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PROJECT 77: Research Program on Fractured Petroleum Reservoirs

Problem: Fractured petroleum reservoirs provide over 20 percent of the oil reserves and production and they are found all over the world, in all types of lithologies and throughout the geologic stratigraphic column. Depending upon the matrix and fracture characteristics of the geological formations, the ultimate recovery of oil from these reservoirs could vary over a wide margin, from less than 10 percent to over 60 percent. Water and gas injection in fractured reservoirs differs significantly from that in unfractured reservoirs and the difference in capillary pressure in matrix and fracture is believed to be the main reason for the performance difference in these two types of rocks. Capillary pressure contrast between matrix and the fracture does not allow any type of averaging and scale-up in heterogeneous, layered and fractured media. In addition to capillarity, there are certain other important issues that strongly affect hydrocarbon recovery from fractured reservoirs, such as the effect of fractures on composition variation in a hydrocarbon reservoir, which needs to be addressed also.

A comprehensive research program by the Reservoir Engineering Research Institute (RERI) of Palo Alto, California is being implemented in this project to address a number of important issues relating to the characterization and production performance of different types of fractured reservoirs. The major themes of research relate to water injection and characterization of fractured petroleum reservoirs.

Project Objective: The main objectives of research in this project, i.e., improving water injection and characterization of fractured petroleum reservoirs are being implemented through the completion of five tasks described below:

- In some fractured reservoirs where the bulk of the hydrocarbon resides in the fractures, the compressibility of the fracture in the course of depletion may play a dominant role in recovery. If a full expression for the gravitational attraction due to the sun and the moon could be derived, then one may use the response of the gravitational effects on the reservoir to estimate the pore volume compressibility and the effective permeability for a large portion of a fractured reservoir. The objectives of this task will be to develop an inexpensive technique to infer average bulk properties of the reservoir, such as pore volume compressibility and permeability.

- A large number of reservoirs have shown promising recovery by production without steam under natural depletion, which is called the cold production in heavy oil industry. The actual mechanism for the high efficiency of oil production from these reservoirs should be investigated for more efficient production from these reservoirs.

  Research also needs to be conducted to improve gas production from certain types of reservoirs where gas production decreases sharply when liquid saturation around well bore increases. Several methods are routinely applied to improve gas productivity, but most of these methods are not always economical or cost effective. If one can alter the wettability around the wellbore permanently to gas wetting, then there will be no liquid accumulation. More research is needed to understand the process parameters and the use of environmentally acceptable chemicals that can alter wettability to gas wetting.

- Previous studies at RERI indicated basic differences between the species distribution in fractured and unfractured reservoirs. The multicomponent diffusion and convection model developed at RERI needs to be applied to several actual fractured and unfractured reservoirs to determine the mechanisms for species distribution in fractured petroleum reservoirs.

- In this task, factors effecting water injection efficiency in fractured petroleum reservoirs are investigated from a study of the effect of the capillary drive and viscous forces on recovery efficiency. Work will also be done on measuring fracture relative permeability and capillary pressure. Once the measurements have been completed, analytical/numerical techniques will be developed to interpret the experimental results.

- There are two basic models for the descriptions of fractured porous media: 1) the sugar-cube model which assumes a continuous fracture media with matrix block feeding the fracture network that has been used extensively in the industry to describe dual porosity and dual porosity, dual permeability processes, and 2) the discrete fracture network (DFN). The DFN model idealizes fractured porous media with fractures of finite discrete discontinuities within a rock matrix, but its use so far has been limited to single phase flow. In view of the fact that the DFN method provides a better general description of fractured porous media, a simulator needs to be developed that adequately describes multiphase flow in fractured petroleum reservoirs.

***Project Costs**:* The total estimated cost of the project is $1,292,000 out of which the DOE share is $350,000. The rest is from non-DOE funding. The Reservoir Engineering Research Institute (RERI) received two other research grants from the US Department of Energy in 2001.

Oil Industry Support for research conducted by RERI was available from the following companies**:**

1. Abu Dhabi National Oil Company (ADNOC)
2. BHP Petroleum Pty. Ltd.
3. BPAmoco
4. Chevron Petroleum Technology Company
5. Conoco, Inc.
6. ExxonMobil Upstream Research Company
7. Japan Exploration Co. Ltd. (JAPEX)
8. Maersk Oil and Gas
9. Norsk Hydro Production, A. S.

10.Petrobras, S. A.
11. Phillips Petroleum Company
12. Saudi Aramco
13. Shell International Exploration and Production Company
14. Texaco, Inc.
15. TotalFinaElf
16. UK Department of Trade and Industry (UK)

Technology Change: The project is scheduled to be completed by 03/30/2002 and approximately 80% of the tasks have so far been completed. Important technological contributions and changes made thus far are briefly described below:

Use of tidal force induced pressure transients for estimating PV compressibility and permeability of fractured reservoirs.

Three important tasks were completed for this task:

- An expression for the gravitational potential due to the most important sources, the moon and the sun was derived.
- The dilatational response as a function of the magnitude of the gravitational potential was obtained.
- The dilatation, or differential compaction of the earth near the surface was related to the observed pressure through the parameters that it is desirable to evaluate.

The total compressibility C_f, calculated for the reservoir was 1.7×10^{-5} psi^{-1} that was in fair agreement with total compressibility estimated from extended production testing. The pressure data show a phase lag (about 12 hours), which is an avenue for estimating the fluid mobility and an analysis of this will be carried out in the future. See Appendix A for more details.

