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Multiwell Experiment: Reservoir Modeling Analysis, Volume II

Technical Note

By
A.I. Horton

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May 1985

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210

TABLE OF CONTENTS

	<u>Page</u>
Summary	1
Introduction	1
Background	2
Procedure	2
Analysis Setup	5
Natural Fractures Representation	5
Water Saturation	6
Paludal Interval Poststimulation Analysis	6
Discussion -- Paludal Poststimulation Analysis	9
Coastal Interval Test Analysis	9
Well-to-Well Interference	9
References	15

LIST OF FIGURES

<u>Figure</u>		<u>Page</u>
1	Location of Multiwell Experiment	3
2	MWX Test Intervals	4
3	History Match of Paludal Post Mini-Fracture Tests Using GAS3D2	8
4	Coastal Zone Well-to-Well Log Correlation	10
5	History Match of Prestimulation Yellow Coastal Zone Well Tests Using GAS3D2	11
6	History Match of Prestimulation Yellow Coastal Zone Well Tests Using SUGAR-MD	12
7	History Match of Prestimulation Red Coastal Zone Well Tests Using GAS3D2	13

LIST OF TABLES

<u>Table</u>		<u>Page</u>
1	Paludal Zones 3 and 4. Base History Match Simulator Input Data	7
2	Coastal Red and Yellow Zones. History Match Simulation Input Data	14

Summary

This report updates an ongoing analysis by reservoir modelers at the Morgantown Energy Technology Center (METC) of well test data from the Department of Energy's Multiwell Experiment (MWX). Results of previous efforts were presented in a recent METC Technical Note (Horton 1985).

Results included in this report pertain to the poststimulation well tests of Zones 3 and 4 of the Paludal Sandstone Interval and the prestimulation well tests of the Red and Yellow Zones of the Coastal Sandstone Interval.

The following results were obtained by using a reservoir model and history matching procedures:

- Post-minifracure analysis indicated that the minifracure stimulation of the Paludal Interval did not produce an induced fracture, and extreme formation damage did occur, since a 65 percent permeability reduction around the wellbore was estimated. The design for this minifracure was from 200 to 300 feet on each side of the wellbore.
- Post full-scale stimulation analysis for the Paludal Interval also showed that extreme formation damage occurred during the stimulation as indicated by a 75 percent permeability reduction 20 feet on each side of the induced fracture. Also, an induced fracture half-length of 100 feet was determined to have occurred, as compared to a designed fracture half-length of 500 to 600 feet.
- Analysis of prestimulation well test data from the Coastal Interval agreed with previous well-to-well interference tests that showed extreme permeability anisotropy was not a factor for this zone. This lack of permeability anisotropy was also verified by a nitrogen injection test performed on the Coastal Red and Yellow Zones.

Introduction

Reservoir modeling analysis of measured data from pressure buildup and drawdown tests at the MWX continues at METC. Recent efforts have attempted to evaluate tests conducted on Zones 3 and 4 of the Paludal Interval and the Red and Yellow Zones of the Coastal Interval. Both of these intervals are part of the Mesa-verde lenticular sandstone formation.

The Paludal analysis presented here is a continuation of work previously discussed in Technical Note No. DOE/METC-85/4007 (Horton 1985). Well tests conducted in March 1984, after minifracure treatments (small-scale, unpropped hydraulic fracture treatments), and in June 1984, after full-scale hydraulic fracture treatments, were studied to obtain a better understanding of the stimulation effects. This poststimulation analysis followed from the prestimulation studies in assuming that the previous modeling analysis was sufficient to characterize the production-controlling mechanisms. The simulator of the previous modeling analysis could thus be assumed to behave as the actual reservoir. Using this rationale, the same simulator input data are used for the poststimulation modeling, and only parameters that might have been changed by the stimulation operation are varied to simulate the well tests. These

parameters (formation damage and induced fracture length) can be combined in various ways to simulate pressure responses similar to the measured well test responses. This will be discussed further in the "Paludal Interval Poststimulation Analysis" Section.

Analysis of the Red and Yellow Zones of the Coastal Interval (tested September through December 1984) was performed to characterize and develop an understanding of the Coastal reservoir properties prior to further testing and stimulation of these zones (scheduled for mid-1985).

