WATERFLOOD OPTIMIZATION

TECHNOLOGIES FROM THE DEPARTMENT OF ENERGY'S FIELD DEMONSTRATION PROGRAM

Michael L. Fowler --- BDM Petroleum Technologies

June 1997

BDM PETROLEUM TECHNOLOGIES

Waterflood Optimization

Technologies from the Department of Energy's Field Demonstration Program

Michael L. Fowler
BDM Petroleum Technologies

BDM-PT-MLF-97-3016

WATERFLOOD OPTIMIZATION

In this presentation an attempt is made to review the key considerations in optimizing existing waterfloods. It is assumed that basic waterflood compatibility has already been established; no discussion of screening for such compatibility will be presented.

The primary objective is to show how profits can be increased and reservoir life extended, mainly through emphasis on improving oil recovery. It is intended that the approaches addressed will provide benefits for both the large and the small reservoir and for both the large and the small operator.

Discussions will be illustrated with applications of new, innovative, and routine technologies to waterflood optimization from projects in the Department of Energy's Field Demonstration Program. This program consists of both cost shared and cooperative research and development projects aimed at rapid identification and dissemination of promising technologies throughout the oil industry.

A further emphasis of this presentation will be on those aspects (both positive and negative) of waterflood optimization that are especially pertinent and/or unique to California reservoirs. This emphasis will be accompanied by examples from the Field Demonstration Program and by examples from the voluminous literature on California reservoirs.

Waterflood Optimization

- Technical Aspects (Reservoir Characterization Models)
  - Identifying the target
  - Getting the best well geometry
  - Optimizing operational procedures and technologies
- Business Aspects
  - Resources
  - Teamwork
  - Environmental
- Conclusions

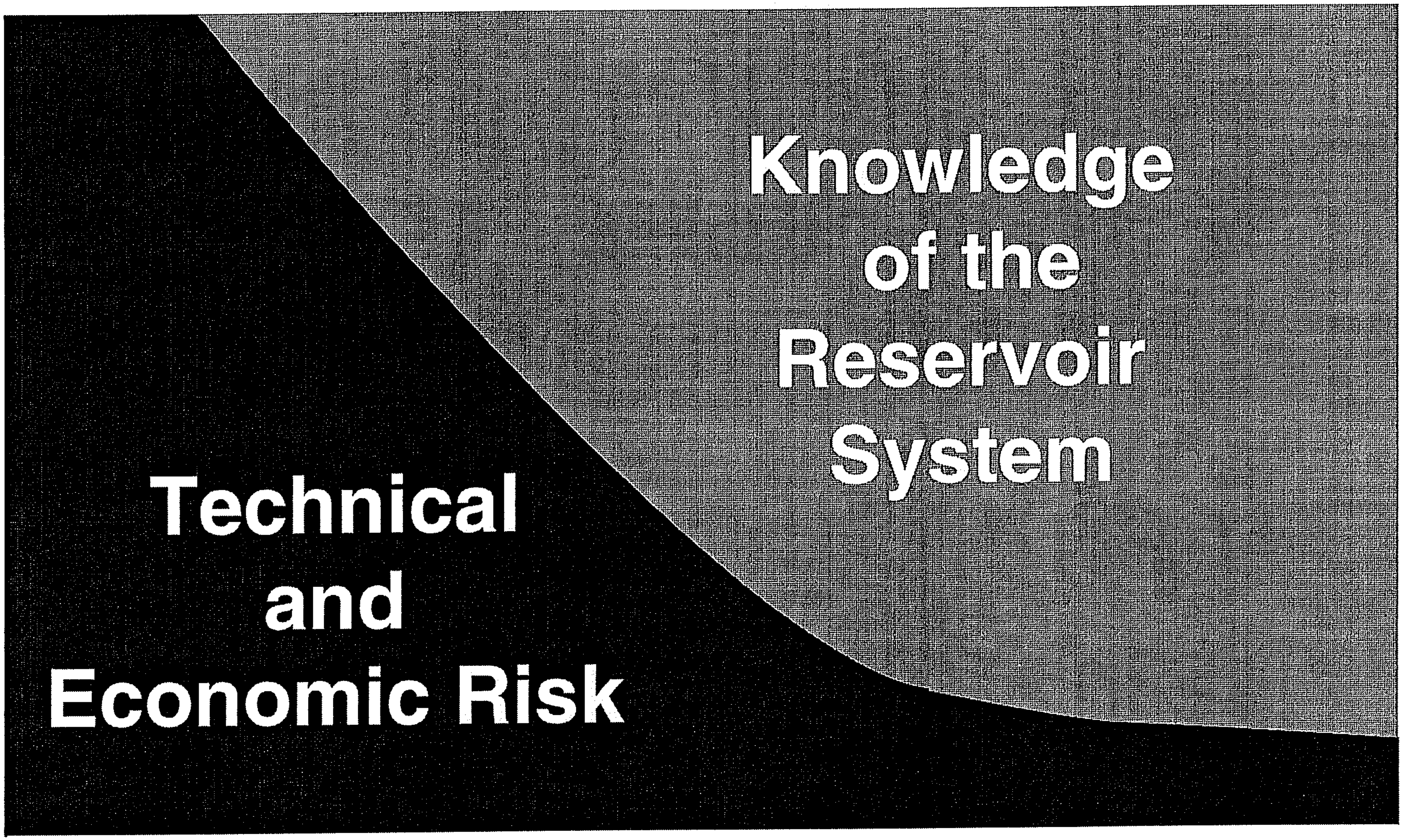
WATERFLOOD OPTIMIZATION
(Content)

