Example Problem 14
Methane Hydrate Dissociation via Depressurization without Ice Formation in a One-Dimensional Open Domain

Abstract: *This problem is the second in a trilogy of methane hydrate dissociation problems involving methane production from a one-dimensional open domain using conventional approaches to dissociate methane hydrate into liquid water and methane gas. This problem involves the production of methane hydrate using depressurization; where, the outlet pressure is maintained at a point above the freezing point of water on the hydrate stability curve (i.e., above the Q point). The first problem (Problem 13) in the trilogy uses thermal stimulation to dissociate methane hydrate, and the third problem (Problem 15) uses depressurization to a point below the freezing point of water on the hydrate stability curve, leading to ice formation. This problem is solved with STOMP-WCMSE (a.k.a., STOMP-HYD), but does not involve* CO_2 *or salt. This operational mode includes options for eliminating the salt-mass and energy conservation equations. This problem is solved with the salt-mass conservation equation eliminated. This problem involves the release of methane from hydrate and the production of gaseous methane across the open domain. This problem involves three phases: aqueous, gas, and methane hydrate, but not ice.*

14.1 Problem Description

This problem involves a one-dimensional domain open on one end and closed on the other that initially contains methane hydrate in equilibrium with liquid water within the hydrate stability limit, but above the freezing point of water. At time zero, the pressure at the open end of the domain is lowered and the temperature is slightly elevated to a point outside the hydrate stability region, causing hydrate dissociation. The outlet pressure is lowered to a point above the freezing point of water on the hydrate stability curve. With the outlet pressure maintained at this point, ice does not form in the column during the dissociation process. Mobile fluids (i.e., aqueous and gas) move across the open boundary in response to the dissociating hydrate and constant boundary pressure. Hydrologic properties, thermal transport properties, initial conditions and

boundary conditions for this thermal stimulation problem are provided in Table 14.1. The problem domain (length x width x height =1.5 m x 1.0 m x 1.0 m) is discretized into 30 uniform nodes (0.05 m) along the column length. The simulation period is 5 days.

The reduced pressure at the open boundary causes aqueous phase to flow out of the domain, which reduces the pressure within the domain below the stability point, leading to hydrate dissociation. Initially hydrate dissociation is driven by depressurization; where, the energy of dissociation is derived from the reduction in sensible heat (i.e, temperature drop). However, the temperature rapidly drops to the hydrate stability point for the boundary pressure, at which point the hydrate dissociation along the column is controlled by the rate of heat transfer into the column. The dissociating hydrate liberates methane, but does not yield an elevated pressure because of the reduced boundary pressure at the open boundary. Methane liberated from the hydrate is referred to as released methane and methane crossing the open boundary is referred to as produced methane. Data to be reported from the simulation is the pressure, temperature, aqueous saturation, hydrate saturation, gas saturation, mass rate and integral of methane released, and mass rate and integral of methane produced. Field data are to be reported along the column at 2 min, 5 min, 20 min, 1 hr, 12 hrs, 1 day, 2 days, 3 days, and 5 days. Mass rates and integrals of released and produced methane are to be reported for all simulation time. In terms of the STOMP simulator, reporting field data for all nodes at selected times is achieved through plot file output.

