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**SHALE RECHARGE AND PRODUCTION BEHAVIOR OF GEOPRESSURED
RESERVOIRS**

TOPICAL REPORT

S. K. GARG

APRIL 1980

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**SYSTEMS, SCIENCE AND SOFTWARE
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ABSTRACT

The reservoir simulator MUSHRM was used to study the conditions under which significant shale recharge may be expected. The calculations presented herein show that shale recharge is a strong function of the vertical shale permeability but is not greatly influenced by the shale compressibility. Significant shale recharge will occur only if the vertical shale permeability is at least of the order of $0.01 \mu d$.

I. INTRODUCTION

Wallace, et al.^[1] have recently estimated the accessible volume of water stored in the geopressed sandstone and shale beds of the northern Gulf of Mexico basin. Approximately 10 percent of this volume occurs in sandstone, and about 90 percent occurs in shale. On the basis of sandstone percentage, three generalized depositional facies can be identified in the Gulf basin:

1. A massive sandstone facies in which sandstone constitutes at least 50 percent of the total volume,
2. An alternating sequence of sandstone and shale facies with sandstone comprising 15 to 50 percent of the sedimentary volume, and
3. A massive shale facies in which sandstone constitutes no more than 15 percent of the sediments.

Fluid pressures higher than normal (geopressures) are most commonly associated with the alternating sandstone and shale facies, and with the massive shale facies^[1]. Thus, the sandstone reservoirs having greatest potential for development are likely to occur within the alternating sandstone and shale facies. Although the shales which contain the bulk of the accessible fluid resource have too low permeabilities to allow their direct development for fluid production, it has been suggested^[1] that the shales may yield significant quantities of water to the permeable sandstone when subjected to production stress. The shales could thus act as sources of recharge for the sandstones and permit greater fluid recovery than that obtainable by pressure depletion of the sandstone reservoirs alone.

The concept of shale recharge (i.e., water influx from the surrounding shale) was apparently first discussed by Wallace^[2]. Wallace was mainly concerned with the production of gas from geopressed reservoirs along the Gulf Coast. These reservoirs typically contain many thick sections of undercompacted shales with interspersed sand lenses. When pressures within the sand lenses are reduced by gas production, the compaction process (of the shales) is allowed to resume, and water is expelled from the shales into the sands. According to Wallace, the shale water influx is governed by (1) the permeability and compressibility of the shale, (2) the pressure differential across the shale/sandstone interface, and (3) the contact area of the sand/shale interface. For geopressed geothermal reservoirs, Garg, et al.^[3] and Pritchett, et al.^[4] present some preliminary theoretical calculations on the effects of shale permeability and compressibility and shale/sand arrangement (i.e., sand/shale thickness) on shale water influx. The latter authors conclude that for vertical shale permeabilities of the order of 10^{-5} md, significant shale influx would occur only for production times longer than two to three years. Also shale water influx declines with a decrease in shale compressibility and an increase in sand thickness. Garg, et al.^[3] note that the effects of shale compressibility will become evident only for long production times.

One of the main difficulties in assessing the importance of shale water influx in geopressed geothermal reservoirs is the current paucity of data on the relevant shale properties. Seevers^[5] applied Nuclear Magnetic Resonance technique to calculate shale permeabilities from chips collected from a Gulf Coast Well. The shale permeability ranges from a low of approximately 10^{-5} md in the normally pressured region to a high of 4×10^{-5} md in the geopressed region. The latter values

have, however, not been confirmed with direct measurements of permeability on shales^[5]. Bredehoeft and Hanshaw^[6] presented a hydrodynamic compaction model which possibly describes the creation of geopressed reservoirs; the results of this model imply that geopressures will exist if permeability is 10^{-2} md or lower. The value of 10^{-2} md is thus an upper limit on vertical shale permeability, and is apparently much larger than the permeability required for significant shale water influx due to production stress (see below). It is also appropriate to mention here the U. S. Department of Energy sponsored ongoing work on the laboratory determination of shale properties at the University of Texas at Austin (UTA). Preliminary UTA data suggest that the shale compressibility is of the order of 10^{-6} psi⁻¹ [7].

The purpose of the present study is to determine the conditions under which significant shale recharge may be expected. We employ the reservoir simulator MUSHRM in its axisymmetric configuration to examine the effects of shale compressibility and vertical permeability on shale recharge. MUSHRM calculations yield the amount of fluids (brine and/or methane) produced, and also the bottom-hole production well pressures. Shale recharge helps to maintain the pore pressure in the sandstones, and thus allows greater fluid production. The present calculations suggest that shale recharge is a strong function of the vertical shale permeability but is not greatly influenced by the shale compressibility. For significant shale recharge to occur, the vertical shale permeability must be at least of the order of 0.01 μ darcies.

