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Detecting Compartmented Gas Reservoirs Through Production Performance

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ABSTRACT

A technique for using production data to detect and quantify poorly drained compartments in gas reservoirs is described. The method is based upon a multi-compartment, tank-like model with well performance specified by an in-flow relationship. The technique is validated against a detailed finite element simulation. Field examples are presented illustrating the utility of the technique to improve reservoir development strategies.

INTRODUCTION

Reservoir heterogeneity is well recognized as a factor limiting recovery in oil and gas reservoirs. Simulation techniques for characterizing reservoir variability have appeared recently in the literature. Stewart and Whaballa[1] have shown that a material balance simulator can be used with pressure histories from well tests in compartmented oil reservoirs to identify geological structures. Haldorsen and Damsleth[2] demonstrated that stochastic modeling, together with classic geological principles, allows one to quantify the effect of geological variability on future reservoir performance. Hower and Collins[3] also used a material balance model for a two-compartment gas reservoir, in which the compartments are coupled by a low permeability barrier. This was shown to provide a technique for identifying compartment structure through history matching field pressure data. Furthermore, these authors presented a rigorous criterion which specifies when observed shut-in pressures are representative of average reservoir pressures. This criterion is necessary for the application of the compartment model.

References and illustrations at end of paper.

The study presented here generalizes these material balance models. The model considers any number of compartments with communication between any compartment pair through a permeable barrier. An important property of the model is the ability to history match observed production rates. This requires the specification of a well inflow performance equation relating the average reservoir pressure, flowing wellbore pressure and well rate. This inflow performance relation is rigorously valid only for pseudo steady-state conditions and will not accurately describe conditions during transient periods following rate changes. Validation of the inflow performance equation is obtained by comparison of the compartment model performance with a detailed finite element simulation[4].

The ability of the compartment model to predict drained pore volumes and barrier transmissibility is demonstrated for structures representative of fluvial deltaic deposition in the Middle Frio formation of the Texas Gulf Coast.

MODEL FORMULATION

The physical laws which constitute the basis of the model are: the conservation of mass, the real gas equation of state and Darcy's Law for flow through the porous permeable barrier. The reservoir structure is described by one or more compartments with each pair of compartments in communication through a permeable barrier. The conservation of mass for the ith compartment is assured by the equation

$$\frac{d(V_i \rho_i)}{dt} = -\sum_{w=1}^{N_w} \rho_{sc} q_{iw} - \sum_{j=1}^{N_c} \psi_{ij} \quad i = 1,2,\ldots,N_c \quad \text{.................(1)}$$

In writing the conservation of mass in the above form it is assumed that gas storage, or more specifically, changes in gas storage, within any low permeability barrier is negligible. Thus for linear flow normal to the plane of a barrier of uniform thickness L, the mass flow rate into one face is always equal to the mass flow rate out of the opposite face. Hence, this mass rate given by

$$\psi = -\rho \frac{KA}{\mu} \frac{\partial P}{\partial x} \quad \text{......(2)}$$

has the same value at any plane parallel to the face within the barrier. Using the definition of compressibility

$$c = \frac{1}{\rho} \frac{d\rho}{dP} \quad \text{......(3)}$$

together with the real gas equation of state

$$\rho = \frac{M}{RT_R} \frac{P}{Z} \quad \text{......(4)}$$

this mass flux is written as

$$\psi = -\frac{KA}{\mu c} \frac{d\rho}{dP} \frac{\partial P}{\partial x} = -\frac{KA}{\mu c} \frac{\partial \rho}{\partial x} \quad \text{......(5)}$$

Since ψ has the same value for all x this gives the approximation for the flow between the ith and jth compartments as

$$\psi_{ij} = \frac{KA}{\mu c L} \left(\rho_i - \rho_j \right) \quad \text{......(6)}$$

where μc is evaluated at the mean pressure between the two faces and L is thickness across the barrier. This approximation is incorporated in the model with the real gas equation of state to write the conservation of mass in the ith compartment as

$$V_i \frac{d}{dt}\left(\frac{P}{Z}\right)_i = -\frac{T_R P_{sc}}{T_{sc}} \sum_{w=1}^{N_w} q_{iw} - \sum_{j=1}^{N_c} \frac{T_{ij}}{(\mu c)_{ij}} \left[\left(\frac{P}{Z}\right)_i - \left(\frac{P}{Z}\right)_j \right], i = 1,2,\ldots,N_c, \quad \text{....(7)}$$

