing). Once the hydrates have fully decomposed on top and bottom, and the decomposition zone moves perpendicular to the bedding, rate of gas generation decreases (as rate of heat conduction decreases).

To demonstrate these effects we will simulate a cylindrical hydrate layer of 10 m thickness that is sandwiched between two shale layers (of 50 m thickness). The radius of the reservoir is 540 m. The rest of the parameters are similar to those of Case 1 (1D studies) and given in Table 1. Table 3 gives the list of cases studied, where highlighted parameters are those that are different from the base case.

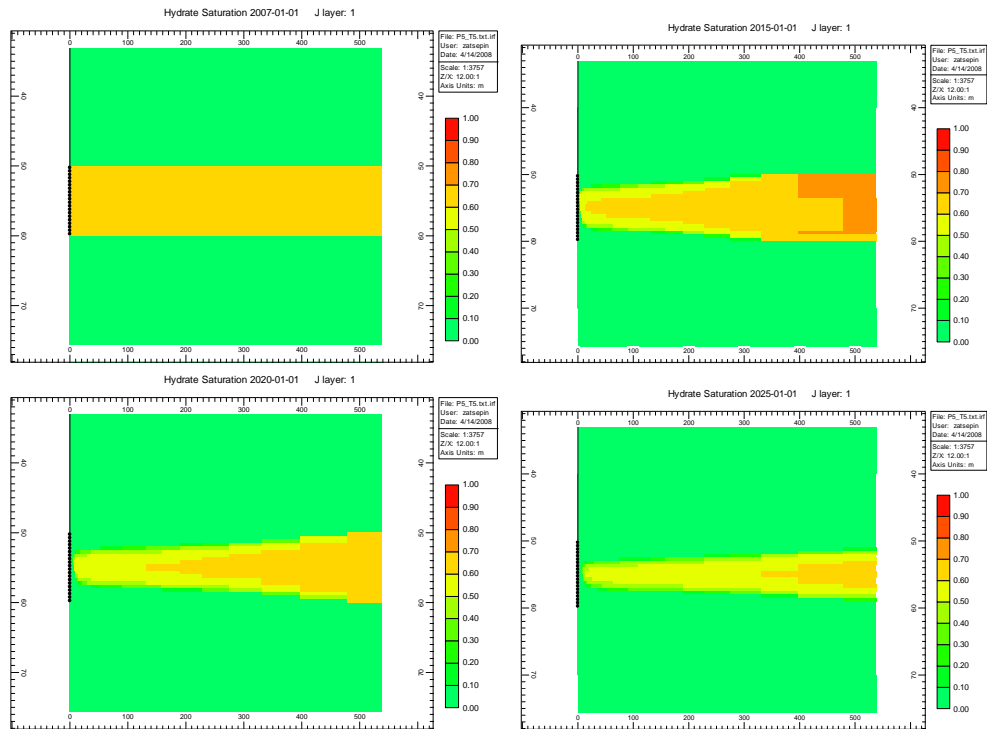
**Table 3: 2-D Cases studied**

	$p_i$ , MPa	$T_i$ , C
Case 6	<b>10</b>	<b>12</b>
Case 7	<b>5</b>	<b>5</b>
Case 8	<b>Fine vertical grids in the hydrate</b>	
Case 9	<b>Fine vertical grids in shale</b>	
Case 10	<b>Fine radial grids</b>	
Case 11	<b>Fine radial and vertical grids</b>	

**Base Case:** Figures 9 (a) to (d) show the hydrate saturation at 1.5 year intervals for Case 6 (Base Case). These figures exhibit the 10 m hydrate layer with 20 m of the 50 m shale on top and bottom. The vertical direction is significantly exaggerated. Figure 9 demonstrates that the preferential direction of hydrate decomposition is radial. By 2010 (3 years since start of decomposition), hydrates on top and bottom have decomposed to the outer radius of the reservoir (540 m), however the 10 m thickness of the hydrate has been affected only slightly. The heat conduction from top and bottom has led to formation of decomposed “fingers” that move radially outwards. The hydrates in the middle are insulated by the hydrates on top and bottom that consume all the conducted heat. When this thin layer of hydrate close to the top and bottom has fully dissociated, the heat of conduction arrives at the next hydrate grid block. This process continues until all the hydrate decomposes (at about 7.5 years for this case). The 100% hydrate recovery in this case is in stark contrast with 33% hydrate recovery in the 1-D case, where the only source of heat was the sensible heat of the hydrate-bearing formation.



