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A Review and Statistical Analysis of Micellar-Polymer Field Test Data

Topical Report

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November 1986

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SUMMARY

A statistical analysis study has been made of 21 micellar-polymer field test projects to evaluate the significance of key parameters upon performance. In this study, the term micellar-polymer is used to describe surfactant recovery processes of which the most common are the water phase low tension and the soluble oil. The micellar slug is usually followed by a drive slug containing a polymer for mobility control. The data include 10 projects that were used in a previous study and 11 other well documented projects which have been completed recently.

A major effort in the study was to collect and convert the data into a consistent form which would allow for statistical analysis. The study was conducted by correlating oil recovery efficiency and various parameters with a linear regression analysis using the least squares method. The accuracy of a particular correlation is expressed in terms of the "correlation coefficient" and the "confidence limit", which are discussed in the report.

The study indicates three significant correlations. The most important of these is the correlation showing that oil recovery is inversely related to the log of the reservoir connate water salinity. This suggests that prior flooding with a water near the design salinity or use of preflushes to adjust salinity and remove hardness have, at best, been only partially effective. Exxon was successful in their second Loudon pilot when using a specifically designed salt tolerant surfactant, with no preflush. The results of this study, coupled with the results of the Exxon second Loudon pilot, suggest that future research in micellar-polymer flooding should focus on the development of surfactants which can tolerate the connate water salinity and hardness in the reservoir.

A second correlation showed that oil recovery increased as the pattern size was decreased. This is attributed to the higher frontal velocities and to the reduced tendency of slug breakdown in smaller patterns. Low oil cuts at the beginning of the micellar-polymer floods indicated that higher recovery efficiency could not be attributed to infill drilling.

The third correlation showed the expected result that oil recovery is related to the quantity of surfactant used. This quantity is the product of the surfactant slug volume (Vps) and the concentration of surfactant (Cs).

A significant correlation was not observed between recovery efficiency and capillary number. This was surprising since the frontal velocity (which is a function of pattern area) and the interfacial tension (which is related to the quantity of surfactant) are components of the capillary number. The lack of correlation apparently was caused by inappropriate values for interfacial tension under flowing reservoir conditions.

In addition to capillary number, suitable correlations were not found for other theoretically important parameters, including temperature, viscosity ratio, bond number, adsorption, and heterogeneity. The failure to obtain definitive correlations with parameters proven in the laboratory to be significant implies the inability to predict variable behavior in the reservoir, rather than a contradiction of theory.

INTRODUCTION AND PURPOSE

The primary goal of this study is to identify, using statistical methods, variables limiting oil recovery of a micellar-polymer process. There are several statistical analyses of micellar-polymer projects available[1,2,3,4]. However, these studies showed either weak correlations or failed to examine relationships indicated by laboratory and simulation studies to control recovery[5-9].

Data from 12 additional micellar-polymer flood field tests have become available since the latest statistical analyses. These data are generally for the larger Department of Energy and industry cost-shared projects, in more diverse geographical areas, and in which more advanced technology was applied. Another purpose of this study is to collect these new data and convert them to a consistent form which would allow for statistical analysis. Data for all projects reviewed are included in Table 1. The 12 projects not included in previous statistical studies are listed in Table 1 with asterisks.

Another purpose of this study is to re-evaluate, in the light of the new data, possible correlations between recovery efficiency and the variables which control the performance of the micellar-polymer process.

The success of the Exxon second Loudon high salinity test, which utilized a salt tolerant surfactant, necessitates a review of current micellar-polymer technology. The second Loudon test was not completed at the time of previous studies. Of the 22 projects selected for analysis, the second Loudon test had a higher recovery by 21 percent, making it far more successful than the remainder of more recently completed projects and clearly demonstrating the importance of considering salinity in micellar fluid design.

The results of this study will be useful in identifying the parameters which are critical to the success of micellar-polymer flooding. The analysis will also be helpful in setting the directions and priorities of research to insure that maximum benefit is derived.

METHODS

A micellar-polymer project should recover about 60 percent of the residual oil after waterflood and achieve an oil cut upward of 20 percent in order to be of commercial interest. Although laboratory experiments and computer simulation model studies indicate that this performance is achievable, only three floods in sandstones have been reported with recoveries near 60 percent:

Exxon Second Loudon[10]

Marathon Henry West[11]

Pennzoil Bingham[12]

After closer inspection, we believe that only the Exxon second Loudon test had consistent, unqualified performance data to support the high recovery. Recovery estimates for the Henry West were clouded because of inconsistencies in oil cuts and production rates from each of the four pilot producers in the inverted 5-spot pattern. Because of these inconsistencies, Henry West was not used in the study. Recovery from the Bingham project was drastically revised from 57 to 39 percent because the reported high recovery was extrapolated. The peak oil cuts only reached about 12 percent, suggesting that the extrapolated recovery was optimistic. The Bingham project was used in this study with the revised recovery figures.

The Exxon second Loudon high salinity test was not used in this analysis since it used a surfactant which is greatly different from the conventional petroleum sulfonates[13]. Various conventional surfactants are discussed in the literature including petroleum sulfonates[14], alkylaryl sulfonates[15], and olefin sulfonates[16].

Keplinger Technology Consultants, Inc. has identified 21 projects (not including the Exxon second Loudon) for which design, implementation, and production data are comprehensively reported. Data for all 21 projects were used for the analysis of salinity. The surfactant concentration was not available for the Amoco Torchlight project[68]. Therefore, it was not included in the analysis of the quantity of surfactant. The Gary Bell Creek project[17] appeared to be well designed and operated; however, it was on a much larger spacing than the other projects. The 40-acre pattern is anomalously high with respect to the next smaller pattern area (10 acres). Because of the distortion of the area data distribution caused by the 40-acre pattern, the Bell Creek project was dropped from the analysis of pattern area, leaving 20 projects. Only the above criteria were used for data screening. Table 1 includes the list of project data and literature references.

Data were collected in four basic categories: Field/Project identification, reservoir characteristics, injected chemicals, and project performance. The data were obtained from published sources and converted to a consistent format or calculated from data presented. The data from the field tests were often not reported in a consistent manner or in the terms necessary for statistical analysis and in some cases could not be obtained directly. A detailed understanding of micellar-polymer flood technology was necessary to obtain consistent data from literature. Although data were not independently checked for accuracy, every effort was made to be consistent and accurate.

In order to determine the correlation between recovery efficiency and various parameters, linear regression analysis was performed using the least squares method. The line that represents the best fit to the data is described by a y intercept and slope. It is comprised of a locus of points including regression values for recovery efficiency at each known parameter value[18].

The correlation coefficient, r, was calculated during the regression analysis and was used as the indicator of a relationship between the recovery efficiency and a parameter. The value of r ranges from -1, indicating an inverse correlation, to 0 indicating no correlation, and to 1 which indicates a perfect direct correlation.

If the absolute value of the correlation coefficient has a value less than 1, the magnitude of the coefficient does not accurately relate the reliability of the correlation. To express this reliability, a probability value is calculated from the r value and number of samples which is called the confidence limit. The confidence limit is the probability, expressed as a percent, that a straight line better describes the data set than does a normal distribution[18]. A confidence limit of 90 percent or higher indicates that a linear relationship exists between the recovery efficiency and the parameter. Table 2 includes the parameters analyzed for correlation with recovery efficiency, the r values, sample sizes, and confidence limits for the r values, sorted by confidence limit.

DISCUSSION

SALINITY

Connate water salinity values for 21 projects were obtained. The values range from a minimum of 2,500 ppm to a maximum of 150,000 ppm. The mean salinity is 51,004 ppm and the standard deviation is 49,702 ppm. The regression between recovery efficiency and the common log of salinity yielded an r value of 0.47 for 21 samples which has a confidence limit of 96 percent (see Figure 1). Visually, the data appear to be scattered. However, the confidence limit of 96 percent indicates a significant correlation between the data and the regression line.

