PRRC 99-32

FOURTH ANNUAL TECHNICAL PROGRESS REPORT

ADVANCED OIL RECOVERY TECHNOLOGIES FOR IMPROVED RECOVERY FROM SLOPE BASIN CLASTIC RESERVOIRS, NASH DRAW BRUSHY CANYON POOL, EDDY COUNTY, NM

DOE Cooperative Agreement No. DE-FC-95BC14941

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Award Date:	September 25, 1995
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	September 25, 2001 - Budget Period II
Award Amount for Current Fiscal Year:	$2,017,435
Award Amount for Budget Period II:	$5,013,760
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Contracting Officer's Representative:	Dan Ferguson
Reporting Period:	October 1, 1998 - September 30, 1999

ABSTRACT

The Nash Draw Brushy Canyon Pool (NDP) in southeast New Mexico is one of the nine projects selected in 1995 by the U.S. Department of Energy (DOE) for participation in the Class III Reservoir Field Demonstration Program. The goals of the DOE cost-shared Class Program are to: (1) extend economic production, (2) increase ultimate recovery, and (3) broaden information exchange and technology application. Reservoirs in the Class III Program are focused on slope-basin and deep-basin clastic depositional types.

Production at the NDP is from the Brushy Canyon formation, a low-permeability turbidite reservoir in the Delaware Mountain Group of Permian, Guadalupian age. A major challenge in this marginal-quality reservoir is to distinguish oil-productive pay intervals from water-saturated non-pay intervals. Because initial reservoir pressure is only slightly above bubblepoint pressure, rapid oil decline rates and high gas/oil ratios are typically observed in the first year of primary production. Limited surface access, caused by the proximity of underground potash mining and surface playa lakes, prohibits development with conventional drilling.

Reservoir characterization results obtained to date at the NDP show that a proposed pilot injection area appears to be compartmentalized. Because reservoir discontinuities will reduce effectiveness of a pressure maintenance project, the pilot area will be relocated to a more continuous part of the reservoir. Most importantly, the advanced characterization results are being used to design extended-reach/horizontal wells to tap into predicted "sweet spots" that are inaccessible with conventional vertical wells.

The activity at the Nash Draw Project during the past year has been drastically curtailed due to the decline in oil and gas prices in the last quarter of 1998 and the first quarter of 1999. The past year was used to complete the analysis of activities in Phase I, make preparations for Phase II, and apply the techniques that were developed to other wells and develop additional reserves in existing wells.

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EXECUTIVE SUMMARY

In Phase I of the project, advanced oil recovery technologies were applied to the NDP. Geostatistical maps based on well parameters targeted zones of high oil saturation between wells, but were of little value when extrapolating outside the area of well control. A high-resolution 3D seismic survey designed for the thin-bedded turbidite sands provided the information to extrapolate beyond the area of well control. Computational intelligence applied to seismic attributes targeted sweet spots mapped as hydrocarbon pore volume. Reservoir simulation mapped the pressure distribution in a potential pilot waterflood area. Seismic results and simulation indicated that the reservoir flow units in the pilot were limited, and reservoir pressure was low in the pilot area. Positive flood response could be anticipated only if gas injection commenced early in the field development.

The advanced oil recovery technologies revealed that the initial reservoir characterization was too simplistic. A new log interpretation method tuned with core analyses demonstrated that the initial OOIP was too large. However, the log interpretation method has found oil behind-pipe and has reduced completion costs.

Log analysis techniques developed in Phase I were utilized to complete four of the NDP wells in uphole zones. This has allowed the development of economical reserves during a period of low product prices. This program was successful, and four additional wells are being evaluated for completions in shallower zones.

INTRODUCTION

The Nash Draw Pool (NDP) in Eddy County, New Mexico produces oil and associated gas from the Permian (Guadalupian) Brushy Canyon Formation. The Brushy Canyon is a relatively new producer in the Delaware Basin of West Texas–New Mexico, with most drilling having occurred since the late 1980s and many discoveries occurring in the 1990s. Regionally, the fine-grained sandstones of the Brushy Canyon contain as much as 400-800 MMbbls of oil-in-place[*] and thus this formation represents a significant reservoir interval in the Permian Basin. However, low permeability and petrophysical heterogeneity limit primary recovery to only 10-16%.

The NDP is one of the project sites in the Department of Energy (DOE) Class III field demonstration program for slope-basin clastic reservoirs. The objective of the NDP Class III project is to demonstrate that an advanced development drilling and pressure maintenance program can significantly improve oil recovery compared to existing technology applications. A further goal of the project is to transfer these advanced methodologies to oil and gas producers in the Permian Basin and elsewhere throughout the U.S. oil and gas industry.

In the first phase of the NDP project, an integrated reservoir characterization study was performed to better understand the nature of Brushy Canyon production and to explore options for enhanced recovery. Results obtained in the NDP project indicate that a combination of early pressure maintenance (gas injection) and secondary carbon dioxide flooding may maximize production in these complex, laterally variable reservoirs. Because of low permeabilities involved and high water-to-oil relative permeabilities, the use of gas instead of water is suggested as preferrable as an oil-mobilizing agent.

The plan submitted and approved for Phase II is to include directional/horizontal drilling and early pressure maintenance to develop reserves under surface-restricted areas and potash mines in order to enhance the ultimate recovery from the project.

RESULTS AND DISCUSSION

This is the fourth annual progress report on the project. Results obtained in the first three years of the project are discussed in previous annual reports[1-3] and in technical papers.[4-9] Results obtained during this reporting period are summarized in this progress report.

Project Management

Reporting

Early in the current project year, reports required to complete Phase I were prepared and submitted to the DOE. These reports included the Third Annual Technical Progress

[*] TORIS Database, 1994

Report, a Final Technical Report on Phase I, and a Topical Report-Request for Data and Hazardous Substance Report for Budget Period I.