Cold production from heavy oil reservoirs

- The results for cold production experiments with two vastly different viscous oils indicate that the main mechanisms for high recovery efficiency under solution gas drive is low gas mobility and is therefore mainly due to the shape of the gas relative permeability curve. The mobility of the evolved gas at $S_g<10\%$ is of the order of magnitude of 10^{-5} to 10^{-6}, which is several orders of magnitudes lower than that in light oil. Increase in temperature would reduce oil viscosity therefore increase gas mobility. But still in the temperature range of our investigation, the gas mobility remains low.

- At the room temperature of $T = 24^{o}$ C, the critical gas saturation, and gas-bubble density for silicon oil are about 1.1% and 0.2 bubbles/ cm^2 (bubbles per surface area), respectively, which are far less than those for oil-E (critical-gas saturations ~5.5% and gas bubble density is about 2 bubbles/cm^2 for test 5). However, these differences do not have a significant influence on the recovery performance and gas and oil relative permeabilities.

- The viscosities at $T = 24^{O}$ C for silicon-mineral oil and heavy crude are 32,000 and 85,000 cp, respectively. From results of all the tests presented in this task, it may be concluded that viscosity is the major parameter in solution-gas drive of heavy oils.

- Results from two oil recovery performances demonstrate that the widely held belief that foamy crudes contribute to high recovery efficiency is unjustified.

See Appendix A for details.

Characterization of fractured reservoirs from PVT samples

The theoretical model developed at RERI on the mechanism that affect the distribution of various species in hydrocarbon reservoirs was used to provide an interpretation of the unusual density distribution versus depth in a hydrocarbon formation and a deep well as well as the unusual species distribution in the hydrocarbon formation. The results reveal that thermal diffusion (due to geothermal temperature gradient) causes the segregation of heavy components in the subsurface fluid mixture to the cold side in the earth (that is to the top), overriding pressure and molecular diffusion (Fickian diffusion). As a consequence of the competition of these three diffusion effects, a heavy fluid mixture can float at the top with a light fluid-mixture underneath. In the past, thermal diffusion has been thought of as a second-order effect. For the fluid mixture investigated, thermal diffusion is the phenomenon affecting the spatial density and species distribution.

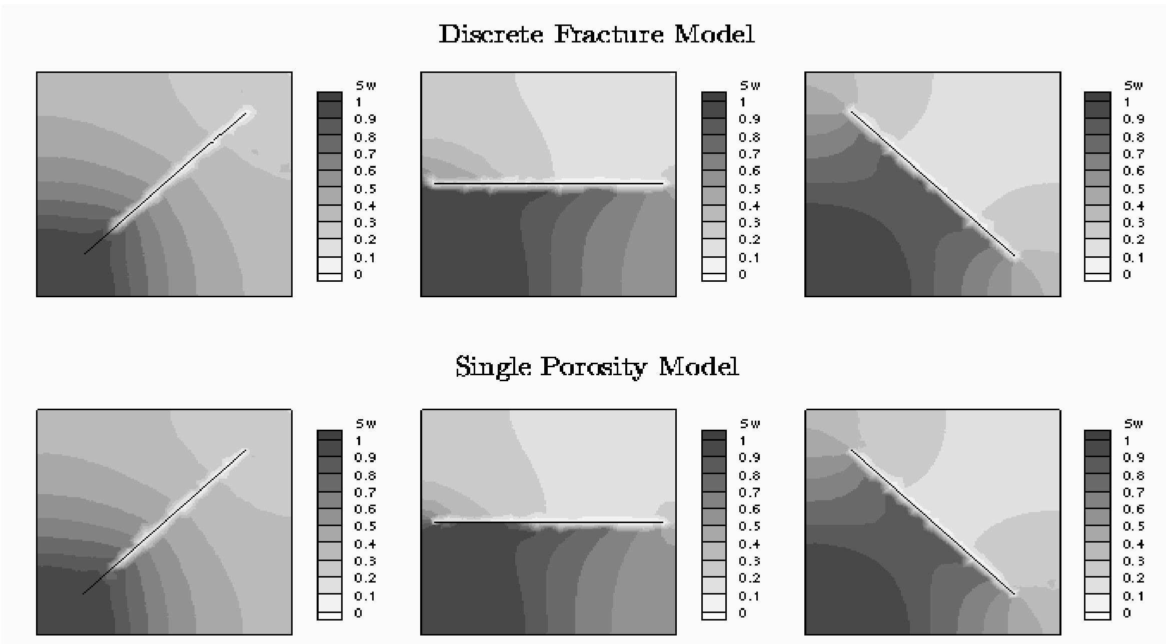
Effect of viscous forces and initial water saturation on water injection in water-wet and weakly water-wet fractured porous media

A systematic study of the effect of wettability and initial water saturation on water injection and imbibition was conducted on an extensive set of laboratory measurements on the Kansas outcrop chalk with a porosity of about 30% and permeability of some 1-5 md. Based on a large number of carefully conducted tests, the following conclusions are drawn (see Appendix A for details) from this work:

- Initial water saturation has a very pronounced effect on water injection in an intermediate wet chalk. This effect is much less pronounced for a strongly water-wet chalk. The effects are also in opposite directions.
- Viscous forces have a very strong effect on water injection performance on intermediate-wet chalks.

Numerical simulation of oil recovery from fractured petroleum reservoirs

Numerical simulation of fractured reservoir rocks is attempted in this task through the use of a discrete fracture model in which the fractures are discretized as one-dimensional entities and the matrix is dicretized using triangular elements (see Appendix A for details). The thickness of the fractures is accounted through a modified form of flow equations. Different approaches are possible to implement this idea. In this project, the researchers have presented the implementation of discrete fracture model using a Galerkin finite element method and finite element discretization. The robustness and the accuracy of DFN simulations is illustrated here by waterflood simulations performed for three different tilts of the fracture. Capillary pressure is also taken into account in this set of simulations (see figure below). A comparison of the results between the discrete fracture model and the single porosity model indicate very close agreement between the two sets of results.