Background

The MWX is a three-well field laboratory, located in the Rulison Field of the Piceance Basin, near Rifle, Colorado (see Figure 1). The MWX is designed to investigate the gas production potential of lenticular tight gas reservoirs. The three MWX wells were drilled in a closely spaced pattern (less than 200 feet between each well) to a depth of about 8,000 feet. Core samples were extracted and analyzed to determine some formation characteristics for the potentially productive tight sandstone formations. (These zones of interest are shown in Figure 2.) Other formation characteristics are determined by analysis of well test data. Tests are performed separately on selected sandstone intervals, beginning at the bottom of the well. The tests consist of alternately flowing and shutting in one well while monitoring the pressure in the flowing well and the offset, or observation, wells. Data obtained in the tests are analyzed to determine reservoir characteristics controlling gas flow.

Hydraulic fracture treatments are being performed at selected intervals following pressure tests. These intervals are also tested after stimulation. Ideally, if prestimulation tests are sufficient to enable characterization of the untreated formation, stimulation models can be used to predict the extent of hydraulic fracture treatments, and analysis of poststimulation well tests can be used to evaluate the stimulation effects on productivity.

METC modelers are performing separate reservoir analysis and stimulation analysis on the incoming MWX test data. The analyses are being used to (1) aid METC project managers in future Western Gas Sands research planning, (2) develop an in-house technical resource on lenticular gas sands, and (3) aid in testing and validating METC reservoir and stimulation models. The reservoir modeling characterization of MWX well tests is being used in connection with other METC modeling activities on low permeability lenticular reservoirs (Mercer and others 1985) to develop a base on which to build further predictive capabilities for such reservoirs, while developing confidence in the models' abilities to simulate and represent tight gas sands.

Procedure

Reservoir modeling analysis of the well tests is based on history matching of the field-measured well tests. History matching is the procedure of fine-tuning uncertain reservoir model input parameters until the computer model simulates responses that match, or are very close to, the measured response. Most of the model input parameters are derived from measured reservoir properties. The flowing and shut-in sequences of the actual well tests are input to the model by specifying gas flow rates and flow times, and the simulated pressure response in the well is matched with the measured pressure response.

FIGURE 1. Location of Multiwell Experiment (from Northrup 1984)

INTERVALS OF INTEREST

FIGURE 2. MWX Test Intervals (from Northrup 1984)

After history matching, the simulator can be used to evaluate various enhanced recovery scenarios (such as stimulation or infill drilling), deliverability, and reserves.

Analysis Setup

- Grid System

Both the Paludal and Coastal studies used the simulator grid system used in the previous work. This 24 by 25 grid block system is arranged with the x-direction as the maximum permeability direction (N 78° W). The study area covers about 385,000 square feet (642 feet by 601 feet) and contains the three MWX wells.

- Simulated Flow Periods

In all of the well tests studied, the pressure responses were monitored while well number MWX-1 was alternately flowed and shut in. In all except the Paludal Interval post-minifrac tests, pressure responses in the offset wells, MWX-2 and MWX-3, were measured in an attempt to detect reservoir communication or interference.

Natural Fractures Representation

The MWX well tests have indicated the presence of a natural fracture system that contributes significantly to the gas production potential from the sub-microdarcy rock matrix. The natural fractures must be considered when evaluating the well tests by either specifically including them or by inferring their presence by assigning a higher system permeability.

Two reservoir models are being used to evaluate the well tests. The first, GAS3D2 (Sawyer 1983) is a single-porosity gas reservoir model, and the second, SUGAR-MD (Science Applications, Inc. 1983a and b), is a dual-porosity (naturally fractured) gas reservoir model. In using GAS3D2 to simulate the well tests, a bulk system permeability is input. This bulk permeability is the "effective permeability" of the system. In using the dual-porosity SUGAR-MD, the rock matrix serves as a gas source and the fracture system provides the flow path for gas to the producing wellbore. In this case, the fracture system permeability is the "effective permeability." The dual-porosity concept used in SUGAR-MD views the reservoir as a series of matrix blocks separated by natural fractures. The matrix generally has a relatively high porosity and very low permeability, such as that measured in core analysis. The fracture system has a very low porosity and a relatively high permeability. (The concept of a low-porosity fracture system may seem odd, but the fracture system porosity is the fracture void space in relation to the total bulk volume of the reservoir rock.) The average spacing between the fractures is also input to SUGAR-MD so that the entire study area is viewed as a system of homogeneous matrix blocks connected with a fracture system.