II. NUMERICAL CALCULATIONS

We consider a representative hypothetical bounded (no mass or energy flux across the boundaries) geopressed sandstone/shale reservoir. The reservoir is assumed to be a right circular cylinder with radius $R = 5957.842$ ft. (corresponding to a block area of 4 sq. miles) and height $h = 260$ ft. The net sand thickness of 60 ft. The numerical grid, along with the shale/sand arrangement, used is shown in Figure 1. Rock properties employed in the numerical calculations discussed below are given in Tables 1 and 2. The instantaneous porosity (ϕ) and permeability (k_v or k_h) are given by the following relations:

$$\frac{\partial \phi}{\partial t} = (1 - \phi) C_m \Delta p / \Delta t$$

$$k = k_0 \exp \left\{ \frac{\phi - \phi_0}{(1 - \phi_0)(1 - \phi)} \right\}$$

where

p = fluid pressure,

t = time.

The reservoir fluid is assumed to be a brine (salinity by mass $S = 0.12$ corresponding to a TDS of 130,000 ppm) saturated with methane. The initial pore pressure, temperature and methane mass fraction at a depth of 14,670 ft. are $P = 11,503$ psi (~ 793 bars), $T = 280.4^\circ\text{F}$ ($= 138^\circ\text{C}$), and $C = 0.002706$. Initially, the reservoir fluids are assumed to be in hydrostatic equilibrium; the initial conditions assigned by the simulator are listed in Table 3. The total pore volume, brine in pores, and gas in place are given in Table 4. The amount of methane dissolved in brine at the reservoir conditions is approximately 24.4 SCF/STB.

Figure 1. Numerical grid and the shale/sand arrangement. The reservoir is approximated by a 13 x 6 grid ($\Delta Z_1 = \Delta Z_2 = \Delta Z_5 = \Delta Z_6 = 50$ ft., $\Delta Z_3 = \Delta Z_4 = 30$ ft.; $\Delta r_1 = \Delta r_2 = 300$ ft., $\Delta r_3 = 330$ ft., $\Delta r_4 = 365$ ft., $\Delta r_5 = 400$ ft., $\Delta r_6 = 440$ ft., $\Delta r_7 = 485$ ft., $\Delta r_8 = 535$ ft., $\Delta r_9 = \dots = \Delta r_{13} = 560.5684$ ft.). The well is located in blocks $i = 1$ and $j = 3, 4$.

TABLE 1
ROCK PROPERTIES

	<u>Sandstone</u>	<u>Shale</u>
Initial Porosity (ϕ_0)	0.2	0.2
Grain Density (ρ_s)	164.4 lbm/ft ³ (2.633 gm/cm ³)	164.4 lbm/ft ³ (2.633 gm/cm ³)
Rock Grain Specific Heat (C_{vs})	0.23 Btu/lbm [°] F (0.963 x 10 ⁷ ergs/gm [°] C)	0.23 Btu/lbm [°] F (0.963 x 10 ⁷ ergs/gm [°] C)
Rock Grain Thermal Conductivity (κ_s)	3.03 Btu/hr ft [°] F (5.25 x 10 ⁵ ergs/sec cm [°] C)	3.03 Btu/hr ft [°] F (5.25 x 10 ⁵ ergs/sec cm [°] C)
Initial Vertical Permeability (k_{v0})	2 md (2 x 10 ⁻¹¹ cm ²)	see below
Initial Horizontal Permeability (k_{h0})	20 md (2 x 10 ⁻¹⁰ cm ²)	0.1 μ d (10 ⁻¹⁵ cm ²)
Uniaxial Compressibility (C_m)	10 ⁻⁶ psi ⁻¹ (0.145 x 10 ⁻¹⁰ cm ² /dynes)	see below

TABLE 2
RLATIVE PERMEABILITIES

Free Gas Saturation (S _g)	Liquid Relative Permeability (k _{rw})	Gas Relative Permeability (k _{rg})
0	1	0
0.03	0.92	10 ⁻⁴
0.3	0.2	0.3
0.5	10 ⁻⁴	0.5
1	0	1

TABLE 3

INITIAL CONDITIONS ASSIGNED BY THE SIMULATOR

<u>j</u>	<u>Rock Type</u>	<u>Pressure</u>	<u>Methane Mass Fractions</u>
1	Shale	11,550 psi (796.4 bars)	0.002713
2	Shale	11,527 psi (794.8 bars)	0.002710
3	Sand	11,509 psi (793.5 bars)	0.002707
4	Sand	11,496 psi (792.6 bars)	0.002705
5	Shale	11,478 psi (791.3 bars)	0.002703
6	Shale	11,455 psi (789.8 bars)	0.002699

