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Production Characterization of Tight Lenticular Gas Sands in the Rulison Area of Western Colorado

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ABSTRACT

The U.S. Department of Energy's (DOE) Morgantown Energy Technology Center has performed an extensive reservoir simulation study on gas production from tight gas sands in the Rulison Field area of the Piceance Basin in western Colorado. Production behavior was modeled for the low permeability gas sands of both the Wasatch Formation and the lenticular portion of the Mesaverde Group. The study forecasted total gas production for Township 6S, Range 94W for 25 years, based on current well spacing regulations (160 acres [$6.5 \times 10^5 m^2$] for Wasatch wells, 320 acres [$1.3 \times 10^6 m^2$] for Mesaverde wells). The study also predicted the effects on gas recovery of reducing the well spacing to 80 acres ($3.2 \times 10^5 m^2$) and 160 acres ($6.5 \times 10^5 m^2$) for the Wasatch and Mesaverde, respectively. The reservoir study utilized a dual porosity, single-phase gas simulator to characterize reservoir behavior by history matching actual production performance from 23 Wasatch and 12 Mesaverde wells in the Rulison Field.

The study followed two extensive DOE field testing programs, a multiwell experiment and a special Mesaverde test well drilled in Naval Oil Shale Reserve No. 3. These DOE field tests provided geologic information and values for reservoir parameters that control production from this unconventional gas resource. In addition to the results from the two field experiments, the study used a detailed geologic analysis to help characterize the producing formations.

INTRODUCTION

The Morgantown Energy Technology Center (METC) recently completed studies[1,2] on gas migration from Naval Oil Shale Reserve (NOSR) No. 3 (Figure 1) to nearby producing commercial wells in the Rulison Field. Presently there is industry activity in the Rulison Field area and since Township 6S, Range 94W makes up approximately 60 percent of the Rulison Field, this paper is a follow-up to the original work and presents a gas production characterization of Township 6S, Range 94W. The previous studies used hydraulic fracture treatment records, geophysical logs, a geologic study[3], DOE field test data from the multiwell experiment (MWX) and from the special Mesaverde test well (1XM9) (Figure 1), approximately 4 years of production data from 41 industry wells (Figure 2) in the adjacent Rulison Field, reservoir analysis computer codes[4,5,6], and reservoir engineering calculations to determine values of k_f, L_f, and ϕ_f at any point in Township 6S, Range 94W for both the Wasatch Formation and the lenticular portion of the Mesaverde Group. Since these were the critical unknown parameters affecting gas production, the performance of a well located anywhere in Township 6S, Range 94W could then be estimated.

Three possible reservoir configurations were considered for this study. The first assumed that wells completed in the Mesaverde drained gas only from those sandstone lenses in direct contact with the wellbore [1,2]. The second assumed that lenses in the Wasatch were in direct sand-to-sand contact with other remote lenses, thereby allowing drainage from a cluster of lenses and not just from the lenses actually penetrated by the wellbore. The third configuration assumed that the sandstone lenses in the Wasatch were in hydraulic communication through a natural fracture network that extended across both the sandstone lenses and the shale separating the lenses. That is, a wellbore penetrating a lens could also drain gas from remote lenses through the natural fracture network. These two Wasatch characterizations were considered plausible since the previous studies [1,2] had shown that for several Wasatch wells actual gas production

References and illustrations at end of paper.

after four years exceeded calculated gas-in-place for lenses penetrated directly by the wellbore. The sandstone lenses in both the Wasatch and Mesaverde were considered naturally fractured for all cases.

MESAVERDE CHARACTERIZATION

Data from 12 of the 14 available Mesaverde wells were used to history match actual 4-year production against simulated production by varying k_f, L_f, and ϕ_f. Twenty-five year cumulative production was then predicted for each of the 12 wells by using a reservoir simulator. The 25-year cumulative production data was then extrapolated throughout Township 6S, Range 94W so that the 25-year cumulative production for a well located anywhere in the study area could be predicted.