Some dual-porosity models require the specification of a fracture permeability and fracture width. In SUGAR-MD, the fracture width is accounted for by the fracture system porosity which is dependent on the fracture width and the fracture spacing in relation to the study area dimensions. Similarly, the

permeability of one fracture is accounted for by the fracture system permeability and average fracture spacing. This can be viewed by the Craft and Hawkins (1959, 280) permeability equation for beds in parallel, if the layers of fracture and matrix are viewed as beds in parallel.

The equation

$$k_{avg} = \frac{\sum k_i h_i}{\sum h_i} \quad \begin{array}{l} \text{(where } k_i = \text{permeability in millidarcies [md] of} \\ \text{the } i\text{th layer and} \\ h_i = \text{thickness of the } i\text{th layer.)} \end{array}$$

can be applied to SUGAR-MD input parameters by denoting k_{avg} as the "effective" or fracture system permeability, the rock matrix as one layer and the fracture as a second layer. Thus, for example, when this equation is applied to a system such as the MWX Yellow Coastal Interval, where the effective system permeability is approximately 0.015 md, average fracture spacing is about 30 feet, and matrix permeability is on the order of 0.001 md or less, a single crack of width 0.001 inches would have a permeability of 5,400 md.

Water Saturation

Both models used to analyze the MWX well tests are for analysis of single-phase gas flow. Cores from the MWX have exhibited high water saturations (on the order of 30 to 60 percent). Most of this water is held within the tight pores of the reservoir rock by capillary pressure. Therefore, the core-measured system porosity is adjusted to a gas-filled porosity by reducing for the amount of water saturation measured. For example, a core-measured porosity of 8 percent with a water saturation of 50 percent would give a gas-filled porosity of 4 percent (entered to the models as .04).

The well tests have had occasional problems with "slugs" of water during operations. Most of this is attributed to continued clean-up from perforation operations. While it does affect the measured pressure responses periodically, it cannot be accounted for by the modeling analysis.

Paludal Interval Poststimulation Analysis

Both GAS3D2 and SUGAR-MD have been used to evaluate the prestimulation Paludal tests, and results were identical. That is, the "effective" system permeability used to history match test responses with GAS3D2 was identical to the fracture system permeability used in SUGAR-MD. Therefore, poststimulation analysis of Paludal well tests continued using GAS3D2 only.

The analyses began with simulations of the post-minifracure tests during which MWX-1 was alternately flowed and shut in. Unlike the other MWX well tests, pressures at the observation wells (MWX-2 and MWX-3) were not recorded during these tests. Base simulator input data used were those generated by the previous history matches of prestimulation well tests (see Table 1). The "restart" option in GAS3D2 was used to link the new simulations with the previous ones. This option accounts for previous disturbances to the reservoir by using the final reservoir pressure distribution from the previous simulation run as the initial reservoir pressure distribution for the current run. It also builds on

TABLE 1. Paludal Zones 3 and 4.
Base History Match
Simulator Input Data

Parameter	
Gas Gravity	0.67
Reservoir Temperature (°F)	210
Initial Reservoir Pressure (psia)	5,300
Formation Thickness (ft)	30
Gas-Filled Porosity (fraction)	0.05
X-Direction Permeability (md)	0.1
Y-Direction Permeability (md)	0.01
Anisotropy (kx/ky)	10/1

the previous simulation time, cumulative production, and cumulative material balance error.

In history matching the actual well test data, two factors were considered that might have resulted from the stimulation operations. These were an induced fracture of varying lengths, and formation damage, which causes reduced permeability near the wellbore and the induced crack. Formation damage (skin damage) results when the injected fluid reacts with the rock components, causing pore blockage or reduced flow channels.

The minifracture treatments were designed to extend 200 to 300 feet on each side of the wellbore (200- to 300-foot wing lengths). However, reservoir simulation of the post-treatment well tests showed severe damage rather than enhanced response due to the stimulation. Induced fracture lengths of 0, 50, and 200 feet, with no formation damage and with permeability reductions of 25, 35, 50, 65, and 75 percent within the fracture and 10 to 20 feet around the wellbore and fracture were simulated. The best match that could be obtained by this method used no induced fracture and 65 percent permeability reduction around the wellbore (see Figure 3).