Well Drilling Plans

With the low oil prices experienced for much of the past year, the economics of drilling the next Nash Draw well are marginal. Crude prices for 1998 ranged from $15.37 per barrel in January 1998 to a low of $9.72 per barrel in December 1998 and averaged $12.94 for the year. Oil and gas prices continued at low levels through March 1999, but oil prices have increased to $22.07 in September 1999 (Fig. 1). The gas price received reached a low in January 1999 at $1.70 per MCF, and the average price received during the past 12 months is $2.235 per MCF (Fig. 2). The low product prices deter drilling for new reserves because the development cost of $4.35 per barrel and the lifting costs of $4.79 per barrel (less taxes and royalties) are close to the net price received per B.O.E. of $13.50 per barrel.

The December oil price reduced the risked discounted income/investment ratio to 1.69 and a before-tax rate of return of 26.92%. This low ratio and rate of return does not provide sufficient net cash flow to pay debt and provide a profit. The drilling of additional wells are curtailed until prices increase and the risk of lower prices has been reduced. The effects of oil prices on investment income at the NDP are presented in Table 1. The risk associated with the drilling of the next Nash well is outlined in Table 2.

With the return of higher oil prices, Strata plans to initiate the drilling of Nash Draw #36 directional/horizontal data well in the first quarter of 2000. In conjunction with the drilling, Strata plans to complete the supplemental 3-D seismic survey and initiate a pressure maintenance project utilizing the NDP Well #1 as an injection well.

Data and Databases

The production database was updated through August 1999. These data were added to the history of each well to update the decline curves and to project ultimate recoveries as well as to assess the effects of interference and production strategies.

Results of Production Interference Tests

Interpretations of the production interference tests indicate that NDP Well #12 has affected NDP Well #19. The slope of the curve of Cumulative Production vs. Rate changed approximately 11 months ago to a steeper slope. This change in slope indicates Well #19 will recover approximately 60,000 BO less than initially projected, and Well #12 will produce approximately 60,000 BO (see Fig. 3).

The plot of Cumulative Production vs. Rate for NDP Well #10 shows a change in slope that indicates a lower recovery of approximately 30,000 BO than originally estimated for this well. NDP Wells #29 and #38 will recover approximately 15,000 BO and 20,000 BO, respectively (see Fig. 4). This indicates Wells #29 and #38 have partial influence on Well #10.

Using an Advanced Log Analysis Procedure for Recompletions

To develop additional reserves at lower costs, zones in existing wells were evaluated using techniques developed for the Brushy Canyon interval. The Advanced Log Analysis program proved to be especially helpful in locating and evaluating potential recompletion intervals. This resulted in a low development cost and a small incremental increase in lifting costs. The zones that were completed, as well as treatment costs, are shown in Table 3.

The workovers on NDP Wells No. 13, 15, 19 and 24 had a full month of production in May 1999. The oil production has increased 2,249 barrels per month, and gas production decreased by 1923 MCFG per month. Table 4 shows the incremental changes in production due to the workovers.

The “J” zone in the Nash Draw #19 well was cement-squeezed to shut off water production. During this procedure, cement communicated with the “K” and “L” zones and shut off production from these zones. In an effort to reestablish production the “L” zone was reperforated. This was unsuccessful and the “L” zone will have to be restimulated to remove the near wellbore blockage.

Sufficient production history is now available to predict the incremental reserves attributable to the four workovers performed in April of this year (Fig. 5). Additional reserves and development costs are also shown in Table 4. The additional reserves from these four wells are estimated to be 160,800 barrels of oil equivalent (BOE) at a low development cost of $2.07/BOE. Based on the initial ultimate recovery predicted from these wells, the workovers are expected to yield an increase of 15%–30% in recoverable reserves.

Based on the technical and economic success of the four workovers, other project wells are being evaluated as workover candidates. Currently, Strata intends to propose the workover of NDP Wells #5, #6, #9 and #11.

Geophysics

Dr. Bob Hardage is designing the seismic survey for the north end of the Nash Draw Unit. It is anticipated that this survey will overlap the original survey in an attempt to determine areas of high gas saturation and depletion. Cost estimates have been obtained from seismic contractors and the cost to shoot the survey is estimated at $15,000 to $18,000 per square mile.

Potential Development of Regional 2D Seismic Attribute Maps

During the last two years, the NDP project has been the subject of the application of computational intelligence for optimizing 3D seismic data through the use of multivariate seismic attribute analysis. Essentially, linear or non-linear (neural network) models are built using a number of seismic attributes (frequency, phase, amplitude, dip, slope, isochron, etc.) to constrain some desired property that can be observed at the wellbore. These properties include standard reservoir properties such as porosity, water saturation, and pay thickness. The resulting correlations were reported the Final Report for Budget Period I.

These are very powerful tools which will gain influence in industry as additional results in other depositional environments are published. It appears that existing 2D seismic data could benefit from the application of this technology. Seismic attributes can be calculated from 2D data and, since that covers much larger areas of petroleum basins (at much lower density), properties of interest can be calculated and coarsely mapped over much larger areas than covered by existing 3D surveys.

To test the validity of this idea, an attribute horizon from the NDP was extracted, and subset pseudo-2D lines were separated out. As Fig. 6 illustrates, features having a width of one-half the spacing between 2D lines can be reliably identified and mapped using traditional geostatistical methods, such as kriging. Maps of reservoir properties at the scale of large grids of 2D seismic lines could help in determining large-scale structural features, permeability variations, as well as porosity or water/oil saturation trends, and possibly fractures. Even single or crossing lines could provide additional data for generating regional scale cross-sections, which may help reduce risk in drilling step-out wells as fields are developed where 3D seismic data is not economical.