Table 14.1. Problem Parameters

Property	Value
Intrinsic Permeability	$k = 3.0\ x\ 10^{-13}\ m^2$
Porosity	$\phi = 0.3$
Pore Compressibility	$\beta = 5.0\ x\ 10^{-9}\ 1/Pa$
Grain Density	$\rho_{grain} = 2.6\ x\ 10^3\ kg/m^3$
Grain Specific Heat	$c_{grain} = 1.0\ x\ 10^3\ J/kg\ K$
Dry Thermal Conductivity	$k_{dry} = 2.0\ W/m\ K$
Grain Thermal Conductivity	$k_{grain} = \dfrac{k_{dry}}{(1-\phi)}$
Thermal Conductivity Model	$k_e = k_{dry} + \phi\,(s_l\,k_l + s_g\,k_g + s_h\,k_h)$
Aqueous Relative Permeability	$k_{rl} = \left(\dfrac{s_l - s_{lr}}{1 - s_{lr}}\right)^n$; $s_{lr} = 0.12,\ n = 3.0$
Gas Relative Permeability	$k_{rg} = \left(\dfrac{s_g - s_{gr}}{1 - s_{lr}}\right)^n$; $s_{gr} = 0.02,\ s_{lr} = 0.12,\ n = 3.0$
Initial Conditions	$T = 6°\ C;\ P = 8\ MPa;\ s_h = 0.5;\ s_l = 0.5$
Boundary Conditions @ x = 0.0 m	$T = 6°\ C;\ P = 2.8\ MPa;\ s_l = 1.0$
Boundary Conditions @ x = 1.5 m	Adiabatic, Zero Mass Flux

14.2 Exercises

1. Execute the problem using the input file described in section 14.3. Using the plotTo.pl perl script, make plots of pressure, temperature, aqueous saturation, hydrate saturation, gas saturation, and aqueous relative permeability, at 2 min, 5 min, 20 min, 1 hr, 12 hrs, 1 day, 2 days, 3 days, and 5 days. Each plot should show a single field variable plotted against distance along the column length, using a unique line for each time.
2. Use the outputTo.pl perl script to make plots of mass rates and integrals of methane released and produced versus time. These plots can be produced using the reference node variables

"Integrated CH_4 Hydrate Mass" and "Integrated CH_4 Mass," where, the former is used to calculate the methane released and the later to calculate the methane produced.

3. Increase and decrease the boundary temperature by 10° C and compare the simulation results against the described problem.
4. Adjust the moisture retention characteristics to investigate the effect of capillary pressure on the dissociation of methane hydrate, keeping in mind that zero capillary pressure is equivalent to laboratory beaker conditions.

14.3 Input File

```
~Simulation Title Card
3.2,
STOMP Short Course Problem 14,
M.D. White,
Pacific Northwest Laboratory,
31 January 2006,
08:52 AM PST,
1,
Methane Hydrate Dissociation via Depressurization in a 1-Dimensional Open Domain

~Solution Control Card
Normal,
H2O-CO2-CH4-NaCl-E w/Isobrine,
1,
0,day,5,day,0.1,s,0.1,day,1.25,8,1.e-06,
100000,
Variable Aqueous Diffusion,
Variable Gas Diffusion,
Equilibrium Hydrate,
0,

~Grid Card
Uniform Cartesian,
30,1,1,
0.05,m,
1,m,
1,m,

~Rock/Soil Zonation Card
1,
Medium,1,30,1,1,1,1,

~Mechanical Properties Card
Medium,2600,kg/m^3,0.3,0.3,Compressibility,5.0e-9,1/Pa,8.0,MPa,Millington and Quirk,,,

~Hydraulic Properties Card
Medium,3.e-13,m^2,3.e-13,m^2,3.e-13,m^2,
```

```
~Saturation Function Card
72.0,dynes/cm,24.0,dynes/cm,,,26.7,dynes/cm,
Medium,van Genuchten,0.132,1/m,2.823,0.0,,72.0,dynes/cm,

~Aqueous Relative Permeability Card
Medium,Free Corey,1.0,3.0,0.12,0.02,

~Gas Relative Permeability Card
Medium,Free Corey,1.0,3.0,0.12,0.02,

~Liquid-CO2 Relative Permeability Card
Medium,Mualem,,

~Thermal Properties Card
Medium,2.857143,W/m K,2.857143,W/m K,2.857143,W/m K,1000,J/kg K,

~Salt Transport Card
Medium,0.0,ft,0.0,ft,

~Initial Conditions Card
4,
Aqueous Pressure,8.0,MPa,,,,,,,1,30,1,1,1,1,
Temperature,6.0,C,,,,,,,1,30,1,1,1,1,
Hydrate Saturation,0.5,,,,,,,,1,30,1,1,1,1,
CH4 Mass Fraction of Hydrate Formers,1.0,,,,,,,,1,30,1,1,1,1,

~Boundary Conditions Card
1,
West,Energy Dirichlet,Aqueous Dirichlet,Gas Dirichlet,Liquid CO2 Zero Flux,
1,1,1,1,1,1,1,
0,day,45,C,2.8,MPa,0.0,0.0,0.0,0.0,2.8,MPa,0.0,1.0,2.8,MPa,

~Output Options Card
8,
1,1,1,
2,1,1,
3,1,1,
4,1,1,
5,1,1,
10,1,1,
20,1,1,
30,1,1,
1,1,hr,m,6,6,6,
12,
Temperature,C,
Aqueous Pressure,MPa,
Gas Pressure,MPa,
Gas Saturation,,
Aqueous Saturation,,
Hydrate Saturation,,
Aqueous Relative Permeability,,
Integrated CH4 Mass,kg,
Integrated CH4 Aqueous Mass,kg,
Integrated CH4 Hydrate Mass,kg,
CH4 Aqueous Mass Fraction,,
CH4 Gas Mass Fraction,,
7,
1,hr,
```

```
3,hr,
6,hr,
12,hr,
1,day,
2,day,
3,day,
9,
Temperature,C,
Aqueous Pressure,MPa,
Gas Pressure,MPa,
Gas Saturation,,
Aqueous Saturation,,
Hydrate Saturation,,
Aqueous Relative Permeability,,
CH4 Aqueous Mass Fraction,,
CH4 Gas Mass Fraction,,

~Surface Flux Card
1,
Heat Flux,W,J,West,1,1,1,1,1,1,
```