where the T_{ij} are the constant values of the transmissibilities KA/L between the ith and jth compartments. If all fixed parameters are given specified values, that is, the pore volumes V_i, transmissibilities T_{ij}, together with initial pressure, gas gravity and reservoir temperature, then the model is completely defined if the well rates, q_{iw}, are given functions of time. Thus the pressure histories are computed by integrating this system of equations numerically. The solution of this initial value problem is performed numerically by the Burlirsch-Stoer method[5]. In this integration Z-factor, viscosity and compressibility are given functions of pressure and temperature based on accepted industry correlations.

INFLOW PERFORMANCE EQUATION

The model incorporates commingled production in wells. Thus well w has production rate

$$q_w = \sum_{i=1}^{N_c} q_{iw} \quad \text{......(8)}$$

where q_{iw} is the rate of production from compartment i through well w. Typically, a well is completed in only one compartment, but it may have multiple completions.

Another important element of the model allows specification of the history of pressure draw-down at a well instead of the production rate history. Clearly, this is the more realistic and natural way to represent well history since gas wells normally produce into a fixed line pressure. Dake[6] demonstrates that, to a very good approximation, for pseudo steady-state flow of a single well in a volumetric reservoir, the flow rate, q, is related to the wellbore bottomhole pressure, P_{wf}, and the average reservoir pressure, P, in terms of pseudo pressure

$$m(P) = 2 \int_{P_{rf}}^{P} \frac{P\,dP}{\mu(P)\,Z(P)} \quad \text{......(9)}$$

by the two-parameter relationship

$$m(P) - m(P_{wf}) = Bq + Fq^2 \quad \text{......(10)}$$

Here B is the Darcy coefficient while F is the non-Darcy coefficient. Expressions for B and F are obtained in Dake[6], however, in this study these coefficients are adjustable parameters in the history match process. A similar expression can also be used to include frictional pressure drops in the wellbore and pipe line such that P_{wf} is replaced by line pressure and a hydrostatic correction is included.

Theoretically, this inflow relationship is valid only after a pseudo steady-state pressure distribution has evolved in the reservoir. This means that following a rate change a time period would elapse before this relationship would be valid. Hence, it was necessary to determine criteria for the applicability of this relationship in the compartment model.

Validity of the inflow performance equation was determined by finite element numerical simulation of a fully penetrating well. The well was operated at fixed wellbore pressure. In the absence of non-Darcy flow, as modeled in the finite element simulator, the solution for a fixed P_{wf} determines a well flow rate, q. Thus, a Darcy coefficient can be computed in terms of the average reservoir pressure, P, at any time using

$$B = \frac{m(P) - m(P_{wf})}{q} \quad \text{......(11)}$$

This Darcy coefficient will be variable as P and q change but is found to converge in time to a constant value. If one uses this constant value of B to compute a rate q from P and P_{wf} then the point in time at which the two rates agree defines the time required to establish pseudo steady-state flow. This implies that after a change in production rate there will be a transient period in which the inflow performance equation does not accurately represent the well rate. However, after this period of time, the flow rate is represented by the inflow performance equation. In order to present the results of this numerical investigation, we define the elapsed time, since the change in P_{wf} was made, in the dimensionless form

$$t_D = \frac{.0063265Kt}{\phi(\mu c)_i A} \quad \text{......(12)}$$

We also define the dimensionless flow rate

$$q_D = \frac{50325 T_R P_{sc} q_{sc}}{T_{sc} Kh(m_i - m_{wf})} \quad (13)$$

For a well located at the center of a near circular reservoir, the results of the numerical simulation are shown in Figure 1 with dimensionless flow rate plotted as a function of dimensionless time. For $t_D > 0.1$ the inflow performance equation is a valid representation for the behavior of a well operated at a fixed wellbore pressure P_{wf}. Figure 2 shows a similar study for a well located in a rectangular reservoir.

Typical values of the key parameters in the Stratton Field included in this study are

$K = 100$ md
$\phi = 0.15$
$(\mu c)_i = 1.5 \times 10^{-5}$ psi^{-1} cp

Then for a well located in the center of a circular drainage area, A = 10 x 10^6 ft^2 (230 acres) the time required to reach $t_D = 0.1$ is

$$t = \frac{\phi(\mu c)_i A t_D}{.0063265K} = 3.6 \text{ days} \quad (14)$$

The existence of errors in pressure and rate during this short transient period will not invalidate responses predicted by the compartment model on longer time scales.