Colorado spacing regulations for Mesaverde completions permit one well per 320 acres ($1.3 \times 10^6 m^2$). Current practice in the Rulison Field is to locate one well in the southwestern corner of a section and the other in the northeastern corner of that section. For this study four Mesaverde wells were placed in each section, in effect cutting average well spacing in half. That is, each well was placed at a point located 880 feet (270 m) horizontally and 880 feet (270 m) vertically from the corners of a section. Twenty-five year cumulative production was then predicted for the four wells in each section. The sections were then rank ordered based on cumulative gas production at 25 years for the section. (See Figure 3.) The northwest quadrant of Township 6S, Range 94W turned out to contain 8 of the best 9 gas producing sections. Section 17 was predicted to be the top producer with 5,900 MMcf ($1.7 \times 10^8 m^3$) at 25 years. The worst producer was Section 12 with 700 MMcf ($2.0 \times 10^7 m^3$) at 25 years.

Decreasing the actual well spacing from 320 acres ($1.3 \times 10^6 m^2$) to 160 acres ($6.5 \times 10^5 m^2$) at this point seemed appropriate for the Mesaverde wells. However, one question in cutting the spacing was whether this would result in well-to-well interference. This question was answered by calculating the percentage of available sandstone being drained for each of the 12 Mesaverde wells. An estimate of the maximum volume of producing sandstone available in a section was calculated for each well using the following equation and input values from geophysical well logs:

$$V_{sd} = 5{,}280 \times 5{,}280 \times H \times \frac{\Sigma h}{H} \quad (1)$$

This calculation for V_{sd} assumes that little variability in h and H exists across a section. The $\Sigma h/H$ ratio is then a reasonable estimation of the percentage of productive sandstone that would be intersected by any well located in that section.

The volume of sandstone expected to be drained at 25 years was then calculated using the following equation:

$$V = \frac{G_p \times B_g}{RF \times \phi \times S_g} \quad (2)$$

The percentage of net sandstone estimated to be drained varied from 11 percent for MV 7 and MV19 to 1 percent for MV 8, MV 13, and MV18. These differences were caused by the number and sizes of the lenses intersected by the wells as well as the variability in k_f between sections. Table 1 gives the percentages for all 12 Mesaverde wells. This analysis shows that increasing the number of wells per section, or infill drilling, is a viable development strategy for Mesaverde completions since only a small amount of available gas in a section appears to be drained with two wells per section (320-acre [$1.3 \times 10^6 m^2$] spacing).

WASATCH CHARACTERIZATION CASE 1

Twenty-three of the 27 Wasatch wells available (4 wells were completed at different depths) were used for this analysis for this study. Case 1 assumed the lenses penetrated by a well bore were in direct sand-to-sand contact with other lenses. Hence, drainage was from a much larger rock volume than indicated by log sand counts. Again, actual 4-year production was history matched by varying k_f, L_f, and ϕ_f for each Wasatch well. The total 25-year cumulative production for the four wells in each section was then predicted as it was for the Mesaverde wells, with the each of wells located in a quarter section. The percentages of sands drained were then calculated for all the Wasatch wells using Equations (1) and (2). The largest percentage was 53 for W114 and the smallest was 2 for W126. The percentage of sandstone drained by each well is listed in Table 2. The sections were then rank ordered by total cumulative production for four wells per section at 25 years. Figure 4 gives this rank ordering. Eight of the nine best producing sections are located in the south central part of the study area (Sections 20-22, 27-29, and 32-34). Section 21 had the highest predicted production of 4,900 MMcf ($1.4 \times 10^8 m^3$); Section 13 the least with 500 MMcf ($1.4 \times 10^7 m^3$).

Table 2 indicates that the four Wasatch wells per section permitted by Colorado are sufficient to produce most of the available gas from several of the sections in Township 6S, Range 94W. However, W118 and W119, located in Section 11, showed only 8 and 9 percent sandstone drainage respectively. Since Section 11 with its predicted low recovery showed a four well cumulative production of 1,200 MMcf ($3.4 \times 10^7 m^3$) at 25 years, a value of 1,500 MMcf ($4.3 \times 10^7 m^3$) was chosen as the selection criterion for identifying sections where infill drilling is a viable development option. Figure 4 shows most of these low recovery sections on or above a diagonal running from the northwest corner to the southeast corner of Township 6S, Range 94W. That is, Sections 1-4, 9-12, 13-15, 23-26, and 36 are likely candidates for locally decreasing well spacing by drilling eight wells (80-acre [$3.2 \times 10^5 m^2$] spacing) or more in these sections.