14.4 Solutions to Selected Exercises

Exercise 1

Depressurization of the column, as shown by the gas pressure profiles in Figure 14.1, occurs rapidly; where, near-constant gas pressures along the length of the column occur after a few hours.

Gas pressure increases with dissociation of the methane hydrate. However, the gas pressure within the column, as shown in Figure 14.1, is moderated by the 8-MPa fixed boundary condition at the open column end (i.e., x = 0). Temperature profiles, shown in Figure 14.2, are dominated by the 40-C boundary condition at the open column end (i.e., x = 0). The constant-temperature portions of the profiles occur within the hydrate dissociation-formation regions of the domain. Without capillary effects the constant-temperature portions of the profile are diminished in length. Hydrate saturations, shown in Figure 14.3, show the expected sharp dissociation fronts on the open-end-side of the column, but additionally show hydrate accumulations adjacent to, but behind the dissociation front. The dissociation process liberates methane gas, yielding elevated gas pressures that advect methane gas both toward and away from the open end of the column. Gaseous methane that migrates away from the open end of the column moves into the hydrate stability region; thus, forming hydrates. The

aqueous saturation profiles are shown in Figure 14.4; where, saturations vary smoothly from the imposed value of 1.0 at the open end of the column and the dissociation front. Across the dissociation front the aqueous saturation drops sharply, as the pore space is occupied by undissociated hydrate. Gas saturation profiles, shown in Figure 14.5, drop to 0.0 at the open end of the column; however, as the gas relative permeability is upwind weighted gas fluxes out of the domain. It should be noted that gas saturations are greater than 0.0 in the regions hydrate is forming behind the dissociation front, in support of the discussions above. The released and produced methane mass integrals are shown in Figure 14.6, along with the energy flux integral through the open end of the column. Co-plotted in a normalized fashion, it is evident that the released methane mass tracks with the energy fluxing into the domain, which suggests that technologies that could increase the heat transfer into the dissociation zone, would increase production rates. Produced methane mass lags the released mass, because of delay in transporting the released mass across the open end of the column.