2. Discrete fracture model is physically equivalent to single porosity model
3. The method is more efficient than single porosity model

Technology Transfer: Technology transfer was achieved mainly through 22 technical presentations in various leading technical society meetings with 4 additional papers scheduled for presentation at the SPE Fall Meeting this year. Twenty-six seminars have also been presented by members of RERI at various oil companies and universities. Another mode of technology transfer was through the strong interaction with the consortium of 16 oil companies who actively participated in this research (see list of participating companies above). A list of papers and presentations is included as Attachment I.

Technology Implementation: The technology developed in this project will be implemented through the various computer programs such as the Discrete Fracture Network (DFN) model for simulation of fractured petroleum reservoirs used by the member companies (see list of participating companies above). The results of experimental research have been published in numerous articles (see list below) and these technologies are available for implementation.

End Users: The main users of the technologies developed in this project will be the oil and gas companies, independent explorationists and researches engaged in the exploration of fractured petroleum reservoirs. The 16 oil and gas companies (see list under project cost) that are directly involved in RERI research are expected to be the first ones who will take advantage of this research.

Impacts: The performance period of the project is from 3/32/99 through 3/30/2002, and till the time of writing, this project is about 80% complete. The successful development of technology for exploitation of fractured petroleum reservoirs should be very useful to all explorers of oil and gas since fractured reservoirs constitute one of the important classes of reservoirs where significant accumulations of oil and gas occur. The table below shows the important basins in North America where oil and gas is produced from fractured petroleum reservoirs. In one column in this table is shown the basins

North America	Horizontal Drilling	North America	Horizontal Drilling
Alberta	X	North Slope	X
Anadarko	X	Palo Duro	X
Appalachian	X	Paradox	X
Ardmore	X	Permian	X
Arkoma		Piceance	X
Bear Lake	X	Powder River	X
Big Horn	X	Sabinas	
Black Warrior	X	Salinas (Mexico)	
Campeche		Salinas	
Cincinnati Arch	X	Salina/Forest City	X
Crazy Mountain	X	San Joaquin	X
Denver	X	San Juan	X
East Texas Salt Dome		Sand Wash	X
Fort Worth	X	Santa Maria	X
Green River	X	South Texas Salt Dome	X
Laramie		Uinta	
Los Angeles		Ventura	
Louisana Salt Dome	X	Williston	X
Michigan	X	Wind River	
Mississippi Salt Dome	X		

where horizontal drilling has been implemented for hydrocarbon recovery. As mentioned earlier, the reservoirs in the above list are made up of all types of lithologies, such as sandstones, limestones, chalks, shales, etc. The technologies developed in this project are likely to find applications in fractured reservoirs in North America as well as overseas.

Additions to Reserves: Significant oil and gas reserves are expected to occur in fractured rocks (Energy Information Administration, U.S. Crude Oil, Natural Gas, Natural Gas Liquids Reserves 1998 Annual Report) in what the USGS defines as undiscovered, technically recoverable resources in conterminous U.S. oil and gas fields. Such undiscovered reserves are likely to be found in several domestic basins such as the Permian Basin in West Texas and the Rocky Mountain basins, the Williston Basin, the Cottonwood Creek and the Oklahoma City fields of Oklahoma, the Appalachian Basin, (see list of basins above) as well as in several offshore basins. The total reserves in this category of undiscovered but technically recoverable reserves in all the domestic basins in U.S. is estimated to be about 91 BBO of oil and Natural gas liquids and 885 TCF of natural gas. A significant part of this reserves are expected to be found in fractured reservoirs. Even if a fifth (from present overall production statistics) of the of reserves in this category is found in fractured reservoirs then at least 18.2 BBO of oil and 177 TCF of gas will be found in this category of undiscovered but technically recoverable reserves.

Some of the technologies developed in this project will help to recover at least 1.82 BBO of oil and natural gas liquids and 17.7 TCF of natural gas, assuming that the new technologies will help to recover at least a tenth of the reserves. Such significant additions to national reserves will generate 10.7 and 3.9 billion dollars in royalty and tax incomes respectively, not counting the other benefits such incomes will have on other sectors of the economy.

Environmental: Successful application of this technology will help to reduce surface imprint through efficient management of the reservoir, effective placement of wells (thereby reducing number of wells needed for reservoir drainage), reliable forecasting of possible production problems and implementation of appropriate remedial measures for efficient exploitation of the fractured petroleum reservoirs.

Economic Impact & Job Creation: Even if a tenth of the income generated from sale of oil and gas resources is ploughed back into the oil drilling and production sector of the economy then it will have ripple effect in the economy by creating new earnings and generating new jobs in different sectors of the economy. To estimate these indirect benefits, the Regional Input-Output Modeling System (RIMS II) economic multipliers developed by the Bureau of Economic Analysis within the Department of Commerce can be utilized. In this report they have adopted a set of multipliers from the " Calculated Oil and Gas Industry Multipliers" published in Marginal Oil and Gas: Fuel for Economic Growth , 1997 Edition, from the Interstate Oil and Gas Compact Commission (IOGCC). These multipliers have been used to approximately calculate the indirect economic benefits in the entire U.S. as a result of investment of 1/10 of the income generated from oil and gas production in this state.

Estimate of Indirect Economic Benefits Using Final Demand Multipliers
In the entire U.S.