WASATCH CHARACTERIZATION CASE 2

Case 2 assumed the lenses were in hydraulic communication through natural fractures in the shale. That is, if a wellbore penetrated a lens, drainage would also occur from remote lenses through the natural fracture system. Again, history matching was used to determine k_f, L_f, and ϕ_f for the 23 Wasatch wells used in the analysis. These values were used to simulate production for each well over 25 years. The 25-year cumulative production values determined by the simulator were then extrapolated throughout Township 6S, Range 94W. Four wells were again placed near the corners of each section and 25-year cumulative production was summed. The sections were rank ordered according to the sum of the forecasted 25-year cumulative production for the four wells. (See Figure 5.) The best producer was Section 21 with 5,000 MMcf (1.4 x $10^8 m^3$) forecast and the worst was Section 13 with 500 MMcf (1.4 x $10^7 m^3$) forecast. Cases 1 and 2 Wasatch rank orderings were very similar. (See Figures 4 and 5.)

An investigation was made to determine the possible well-to-well interference when four wells were produced simultaneously in a section where the shale was considered naturally fractured, and to determine if all the producible gas in a section would be recovered with the current well spacing regulation for Wasatch wells in Colorado (160-acre [6.5 x $10^5 m^2$] well spacing). Section 12 was chosen for this analysis. Four wells were placed in Section 12 near the corners of the section. A 25 by 25 grid was overlaid on the section and the key reservoir parameter values for k_f, ϕ_f, h, and P_i were then determined for each grid block in the system by extrapolating from the known values at the 23 Wasatch well sites. A previous geologic study[3] had estimated 20 percent of the rocks in the Wasatch Formation to be sandstone. In order to simulate this condition, the grid blocks were randomly assigned properties of either shale or sandstone so that 20 percent of the blocks were sandstone. The shale blocks were modeled as zero matrix porosity blocks that were in communication with other blocks through the natural fracture networks. Twenty-five years of production was simulated for Section 12 with a single well producing. Well-to-well interference could easily be predicted since every grid block in the system showed a pressure drop of at least 200 psi (1,400 Pa). Twenty-five years of production was then simulated for Section 12 with all four wells producing. It was clear that four wells per section were sufficient to produce all the available gas in Section 12 since the initial pressure profile distribution for the grid blocks which overlaid Section 12 was 720 to 830 psi (5,000 to 5,700 Pa) and the pressure profile distribution after the simulation was 160 to 210 psi (1,100 to 1,400 Pa).

CONCLUSIONS

The following conclusions are supported by the analyses presented in this paper:

- Reducing current spacing from 320 acres (1.3 x $10^6 m^2$) to 160 acres (6.5 x $10^5 m^2$) or less for Mesaverde wells through infill drilling, or by placing four wells or more per section in undeveloped sections, is a viable development strategy for the Rulison Field.

- Decreasing well spacing to 80 acres (3.2 x $10^5 m^2$) (8 wells per section) or less for Wasatch wells is a viable development strategy in some sections of Township 6S, Range 64W if the sandstone lenses are in clusters and the shale separating the clusters is not naturally fractured.

- Current well spacing practice (160 acres [6.5 x $10^5 m^2$]) for Wasatch wells is adequate to produce most of the gas in the Rulison Field if the shale separating the sandstone lenses is naturally fractured.

- Effective well spacing is a strong function of the natural fracture system in the shale, as well as the size and distribution of the sandstone lenses.