This study showed the overwhelming effect of original or connate reservoir salinity on oil recovery by micellar processes. It should be emphasized that the correlation is with the connate water, and not the water which is resident in the reservoir from waterflooding. This result was somewhat surprising since other works have shown only a minor effect of salinity on recovery[1]. Oil recovery versus the log of the original reservoir salinity is also shown in Figure 2, which is the same as Figure 1 except that Exxon's Loudon salt resistant surfactant test is included. The Loudon salt resistant test stands strikingly above the other projects. An attempt to understand why, brought the significance of salinity into perspective.

If the reservoir salinity and/or hardness are different from the design criteria, the micellar solution will lose effectiveness and encounter high adsorption. Changes in optimal conditions may occur because of unexpected mixing with reservoir water or because of ion exchange from clays and dissolution of multivalent ions from the rock surface into the micellar fluid.

Another relationship evaluated was the oil recovery and the absolute difference between the connate water and design water salinities. A design salinity of 15,000 ppm was assumed, although it is recognized that the optimum salinity level can vary. A confidence limit of 90.5 percent was obtained as shown in Table 2, indicating a significant inverse relationship between recovery efficiency and divergence of connate water salinity from the design level. This relationship is not as significant as with salinity alone, probably reflecting the variances in optimum design salinity and also indicating that the higher level salinities (rather than the lower levels) are controlling the performance.

Various techniques of preflushing and additive agents were used in most of the field tests in an attempt to offset the deleterious effect of salinity and hardness. For the most part, efforts to nullify salinity have failed, as exemplified by two marginal projects which found that the preflush volume was too small (first Loudon test)[20] or the sequestering agent was lost (Benton test)[21].

The role of salinity on the physical and chemical properties of the micellar solution have been reported: interfacial tension[6,8,19], adsorption and/or retention[22-25], phase relationship[26-29], viscosity[6,11,30], and co-surfactant[31,32]. In spite of the awareness of the effect of salinity on micellar properties, it is believed that the full impact of salinity on oil recovery has generally not been perceived.

Healy and Reed[33] showed that all micellar recovery processes may be studied in terms of a ternary diagram. The oil external microemulsions are diluted with brine at both the leading and trailing boundaries of the micellar slug and form two phases in the reservoir. Likewise, the water-external microemulsion formulations pass into the multiphase region by mixing with oil at the leading boundary. The displacement process in either case can become predominantly an immiscible displacement.

Therefore, it is important to minimize the multiphase region described on the ternary diagram to prolong a miscible displacement. However, Healy and Reed[33] and Nelson[29] showed that the salt concentration had a dominant effect on the size and shape of the multiphase region on the ternary diagram and that both the magnitude and the distribution of the interfacial tension were greatly affected by salinity. In another work, Healy, Reed, and Carpenter[7] established experimentally that much of the oil is recovered by an immiscible displacement. It is important that the interfacial tension remain very low, even after dilution occurs. Displacement efficiency is often related to the capillary number (N_c), which is defined as follows:

$$N_c = \frac{V\mu}{\sigma}$$

Healy, _et al._,[34] showed that surfactant retention increases with increased slug deterioration, and Gilliland[23] and Salter[31] showed that the retention is sensitive to the surfactant:co-surfactant ratio. However, for a constant surfactant:co-surfactant ratio, the sulfonate retention nearly doubled as the salinity increased from 5,000 ppm to 20,000 ppm. Gilliland[23] also showed that interfacial tension was affected by both total salinity and surfactant concentrations. Paul[22] showed that the surfactant retention was generally much higher in the reservoir than measured in the laboratory suggesting, as Gilliland and Healy indicated, that some of the sulfonate loss is apparently due to partitioning into the oil phase.

In summary, the above discussion demonstrates that the micellar slug is diluted with reservoir brine and oil. Multiphase solutions can form as dilution occurs, resulting in a loss of miscibility. Additional dilution greatly increases the surfactant retention and greatly increases the interfacial tension. Further, if the connate water salinity is different from the laboratory design, the deleterious effect on retention and interfacial tension is multiplied.

The performance of the Exxon second Loudon test which used surfactants tolerant to the original reservoir cannate water salinity nearly matched predictions, but the tests embodying preflushes all fell short of predictions, with some recovering only about 20 percent of predicted. A possible explanation of this contrast may be that zones or pockets of reservoir connate water are trapped during waterflooding. The preflushes had the same mobility and interfacial properties as the waterflood and, therefore, also failed to sweep out the trapped connate water. On the other hand, the micellar solution having lower mobility and very much lower interfacial tension probably contacted and mixed with the trapped connate water.

Seen in the perspective discussed above, the reservoir salinity is a controlling process variable. Based upon these results, it appears that preflushes have been only partially successful in removing excessive salinity and hardness. Therefore, the process can best be improved by developing chemical compositions which are effective at the salinity and hardness levels which exist in the reservoir.

PATTERN AREA

The second most significant relationship is between recovery efficiency and the log of the pattern area. The pattern areas of the 20 projects analyzed range from 0.68 acres to 10 acres. The mean area is 4.98 acres, and the standard deviation is 3.59 acres. The correlation of recovery efficiency to the log of the pattern area has an r value of 0.46 and a confidence limit of 95 percent.

These results indicated that displacement efficiency is higher as the pattern size is decreased. This is attributed to the higher frontal velocities which can be achieved in the smaller patterns and the experimental observation that recovery is more efficient at higher displacement rates[5,35]. In addition, micellar floods conducted in larger patterns have a greater probability of incurring higher than predicted heterogeneity, adsorption, contact with undiluted connate water, and loss of fluid viscosity, all of which tend to reduce recovery efficiency. Infill drilling is not thought to have caused the higher recovery efficiency. High oil cuts indicative of additional reserves not displaced by waterflood were not observed.

SURFACTANT QUANTITY

Lake and Pope[1] and Selvidge[4] studied the relationship of recovery efficiency to the quantity of surfactant. The quantity of surfactant is defined as the product of the volume of micellar slug in pore volume (Vps) and the concentration of active surfactant in weight percent (Cs). The previous studies did not show a significant correlation.

The values for quantity of surfactant used in 20 projects vary over an order of magnitude from 0.002 to 0.011. Therefore, the log of the quantity of surfactant was used in relation to recovery efficiency. The regression is significant with an $\underline{r}$ value of 0.40 with a confidence limit of 91 percent.

This analysis showed the expected result that oil recovery is increased with larger quantities of the surfactant. These results indicate that sufficient surfactant is required to maintain a single phase with low interfacial tension by offsetting losses due to adsorption, phase transfer, or dilution.

OTHER PARAMETERS

There was an attempt to correlate recovery efficiency (E_R) with the parameters listed in Table 2. The parameters are listed in decreasing order of the confidence limits. Table 2 shows the $\underline{r}$ value calculated, the number of samples, and the confidence limits for each of the tests performed. Several important design parameters in micellar-polymer recovery processes, including capillary number, viscosity ratio, bond number, reservoir temperature, heterogeneity and adsorption, failed to show a significant relationship to recovery efficiency.

Capillary Number

Our work failed to show a significant correlation with capillary number. This finding appears contradictory to laboratory studies[35] and previous statistical studies[1,2]. We believe the contradiction can be explained by examination of the equation which Lake and Pope[1] derived for capillary number from Muskat's equation for velocity in a 5-spot pattern:

$$N_c5 = \frac{(5.5 \times 10^{-5})\ C'pKD\sigma}{\sqrt{A}\ (5.58 + \frac{1}{2}\ln A)}$$

In this equation, capillary number (Nc) is expressed as a function of area, depth, average injection pressure gradient (C'p), and interfacial tension. The equation is valid and would give acceptable results, except that there were some inconsistencies in the methods used to handle some of the data.

One of the major variables is interfacial tension. Only a few of the projects reported laboratory values and the others were assumed to have an interfacial tension of 0.001 dyne/cm. Even the few measured values were at optimum conditions and probably do not reflect the value in the reservoir, particularly after some dilution and phase separation occurs.