Total Investment	= 1.46 billion dollars
Addition to U.S. Economy	= 2.16 billion dollars
Creation of Earnings in U.S.	= 275.6 million dollars
Total No. of Jobs created in all sectors of economy in U.S.	= 12,800

Attachment I

Presentations/Publications

1. Pooladi-Darvish, M. and Firoozabadi, A: "Solution-Gas Drive in Heavy Oil Reservoirs," J. of Canadian Petroleum Technology (April 1999) 54-61.

2. Shukla, K. and Firoozabadi, A.: "A New Model of Thermal Diffusion Coefficients in Binary Hydrocarbon Mixtures," I&EC Research(Aug. 1998) 3331-3342.

3. Terez, I. and Firoozabadi, A.: "Water Injection in Water-Wet Fractured Porous Media: Experiments and a New Model Using Modified Buckley-Leverett Theory," SPE Journal (June 1999) 134-141.

4. Firoozabadi, A. and Aronson, A.: "Visualization and Measurement of Gas Evolution and Flow of Heavy and Light Oils in Porous Media," SPE Reservoir Evaluation and Engineering (Dec. 1999)550-557.

5. Pooladi-Darvish, M., and Firoozabadi, A.: "Co-Current and Counter-Current Imbibition in a Water-Wet Matrix Block," SPE Journal (March 2000) 3-11.

6. Ghorayeb, K., and Firoozabadi, A., "Natural Convection and Diffusion in Fractured Porous Media," SPE Journal (March 2000) 11-20.

7. Li, K., and Firoozabadi, A., "Wettability Alteration to Preferential Gas-Wetness in Porous Media and Its Effects", SPE Reservoir Evaluation and Engineering (March 2000) 139-149.

8. Pooladi-Darvish, M. and Firoozabadi, A.: "Experiments and Modeling of Water Injection in Water-Wet Fractured Porous Media," Journal of Canadian Petroleum Technology (March 2000) 31-42.

9. Ghorayeb, K., and Firoozabadi A., "Pressure, Molecular and Thermal Diffusion Flux in Non-Ideal Multicomponent Mixtures," AIChE Journal (May 2000) 883-891.

10. Firoozabadi, A., Ghorayeb, K., and Shukla, K.:" Theoretical Model of Thermal Diffusion Factors in Multicomponent Mixtures," AIChE Journal (May 2000) 892-900.

11. Ghorayeb, K., and Firoozabadi, A., "Modeling Multicomponent Diffusions and Convection in Porous Media," SPE Journal (June 2000) 157-171.

12. Li, K., and Firoozabadi, A., "Phenomenological Modeling of Critical Condensate Saturation and Relative Permeabilities in Gas Condensate Systems," SPE Journal (June 2000) 137-147.

13. Firoozabadi, A. and Pan, H.: “Two-Phase Isentropic Compressibility and Sonic Velocity for Multicomponent Hydrocarbon Systems,” SPE Reservoir Evaluation and Engineering (Aug. 2000) 335-341.

14. Firoozabadi, A.: “Recovery Mechanisms in Fractured Reservoirs and Field Performance,” Distinguished Author Paper, Journal of Canadian Petroleum Technology (Nov. 2000).

15. Chang, E. and Firoozabadi, A.: “Gravitational Potential Variations of the Sun and Moon for the Estimation of Reservoir Compressibility," SPE Journal (Dec. 2000)456-465.

16. Ghorayeb, K. and Firoozabadi, A., “Features of Convection and Diffusion in Porous Media for Binary Systems,” Journal of Canadian Petroleum Technology (Feb. 2001).

17. Firoozabadi, A.: “Solution Gas Drive in Heavv Oil Reservoirs,” Distinguished Author Paper ,Journal of Canadian Petroleum Technology (March 2001).

18. Tang, T. and Firoozabadi, A.:” Effect of Viscous Forces and Initial Water Saturation on Water Injection in water-wet and weakly water-wet fractured Porous Media”, SPE 59291,proceedings of the SPE/DOE symposium on Improved Oil Recovery, April 3-5, 2000, Tulsa, Ok, SPE Reservoir Evaluation and Engineering (to appear).

19. Tang, T. and Firoozabadi, A.: “Gas and Oil Relative Permeabilities for Solution-Gas-Drive in Heavy Oil Reservoirs,” SPE 56540, presented at the 1999 SPE Annual Meeting, Houston, Oct. 3-6, SPE Reservoir Evaluation and Engineering (In review).

20. Ghorayeb, K., Firoozabadi, A., and Anraku, T. “Unusual Fluid Distribution in the Earth’s Subsurface When Heavy Fluids Float Above Light Fluids,” Journal of Geophysical Research (In Review).

21. Firoozabadi, A. and Kashchiev, D.: “Analytical Modeling of Countercurrent Imbibition in Water-Wet Porous Media,”, Water Resources Research (submitted).

22. Ghorayeb, K. and Firoozabadi, A. :"Two-Phase Multicomponent Diffusion and Convection in Porous Media for Reservoir Initialization,” SPE 66365, presented at the 16th Reservoir Simulation Symposium, Feb. 11-12, 2001, Houston, SPE Reservoir Evaluation and Engineering (to be submitted).

Papers Scheduled for Presentation at the 2001 SPE Fall Meeting

23. Chang, E. and Firoozabadi, A.: “Gravitational Potential Variation of the Sun and Moon for the Estimation of Reservoir Permeability”, SPE 71575,Paper to be presented at the 2001 SPE Annual Meeting , Sept. 3-Oct.3, New Orleans, La.

24. Tang, T. and Firoozabadi, A.: "Effect of GOR, Temperature, and Initial Water Saturation on Solution Gas Drive in Heavy Oil Reservoirs". SPE 71499,Paper to be presented at the 2001 SPE Annual Meeting, Sept. 3-Oct.3, New Orleans, La.