After obtaining the best match of post-minifracture well tests by varying only stimulation-controlled parameters, the GAS3D2 restart option was used again for simulation of post full-scale stimulation well tests. Again, various combinations of induced fracture length and formation damage were input to the model. The combination of fracture length and damage that showed the best comparison of simulated and actual response used a fracture length of 100 feet and permeability reduction of 75 percent, 20 feet on each side of the fracture. This is in extreme contrast to the designed and computed propped fracture lengths of 500 to 600 feet.

POST MINI-FRAC TESTS--PALUDAL ZONES 3 & 4
MWX #1--BOTTOMHOLE PRESSURE

FIGURE 3. History Match of Paludal Post Mini-Fracture Tests Using GAS3D2

Discussion -- Paludal Poststimulation Analysis

It is obvious that extreme formation damage resulted from the stimulation operations on the Paludal Interval. In the case of the mini-fracture treatment, the permeability damage introduced by the treatments had the effect of diminishing the production potential to the point where the reservoir performed worse than if there had been no treatment. The effective length of the fracture was just 10 to 20 percent of the design length, with the extensive damage on top of the reduced effective length. In the case of full-scale treatment, the treatment again did more harm than good. It should be noted that the gelled-water treatments used in this stimulation are the conventional treatments used by industry in this area on the same or similar formations. Therefore, extreme formation damage preventive methods should be used when hydraulic fracturing tight lenticular sandstones such as those at the MWX. Plans for future MWX stimulations are carefully evaluating formation damage prevention.

Coastal Interval Test Analysis

Testing of the Coastal Interval consisted of a 7-week test on the Red Zone and a 5-week test on the Yellow Zone. Figure 4 shows a gamma ray log correlation of the Coastal Interval in MWX-1, MWX-2, and MWX-3.

In METC's modeling analysis of these tests, emphasis was placed on the Yellow Zone well tests, and all sensitivity runs were made on the Yellow Zone data. (This emphasis was initially an arbitrary decision, but revised MWX plans have designated the Yellow Zone as the target interval for extensive stimulation and testing operations.)

Complete sensitivity analysis of Yellow Zone well test responses was performed, using both the GAS3D2 single-porosity model and the SUGAR-MD dual-porosity (naturally fractured) reservoir model. The parameters tested were permeability, gas-filled porosity, permeability anisotropy at various average permeabilities ($\bar{k} = \sqrt{k_x \cdot k_y}$), wellbore damage, wellbore storage, and formation thickness. In SUGAR-MD, fracture and matrix properties and fracture spacing were also tested. The parameter which most affected the response in MWX-1 was fracture or "effective" system permeability. Those which most affected the response in MWX-2 and MWX-3 were permeability, anisotropy, and gas-filled porosity.

History matches of the Red and Yellow Zone tests were obtained by varying the "effective" or fracture system permeability. All other parameters were obtained from core analysis. Both SUGAR-MD and GAS3D2 were used to history match the Red Zone tests. Parameters used in both matches are shown in Table 2. Figures 5, 6, and 7 show the history matches obtained.

Well-to-Well Interference

In the Coastal tests, as well as in the previous Paludal tests, no well-to-well interference was detected. That is, disturbances in MWX-1, caused by periodic shut-in and flowing times, had no apparent effect on the pressures measured in MWX-2 and MWX-3. Lack of interference could be due to several factors, including (1) the tight rock characteristics and lack of natural fracture interconnectivity or (2) the lack of well-to-well sandstone continuity. Geologic studies indicate that all three wells are located in the same sandstone lenses.