Consideration of the effect of salinity suggests that the theoretically attainable interfacial tension may not have been reached in the reservoir. The capillary numbers used in the correlation probably do not represent reservoir conditions and, therefore, have little relationship to recovery efficiency.

Another critical parameter to the calculation of the capillary number is the injection pressure gradient (C'p). In calculating C'p the average injection rate per injection well per flood pattern must be known. Unfortunately, some publications on projects report injection rate as a per well average, but others report it by well for the entire project and by pattern. Thereby, the researcher has to calculate the required average well injection rate. Examination of the data presented by Lake and Pope[1] indicated that some injection rates were for more than one well, leading to a calculated average C'p of 0.33 psia per foot which exceeds fracture pressure for most of the projects analyzed. Per well average injection rates for 19 of the projects in this study gave an average C'p of 0.17 psia per foot, which is significantly lower and does not exceed fracture pressure. Therefore, 0.17 psia per foot appears to be a more accurate value and was used in calculation of the capillary number.

Even with the corrected C'p, the capillary number does not correlate with recovery efficiency. Allowing for a small margin of error in permeability (K), thickness (h), depth (D), and pressure (C'p), the failure to correlate capillary number implies that the actual in situ interfacial tension (σ) is far less than predicted from laboratory data. Contact and mixing with solutions of different salinity and hardness could be a possible explanations for the lower interfacial tension under reservoir flowing conditions.

Viscosity Ratio

The ratio of the viscosity of the surfactant slug to that of the reservoir oil (μ_s/μ_o) should have a bearing on the ability of the micellar slug to resist fingering and to mobilize an oil bank[6]. The regression of recovery efficiency to the viscosity ratio did not yield a significant correlation. Salinity may be the overriding factor causing failure of the micellar slug in ways described above, as well as possibly altering slug viscosity unpredictably. The lack of correlation of field test recovery efficiency to viscosity ratio suggests that the flowing viscosities in the reservoir are probably different than estimated rather than the theoretical relationship being in doubt.

Bond Number

The bond number $\frac{(\rho_w - \rho_o)\, g}{\emptyset \sigma}$, a theoretical dimensionless group of the gravity and interfacial tension discussed by Foster[6] was studied.

Like the variables of capillary number and viscosity ratio, the bond number may also be dominated by the effects of salinity. The buoyancy effects, due to density differences between different phases of the micellar slug, may not come into play because the micellar slug is involved in salinity related reactions. The interfacial tension which would be reached due to the micellar slug may not be reached due to breakdown of the micellar solution.

Adsorption and Heterogeneity

Theoretically, adsorption (a_s or D_s)[24,25] and heterogeneity (DP)[36,37] should also have a bearing on the success of the micellar-polymer flood. However, these parameters showed no significant correlation. An attempt was made to correlate adsorption expressed as surfactant retention per gram of rock (a_s) to recovery efficiency. After a simple direct relationship failed to correlate, a more complex relationship involving the ratio (Vps/Ds) which is analogous to the excess surfactant injected above that required for adsorption was tested. The adsorption (Ds) term taken from Paul[22] is defined as:

$$D_s = \frac{1 - \emptyset}{\emptyset} \quad \frac{\rho_r a_s}{\rho_s C_s} \quad \frac{1}{1{,}000}$$

This ratio failed to improve the correlation.

Heterogeneity was assumed to be expressed by the Dykstra-Parsons coefficient (DP). Since both adsorption and heterogeneity individually failed to correlate, a compound variable combining both was tested. The compound variable was adsorption (Vps/Ds) divided by heterogeneity (H), where H is the Koval[38] expression for heterogeneity derived from the Dykstra-Parsons coefficient (DP). It was reasoned that heterogeneity should interact with adsorption since the practical correction for each was a larger slug size; however, the combined term also failed to correlate with recovery.

CONCLUSIONS

A statistical analysis of 21 micellar-polymer field test projects which used a micellar solution composed of a conventional sulfonate indicated that several parameters significantly affect the process performance. These parameters, listed in the order of significance, are as follows:

1. Salinity of Connate Reservoir Water. The study indicates that the salinity of the connate water is a dominant factor in oil recovery performance. A statistically significant inverse correlation was developed between the recovery efficiency and the log of connate water salinity for 21 projects. An inverse relationship was also seen between recovery efficiency and the absolute value of the difference between the connate water salinity and an estimated average design salinity. This observation indicates that preflushes to adjust salinity and hardness have been only partially effective.

2. Pattern Area. The study further indicates that oil recovery is higher in the smaller pattern areas. The higher recovery is attributed primarily to the higher frontal velocities that are achieved and, secondarily, to the reduced effects of other parameters such as heterogeneity, adsorption, dilution with formation water, and loss of fluid viscosity.

3. Surfactant Quantity. This study also shows the expected effect that oil recovery is increased with larger quantities of surfactants.

We were unable to establish significant correlations with other parameters which are theoretically significant, including capillary number, temperature, viscosity ratio, bond number, adsorption, and heterogeneity. Lack of correlation with these parameters suggests either an interference with other parameters or that important reservoir variables are not accurately known.

The agreement between predicted and actual performance of the field test by Exxon of a salt tolerant surfactant demonstrates that micellar flooding can be very effective in recovering oil. Salt tolerant surfactants have not yet been used in other field tests, and the properties, performance, and design of micellar solutions using these surfactants have seldom been mentioned in the publications normally referred to by technical people in the industry. There does appear to be an active on-going research program by a few companies to develop salt tolerant surfactant, as shown by patents (References 13, 39, 40, 41, 42, and 43).

We believe that an important area for further research is the development of surfactants which are effective at the salinity and hardness levels which exist in the reservoir. We recommend that the DOE support research into the manufacturing and use of salt tolerant surfactants to hasten this technology into development by industry.

REFERENCES

1. Lake, L. W., and Pope, G. A., "Status of Micellar-Polymer Field Tests", Petroleum Engineer International, pp. 38-60, November 1979.

2. Holm, L. W., "Status of Micellar-Polymer Field Test - Another View", Petroleum Engineer International, pp. 100-116, April 1980.

3. Selvidge, J. E., "Review of Statistical Methods Used in Enhanced Oil Recovery Research and Performance Prediction", DOE/BC/10033-1, 77 p., June 1982.

4. Selvidge, J. E., Bujnowski, S. W., Hoehn, W. T., Fanchi, J. R., and Peterson, R. M., "Statistical Analysis of Micellar-Polymer Data", The BDM Corporation, 1982.

5. Tabor, J. J., "Dynamic and Static Forces Required to Remove a Discontinuous Oil Phase From Porous Media Containing Both Oil and Water", Society of Petroleum Engineers Journal, pp. 3-12, March 1969.

6. Foster, W. R., "A Low-Tension Waterflooding Process", Journal of Petroleum Technology, Vol. 25, pp. 205-210, February 1973.

7. Healy, R. N., Reed, R. L., and Carpenter, C. W., "Laboratory Study of Microemulsion Flooding", SPE Paper 4752, Presented at the SPE-AIME Third Symposium on Improved Oil Recovery, Tulsa, Oklahoma, April 22-24, 1974.

8. Wade, William H., Schechter, R. S., Morgan, J. C., and Jacobson, J. K., "Low Interfacial Tensions Involving Mixtures of Surfactants", SPE Paper 6002 presented at the 51st Annual Fall Technical Conference and Exhibition, New Orleans, Louisiana, October 3-6, 1976.

9. Bennett, Karl E., Phelps, Craig H. H., Davis, H. Ted, and Scriven, L. E., "Microemulsion Phase Behavior - Observations, Thermodynamic Essentials, Mathematical Simulation", Society of Petroleum Engineers Journal, Vol. 21, No. 6, pp. 747-762, December 1981.

10. Bragg, J. R., Gale, W. W., McElhannor, W. A., Davenport, O. W., Patrichok, M. D., and Ashcraft, T. L., "Loudon Surfactant Flood Pilot Test", SPE/DOE Paper 10862 presented at the SPE/DOE Third Joint Symposium on Enhanced Oil Recovery, Tulsa, Oklahoma, April 1982.