25. Karimi-Fard, M. and Firoozabadi, A.: "Numerical Simulation of Two-Phase Flow in Discrete and Connected Fractured Media Using the Galerkin Method: Part 1-Water Injection," SPE 71615,Paper to be presented at the 2001 SPE Annual Meeting, Sept. 3-Oct.3, New Orleans, LA.

SEMINARS

1999

1. (a) "Multiphase Flow in Fractured Porous Media" and (b) "Irreversible Phenomena in Hydrocarbon Reservoirs," Mobil Technology Corporation, Jan. 18.

2. "Irreversible Phenomena in Hydrocarbon Reservoirs," ARCO Oil and Gas, Plano, TX, Jan. 19.

3. "Multicomponent Diffusion and Convection in Porous Media from Irreversible Thermodynamics," Graduate Seminar, Petroleum Engineering Department, Stanford University, Stanford, CA, Jan. 26.

4. "Spatial Variation of Species in Hydrocarbon Reservoirs", Exxon Production Research Company, Houston, March 15.

5. (a) "Gas Condensate Reservoir Deliverability Increase by Wettability Alteration to Gas-Wetting" and (b) "Solution Gas Drive in Heavy Oil Reservoirs," Texaco Exploration and Production Technology Center, Houston, TX, March 16.

6. "Gravitational Potential Variation of the Sun and the Moon for the Estimation of Some Reservoir Properties," Norsk Hydro Research Center, Bergen, Norway, June 23.

7. "Compositional Variation in Hydrocarbon Reservoirs from Irreversible Thermodynamics," GeoQuest Simulation Software Development, Abingdon, UK, June 24.

8. (a) "Thermodynamics of Hydrocarbon Reservoirs," (b) "Water Injection in Water-Wet and Mixed-Wet Fractured Media," Marathon Petroleum Technology Center, Denver, Aug. 12.

9. (a) "Thermodynamics of Hydrocarbon Reservoirs," (b) "Water Injection in Water-Wet and Mixed-Wet Porous Media," Phillips Petroleum Company, Bartlesville, OK, Aug. 13.

10. “Phenomenological Laws of Irreversible Thermodynamics and their Extension for the Solution of Some Key Problems in Petroleum Production,” six hours of lectures at Imperial College, London, Nov. 15-16.

11. “Multiphase Flow in Fracture Media,” BP-Amoco, Sunbury, UK, Nov. 18.

12. (a) “Thermodynamics of Wax and Asphaltene Precipitation,” (b) Irreversible Phenomena in Hydrocarbon Reservoirs,” Shell E&P International, Houston, TX, Dec. 1.

13. “Diffusion and Convection in Porous Media,” Chemical Engineering Department (Graduate Seminar) Colorado School of Mines, Dec. 2.

<u>2000</u>

1. “Wettability Alteration to Gas-Wetting and Implications in Productivity Improvement in Gas Well Deliverability,” Conoco, Ponca City, Jan. 14.

2. “Formulation of Diffusion Processes from Irreversible Thermodynamics,” ,Graduate Seminar, Chemical Engineering Department, Massachusetts Institute of Technology (MIT), Cambridge, MA, Jan. 18.

3. “Non-Equilibrium Phenomena in Hydrocarbon Reservoirs: Yufutsu Fractured Gas Condensate Reservoirs (Japan),” Professor Handy’s Colloquium, University of Southern California (USC), Los Angeles, CA, Feb. 25.

4. “Estimation of Reservoir Properties from the Variation of the Gravitational Potential of the Moon and the Sun,” SPE Golden Gate Section, San Ramon, CA, March 16.
5. Multicomponent Convection and Diffusion in Porous Media from Irreversible Thermodynamics,” Petroleum Engineering Department, University of Tulsa, Tulsa, OK, April. 7.

6. “Wettability Alteration to Preferential Gas-Wetting in Porous Media and Two-Phase Gas-Liquid Flow,” Graduate Seminar, Petroleum Engineering Department, Stanford University, Stanford, CA, May 14.

7. “Multicomponent Diffusion from Irreversible Thermodynamics: Convection and Diffusion in Petroleum Reservoirs” BP Institute, Cambridge University, Cambridge, May 25.

8. (a) “Water Injection in Mixed-Wet Fractured Media,” BP-Amoco, Houston, Oct. 31.

9. “Multicomponent Diffusion from Irreversible Thermodynamics: Application to Yufutsu Gas-Condensate Field,” Graduate Seminar, Department of Petroleum Engineering, Texas A&M University, College Station, Texas, Nov. 2.

2001

1. (a) "The Use of Equilibrium Thermodynamics, Surface Thermodynamics, and Thermodynamics of Irreversible Processes for Solving Various Problems in Hydrocarbon Reservoirs and Production Facilities," (b) "Solution Gas Drive in Heavy Oil Reservoirs," TotalFinaElf, Pau, France, Jan. 22.

2. (a) "The Use of Equilibrium Thermodynamics, Surface Thermodynamics, and Thermodynamics of Irreversible Processes for Solving Various Problems in Hydrocarbon Reservoirs and Production Facilities," (b) Numerical Simulation of Water Injection in Fractured Porous Media by the Galerkin Finite Element Method," Shell Technology, Rijswijk, The Netherlands, Jan. 23.

3. (a) "Water Injection in Water-Wet and Mixed-Wet Fractured Reservoirs," (b) "Numerical Simulation of Water Injection in Connected and Discrete Fractured Media Using the Galerkin Finite Element Method," Maersk Oil and Gas, Copenhagen, Denmark, Jan. 24.