NOMENCLATURE

B_g = Gas formation volume factor (Rcf/Scf)

G_p = Gas produced (MMcf)

Σh = Cumulative thickness for all sand lenses penetrated by a wellbore (ft)

H = Gross formation thickness drilled in Wasatch or Mesaverde

k_f = Natural fracture permeability (md)

L_f = Induced fracture winglength (ft)

P_i = Initial reservoir pressure (psig)

Rcf = Reservoir cubic feet (ft^3)

RF = Recovery factor (fraction)

Scf = Standard cubic feet (ft^3)

S_g = Gas saturation (fraction)

ϕ = Porosity (fraction)

ϕ_f = Natural fracture porosity (fraction)

V = Volume of sandstone actually draining at 25 years (ft^3)

V_{sd} = Estimate of the volume of sandstone available to a well (ft^3)

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REFERENCES

1. Mercer, J. C., J. R. Ammer, and K-H. Frohne, "Case Study of Gas Migration in the Wasatch and Mesaverde Formations of the Piceance Basin, Colorado," SPE 14360, Presented at the 60th Annual Technical Conference and Exhibition of

the Society of Petroleum Engineers, Las Vegas, Nevada, September 22-25, 1985.

2. Mercer, J. C., J. R. Ammer, C. O. Okoye, R. A. Moore, A. W. Layne, and K-H. Frohne, "Study of Gas Migration from Naval Oil Shale Reserve No. 3 to the Rulison Field," DOE Research Report, December 1985, DOE/METC-85/2020, NTIS/DE86001020.

3. Knutson, C. F., "Mesaverde/Wasatch Formation Characterization in Anvil Points Area Near Rifle, Colorado," Final Report to DOE (Purchase Order No. DE-AP21-85MC03280), February 1985.

4. Advani, S. H., and J. K. Lee, "Stress Trajectory and Advanced Hydraulic Fracture Simulations for the Eastern Gas Shales Project," *Final Report to* DOE, July 1983, DOE/MC/16333-1448, NTIS/DE83017036.

5. Science Applications, Inc., "Simulator for Unconventional Gas Resources Multidimensional Model 'SUGAR-MD' -- Volume I: Reservoir Model Analysis and Validation," Report to DOE, September 1983, DOE/MC/08216-1440, NTIS/DE83017035.

6. Science Applications, Inc., Math and Computer Services, Inc., "Simulator for Unconventional Gas Resources Multidimensional Model 'SUGAR-MD' -- Volume II: User's Guide," Report to DOE, September 1983, DOE/MC/08216-1440, NTIS/DE84000307.

TABLE 1. Percent of Sandstone Drained at 25 Years by Mesaverde Wells

Well Number	Percent Drained
MV1	10
MV2	9
MV3	6
MV4	3
MV6	2
MV7	11
MV8	1
MV13	1
MV18	1
MV19	11
MV20	4
MV26	6

TABLE 2. Percent of Sandstone Drained at 25 Years by Wasatch Wells (Case 1)

Well Number	Percent Drained
W101	39
W102	5
W103	22
W104	25
W107	4
W108	15
W109	13
W110	4
W111	31
W112	34
W113	43
W114	53
W115	27
W118	8
W119	9
W121	7
W122	6
W126	2
W128	3
W134	49
W136	25
W138	6
W139	16