Computational Intelligence Tools for Improved Log Analysis

The purpose of this study is to use a neural network to correlate the wireline log data in Nash Draw #23 with the corresponding full core measurements. Once this is accomplished the neural network is used to make predictions of core parameters such as F, S_w, and S_o using the wireline log data from the other 16 wells. Each of these wells also has core plug measurements that will validate the neural network's ability to make reasonable predictions.

A dataset consisting of a full suite of logs and whole core data through a 200-ft interval of the Brushy Canyon zone provides the information required to develop correlations of measured core data with log measurements. The following procedure details the correlating method.

A suite of 17 wells from the Nash Draw field was used for correlation of wireline log data with core data. One well, Nash Draw #23, had full core data including permeability (K_{air}), porosity (F), grain density (GD), water saturation (S_w), oil saturation (S_o) and fluorescence while the other wells within the field had core plug measurements with these same parameters. All of the wells had wireline logs that included caliper, DPHI, DRHO, GR, LLD, LLS, MSFL, NPHI, NPOR, PEF, RHOB, SP and TNPH. A fuzzy ranking technique demonstrated that core porosity best correlates with the density porosity (DPHI), deep resistivity (LLD), and shallow resistivity logs (LLS).

A cross-plot, best-fit line of the density porosity log with core porosity has a correlation coefficient of 76%, as shown in Fig. 7. Adding the LLD and LLS logs through a Radial Basis Function (RBF) neural network improved the correlation coefficient to 93% as illustrated in Fig. 8. The ability of the trained RBF neural network to predict the product of porosity and oil saturation ($\Phi * s_o$) is displayed in Fig. 9.

Technology Transfer

Disseminating technical information generated during the course of this project is a prime objective of the project. A summary of technology transfer activities during the current year is outlined below.

Internet Homepage: The address of the Website for the Nash Draw project is: http://baervan.nmt.edu/REACT/Links/nash/strata.html. This site includes an interactive map of logs and production data for the project and the second annual report, including graphics.

AAPG Publication
The paper "Advanced Reservoir Characterization for Improved Oil Recovery in a New Mexico Delaware Basin Project," presented at the Fourth International Reservoir Characterization Technical Conference in March 1997 at Houston, TX, was peer-reviewed by the American Association of Petroleum Geologists. This paper was revised for publication in *Reservoir Characterization—Recent Advances*, a book on the conference, published by the AAPG as Memoir 71.

SPE Paper 56007
SPE Paper 38916, "Reservoir Characterization as a Risk Reduction Tool at the Nash Draw Pool," presented at the 1997 SPE Annual Technical Conference and Exhibition in San Antonio, TX, October 5–8, was peer-reviewed by SPE. This paper was revised and published as SPE Paper 56007 in the April 1999 issue of *SPE Reservoir Evaluation & Engineering*.

West Texas Geological Society Presentation
The 3D seismic attribute analysis of the NDP data and interpretation of predictions of areas for targeted drilling was presented at a meeting of the West Texas Geological Society in Midland, Texas on October 29-30, 1998.

1999 Oil and Gas Conference–Technology Options for Producers' Survival: A summary of project results was prepared for presentation at this conference in Dallas, TX on June 28–30, 1999. The National Petroleum Technology Office and the Federal Energy Technology Center, under the guidance of the DOE Office of Fossil Energy, sponsored the conference. About 225 industry representatives, DOE personnel, and R&D contractors attended the conference. The title of the presentation was "Advanced Oil Recovery Technologies for Improved Recovery from Slope Basin Clastic Reservoirs, Nash Draw Brushy Canyon Pool, Eddy County, New Mexico." The focus of the presentation was a new log interpretation method for estimating thin-bed resistivity from conventional wireline logs. A computational intelligence method to correlate 3D seismic attributes with well properties to produce a "drill here" map was presented. The results of the numerical simulation used to predict pilot flood results were reviewed along with the use of 3D seismic interpretation used to characterize the simulation area. The audience was most interested in the log analysis technique.

Petroleum Frontiers

The Nash Draw Project was chosen by IHS Energy Group to be published in Volume 16, No. 2 of Petroleum Frontiers. The title of the publication is "Nash Draw Field, Delaware Basin: An Integrated Reservoir Characterization Study." This study is a summation of all the information presented to date along with correlations to other Delaware fields in the area.

Hart's *Oil and Gas World*

Strata's advanced log analysis program and database management system has won Hart's *Oil and Gas World*'s "Best of the Permian Basin–Best New Technology" project award. The project was selected by a panel of judges chosen by the Permian Basin Petroleum Association. The award will be presented at the Permian Basin Petroleum Association awards breakfast at the annual meeting held on October 28, 1999 in Midland, TX.

Reducing Exploration Risk with the Fuzzy Expert Exploration Tool

The Nash Draw Brushy Canyon data and interpretation was presented by The REACT Group at the Petroleum Recovery Research Center at a conference held in Albuquerque, New Mexico on September 9-10, 1999.

SPE Paper #56733

Balch, R.S.; Stubbs, B.A.; Weiss, W.W.; Wo, S.; "Using Artificial Intelligence to Correlate Multiple Seismic Attributes to Reservoir Properties", SPE #56733 presented at the Society of Petroleum Engineer Annual Convention in Houston, Texas on October 3-7, 1999.

CONCLUSIONS

Several conclusions can be drawn from the work done during the fourth year of the NDP project**.** Fluctuating oil and gas prices result in uncertainties and reduce the ability of oil and gas operators to fund drilling and workover projects. The use of the Advanced Log Analysis techniques developed from the Nash Draw Project have proven useful in defining additional productive zones and refined completion techniques. The continued interpretation of the 3-D seismic survey using geostatistics has resulted in a more complete characterization of the Brushy Canyon reservoir.