4. (a) "Compositional Variation in Hydrocarbon Reservoirs from Irreversible Thermodynamics," (b) "Numerical Simulation of Water Injection in Connected and Discrete Fractured Media Using the Galerkin Finite Element Method," Statoil, Stavanger, Norway, Jan. 25.

APPENDIX -A

Use of tidal force induced pressure transients for estimating PV compressibility and permeability of fractured reservoirs.

The pressure response due to the gravitational potential variations of the sun and the moon was investigated for estimating the compressibility of a fractured reservoir. A full (multi-spectral) expression for the gravitational forces potential is first derived for both the sun and the moon. To compute the total compressibility of the formation, the gravitational potential is then compared with the observed pressure fluctuations in an observation well from a fractured reservoir that had a clear semidiurnal signal that is well above both the noise and trend threshold. An important contribution to compressibility estimation from present research is the inclusion of transient effects that are not accounted for in the current models.

An independent oil company in Houston provided the tidal data on several wells. The data was analyzed and results of analyses provided to the independent oil company with estimates of compressibility of the reservoir. The independent oil company was very impressed by the results of the model. There are three tasks that needed to be completed in order to use the pressure variation data to estimate the bulk reservoir properties. First, an expression for the gravitational potential due to the most important sources, the moon and the sun, had to be derived. Although this has been done previously in the literature, it is not in a form suitable for the current analysis. Second, the dilatational response as a function of the magnitude of the gravitational potential is required . Unlike the ocean tide, the earth tide is restrained by the elastic properties of the solid earth. Thus the pressure response to a varying gravitational field is influenced by the constitutive model with three

parameters (density, rigidity, and elasticity) selected for the interior of the earth. Third, the dilatation, or differential compaction of the earth near the surface had to be related to the observed pressure through the parameters that it is desirable to evaluate.
The analysis of the well pressure data showed that it is possible to make compressibility estimates provided the measurements are of sufficiently high quality. In this case, the resolution was high enough so that the tidally-driven sinusoidal variations were clearly visible. Also, as shown by the temporal plots, the noise, or the scatter in the data was well below the signal strength (see potential-pressure plot below). These criteria can be attained with modern high-quality crystal strain devices. In addition, the location of the reservoir is sufficiently close to the equator ($\phi = 40^0$) so that the potential varies with a significant span. Finally, low fracture porosity, in conjunction with a high total compressibility, insured a strong pressure signal. It was shown that although an estimate of the compressibility could not be obtained by comparing the cyclical variation of the pressure with the dominant harmonic component of the earth tide, a good estimate could be made by admitting the full expression for the lunar-solar gravitational potential, since the former could be off by a large factor, depending on the time interval on which it was computed.

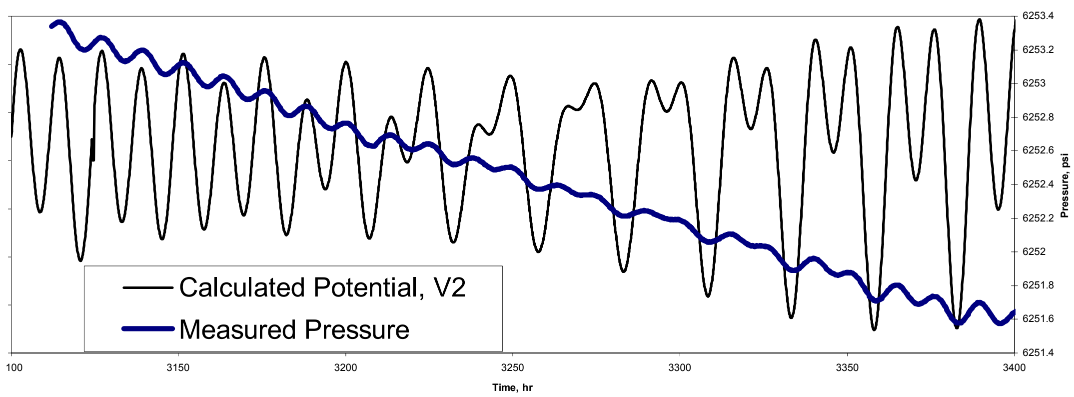
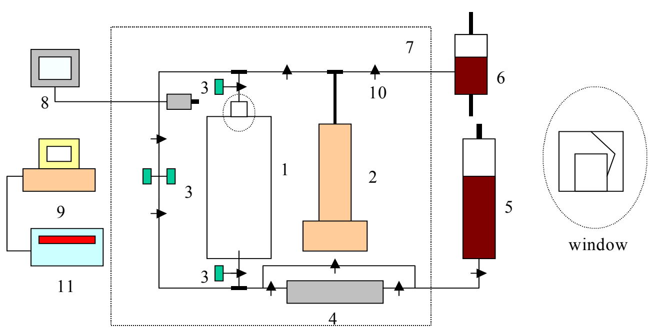


Figure 4c. Potential and Pressure from Well T: Starting at 1215 10/17/96 (time lag adjusted).

In the above figure, the combined lunar-solar potential is computed and plotted along with the pressure data from the observation well T of a fractured reservoir. From the peak to peak variations in potential and pressure, an estimate of C_f, the total compressibility of reservoir has been estimated. The total compressibility C_f, calculated for the reservoir was 1.7×10^{-5} psi^{-1} that was in fair agreement with total compressibility estimated from extended production testing. The pressure data show a phase lag (about 12 hours) with respect to the potential. This lag arises from the fact that the characteristic time associated with fluid flow around the wellbore is comparable to the semi-diurnal time scale over which the most rapid oscillations in the potential take place. The phase lag is an avenue for estimating the fluid mobility and an analysis of this will be carried out in the future.