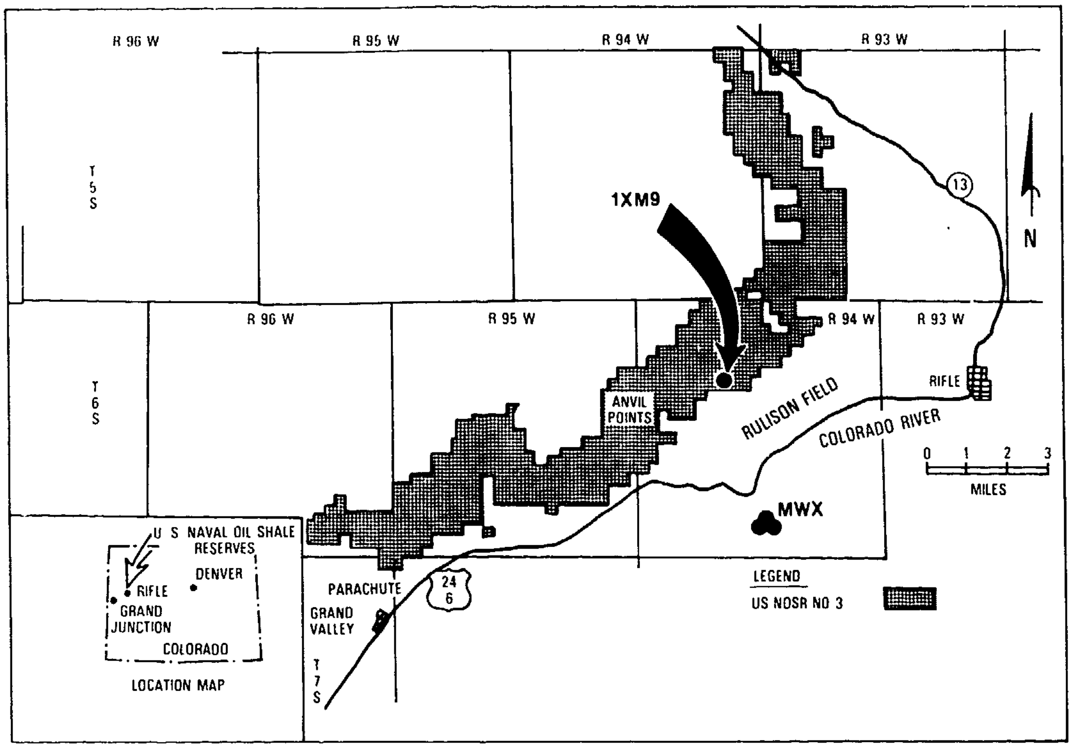

Fig. 1—General location map.

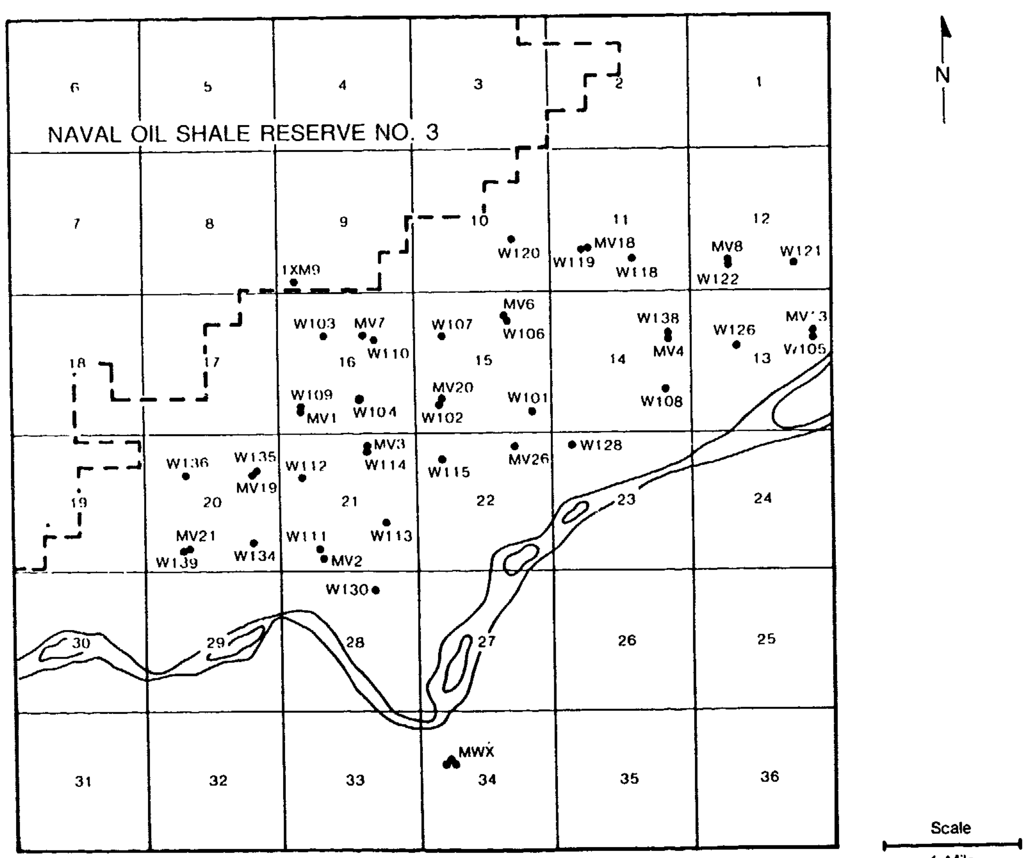

Fig. 2—Well location map for Township 6S, Range 94W.