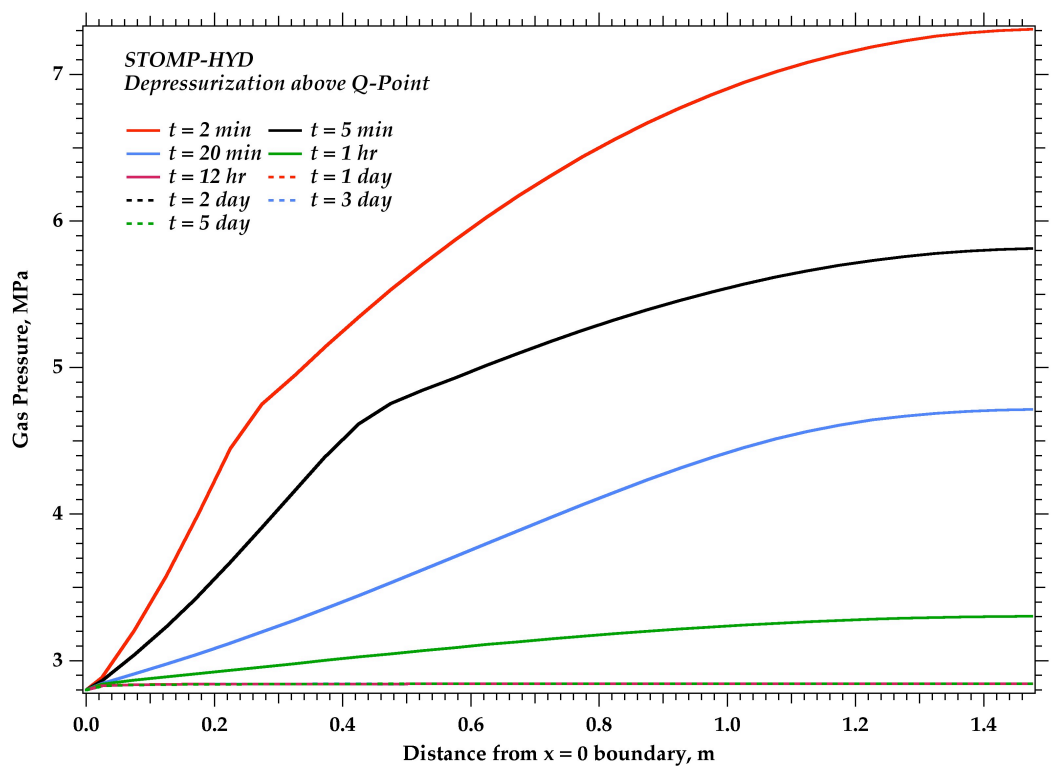

Figure 14.1. Pressure Profiles

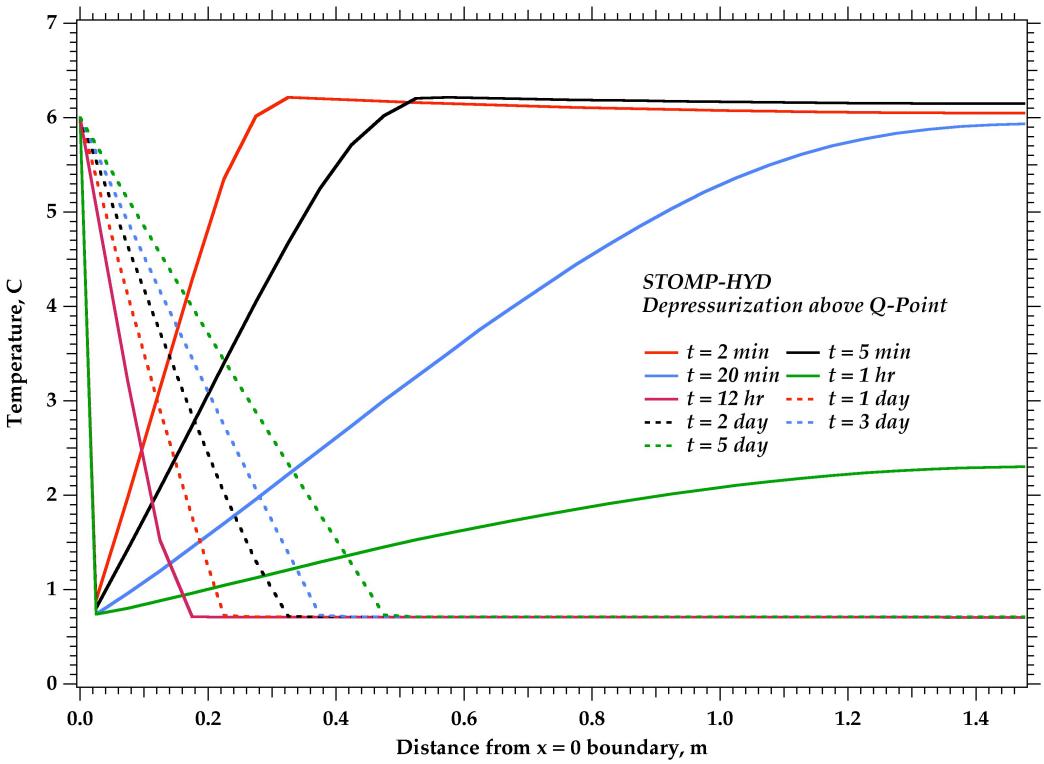