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Martin F.D., et al: “Advanced Reservoir Characterization for Improved Oil Recovery in a New Mexico Delaware Basin Project,” *Proc.* Fourth International Reservoir Characterization Technical Conference, Houston, (1997) March 2–4, 703-26, and revised in *Reservoir Characterization—Recent Advances*, AAPG Memoir 71, R.A. Schatzinger and J.F. Jordan (eds.), AAPG, Tulsa, (1999) 93-107.

Martin, F.D., et al: “Reservoir Characterization as a Risk Reduction Tool at the Nash Draw Pool,” paper SPE 38916 presented at the 1997 SPE Annual Technical Conference & Exhibition, San Antonio, Oct. 5-8, *Proc.* SPE Reservoir Engineering, 751-66, and revised in SPE Reservoir Eval. & Eng., **2** (2), (April 1999) 169-79.

Stubbs, B.A., et al: “Using Reservoir Characterization Results at the Nash Draw Pool to Improve Completion Design and Stimulation Treatments,” paper SPE 39775 presented at the 1998 SPE Permian Basin Oil and Gas Recovery Conference, Midland, March 23-26.

Martin, F.D., et al: “Implementation of a Virtual Enterprise for Reservoir Management Applications,” paper SPE 38868 presented at the 1997 SPE Annual Technical Conference & Exhibition, San Antonio, Oct. 5-8.

Hardage, B.A., et al: “3-D Seismic Imaging and Interpretation of Brushy Canyon Slope and Basin Thin-Bed Reservoirs, Northwest Delaware Basin,“ *GEOPHYSICS*, Vol. 63 No. 5 (September-October 1998) 1507-19.

Hardage, B.A., et al: “3-D Instantaneous Frequency Used as a Coherency/Continuity Parameter to Interpret Reservoir Compartment Boundaries Across an Area of Complex Turbidite Deposition,” *GEOPHYSICS*, Vol. 63 No. 5 (September-October 1998) 1520-31.

Table 1. Income/Investment vs. Oil Price

Oil Price	Unrisked Income/Investment Discounted @ 9%	Risked Income/Investment Discounted @ 9%
$11.68 Low	2.41	1.69
$13.79 Avg.	2.66	1.88
$18.21 High	3.21	2.28

Table 2. Risk Weighted Reserves

Possible Outcome	Risk Percentage	Result, BO
Dry hole – mechanical failure	5%	0
50, 000 BO	10%	5,000
100,000 BO	25%	25,000
150,000 BO	30%	45,000
200,000 BO	30%	60,000
Total	100%	135,000

Table 3. Workover Net Increase In Production

Well	Net Increase BOPM	Net Increase MCFGPM	Net Increase BWPM
#13	926	(691)	4,489
#15	292	(765)	2,267
#19	406	(4,463)	5,296
#24	625	3,996	3,159
Total	**2,249**	**(1,923)**	**15,211**

Table 4. Incremental Reserves

Well #	Zones	Reserves BOE	Actual Cost	A.F.E. Estimated Cost	Development Cost, $/BOE
13	“H”, “E” & “C-2”	39,647	$75,123.32	$84,592.50	$1.89
15	“H-4”, “G-3” & “F-3”	26,320	$77,489.38	$75,114.50	$2.94
19	“J” & Bell Canyon-Lower	39,105	$106,421.61	$91,942.00	$2.72
24	“F-3”, “F-2”, “D” & “CC-2”	55,728	$73,166.87	$96,676.00	$1.31
	Total	**160,800**	**$332,201.18**	**$348,325.00**	**$2.07**

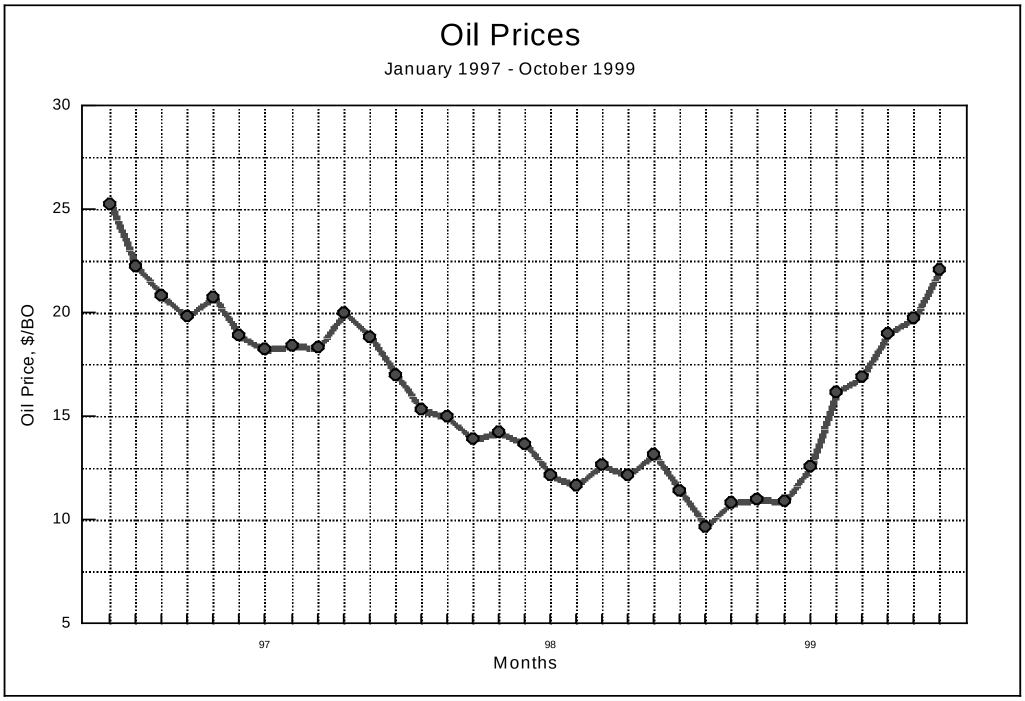


Fig. 1. Historical oil prices.