EXAMPLES OF HISTORY MATCHING FIELD DATA

The first example illustrating the use of the compartment model is Well No. 79L, completed in the F-20 sand of the Wardner unit of the Stratton Field, Kleberg County, Texas. The pressure data shown in Figure 3 are history matched as a one well, two compartment model with rate history specified from Dwight's data. Note pressure data are from two sources; commercial data as reported by Dwights Energy Data, Inc. and operator data. In most cases, pressures reported in Dwights are surface shut-in pressures while operator's data are bottomhole shut-in pressures. The operator's data are considered more reliable and are closely honored in the history match. Reservoir data are:

initial pressure	=	2043 psi
temperature	=	177°F
gas gravity	=	0.69

The two compartment volumes and barrier transmissibility were adjusted until the model simulation matched the observed pressures. The result of the history match is shown in Figure 3 with the rate data also represented. The history match reveals that production is from a pore volume of 12 million cubic feet with supporting flow through a permeable barrier from a similar pore volume of 15 million cubic feet. The barrier transmissibility was 33 md-ft.

With the pore volumes and transmissibility determined from the pressure history match, a rate history match can be determined by specifying the flowing wellbore pressure history and adjusting the inflow performance parameters so that the compartment model well rate is in agreement with the observed field rate. When the well performance parameters are thus determined, the compartment model may be used to predict future production. This would be accomplished by operating the well at prescribed flowing wellbore pressure until the rate declines to a specified economic limit. Estimates of flowing wellbore pressure are obtained from the pressure tests reported in the Dwight's data. These reported flowing wellbore pressures are surface readings, while the model requires bottomhole flowing wellbore pressure. Thus only the trend in the reported flowing wellbore pressures is honored in the model simulation. The following flowing wellbore pressure schedule was assigned for the Wardner 79L:

Date	P_{wf}(psi)
Nov 1976	1000
June 1978	700
Jan 1982	500
Oct 1984	50

The results of the rate history match is shown if Figure 4. This match was obtained with inflow performance parameters

B = 25000 psi^2/cp/Mscf/d
F = 30 (psi^2/cp/Mscf/d)^2

The early time response is not accurately matched. A more detailed operation schedule during this early time is required to better match the early rate data. However, the general behavior of the rate decline is matched. The pressure response from the rate history match is compared with the original pressure history match in Figure 5. The pressure response from the rate history match is in excellent agreement with the pressure response from the pressure history match and the field data.

A basic question in the presence of compartmented reservoir behavior concerns the quantity of gas in the secondary, untapped compartment as yet unrecovered. If this quantity of untapped gas is significant, then location of this gas must be determined and future operation strategies investigated. The compartment model is capable of detecting and quantifying compartmented reservoir drainage behavior. The problem of locating untapped gas must be done by detailed geological modeling and by pressure interference testing.

For the Wardner 79L well the model simulation obtained from the history match yields gas in place in both the primary produced volume and the secondary untapped volume. The compartment model simulation determines the gas in place for the Wardner 79L well as reported in Figure 6. The first column in Figure 6 is the original gas in place, while the second column reports the gas in place at the end of the history match. A prediction run is made in which the well is operated at the historical rate through March 1991 and is then operated at P_{wf} = 50 psi for future time. The prediction run is terminated when the well rate does not meet an economic rate limit of 30 Mscf/d. With this operational constraint the well is abandoned in March 2006. The third column of Figure 6 lists the gas in place at the end of the prediction run. The difference between the gas-in-place at times March 2006 and March 1991 represents the incremental gas recovery. This study suggests that conventional operation of the Wardner well 79L should produce most of the available gas in both primary and secondary compartments even though there is evidence of compartmented reservoir structure.