Cold production from heavy oil reservoirs
Basic mechanisms and reservoir engineering parameters involved in solution-gas recovery from heavy oil reservoirs were investigated. The high efficiency of solution-gas drive in heavy oil reservoirs has been attributed to foam; the term foamy crude is used to describe the process. The work in this task centers around two important issues related to cold production from heavy oil reservoirs; the first relates to the relevance of the foamy nature of a heavy crude to recovery efficiency and the second issue relates to the gas and liquid phase mobility and the influence of temperature and gravity force on production. The figure below shows the experimental apparatus and the fluid and the rock system.
The most important parameter that needs investigation are the relative permeability data because it is this parameter that ultimately determines the rate of flow of one phase in the presence of the other.
The schematic of the experimental apparatus is shown below. The two heavy oils used in the experiments are 1) a silicone oil with API gravity = 14.4 and crude oil with API gravity = 9. Methane is used as the gas phase and oil and gas are mixed in a high-



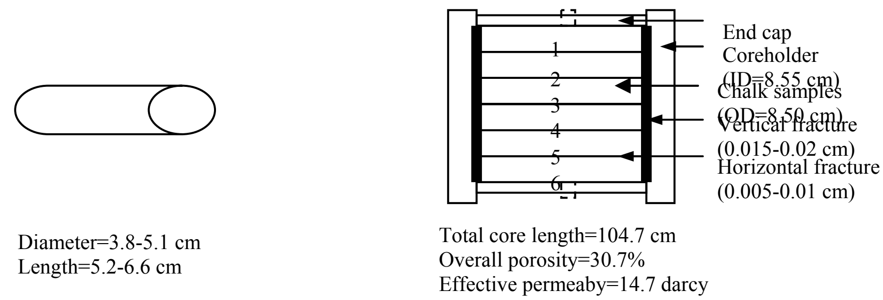
1-visual coreholder; 2-ISCO pump; 3-pressure transducers; 4-capillary viscometer; 5-high pressure cylinder; 6-oil/gas separator; 7-air bath; 8-TV monitoring system; 9-computer; 10-valves; 11-temperature controller

Fig.1-Schematic of the Experimental Apparatus

pressure cylinder as shown in the schematic. The silicone oil is clear and one can observe and conduct video-recording through the window of gas-bubble nucleation, growth, and coalescence and flow behavior from the transparent coreholder. The sand in the coreholder is made up of clean Ottawa sand with a grain size of 212-355 micro-meters. An ISCO pump is used for measuring oil and gas production during the test.

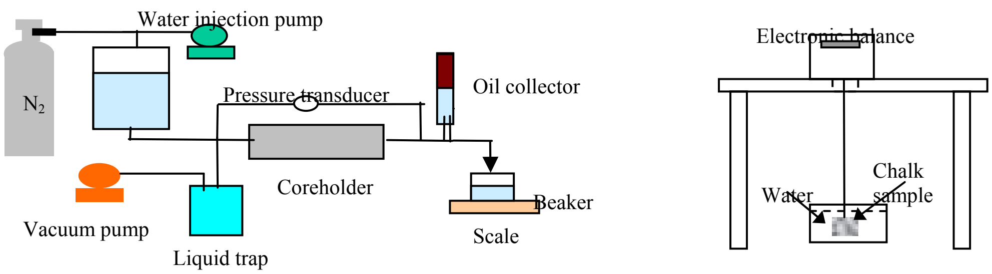
Effect of viscous forces and initial water saturation on water injection in water-wet and weakly water-wet fractured porous media
There is a definite need to interpret the extensive set of results obtained from the systematic laboratory study of the effect of wettability and initial water saturation and relate viscous and gravity forces so that reservoir performance of the chalk fields such as those of the North Sea can be related to laboratory measurements.
Certain experiments performed on the composite chalk core (configuration B) that are of relevance to exploitation of chalk type of fractured reservoirs are as follows:

- The final oil recovery efficiency for strongly water-wet fractured chalk is independent of water injection rate. For the weakly water-wet case, the water production rates were slower. Prior to wettability alteration (strongly water-wet case) it took only 800 minutes to reach the final oil recovery (66% OOIP) at a pressure gradient of 0.025 psi/cm but it took 15,000 minutes to reach the final oil recovery (48% OOIP) at the same pressure gradient for the weakly water-wet system of configuration B.
- For the weakly water-wet case, the experimental results demonstrate that increase in pressure gradient could lead to improvement of oil recovery by water injection in some fractured rocks. The pressure gradient establishes the effect of gravity (that is, the negative capillary force effect), which can lead to appreciable recovery.
- Studies of the effect on oil production due to variation in water saturation in strongly water-wet, fractured chalk indicate that the final oil production rate, water breakthrough and the final oil recovery decreased systematically with increase in initial water saturation. For the weakly water-wet rocks, the oil production rate systematically increased with increase in initial water saturation, although the final oil recovery was not much affected. The experimental graphs also indicate that the time to reach the residual oil saturation appreciably decreases with increase in water saturation. The effect of initial water saturation on the oil recovery efficiency for the weakly water-wet composite system (configuration B) is opposite to that for the strongly water-wet condition. This result is consistent with those observed in Prudhoe Bay where it has been found that residual oil saturation decreased with increase in initial water saturation with depth as water-wetness increased.
- For some fractured reservoirs, the water injection performance can be independent of the state of wettability.
- With increased viscous/gravity forces, the oil recovery efficiency can increase substantially in mixed wet chalk. The same behavior can also occur in mixed-wet fractured porous medium.
- The effect of initial water saturation on oil recovery depends on wettability. For a strongly water-wet condition, oil recovery by water injection can decrease mildly with an increase in initial water saturation. However, for weakly water wetting, the oil recovery by water injection can increase significantly with an increase in initial water saturation.