Figure 14.2. Temperature Profiles

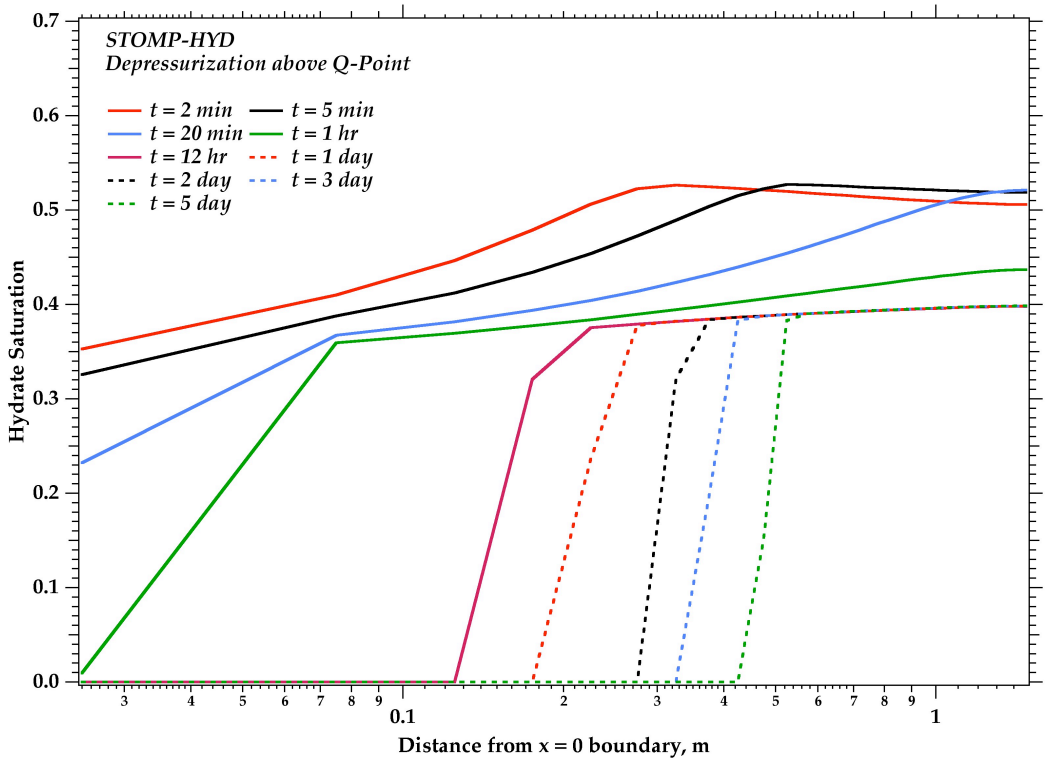

Figure 14.3. Hydrate Saturation Profiles