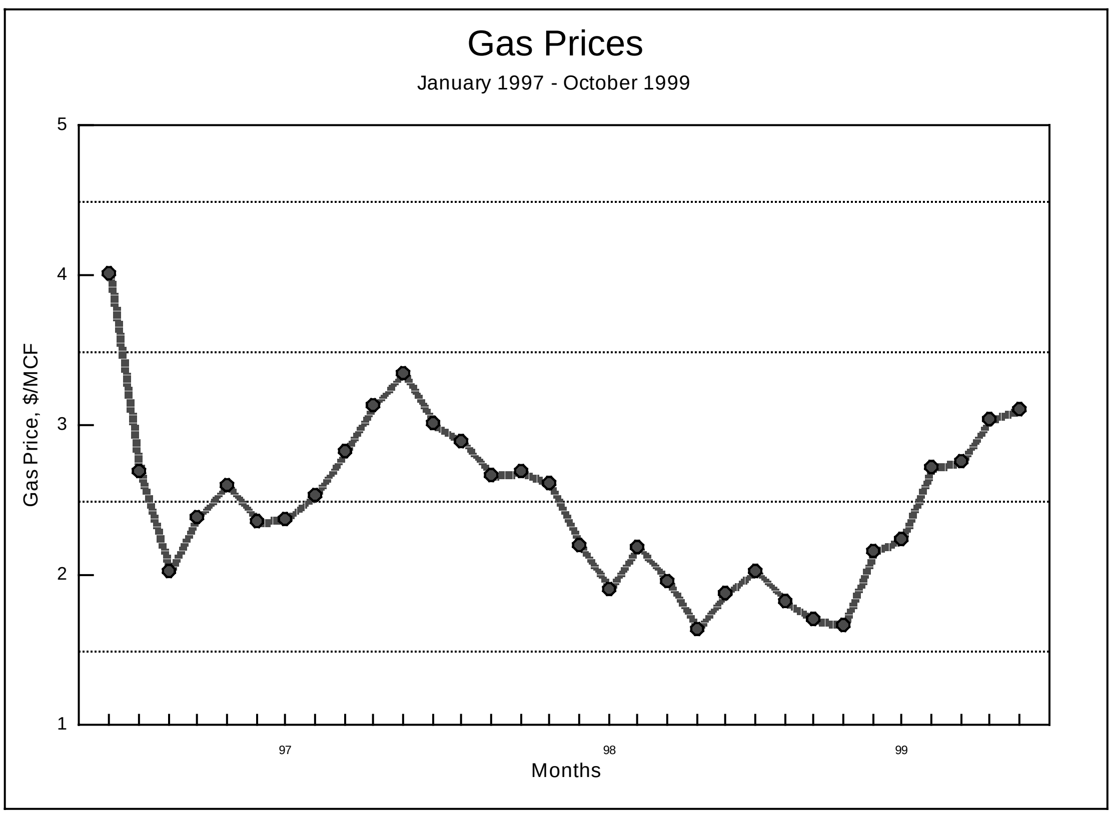
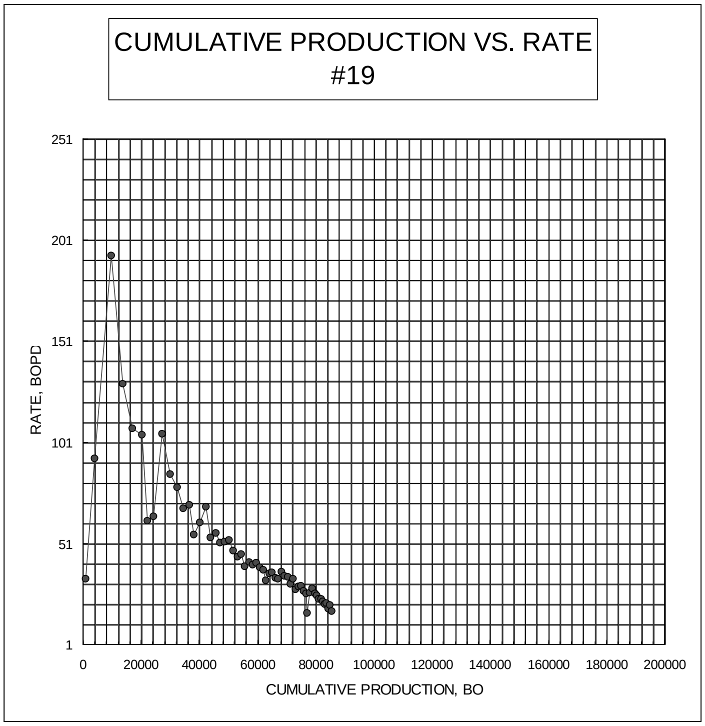


Fig. 2. Historical gas prices.