The presentation will focus on both technical aspects and business aspects that require consideration when waterflood optimization is the goal.

Technical aspects of waterflood optimization revolve closely around developing an understanding of the reservoir (i.e., a reservoir characterization model). This “concept” of the reservoir then, forms the basis for identifying the significance of the oil recovery target, designing the best 3-D spatial arrangement of injection and extraction points, and strategizing the best combination of schedules and technologies for performing injection and extraction and for treatment of injection fluids and produced fluids.

Business aspects of waterflood optimization control the efficiency and the extent to which technical applications can be carried to a successful conclusion. Considerations under this category include available resources of money, manpower, etc. as well as the degree to which knowledge and resources can be integrated for optimal results. A third business aspect, and one that is very important to California reservoirs in particular, is consideration of the effects of compliance with environmental regulations.

The Value of Reservoir Characterization

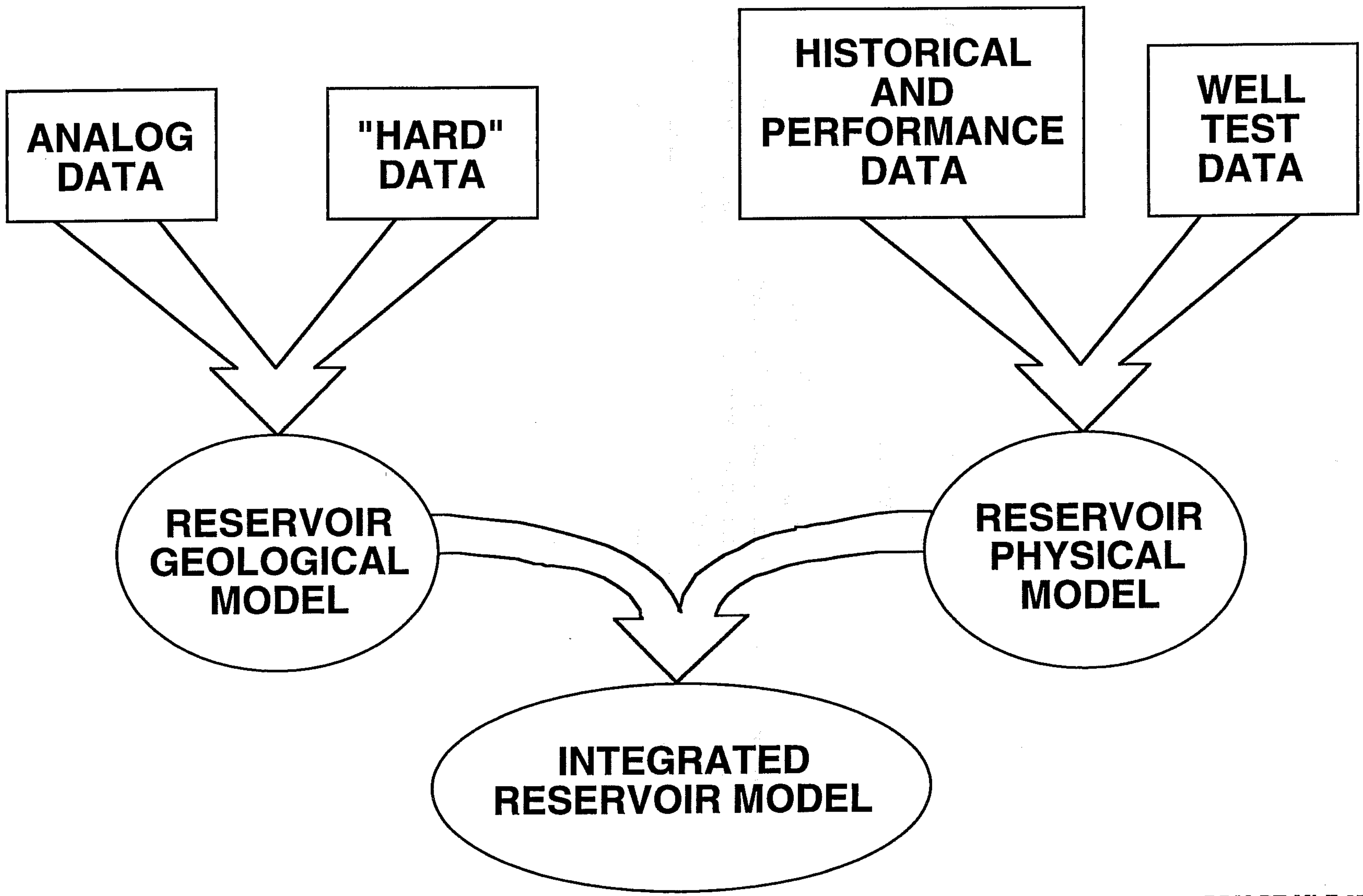


THE VALUE OF RESERVOIR CHARACTERIZATION

Let's look first at the technical aspects of waterflood optimization and the importance of an adequate reservoir characterization model, which, by the way, can be considered to be a conceptual model of the reservoir which predicts rock properties and properties affecting the flow of native reservoir and injected fluids at every point in 3-D reservoir space.

Essentially, the better our knowledge of the reservoir system, the better we can predict (primarily through simulation modeling) the outcome of any changes we make to optimize the waterflood, thus minimizing both technical and economic risk. You might think of these two aspects as having a constant sum over the range of most practical considerations. The fact that it is not possible to attain a perfect knowledge of the reservoir means that, for practical purposes, risk will never go to zero, but we want to reduce it as much as we can economically afford.

Construction of Integrated Reservoir Model



CONSTRUCTING AN INTEGRATED RESERVOIR MODEL