A second study is located in the F-39 reservoir of the Stratton Field. Figure 7 shows the streambed boundaries as determined by well logs. Located on this map are those wells with significant production from the F-39 sand or wells with reported pressure observations. The 80T well produced 6.7 Bcf from June 1954 through January 1963. Production was then curtailed until July 1967. Between July 1967 and March 1991 the 80T produced 6.3 Bcf. The 83J was completed in May 1964 and has produced 2.4 Bcf. The other three wells, 204F, 169D and 182D, were completed late in the life of the reservoir with little significant production. Pressure data from these five wells are shown in Figure 8. Several observations can be made from the pressure data. Although the 80T well had significant production between 1954 and 1963, because of the long curtailment period between January 1963 and initial production of the 83J in May 1964, it is expected that the reservoir was in equilibrium in early 1964. This is confirmed by the agreement of the 1964 pressures observed in the 80T and 83J wells. The pressure decline during production of the 80T and 83J are very dissimilar with the 83J decline suggesting drainage of a much smaller volume than the 80T. Further, pressures in the three offset wells suggests that structural boundaries exist between the 83J and the 204F and between the 80T and the 182D. Good communication is apparent between the 80T and the 169D. A study assuming the 80T produced from a compartment with supporting flow from a secondary compartment containing the 182D is considered. A similar study of the well pair 83J and 204F could be made.

A pressure history match of the production of the 80T well in a two compartment model is shown in Figure 9. Also, shown in Figure 9 is the historical rate of the 80T well. This rate is input for the pressure history match. The results of the history match predict the compartment volumes and barrier transmissibility as

primary drainage volume	=	32 million cubic feet
secondary supporting volume	=	78 million cubic feet
barrier transmissibility	=	18 md-ft

Honoring the parameters determined in the pressure history match, the rate history match shown in Figure 10 determines the inflow performance parameters for the 80T as

Darcy coefficient	=	11000 $psi^2/cp/Mscf/d$
Non-Darcy coefficient	=	7 $(psi^2/cp/Mscf/d)^2$

Because of the erratic production during the early history the actual well rate is assigned between completion date and November 1975. After this date the well is operated by specifying P_{wf}. The pressures from both the pressure history match and the rate history match are compared in Figure 11 with good agreement. A prediction run with economic rate limit of 100 Mcf/d was made using the parameters from the history match. The historical rate was assigned from initial production until March 1991 and future production was determined by P_{wf} = 70 psi. The well is projected to be abandoned in February 2048. Depletion of gas from the primary and secondary compartments is shown in Figure 12. A significant quantity of gas exists in the secondary volume at current time. Existing production practices will leave 4.3 Bcf in the supporting compartment. Also of significance is the long period of time necessary to produce the incremental gas recovered between present time and abandonment. The long recovery time will decrease the present worth of the gas. This study would suggest that further investigation in the area surrounding the 80T well is warranted. A pressure interference test involving the 80T, 182D and 169D would be a likely next step in the study.

CONCLUSIONS

It is demonstrated that a simple material balance model is useful in detecting and quantifying compartmented reservoir structure using field production data. The model gives estimates of pore volumes and barrier transmissibilities. Once a successful history match is obtained, the compartment model can predict future drainage for given production strategies. This capability can assist in directing further engineering studies, such as interference pressure testing, and in detailed geological studies. Finally, these results can assist in targeting future infill development wells.

A part of this study focused on determining conditions under which an inflow performance relating well rate, wellbore pressure and average reservoir pressure is representative of gross material balance for the reservoir. Thus criteria are determined which assure applicability of the compartment model.

NOMENCLATURE

A	=	cross sections area of barrier, ft^2
B	=	Darcy flow coefficient, $psi^2/cp/Mscf/d$
c	=	gas compressibility, psi^{-1}
F	=	non-Darcy flow coefficient, $(psi^2/cp/Mscf/d)^2$
h	=	reservoir thickness, ft
K	=	permeability, md
L	=	barrier thickness, ft
m	=	real gas pseudo pressure, psi^2/cp
M	=	molecular weight, lb/mol
N_c	=	number of compartments
N_w	=	number of wells
P	=	average reservoir pressure, psi
q	=	gas flow rate, scf/d
R	=	universal gas constant, psi-ft^3/mol- ^oR
t	=	time, day
T	=	transmissibility, md-ft
T_R	=	reservoir temperature, ^oR
V	=	pore volume, ft^3
x	=	distance, ft
Z	=	gas compressibility factor
ρ	=	gas density, lb/ft^3
ϕ	=	porosity, fraction
ψ	=	mass flux, lb/d
μ	=	gas viscosity, cp