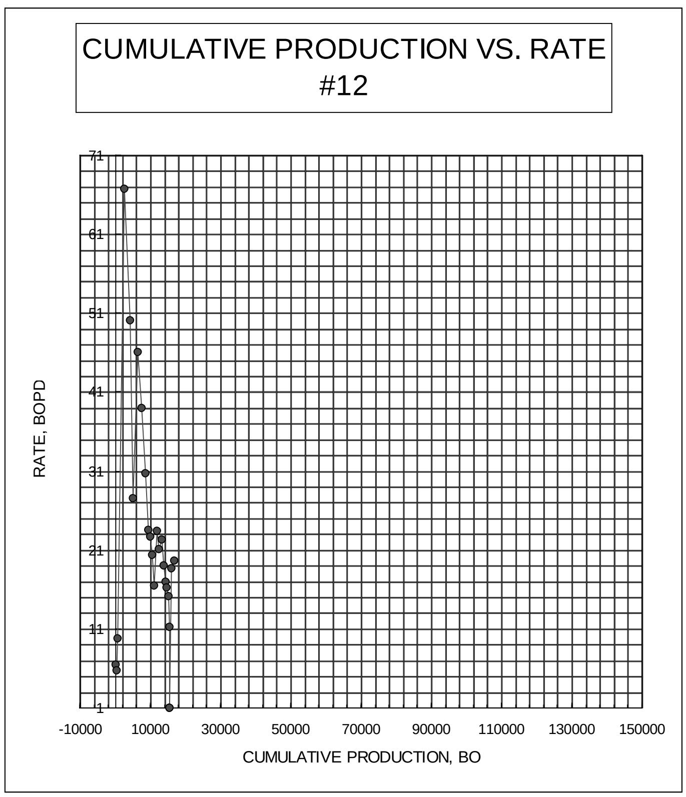


Fig. 3. Wells #19 and #12 production interference.

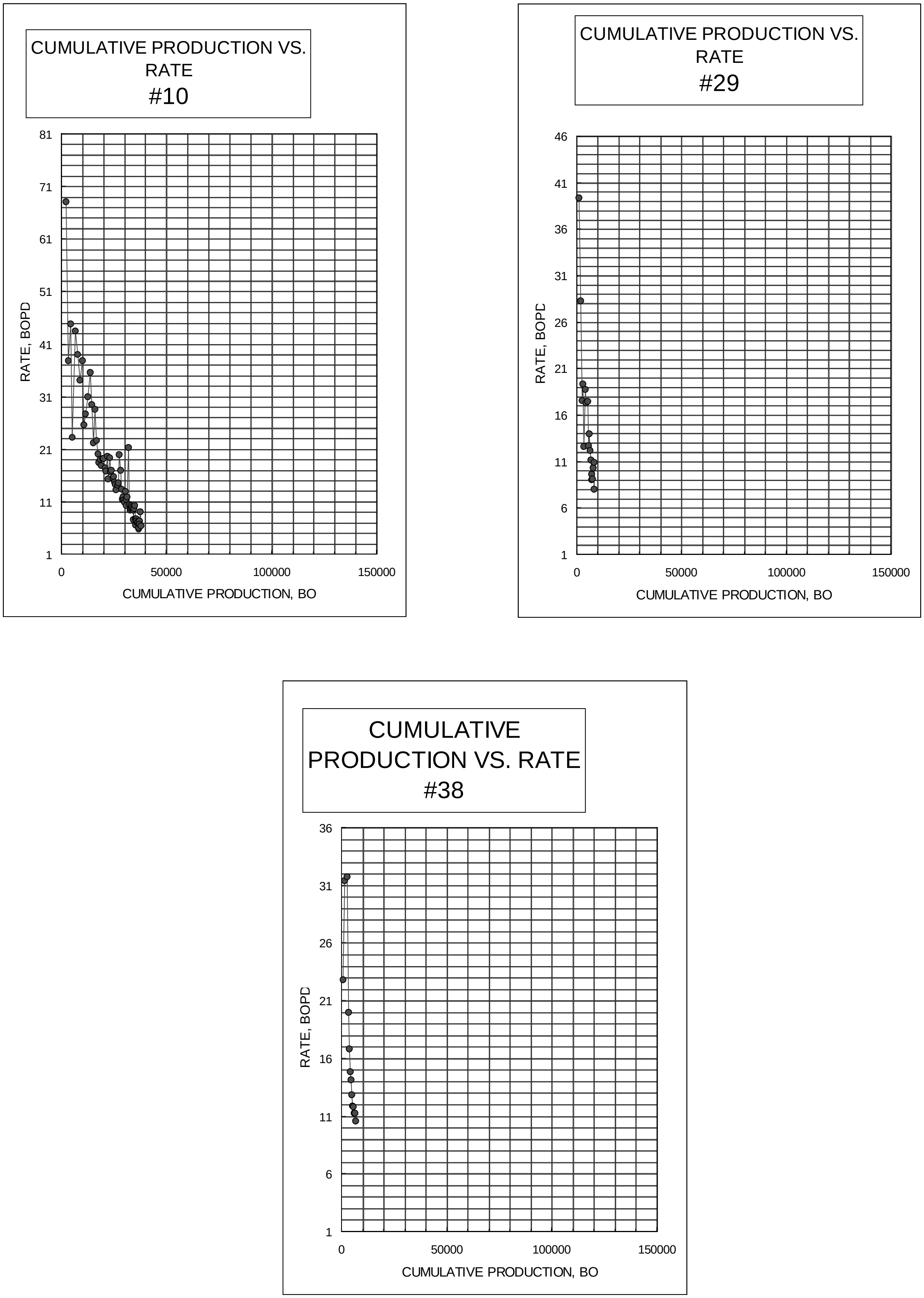


Fig. 4. Wells #11, #29, and #38 production interference.