11. Gogarty, W. B. and Surkalo, H., "A Field Test of Micellar Solution Flooding, Journal of Petroleum Technology, pp. 1161-1169, September 1972.

12. Earlougher, R. L., O'Neal, J. E., Surkalo, H., "Micellar Solution Flooding: Field Test Results and Process Improvements, SPE Paper 5337 presented at the Rocky Mountain Regional Meeting, Denver, Colorado, April 1975.

13. Gale, Walter W., Puerto, Maura, C., Ashcraft, Thomas L., Saunders, Rhoderick K., and Reed, Ronald L., "Propoxylated Ethoxylated Surfactants and Method of Recovery Oil Therewith", U.S. Patent No. 4,293,428, October 6, 1981.

14. Knaggs, Edward A., Nussbaum, Marvin L., Carlson, James B, and Guenzani, Robert C., "Petroleum Sulfonate Utilization in Enhanced Oil Recovery Systems", SPE Paper 6006 presented at the 51st Annual Fall Technical Conference and Exhibition, New Orleans, Louisiana, October 3-6, 1976.

15. Malmberg, Earl W., Gajderowicz, Carolyn C., Martin, F. David, Ward, Jill S., and Tabor, J. J., "Characterization and Oil Recovery Observations on a Series of Synthetic Petroleum Sulfonates", SPE Paper 8323 presented at the 54th Annual Fall Technical Conference and Exhibition, Las Vegas, Nevada, September 23-26, 1979.

16. Barakat, Y., Fortney, L. N., Schechter, R. S., Wade, W. H., and Yiv, S. H., "Alpha-Olefin Sulfonates for Enhanced Oil Recovery", presented at the 2nd European Symposium on Enhanced Oil Recovery, Paris, France, November 8-10, 1982.

17. Aho, Gary E., and Bush, Jim, "Results of the Bell Creek Unit "A" Micellar-Polymer Pilot", SPE Paper 11195 presented at the 57th Annual Fall Technical Conference and Exhibition, New Orleans, Louisiana, September 26-29, 1982.

18. Sokol, Robert R. and Rohlf, James F., "Biometry", W. H. Freeman and Company, San Francisco, California, 1969.

19. Wilson, Peggy M., Murphy, Charles L., and Foster, William R., "The Effects of Sulfonate Molecular Weight and Salt Concentration on the Interfacial Tension of Oil-Brine-Surfactant Systems", SPE Paper 5812 presented at the SPE-AIME Fourth Symposium on Improved Oil Recovery, Tulsa, Oklahoma, March 22-24, 1976.

20. Pursley, S. A., Healy, R. N., and Sandvik, E. I., "A Field Test of Surfactant Flooding, Loudon, Illinois", Journal of Petroleum Technology, pp. 793-802, July 1973.

21. French, M. S., Keys, G. W., Stegemeier, G. L., Veber, R. C., Abrams, A., and Hill, H. J., "Field Test of Aqueous Surfactant System for Oil Recovery, Benton Field, Illinois", Journal of Petroleum Technology, pp. 195-204, February 1973.

22. Paul, George W., Lake, Larry W., and Pope, Gary A., "A Simplified Model for Micellar-Polymer Flooding", SPE Paper 10733 presented at the California Regional Meeting, March 1982.

23. Gilliland, Harold E., and Conley, Francis R., "Pilot Flood Mobilizes Residual Oil", Oil and Gas Journal, pp. 43-48, January 19, 1976.

24. Meyers, K. O., and Salter, S. J., "The Effect of Oil/Brine Ratio on Surfactant Adsorption From Microemulsion", Society of Petroleum Engineers Journal, Vol. 21, No. 4, pp. 500-512, August 1981.

25. Presley, C. Travis, "Sulfonate Retention and Residual Oil Saturation", Society of Petroleum Engineers Journal, Vol. 23, No. 2, pp. 349-357, April 1983.

26. Hirasaki, George J., "Application of the Theory of Multicomponent, Multiphase Displacement to Three-Component, Two-Phase Surfactant Flooding", Society of Petroleum Engineers Journal, Vol. 21, No. 2, pp. 191-204, April 1981.

27. Hirasaki, George J., "Interpretation of the Change in Optimal Salinity With Overall Surfactant Concentration", Society of Petroleum Engineers Journal, Vol. 22, No. 6, pp. 971-982, December 1982.

28. Nelson, R. C., "Further Studies on Phase Relationships in Chemical Flooding", Symposium on Surface Phenomena in Enhanced Oil Recovery, Stockholm, Sweden, pp. 73-104, August 20-25, 1979.

29. Nelson, R. C., and Pope, G. A., "Phase Relationships in Chemical Flooding", Society of Petroleum Engineers Journal, Vol. 22, No. 2, pp. 259-270, April 1982.

30. Ferrell, H. H., Gregory, M. D., and Borak, M. T., "Progress Report: Big Muddy Field Low Tension Flood Demonstration Project With Emphasis on Injectivity and Mobility", SPE/DOE Paper 12682 presented at the SPE/DOE Fourth Joint Symposium on Enhanced Oil Recovery, Tulsa, Oklahoma, April 1984.

31. Salter, Stephen J., "The Influence of Type and Amount of Alcohol on Surfactant-Oil-Brine Phase Behavior and Properties", SPE Paper 6843 presented at the 52nd Annual Fall Technical Conference and Exhibition, Denver, Colorado, October 9-12, 1977.

32. Lelanne-Cassou, C., Carmona, I., Fortney, L., Samii, A., Schechter, R. S., Wade, W. H., Weerasooriya, U., Weerasooriya, V., and Yiv, S., "Binary Surfactant Mixtures for Minimizing Alcohol Cosolvent Requirements", SPE Paper 12035 presented at the 58th Annual Fall Technical Conference and Exhibition, San Francisco, California, October 5-8, 1983.

33. Healy, Robert N., and Reed, Ronald L., "Physiochemical Aspects of Microemulsion Flooding", Society of Petroleum Engineers Journal, Vol. 14, No. 5, pp. 491-501, October 1974.

34. Healy, Robert N., and Reed, Ronald L., "Immiscible Microemulsion Flooding", Society of Petroleum Engineers Journal, Vol. 17, No. 2., pp. 120-139, April 1977.

35. Halbert, L. W., "Low Interfacial Tension Relative Permeability", SPE Paper 12171 presented at the 58th Annual Fall Technical Conference and Exhibition, San Francisco, California, October 5-8, 1983.

36. Craig, F. F., The Reservoir Engineering Aspects of Waterflooding Monograph Series, SPE, Dallas, Texas, 1971.

37. Claridge, E. L., "Design of Graded Viscosity Banks for Enhanced Recovery Processes", PhD Dissertation, University of Houston, Houston, Texas, July 1979.

38. Koval, E. J., "A Method for Predicting the Performance of Unstable Miscible Displacement in Heterogeneous Media", Society of Petroleum Engineers Journal, pp. 145-154, June 1963, Trans. AIME 228.

39. Kalfoglou, George, "Surfactant Oil Recovery Method for Use in High Temperature Formations Containing Water Having High Salinity and Hardness", U.S. Patent No. 4,194,565, March 25, 1980.

40. Maddox, Jim, Jr., and Tate, Jack F., "Surfactant Oil Recovery Process Usable in High Temperature Formations Having High Concentrations of Polyvalent Ions", U.S. Patent No. 4,008,165, February 15, 1977.

41. Kalfoglou, George, "Surfactant Oil Recovery Method for Use in High Temperature Formations Containing Water Having High Salinity and Hardness", U.S. Patent No. 4,120,358, October 17, 1978.

42. Meister, John J., "Ethoxylated Sulfosuccinate Additives for Stabilizing Solutions of Petroleum Sulfonates in Hard Brine", U.S. Patent No. 4,391,719, July 5, 1983.