Subscripts

D	=	dimensionless
i,j	=	compartment index
rf	=	reference conditions
sc	=	standard conditions
w	=	well index
wf	=	flowing wellbore

ACKNOWLEDGEMENTS

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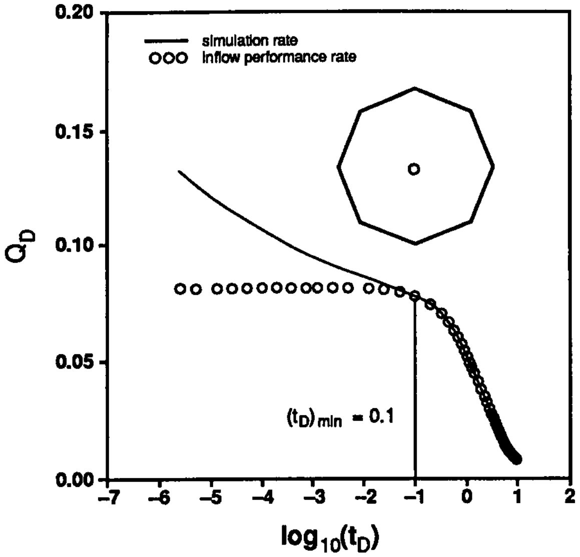

Figure 1
Dimensionless time to achieve inflow performance relation for near circular reservoir.

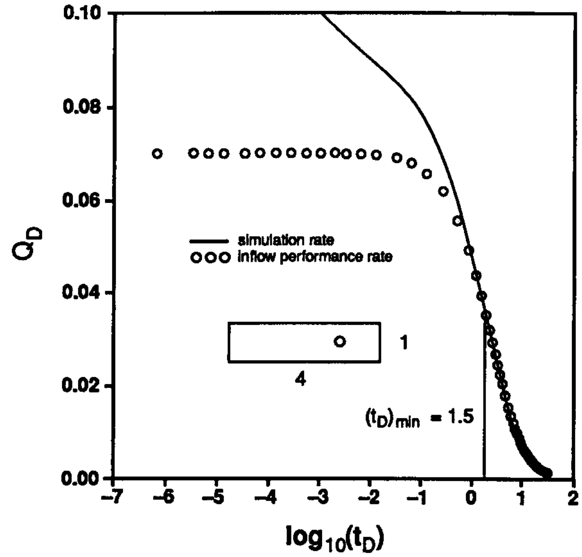

Figure 2
Dimensionless time to achieve inflow performance relation for rectangular reservoir.

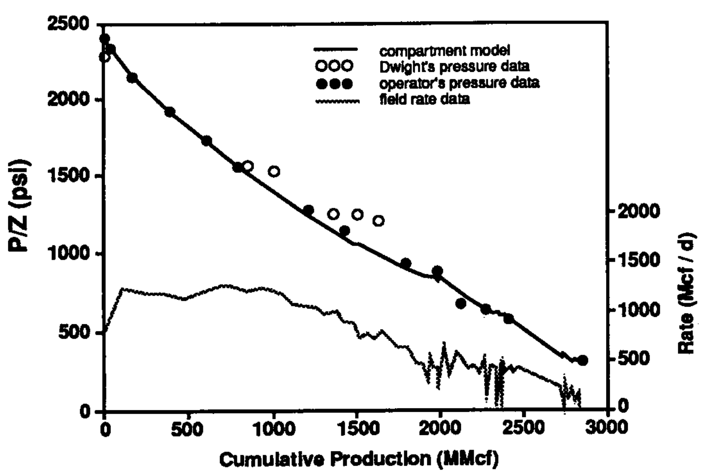

Figure 3
Pressure history match for the Wardner 79 L well.

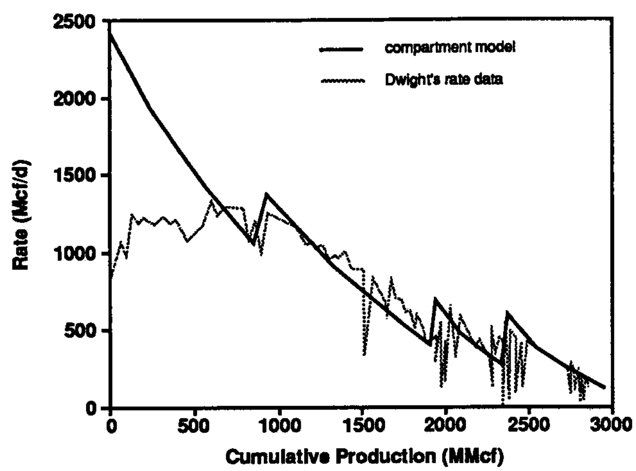

Figure 4
Rate history match for the Wardner 79L well.