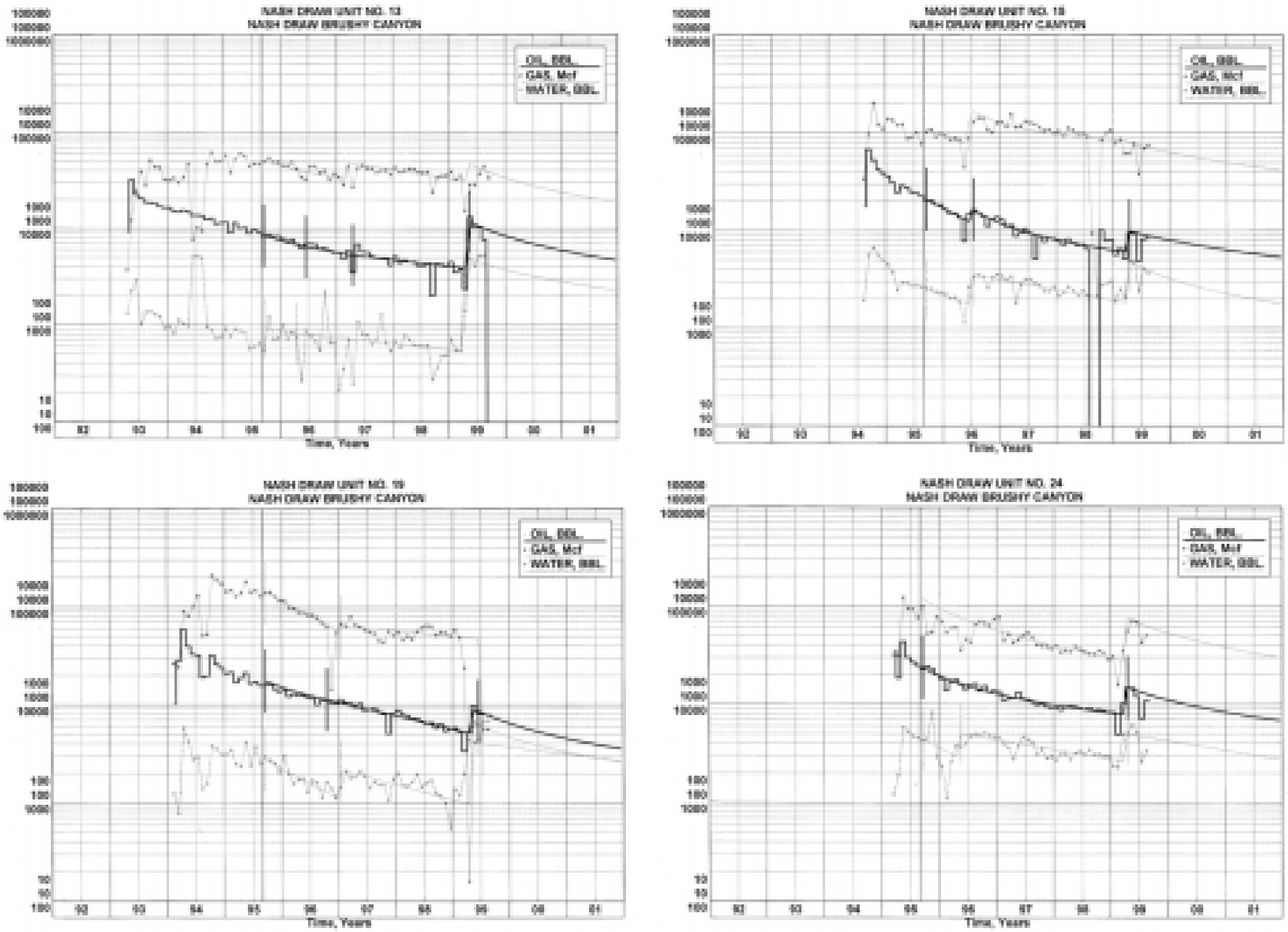


Fig. 5. Workover wells production curves.

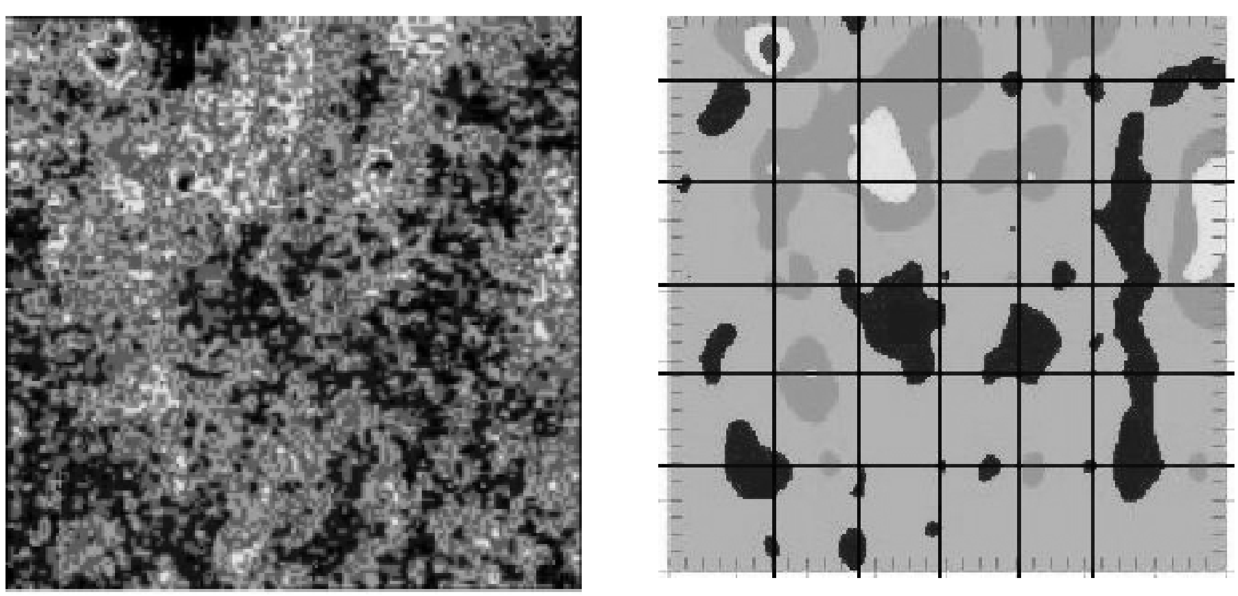


Fig. 6. The real attribute distribution is on the left, and kriging of ten 2D lines is on the right.