43. Chiu, Ying-Chech and Hill, Harold J., "Process for Displacing Oil Using Aqueous Anionic Surfactant Systems Containing Aromatic Ether Polysulfonates", U.S. Patent No. 3,945,437, March 23, 1976.

44. Fanchi, J. R. and Dauben, D. L., "An Evaluation of the Bell Creek Field Micellar Polymer Pilot", DOE/BC/10033-5, 42 p., December 1982.

45. Hartshorne, J. M. and Nikonchik, J. S., "Micellar/Polymer Flood Shows Success in Bell Creek Field", SPE Paper 13122 presented at the SPE 59th Annual Fall Technical Conference and Exhibition, Houston, Texas, September 16-19, 1984.

46. Conoco, Inc., "Big Muddy Field Low Tension Flood Demonstration Project", Sixth Annual Report, April 1983 - March 1984, DOE/SF/01424-51, 1984.

47. Ferrell, H. H., King, D. W., and Seely, C. Q., Jr., "Analysis of Low-Tension Pilot at Big Muddy Field, Wyoming", SPE/DOE Paper 12683 presented at the SPE/DOE Fourth Joint Symposium on Enhanced Oil Recovery, Tulsa, Oklahoma, April 1984.

48. Pursley, S. A. and Graham, H. L., "Borregos Field Surfactant Pilot Test", Journal of Petroleum Technology, pp. 695-700, June 1975.

49. Danielson, H. H., Paynter, W. T., and Milton, H. W., Jr., "Tertiary Recovery by the Maraflood Process in the Bradford Field", Journal of Petroleum Technology, pp. 129-138, February 1976.

50. Hause, W. R., Haws, G. W., and Ondrusek, P. S., "Micellar-Polymer Flood Tested in Bradford Field", Petroleum Engineers International, pp. 42-69, November 1982.

51. "El Dorado Micellar-Polymer Demonstration Project, Eighth and Final Report", DOE/ET/13070-92, September 1981 - November 1982.

52. Knight, R. K. and Baer, P. J., "A Field Test of Soluble-Oil Flooding at Higgs Unit", Journal of Petroleum Technology, pp. 9-15, January 1973.

53. Hamaker, P. E. and Frazier, G. D., "Manvel Enhanced Recovery Pilot - Design and Implementation", SPE Paper 7088 presented at the SPE Fifth Symposium on Improved Methods for Oil Recovery, Tulsa, Oklahoma, April 1978.

54. Widmyer, R. H. and Pindell, R. G., "Manvel Enhanced Recovery Pilot - Performance Evaluation", SPE/DOE Paper 9793 presented at the SPE/DOE Second Joint Symposium on Enhanced Oil Recovery, Tulsa, Oklahoma, April 1981.

55. Phillips Petroleum Company, "North Burbank Unit Tertiary Recovery Pilot Test, Final Report", DOE/ET/13067-60, June 1980.

56. Trantham, J. C. and Clampitt, R. L., "Determination of Oil Saturation After Waterflooding in an Oil-Wet Reservoir - The North Burbank Unit, Tract 97 Project", Journal of Petroleum Technology, pp. 491-500, May 1977.

57. Trantham, J. C., Patterson, H. L., and Boneau, D. F., "The North Burbank Unit, Tract 97 Surfactant/Polymer Pilot - Operation and Control", Journal of Petroleum Technology, pp. 1068-1074, July 1978.

58. Trantham, J. C., Threlkeld, C. B., Patterson, H. L., "Reservoir Description for a Surfactant/Polymer Pilot in a Fractured, Oil-Wet Reservoir - North Burbank Unit, Tract 97", Journal of Petroleum Technology, September 1980.

59. Howell, J. C., McAtee, R. W., Snyder, W. O., and Tonso, K. L., "Large Scale Field Application of Micellar-Polymer Flooding", Journal of Petroleum Technology, pp. 690-696, June 1979.

60. Marathon Oil Company, "Commercial Scale Demonstration - Enhanced Oil Recovery by Micellar-Polymer Flood", Annual Report, BERC/TPR-77/10, October 1976 - September 1977.

61. Marathon Oil Company, "Commercial Scale Demonstration - Enhanced Oil Recovery by Micellar-Polymer Flood", Annual Report, DOE/ET/13077-36, October 1977 - September 1978.

62. Marathon Oil Company, "Commercial Scale Demonstration - Enhanced Oil Recovery by Micellar-Polymer Flood", Annual Report, DOE/ET/13077-63, October 1980 - September 1981.

63. Strange, L. K. and Talash, A. W., "Analysis of Salem Low-Tension Waterflood Test", Journal of Petroleum Technology, pp. 1380-1384, November 1977.

64. Widmyer, R. H., Satter, A., Frazier, G. D., and Graves, R. H., "Low-Tension Waterflood Pilot at the Salem Unit Marion County, Illinois - Part 2: Performance Evaluation", Journal of Petroleum Technology, pp. 933-938, August 1977.

65. Widmyer, R. H., Williams, D. B., and Ware, J. W., "Performance Evaluation of the Salem Unit Surfactant/Polymer Pilot", SPE Paper 14442 presented at the SPE 60th Annual Fall Technical Conference and Exhibition, Las Vegas, Nevada, September 1985.

66. Taggart, D. L. and Russell, G. C., "Sloss Micellar/Polymer Flood Post Test Evaluation Well", SPE/DOE Paper 9781 presented at the SPE/DOE Second Joint Symposium on Enhanced Oil Recovery, Tulsa, Oklahoma, April 1981.

67. Yanosik, J. L., Treiber, L. E., Myal, F. R., and Calvin, J. W., "Sloss Micellar Pilot: Project Design and Performance", SPE Paper 7092 presented at the SPE-AIME Fifth Symposium on Improved Oil Recovery, Tulsa, Oklahoma, April 1978.

68. Shelton, J. L., "Torchlight Field", Enhanced Oil Recovery Field Reports, v. 11, pp. 1783-1790, September 1985.

69. Talash, A. W. and Strange, L. K., "Summary of Performance and Evaluations in the West Burkburnett Chemical Waterflood Project", Journal of Petroleum Technology, pp. 2495-2502, November 1982.

70. Fanchi, J. R., Duane, N. C., and Hill, C. J., "An Evaluation of the Wilmington Field Micellar-Polymer Project", DOE/BC/10033-8, 109 p., October 1983.

71. Staub, H. L., "Results of a Micellar-Polymer Flood in a Flooded-Out, Low Gravity Reservoir", SPE/DOE Paper 9791 presented at the SPE/DOE Second Joint Symposium on Enhanced Oil Recovery, Tulsa, Oklahoma, April 5-8, 1981.