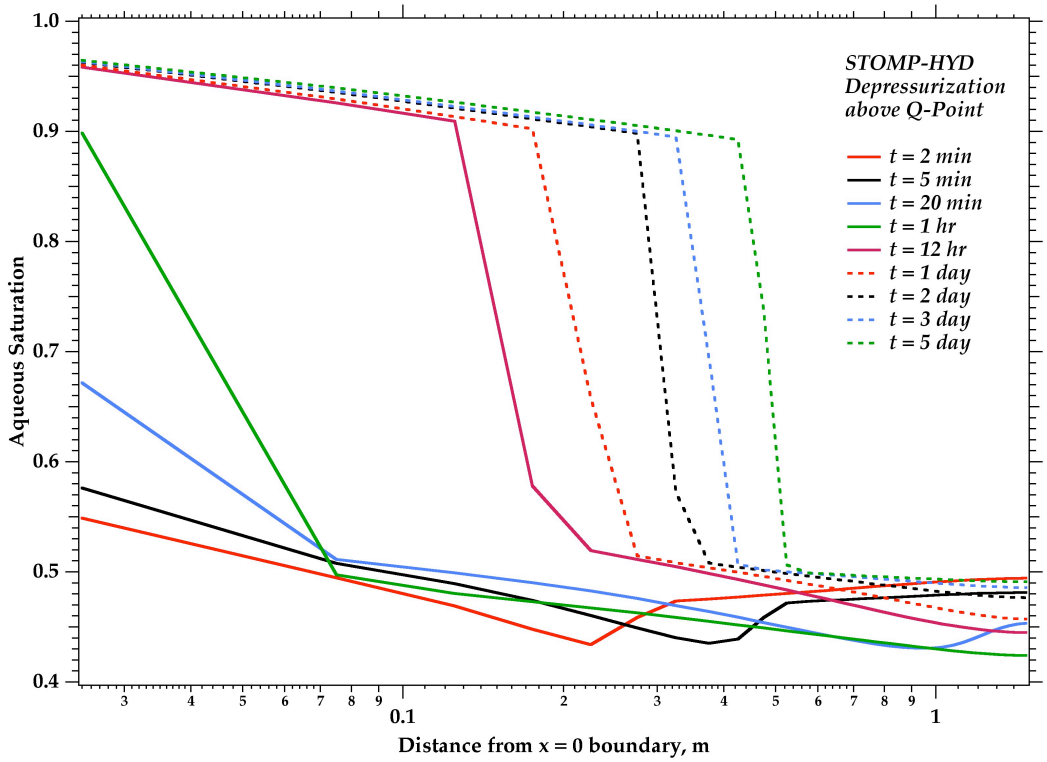

Figure 14.4. Aqueous Saturation Profiles

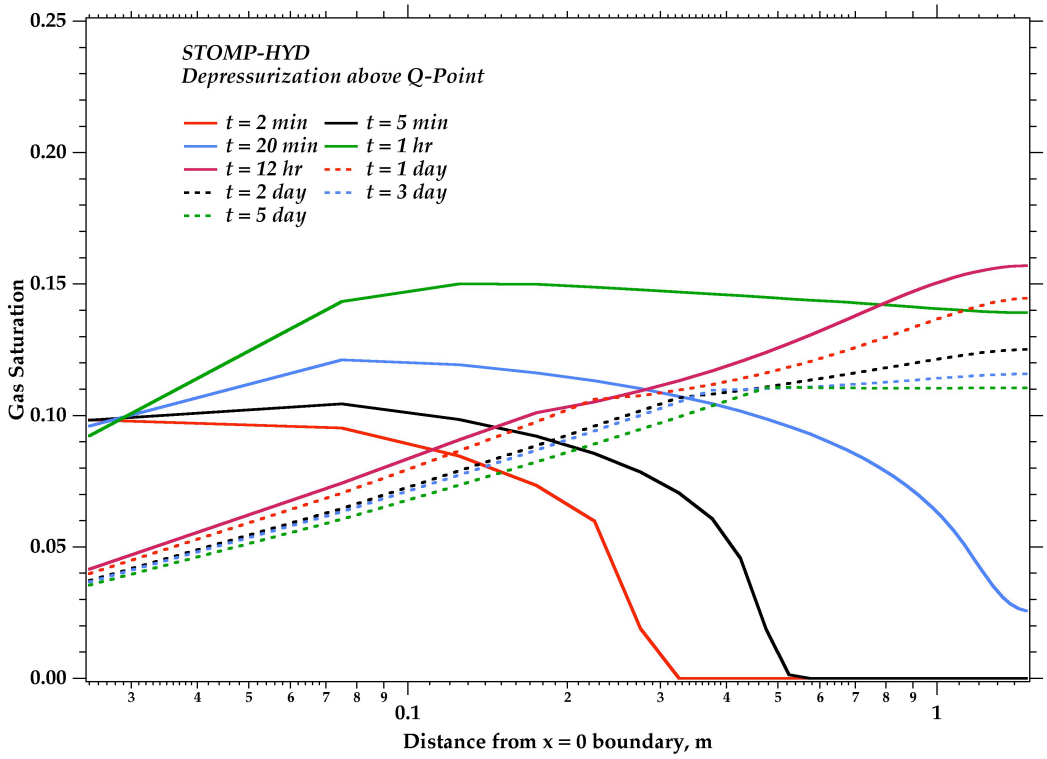