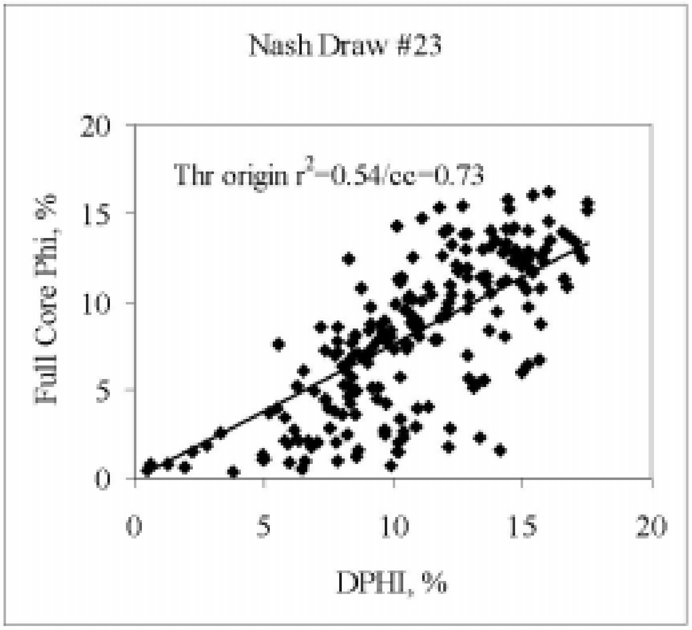


Fig 7. Crossplot of density log porosity vs measured core porosity.

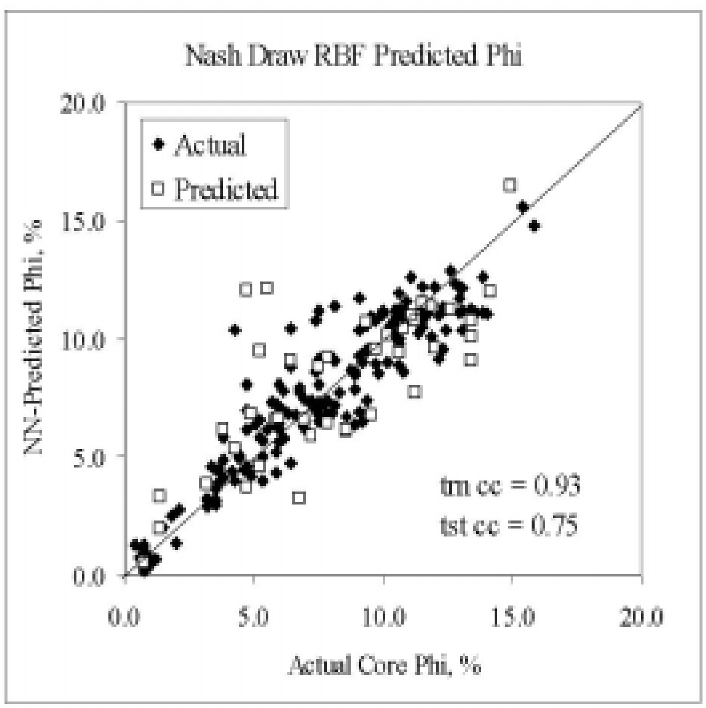


Fig. 8. Better porosity estimate is obtained with the radial basis function.

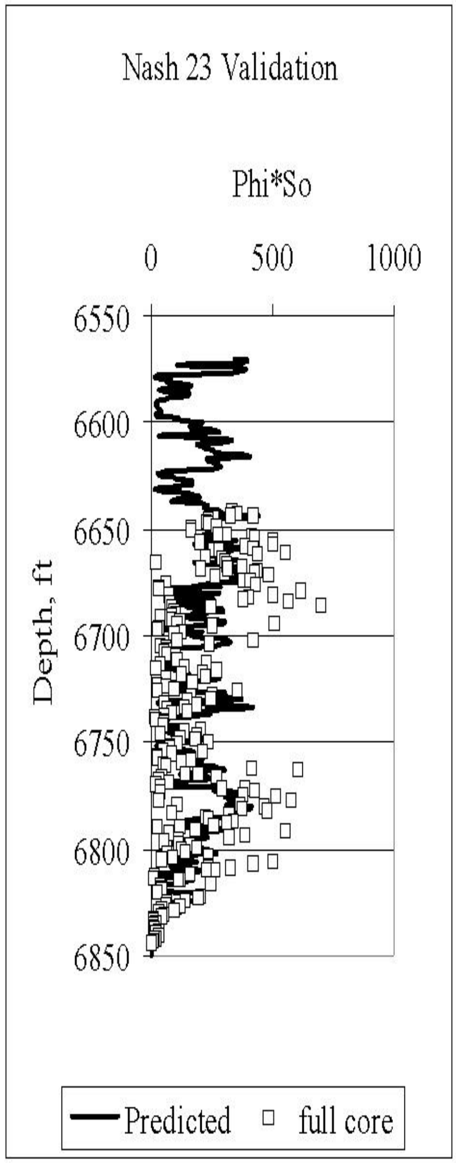


Fig. 9. Radial basis function used to predict the porosity–oil saturation product or an “oil show” from openhole logs.