TABLE 1

FIELD TEST DATA

Field - Project	Operator	State	Patn Size, acres AP	Patn Type	Depth, feet D	Thickness, feet h	Perm, md. K	Perm Var, DP.	Phi, fr.	Clay, fr.	Adspn, mg/grx as	Wtr Vis, cp. μw	Oil Vis, cp. μo	Temp, °F	Res Sal, ppm TDS	Vol Slug, Vps	Conc Surf, Cs	Inj Rate per well b/d	Slug Vis, μs cp	Vol Mob Buff, Vmb	Conc Poly, ppm Cp	Rec Eff, Er	References
1. Bell Creek, Unit A*	Gary Energy	MT	40.0	5	4,650	6	1,050.0	0.70	0.2910	0.060	0.02	0.6	4.6	110	7,400	0.035	0.080	363		1.00	1,250	0.140	17,44
2. Bell Creek, Expansion*	Gary Energy	MT	5.0	5	4,500	22	1,218.0	0.70	0.2490	0.060	0.03	0.6	6.5	110	7,400	0.046	0.080	311		0.75	1,250	0.280	45
3. Benton, Pilot	Shell	IL	1.0	5	3,000	22	73.0	0.42	0.1700	0.050	0.21	0.7	3.5	85	110,000	0.310	0.013	45		0.99	275	0.240	21
4. Big Muddy, Pilot	Conoco	WY	1.3	5	3,050	65	52.0	0.60	0.1900	0.120	0.23	0.7	5.5	115	7,800	0.250	0.025	200	6.0	0.30	1,100	0.360	30,47
5. Big Muddy, 90 Acre Demo*	Conoco	WY	10.0	5	3,050	60	52.0	0.61	0.1940	0.120	0.19	0.7	5.5	115	7,800	0.100	0.030	167	22.0	0.20	1,400	0.220	46
6. Borregos, Borregos	Exxon	TX	1.3	5	4,998	3	434.0	0.70	0.2100	0.085	0.15	0.6	0.4	165	33,000	0.470	0.230			0.00	0	0.200	48
7. Bradford, Bingham 533	Pennzoil	PA	0.8	5	1,860	23	82.0	0.65	0.1800			0.8	5.0	68	2,950	0.060	0.130	106		1.41	1,700	0.390	49
8. Bradford, Bingham Exp.	Pennzoil	PA	2.9	5	1,860	23	82.0	0.84	0.1800			0.8	5.0	68	2,950	0.050	0.120	83	25.0	0.82	1,500	0.370	49
9. Bradford, Lawry Test*	Pennzoil	PA	1.5	5	1,280	29	7.6	0.88	0.1265			0.8	5.0	64	2,950	0.094	0.090	22	8.3	0.41	500	0.053	50
11. El Dorado, Chesney*	Cities	KS	6.4	5	650	18	265.0	0.78	0.2430	0.120	0.16	0.8	4.8	69	86,830	0.094	0.026	29	32.0	0.73	1,125	0.034	51
12. El Dorado, Hegberg*	Cities	KS	6.4	5	650	17	208.0	0.85	0.2450	0.120	0.06	0.8	4.8	69	86,830	0.054	0.070	22		0.82	1,600	0.063	50
13. Jones City Reg., Higgs Unit	Union	TX	8.2	9	1,870	13	500.0		0.2290				4.3	95	85,000	0.040	0.090			0.68		0.084	52
14. Loudon, First Test	Exxon	IL	0.7	5	1,500	15	103.0	0.42	0.2060	0.090	0.17		4.0	80	105,000	0.400	0.023	30	5.1	0.36	558	0.150	20
15. Loudon, High Salinity*	Exxon	IL	0.7	5	1,500	13	150.0	0.42	0.1900	0.090	0.19		5.0	78	105,000	0.400	0.023	56	29.0	0.02	558	0.600	9
16. Manvel, Oligocene A-1*	Texaco	TX	10.0	SLD	5,400	17	500.0		0.3000	0.080	0.08		4.0	165	107,000	0.250	0.025	950		0.50	1,400	0.120	53,54
17. North Burbank, Tract 97	Phillips	OK	10.0	5	2,900	47	24.0	0.61	0.1550				3.0	120	87,100	0.051	0.037	730	24.0	0.47	2,500	0.110	55,56,57,58
18. Robinson, M-1*	Marathon	IL	3.0	5	950	27	103.0	0.59	0.1890	0.085	0.04		7.0		16,575	0.100	0.100			1.05	1,156	0.310	59,60,61,62
19. Salem, Salem	Texaco	IL	5.0	5	1,750	29	150.0	0.34	0.1790				3.6		120,000	0.285	0.019	300		0.30	700	0.170	63,64,65
23. Sloss, Sloss	Amoco	NB	9.0	5	6,300	12	80.0	0.45	0.1700	0.110	0.10		0.8	200	2,500	0.155	0.064	275	5.0	1.00	800	0.220	66,67
24. Torchlight, Torchlight*	Amoco	WY	5.8	5	3,100	33	60.9		0.1420				3.8	100	12,000	0.187		163	5.0	0.40		0.000	68
25. W. Burkburnett, W. Burkburnett*	Mobil	TX	10.0	5	1,800	16	75.0		0.2000					85	150,000	0.150	0.019	300		0.30	500	0.133	69
26. Wilmington, Wilmington*	City of Long Beach	CA	1.5	SLD	2,900	58	439.0		0.3150	0.070	0.02		25.0	145	30,000	0.064	0.080	300	35.5	0.66		0.250	70,71

* New Project Data

SLD: Staggered Line Drive

TABLE 2

STATISTICAL DATA

Parameter	Correlation Coefficient r	Number of Projects With Data	Confidence Limit, percent
Log (Salinity)	-0.47	21	96.2
Log (Patn Area)	-0.46	20	95.1
Patn Size (AP)	-0.45	20	94.5
Salinity	-0.43	21	94.0
Log-Vps*Cs	0.40	20	90.7
Salinity deviation from design (est. design sal. 15,000 ppm TDS)	-0.39	21	90.5
Cs	0.37	20	87.5
Vmb	0.35	21	86.4
Vps*Cs	0.33	20	82.6
Vmb*Cp	0.35	17	80.6
Residual Oil	0.27	21	74.2
Thickness (h)	0.27	21	74.2
Pore Volume	0.25	21	70.2
Vmb/Vps	0.23	20	64.8
Log (Depth)	0.22	21	63.7
VEA (Vs/Dx·H)	0.29	11	56.5
μs	0.29	11	56.5
K*h	0.17	21	51.6
Dykstra-Parsons (DP)	0.19	16	49.1
Clay (Fraction)	0.21	13	47.1
Log (Ncap)	0.13	21	40.4
Depth (D)	0.13	21	40.4
Vps/Ds	0.13	13	30.3
Temperature	0.10	19	29.6
Cp	0.10	17	28.1
as	0.102	13	23.5
$\mu s/\mu o$	0.08	10	15.1
Log (Vps)	0.03	21	9.6
Log (K)	0.02	21	6.4
Permeability (K)	0.01	21	3.2
$1/\mu o$	0.01	20	3.2
Vps	0.01	21	3.2
Bond Number	0.003	21	1.0

DEFINITIONS

A	- Area
AP	- Pattern area
as	- Surfactant retention in mq surfactant/g rock
Cp	- Polymer concentration, ppm
Cs	- Weight fraction surfactant in slug
D	- Depth
D_s	- Dimensionless adsorption (Reference 22)
DP	- Dykstra-Parsons coefficient
g	- Gravitational acceleration (ft/sec^2)
H	- Koval heterogeneity factor derived from DP (Reference 38)
h	- Thickness, feet
K	- Permeability, md
Nc, Ncap	- Capillary number
PV	- Pore volume
V	- Frontal velocity
VEA	- Multiple component parameter, Vps/Ds*H
Vps	- Pore volume surfactant slug
Vmb	- Pore volume mobility buffer
ϕ	- Porosity
μ	- Viscosity
ρ	- Density
σ	- Interfacial tension, dynes/cm