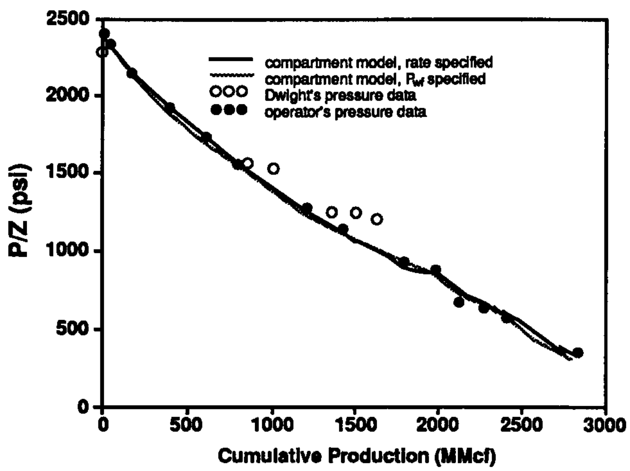

Figure 5
Comparison of rate and pressure history matches of the Wardner 79L well.

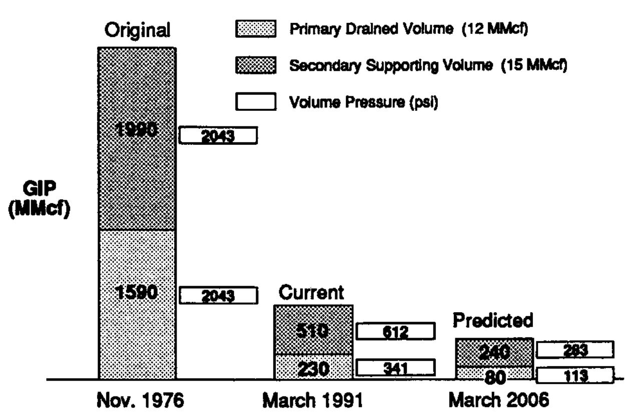

Figure 6
Depletion by compartments for the Wardner 79L well simulation.

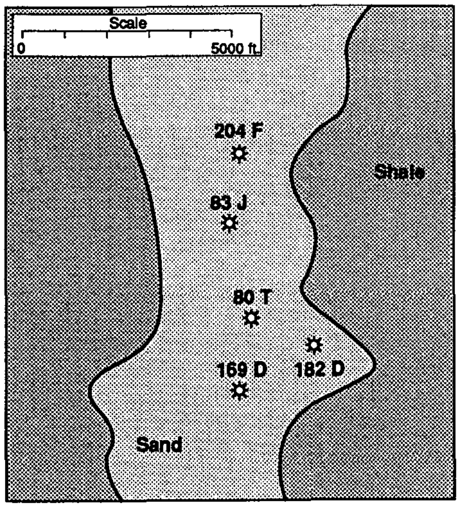

Figure 7
Streambed geometry and well locations in the Stratton field, F-39 reservoir.

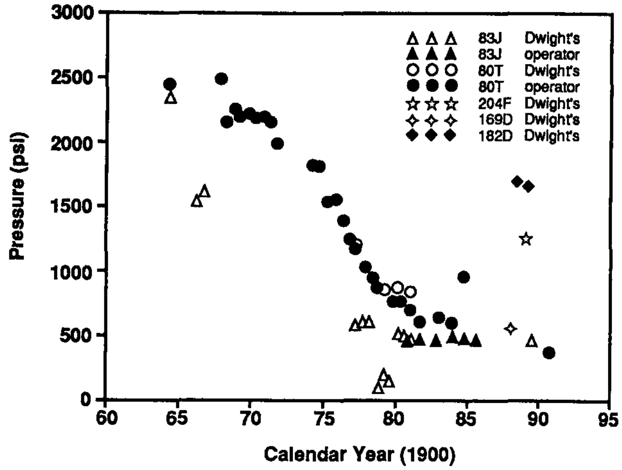

Figure 8
Reported pressures for wells in the F-39 reservoir.