TABLE 4

PORE VOLUME, BRINE IN PORES, AND GAS IN PLACE

<u>Rock Type</u>	<u>Pore Volume</u>	<u>Brine</u>	<u>Gas</u>
Shale	$4.46 \times 10^9 \text{ ft}^3$ ($1.263 \times 10^8 \text{ m}^3$)	$7.64 \times 10^8 \text{ STB}^*$ ($1.319 \times 10^{11} \text{ kg}$)	$1.864 \times 10^{10} \text{ SCF}^{**}$ ($3.58 \times 10^8 \text{ kg}$)
Sand	$1.338 \times 10^9 \text{ ft}^3$ ($3.79 \times 10^7 \text{ m}^3$)	$2.29 \times 10^8 \text{ STB}^*$ ($3.96 \times 10^{10} \text{ kg}$)	$5.59 \times 10^9 \text{ SCF}^{**}$ ($1.074 \times 10^8 \text{ kg}$)

* 1 STB = 1 bbl of brine at standard conditions ($P = 14.5 \text{ psi}$, $T = 60^\circ\text{F}$).
Specific volume of brine ($S = 0.12$) at standard conditions is $5.788614 \times 10^{-3} \text{ STB/kg}$.

** 1 SCF = 1 ft^3 of methane at standard conditions ($P = 14.5 \text{ psi}$, $T = 60^\circ\text{F}$). Specific volume of methane at standard conditions is 52.06 SCF/kg .

The reservoir is produced by a single 5.5 in. (= 13.97 cm) diameter well located at the center of the reservoir (in Zones i = 1, j = 3, 4) at a constant rate of 10,000 STB/D (~ 20 kg/s) until the bottom hole pressure (datum Z = -14,640 bars) falls to 6670 psi (~ 460 bars); thereafter the BHP is maintained at 6670 psi and the fluid production is allowed to decline.* The calculations were terminated if either the production rate fell below 2000 STB/D (~ 4 kg/s) or the production time exceeded 6 years.

In the absence of any shale recharge, the amount of fluid (expressed as a fraction of the fluid initially present in the sands) producible by primary pressure depletion of the reservoir sands is given by $C_{T, \text{ sand}} (P_i - P_h - P_f)$ where P_i is the initial reservoir pressure, and

$$C_{T, \text{ sand}} = \left(\frac{1-\phi}{\phi} \right) C_{m, \text{ sand}} + C_f$$

C_f = Fluid (water/methane) mixture compressibility

Assuming an initial reservoir pressure P_i of 11,490 psi (pressure at the top of the sand layer), an average $(P_h + P_f) \sim 6670$ psi, $\phi \sim 0.2$, $C_{m, \text{ sand}} \sim 10^{-6} \text{ psi}^{-1}$ and $C_f \sim 3.35 \times 10^{-6} \text{ psi}^{-1}$, the fraction of fluid recoverable by pressure depletion of sands is approximately 3.54 percent. The latter figure is an upper limit since declining flow rate will cause abandonment of the wells before the production rate reaches zero.

* The well will flow only if the bottom-hole pressure is maintained above $(P_h + P_f)$ (P_h = hydrostatic pressure, P_f = frictional pressure loss in the tubing). The hydrostatic pressure, based on the fluid density in situ is approximately 6640 psi (~ 458 bars). It is assumed here that two-phase flow occurs in the wellbore and sufficient gas percolates through the liquid column to reduce P_h such that $(P_h + P_f) < 6670$ psi (~ 460 bars).

A series of six cases was considered to assess the sensitivity of shale recharge (and its effect on the production behavior of the well) to variations in vertical shale permeability (Cases 1-4), and uniaxial shale compressibility (Cases 5 and 6). The values of the latter parameters (i.e., k_{vo} and C_m for shale) for the various Cases are listed in Table 5. Figure 2 gives the bottom-hole pressure for Cases 1-4. The bottom-hole pressure, in Cases 1-3, drops to 6670 psi in approximately 0.80 years; in Case 4 ($k_{vo} = 0.1 \mu d$), the bottom-hole pressure stays above 6670 psi for slightly more than 0.95 years. The instantaneous brine production rate for Cases 1-4 is shown in Figure 3. In Cases 1 and 2, the brine production rate drops below 2,000 STB/D in 3.2 years. For $k_{vo} = 0.01 \mu d$ (Case 3), the brine production rate can be maintained above 2,000 STB/D for more than 4.4 years. The most dramatic improvement in brine production rate is seen for Case 4; in this instance, the brine production stays above 6500 STB/D for the duration of the calculation (≈ 6 years). Finally, the cumulative methane production is shown in Figure 4. The cumulative methane production for Cases 1 and 2 is virtually identical; the total methane production for Case 3 is 18 percent more than that for Cases 1 and 2. For Case 4, the cumulative methane production ($t = 6$ years) is more than twice that obtained for Cases 1 and 2. The results of these calculations clearly indicate that for shale recharge to be effective, vertical shale permeability needs to be at least of the order of $0.01 \mu d$. If vertical shale permeability is of 0 ($0.001 \mu d$), little or no shale recharge will occur for practical production times.