Subscripts

o	- Oil
p	- Polymer
r	- Rock
s	- Surfactant

FIGURE 1

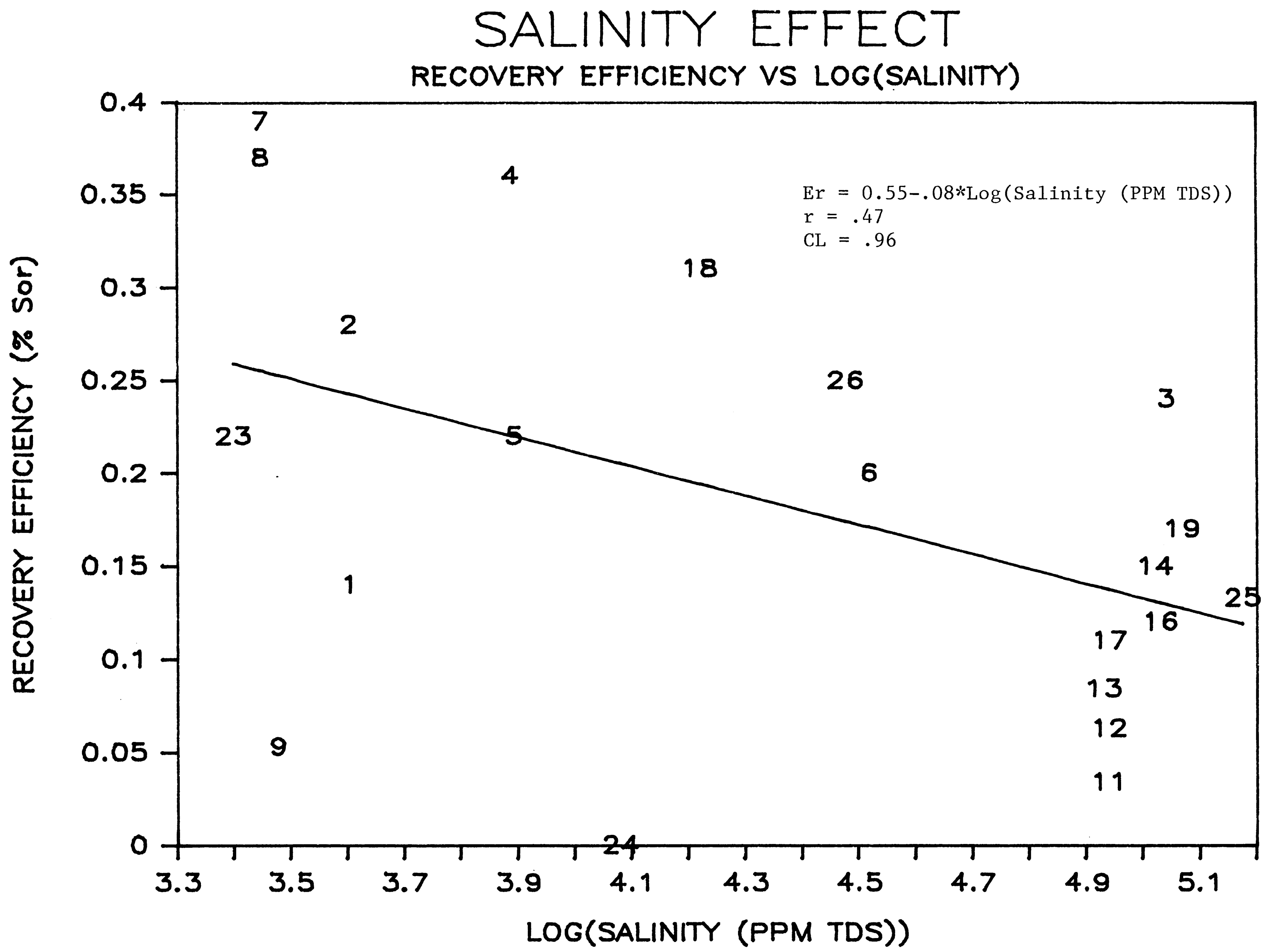

SALINITY EFFECT
RECOVERY EFFICIENCY VS LOG(SALINITY)
Er = 0.55-.08*Log(Salinity (PPM TDS))
r = .47
CL = .96
RECOVERY EFFICIENCY (% Sor)
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
3.3
3.5
3.7
3.9
4.1
4.3
4.5
4.7
4.9
5.1
LOG(SALINITY (PPM TDS))
7
8
4
18
2
26
3
23
5
6
19
14
1
25
16
17
13
12
9
11
24

FIGURE 2

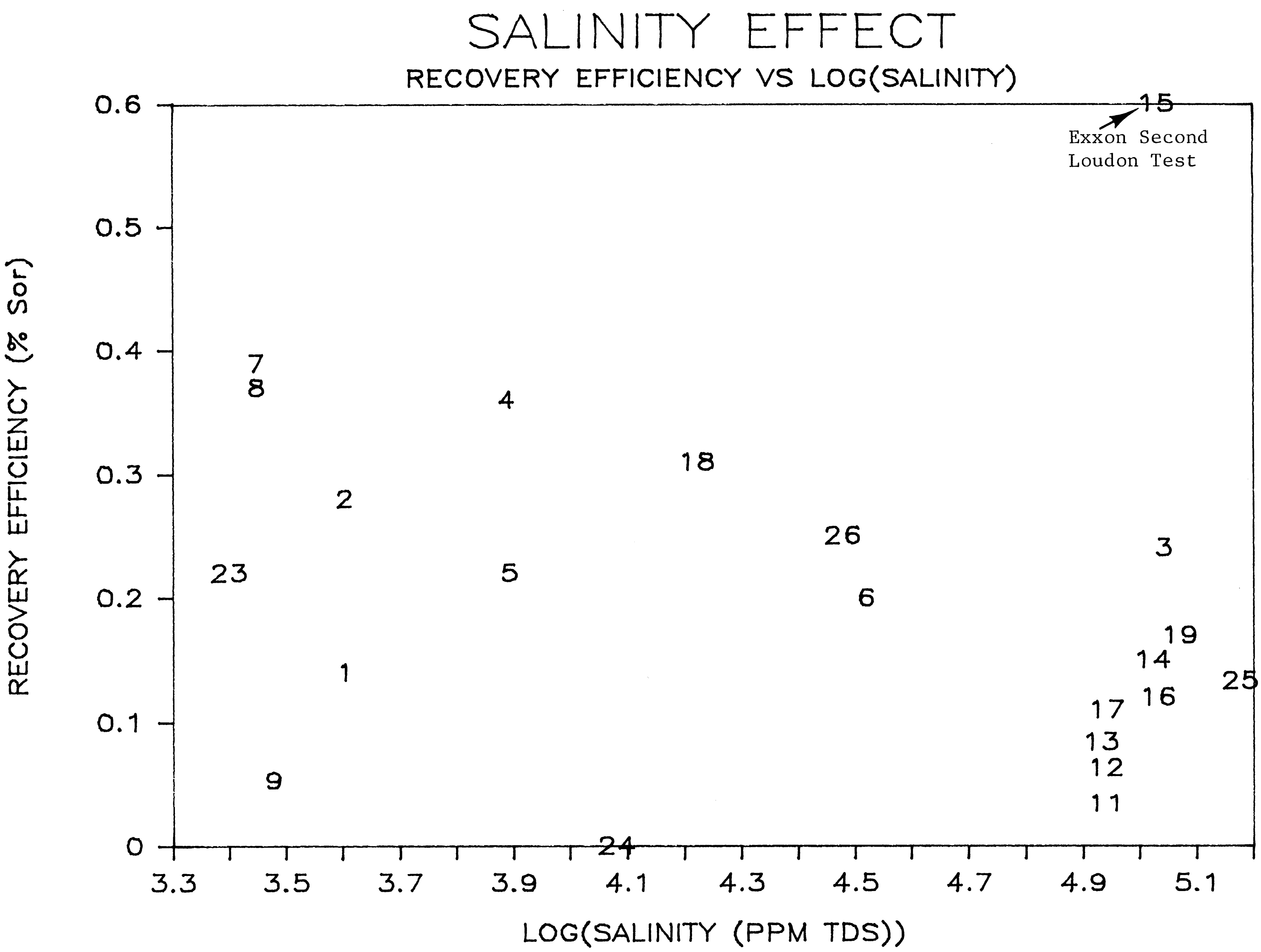
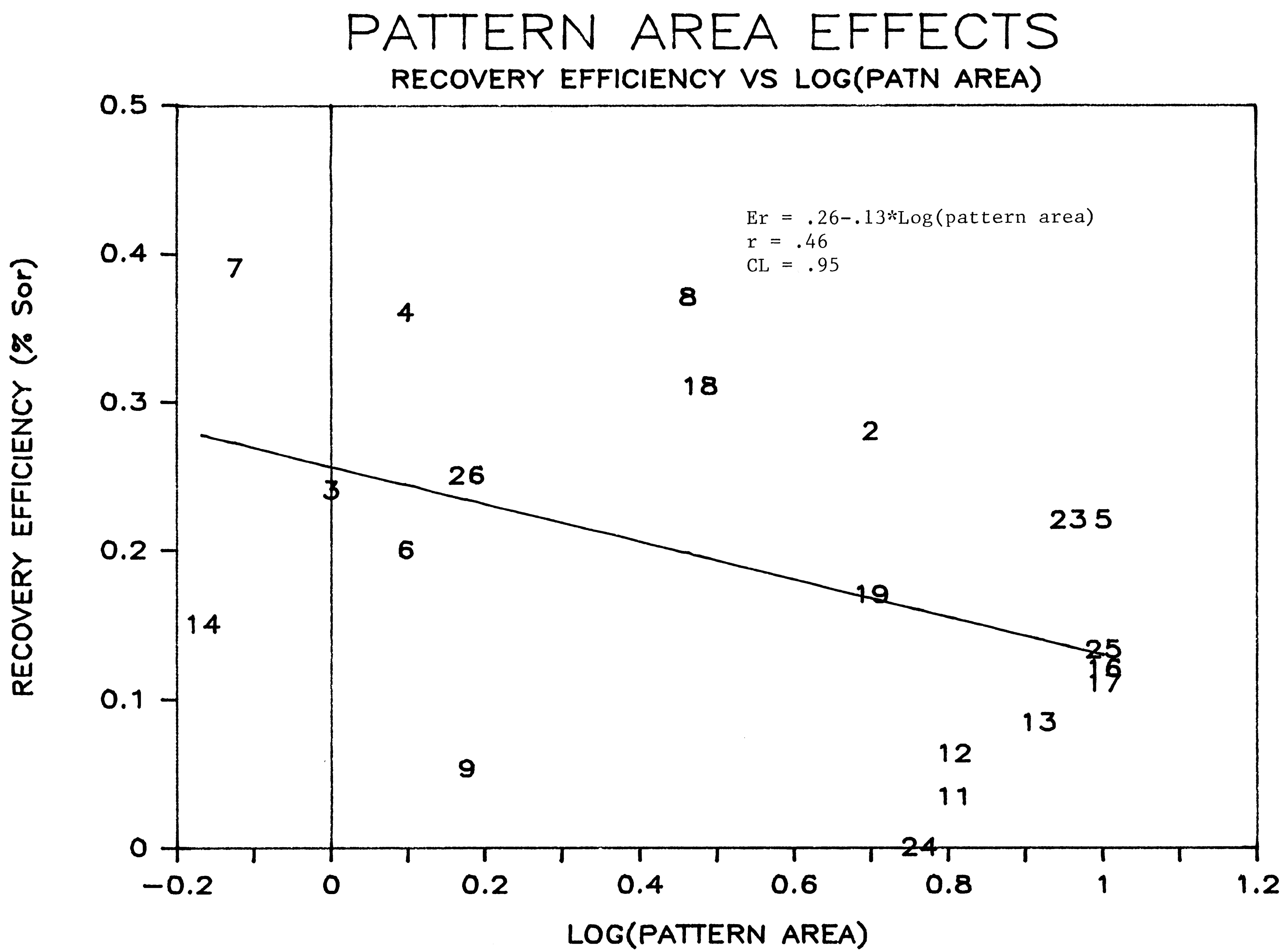