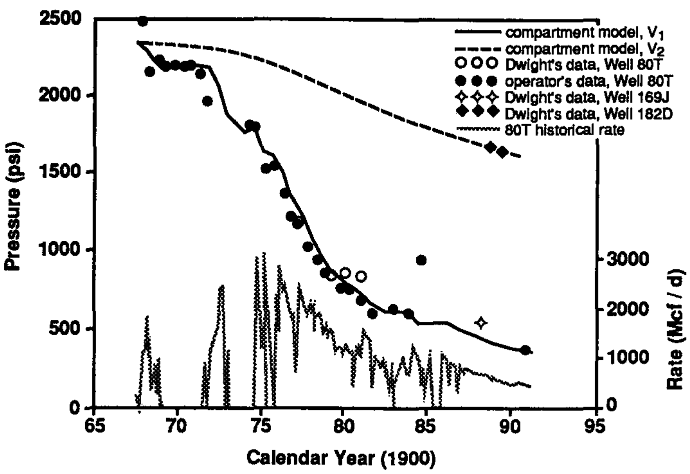

Figure 9
Pressure history match for the Wardner 80T well.

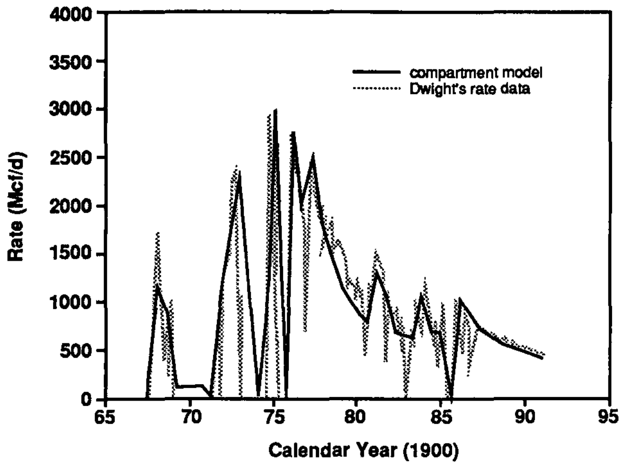

Figure 10
Rate history match for the Wardner 80T well.

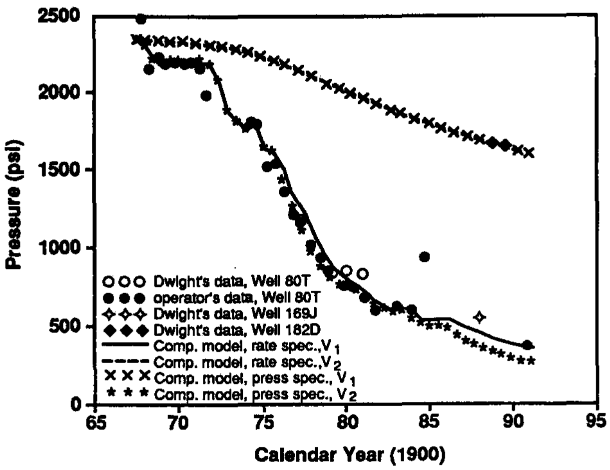

Figure 11
Comparison of rate and pressure history matches of the Wardner 80T well.

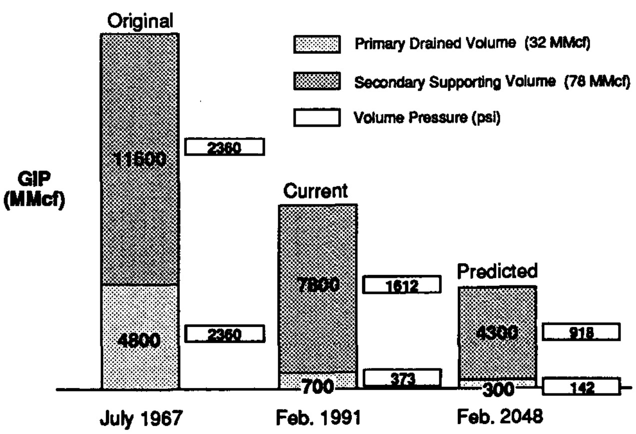

Figure 12
Depletion by compartments for the Wardner 80T well simulation.