Table 6 summarizes the brine and methane production data for all the six cases. Cases 5 and 6 (identical with Cases 3 and 4 except for shale compressibility) were designed to assess the effect of shale compressibility on reservoir production behavior. A comparison of Cases 3 and 4 with Cases 5 and 6 (Table 6) clearly shows that even a ten-fold increase in shale compressibility has no significant impact on reservoir production behavior.

TABLE 5

VERTICAL SHALE PERMEABILITY (k_{vo}) AND UNIAXIAL SHALE
COMPRESSIBILITY (C_m)

<u>Case</u>	<u>Vertical Shale Permeability (k_{vo})</u>	<u>Uniaxial Shale Compressibility C_m</u>
1	0 μd (0 cm^2)	10^{-5} psi-1 (0.145×10^{-9} $cm^2/dynes$)
2	0.001 μd (10^{-17} cm^2)	10^{-5} psi-1 (0.145×10^{-9} $cm^2/dynes$)
3	0.01 μd (10^{-16} cm^2)	10^{-5} psi-1 (0.145×10^{-9} $cm^2/dynes$)
4	0.1 μd (10^{-15} cm^2)	10^{-5} psi-1 (0.145×10^{-9} $cm^2/dynes$)
5	0.01 μd (10^{-16} cm^2)	10^{-4} psi-1 (0.145×10^{-8} $cm^2/dynes$)
6	0.1 μd (10^{-15} cm^2)	10^{-4} psi-1 (0.145×10^{-8} $cm^2/dynes$)

Figure 2. Effect of vertical shale permeability on bottom-hole pressure.

Figure 3. Effect of vertical shale permeability on the instantaneous brine production rate.

Figure 4. Effect of vertical shale permeability on cumulative methane production.

TABLE 6

SUMMARY OF BRINE AND METHANE PRODUCTION

Percentages denote fraction of the brine (methane) in place in sand alone.

<u>Case</u>	<u>Cumulative Brine Produced</u>	<u>Average Brine Production Rate</u>	<u>Cumulative Methane Produced</u>	<u>Average Methane Content of Produced Fluid</u>
1	7.06×10^6 STB ~ 1.22×10^9 kg (3.08%)	6,040 STB/D for 3.2 years	1.49×10^8 SCF ~ 2.86×10^6 kg (2.66%)	21.1 SCF/STB
2	7.19×10^6 STB ~ 1.24×10^9 kg (3.14%)	5,970 STB/D for 3.3 years	1.51×10^8 SCF ~ 2.91×10^6 kg (2.71%)	21.1 SCF/STB
3	8.59×10^6 STB ~ 1.48×10^9 kg (3.75%)	5,230 STB/D for 4.5 years	1.78×10^8 SCF ~ 3.43×10^6 kg (3.19%)	20.8 SCF/STB
4	1.69×10^7 STB ~ 2.91×10^9 kg (7.36%)	7,700 STB/D for 6 years	3.55×10^8 SCF ~ 6.81×10^6 kg (6.34%)	21.0 SCF/STB
5	8.60×10^6 STB ~ 1.49×10^9 kg (3.75%)	5,240 STB/D for 4.5 years	1.79×10^8 SCF ~ 3.43×10^6 kg (3.20%)	20.8 SCF/STB
6	1.76×10^7 STB ~ 3.03×10^9 kg (7.66%)	8,020 STB/D for 6 years	3.71×10^8 SCF ~ 7.12×10^6 kg (6.63%)	21.1 SCF/STB

III. SUMMARY AND CONCLUSIONS

The calculations presented in the preceding section imply that shale recharge strongly depends upon the vertical shale permeability, but is largely unaffected by the uniaxial shale compressibility. For practical production times, significant shale recharge will take place only if the vertical shale permeability is at least of 0 (0.01 μ d). Although present indications are that vertical shale permeabilities of the order of 0.01 μ d are reasonable for geopressed reservoirs, it must be stressed that no direct measurement of shale permeability are currently available. To evaluate the possibility of shale recharge in geopressed reservoirs, it is clearly necessary to obtain reliable estimates of in situ shale permeabilities.

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