SALINITY EFFECT
RECOVERY EFFICIENCY VS LOG(SALINITY)
RECOVERY EFFICIENCY (% Sor)
LOG(SALINITY (PPM TDS))
0.6
0.5
0.4
0.3
0.2
0.1
0
3.3
3.5
3.7
3.9
4.1
4.3
4.5
4.7
4.9
5.1
15
Exxon Second
Loudon Test
7
8
4
18
2
26
3
23
5
6
19
14
25
1
16
17
13
12
9
11
24

FIGURE 3


PATTERN AREA EFFECTS
RECOVERY EFFICIENCY VS LOG(PATN AREA)
Er = .26-.13*Log(pattern area)
r = .46
CL = .95
RECOVERY EFFICIENCY (% Sor)
LOG(PATTERN AREA)
0.5
0.4
0.3
0.2
0.1
0
−0.2
0
0.2
0.4
0.6
0.8
1
1.2
7
4
8
18
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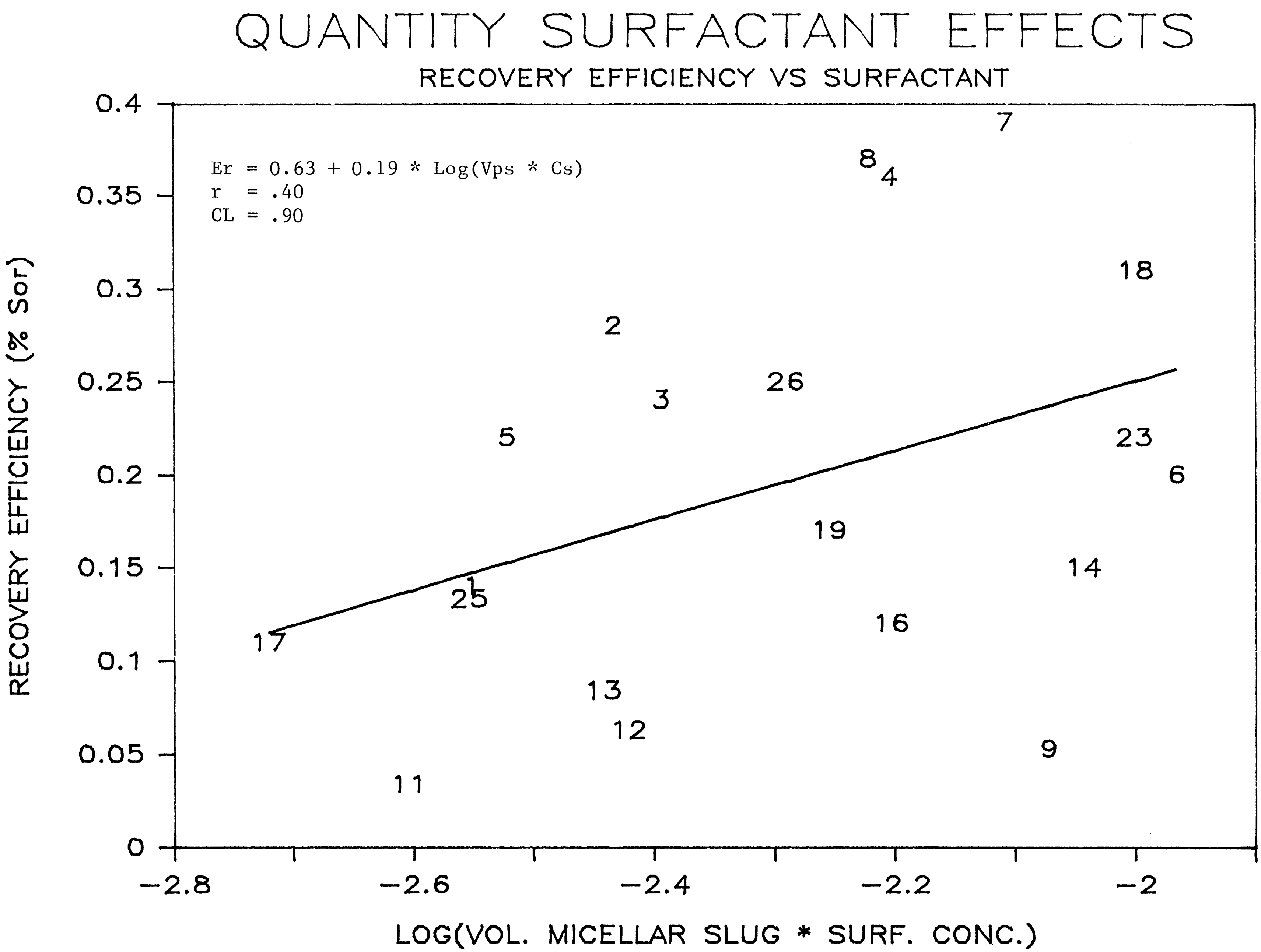
14
25
16
17
13
12
9
11
24

FIGURE 4



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