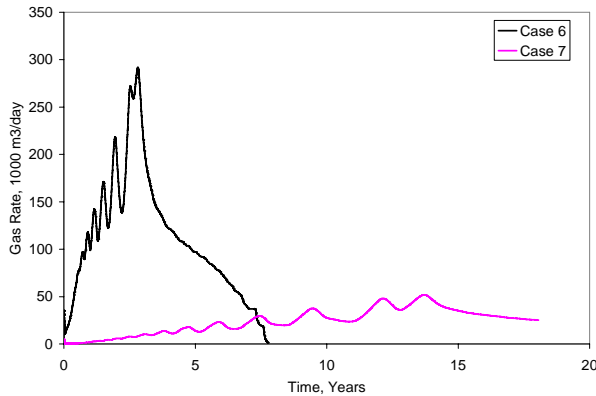
**Figure 9:** Hydrate saturation for Case 6 at 1.5 year intervals



**Figure 10:** Hydrate saturation for Case 7 at 2007, 2015, 2020, and 2025

Figure 10 shows similar plots of hydrate saturation for Case 7, where the time interval is 5 years. The initial temperature in this case is significantly colder than Case 6, leading to slower decomposition. Rate of decomposition is shown in Figure 11. A number features are visible.

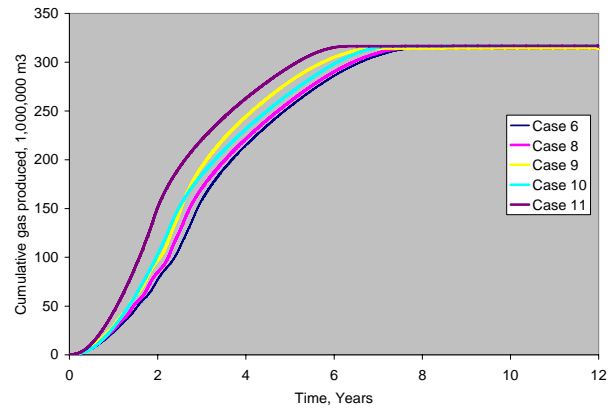
1. Gas rate increases with time before it decreases. The peak of rate for Cases 6 and 7 corresponds approximately to 2010, and 2020, when the decomposed “finger” has reached the outer boundary. Results of other cases (not shown here) confirm this observation. As the radius of the decomposed “finger” increases with time (leading to reduction in temperature there), the surface area for heat transfer increases with square of radius. This increased rate of heat transfer results in an acceleration of hydrate decomposition and gas production.
2. Case 6, exhibits a significant gas rate peaking at about  $300 \times 10^3$  m<sup>3</sup>/day (approximately 10 MMSCF/day). This occurs at about 3 years into simulation.
3. Gas production rate exhibits significant fluctuations. This is because of the size of grid blocks and is addressed below.



**Figure 11:** Gas production rate for cases 6 and 7

**Effect of Gridding:** The radial advance of the thin decomposition “finger” on top and bottom of the hydrate layer, and the importance of vertical heat flow from the shale indicate that grid-sizes need to be sufficiently small. This effect is examined through cases 8 to 11. While Case 6 and 7 used 47 radial grids (distributed logarithmically), 20 vertical

grids in the hydrate layer and 10 vertical layers in the shale, Case 8 used 40 grids in the hydrate, Case 9 used 20 grids in the shale, Case 10 used 80 grids in the radial direction, and Case 11 used 80 radial grids (distributed logarithmically), 40 vertical grids in the hydrate layer and 20 vertical grids in the shale. The results are shown in Figure 12 and indicate an increase in gas production rate with grid-refinement; the peak of gas rate occurs at an earlier time as more refined grids are used. The ultimate gas produced for all cases is similar (as a result of 100% hydrate decomposition), however depending on the number of grid-blocks used, there is a difference of approximately 1.5 years to reach this recovery.



**Figure 12:** Effect of gridding on the cumulative gas produced.

The small size of grid blocks necessary for 3-D simulation studies under actual field conditions could be a limiting factor. Shahbazi et al.<sup>16</sup> have developed an upscaling technique to allow accurate simulation of hydrate decomposition using coarse grids.

## DISCUSSION

As illustrated in this paper, the behavior of hydrate decomposition in Type III reservoirs is complicated because of interactions between heat and fluid flow in two dimensions. Understanding this behavior is further compounded by our lack of understanding of one of the important factors controlling fluid flow, i.e. permeability in the presence of hydrates. Accuracy of numerical models as a result of coarse grid-blocks could further inhibit our understanding.

Some of the phenomena observed in the numerical model, such as formation of a thin “finger” of decomposed zone need be further verified. Effect of heterogeneity and anisotropic permeability, which can affect the competition between heat and fluid flow needs to be further investigated.

## CONCLUSIONS

1D and 2D numerical simulation studies of Type III hydrate reservoirs indicated that:

1. Rate of gas production is strongly affected by the initial p/T conditions and permeability of the hydrate bearing formation.
2. Under favorable conditions a high peak rate (a few MMSCF/day) may be achieved, however this peak rate is obtained after an initial period where rate of gas production increases with time.
3. The increase in gas rate is a result of formation of a decomposition “finger” on top and bottom of hydrate layer which advances away from the wellbore. This leads to an increase in surface area for heat conduction, manifesting itself as increased rate of gas generation.
4. The heat transfer in the direction perpendicular to direction of fluid flow is very important, requiring (at least) 2D modeling.
5. Because of the low permeability of hydrate-bearing formations the hydraulic diffusivity is low. Depending on reservoir properties, this could lead to competition between heat and fluid flow, affecting the behavior of decomposition.

## ACKNOWLEDGMENT

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