(a) Configuration A (b) Configuration B

Configurations of Kansas Outcrop Chalks Used in the Experiments



(a) Water injection (b) Spontaneous imbibition

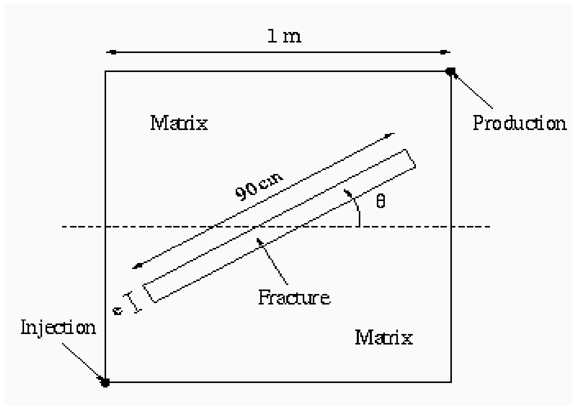
Schematic of Apparatus for Water Injection and Spontaneous Imbibition Tests

Numerical Simulation of Oil Recovery from Fractured Petroleum Reservoirs

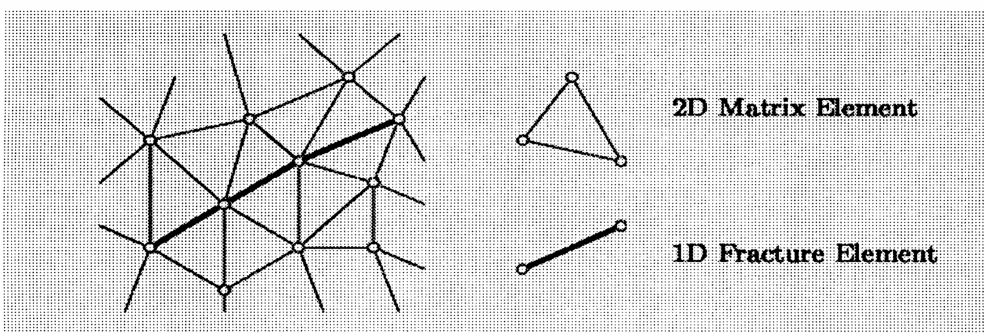
Of the different methods currently in use for simulation of fractured reservoirs, dual porosity models have been used extensively to simulate two-phase flow with connected fractures. This approach, although very efficient, cannot take into account discrete fractures or the effect of heterogeneities in the medium. The single porosity model provides the accuracy, but it is not practical because of the very large number of grids. A large number of grids is required because of two different length scales (matrix size and fracture thickness)

Numerical simulation of fractured reservoir rocks is attempted in this task through the use of a discrete fracture model in which the fractures are discretized as one dimensional entities. The matrix is discretized using linear triangular elements. The thickness of the fractures is accounted through a modified form of flow equations. Different approaches are possible to implement this idea. In this project the researchers have presented the implementation of discrete fracture model using a Galerkin finite element method and finite element discretization.

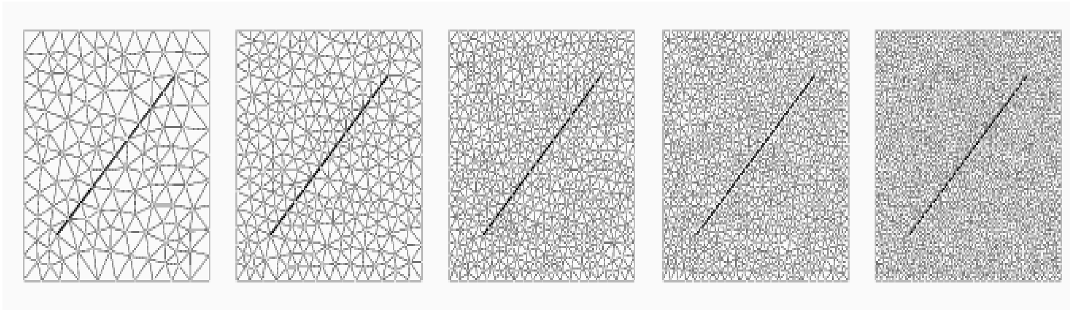
The figure below shows the procedure for representing a fracture inside a matrix block in discrete fracture model



- Example of discretization:



-We use linear triangular elements for the matrix and linear line elements for the fractures.



The Geometry in the Discrete Fracture Model is discretized using five Different Grids

Gridding of the fractured media with different mesh points used to study the grid sensitivity of the fractured model is shown in the above figure. The finest grid is considered as the reference solution for selecting the optimal grid size for DFN simulation

The geometry in the discrete fracture model is discretized using five different grids as shown above.

The combination of the finite element and the discrete fracture model provides a powerful tool to study multi-phase flow in fractured porous media. The unstructured gridding allows an accurate representation of the discrete and connected fractures. Several advantages of the new discrete fracture model may be cited:

- In preprocessing, the mesh generation is simple
- The fracture is not discretized as 2D entity which reduces considerably the number of mesh points
- Avoiding small elements inside the fracture influences the numerical model in two ways:
  1) conditioning of discrete operator is better
  2) time step restriction is less important
- Less mess points, better conditioning and less time step restrictions lead to more efficient numerical solver.

The robustness and the accuracy of this approach are demonstrated by examples for water injection accounting for capillary pressure. First a single fracture inside a matrix block is considered. Water flooding simulations are carried out for three different orientations of the fracture. The medium is initially filled with oil. Water is injected at the bottom left corner and liquid is produced from the top right corner. The geometry is discretized using five different grids and the finest grid is considered as the reference solution.