Figure 14.5. Gas Saturation Profiles

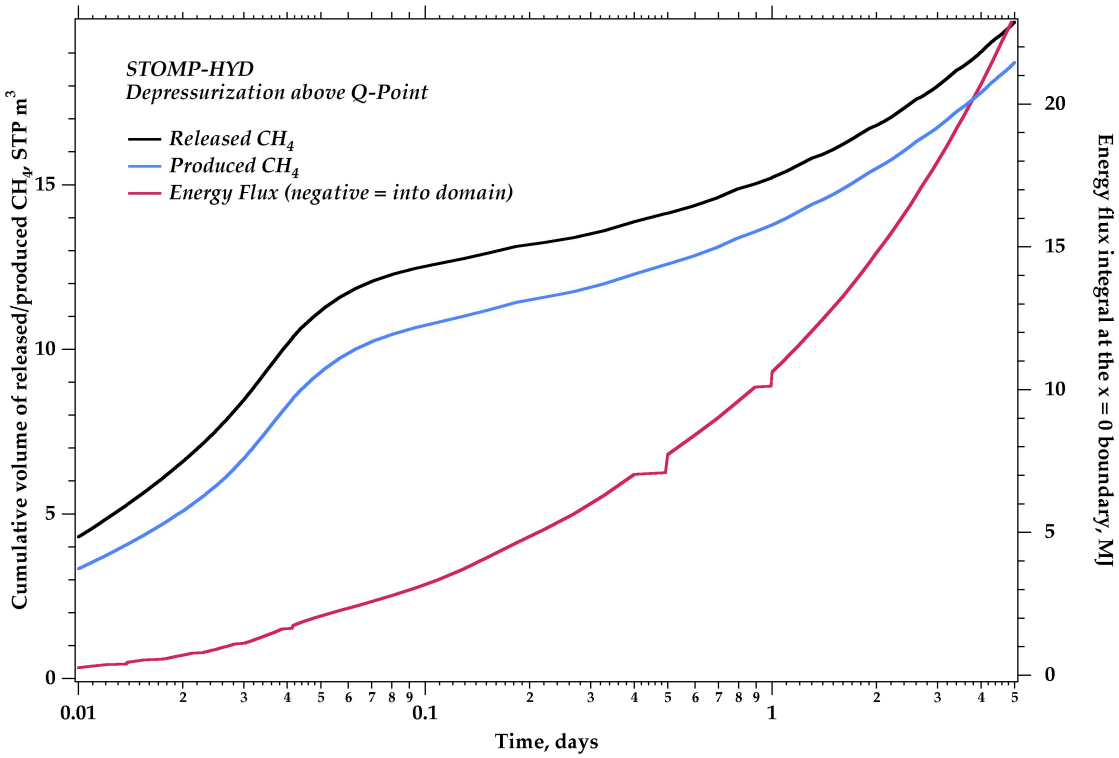

Figure 14.6. Released and Produced CH_4 Integrals