FIGURE 4. Coastal Zone Well-to-Well Log Correlation
(from Lorenz 1984)

PRE-STIMULATION TESTS--YELLOW COASTAL ZONE
MWX #1--BOTTOMHOLE PRESSURE

FIGURE 5. History Match of Prestimulation Yellow Coastal Zone Well Tests Using GAS3D2

PRE-STIMULATION TESTS--YELLOW COASTAL ZONE
MWX #1--BOTTOMHOLE PRESSURE

FIGURE 6. History Match of Prestimulation Yellow Coastal Zone Well Tests Using SUGAR-MD

PRE-STIMULATION TESTS--RED COASTAL ZONE
MWX #1--BOTTOMHOLE PRESSURE

FIGURE 7. History Match of Prestimulation Red Coastal Zone Well Tests Using GAS3D2

TABLE 2. Coastal Red and Yellow Zones.
History Match Simulation Input
Data

	Red Zone Value	Yellow Zone Value
<u>GAS3D2 Parameter</u>		
Gas Gravity	0.67	0.67
Reservoir Temperature (°F)	185	185
Initial Reservoir Pressure (psia)	4,250	3,900
Formation Thickness (ft)	35	28
Gas-Filled Porosity (fraction)	0.375	0.044
X-Direction Permeability (md)	0.009	0.015
Y-Direction Permeability (md)	0.009	0.015
Anisotropy (kx/ky)	1/1	1/1
<u>SUGAR-MD Parameter</u>		
Fracture System Porosity (fraction)	--	0.00001
Fracture System Permeability (md)	--	0.015
Matrix Porosity (fraction)	--	0.044
Matrix Permeability (md)	--	0.001
Average Fracture Spacing (ft)	--	30

Therefore, the natural fractures and tight rock matrix are the most likely causes for lack of interference.

Sensitivity analysis showed that the best way to simulate little or no interference in the two observation wells was to input extremely high permeability anisotropy, where the maximum permeability might be at least 100 times the minimum permeability. (Note that MWX-2 and MWX-3 both lie off the direct trend of maximum permeability.) However, specifying high permeability anisotropy throughout the study area caused the simulated pressure response in MWX-1 to be diminished as well. Therefore, extreme permeability anisotropy was ruled out as a potential factor in our modeling analyses.

Preliminary findings indicate that the lack of well to well pressure interference is caused by scattered, impermeable barriers. Recent nitrogen tracer tests on the Coastal Red and Yellow Zones were designed to determine the potential scale of permeability anisotropy and natural fracture trends. The tests consisted of injecting nitrogen into MWX-2 at pressures far below the formation breakdown pressure while producing MWX-1 and MWX-3. Continuous gas samples were taken from MWX-1 and MWX-3 to determine the time when nitrogen broke through to the observation wells. Nitrogen arrival times were similar in the two wells, indicating a lack of permeability anisotropy. Additional information on these tests and their results will be available in the near future.

References

- Horton, A. I. February 1985. Status of Multiwell Experiment Reservoir Modeling Analysis, Volume I. DOE/METC-85/4007. NTIS/DE85008559.
- Craft, B. C., and M. F. Hawkins. 1959. Applied Petroleum Reservoir Engineering. Englewood Cliffs, NJ: Prentice-Hall, Inc.
- Lorenz, J. C. November 1984. Multiwell Experiment: Site Geology. In Third Annual Western Gas Sands Program Review, ed. K-H. Frohne. DOE/METC/85-7. NTIS/DE85001961. 37-62.
- Mercer, J. C., J. R. Ammer, R. A. Moore, A. W. Layne, and K-H. Frohne. March 1985. Study of Gas Migration from Naval Oil Shale Reserve No. 3 to the Rulison Field. DOE/METC-85/4003. In Press.
- Northrup, D. A. November 1984. Multiwell Experiment: Activities Overview. Third Annual Western Gas Sands Program Review, ed. K-H. Frohne. DOE/METC/85-7. NTIS/DE85001961. 396-419.
- Sawyer, W. K. September 1983. General Purpose Gas Simulator for Single- or Multi-Well Studies, "GAS3D2" Version 1.00. DOE/MC21490-1441. NTIS/DE84000310.
- Science Applications, Inc. September 1983a. Simulator for Unconventional Gas Resources Multi-Dimensional Model "SUGAR-MD" -- Volume II: User's Manual. DOE/MC08216-1440, Volume II. NTIS/DE84000307.
- Science Applications, Inc. September 1983b. Simulator for Unconventional Gas Resources Multi-Dimensional Model "SUGAR-MD" -- Volume I: Reservoir Model Analysis and Validation. DOE/MC08216-1440, Volume I. NTIS/DE83017035.