6 / 2 / 5600	5 / 6 / 5100	4 / 12 / 3300	3 / 30 / 1100	2 / 34 / 700	1 / 35 / 700
7 / 3 / 5600	8 / 4 / 5500	9 / 8 / 4300	10 / 26 / 1500	11 / 33 / 700	12 / 36 / 700
18 / 7 / 4900	17 / 1 / 5900	16 / 5 / 5200	15 / 22 / 1900	14 / 27 / 1500	13 / 32 / 900
19 / 10 / 3900	20 / 11 / 3700	21 / 9 / 4100	22 / 17 / 2100	23 / 25 / 1600	24 / 31 / 1100
30 / 13 / 3300	29 / 15 / 2600	28 / 21 / 1900	27 / 18 / 2000	26 / 24 / 1600	25 / 29 / 1200
31 / 14 / 3000	32 / 16 / 2500	33 / 19 / 1900	34 / 20 / 1900	35 / 23 / 1700	36 / 28 / 1400

Fig. 3—Production rank ordering for the Mesa Verde, Township 6S, Range 94W.

6 / 16 / 2300	5 / 19 / 2000	4 / 22 / 1300	3 / 25 / 1200	2 / 24 / 1200	1 / 30 / 800
7 / 11 / 2500	8 / 20 / 1800	9 / 21 / 1400	10 / 28 / 1000	11 / 23 / 1200	12 / 34 / 700
18 / 13 / 2400	17 / 10 / 2700	16 / 18 / 2000	15 / 29 / 900	14 / 27 / 1000	13 / 36 / 500
19 / 14 / 2300	20 / 8 / 3100	21 / 1 / 4900	22 / 15 / 2300	23 / 31 / 800	24 / 33 / 700
30 / 12 / 2400	29 / 7 / 3400	28 / 2 / 4900	27 / 4 / 4200	26 / 26 / 1000	25 / 32 / 700
31 / 9 / 2700	32 / 6 / 3500	33 / 5 / 3700	34 / 3 / 4900	35 / 17 / 2100	36 / 35 / 700

Fig. 4—Production rank ordering for the Wasatch (Case 1), Township 6S, Range 94W.

6 / 16 / 2200	5 / 20 / 1900	4 / 22 / 1300	3 / 25 / 1200	2 / 24 / 1200	1 / 33 / 800
7 / 11 / 2500	8 / 17 / 2200	9 / 21 / 1300	10 / 28 / 1000	11 / 23 / 1300	12 / 35 / 600
18 / 12 / 2400	17 / 9 / 2700	16 / 19 / 1900	15 / 29 / 900	14 / 26 / 1100	13 / 36 / 500
19 / 15 / 2300	20 / 8 / 3200	21 / 1 / 5000	22 / 13 / 2300	23 / 32 / 800	24 / 30 / 800
30 / 14 / 2300	29 / 7 / 3300	28 / 2 / 4900	27 / 5 / 4200	26 / 27 / 1000	25 / 31 / 800
31 / 10 / 2600	32 / 6 / 3400	33 / 4 / 4700	34 / 3 / 4900	35 / 18 / 2100	36 / 34 / 700

Fig. 5—Production rank ordering for the Wasatch (Case 2), Township 6S, Range 94W.

Key

X / Y / Z

X = SECTION NUMBER
Y = RANK ORDER OF THE SECTION
Z = TOTAL CUMULATIVE PRODUCTION FOR 4 WELLS IN THE SECTION (MMcf)