Coming up with the "best" 3-D model of the reservoir consists of a mutually supportive merger of the reservoir "pictures" that evolve from geological evidence (the circle on the left, which represents the depositional, diagenetic, tectonic, and original fluid content of the reservoir) and engineering evidence (the circle on the right, which represents the physics of the reservoir system).

The geological model is made up of both "hard" reservoir descriptive data and "soft" data obtained by observation of geological analog deposits.

The reservoir physical model incorporates acknowledgment of the history (detailed if possible) of fluids removed and injected and changes induced to reservoir pore systems since discovery as well as the results of tests performed to characterize physical conditions and potential paths of fluid and pressure communication within the reservoir.

“Hard” Data

- Seismic and Related
  - Diversified — Class I
  - Laguna — Class II
  - Luff — Class II
- Wireline Logs
  - Lomax — Class I
  - City of Long Beach — Class III (Project #1)
- Rock and Fluid Sample Analysis
  - City of Long Beach — Class III (Project #2)

“HARD” DATA

“Hard” data, or data based on measurements made on the reservoir or materials taken from the reservoir, consist of either remotely measured properties or measurements made directly on reservoir samples.

Remotely measured data can include data with more or less complete areal coverage of the reservoir (i.e., including interwell areas) such as seismic surveys, electromagnetic surveys, satellite imagery, aerial photography, and surface geochemical surveys.

Both 2-D and 3-D seismic are contributing to reservoir characterization in Class Program waterflood projects. In particular, analysis of 3-D seismic attributes has been a critical tool for delineating reservoir property variation on the interwell scale:

Diversified Operating Corporation, Class I, Sooner Unit, CO -- In this completed project, 3-D seismic attributes were correlated with electric log petrophysical properties. Results showed that reservoir heterogeneity dictates the use of unconventional well patterns and spacings for successful waterflood optimization. Incremental oil due to project is 305,000 bbl and a recovery boost of from 15 to 20% of OOIP.

Laguna Petroleum Corp., Class II, Foster and South Cowden Fields, TX -- 3-D seismic attributes are being used in this project to delineate porosity trends leading to infill drilling and recompletions.

Luff Exploration Company, Class II, North Sioux Pass and North Buffalo Fields, ND, SD, MT -- 2-D seismic and 3-D seismic attribute analysis indicates reservoir compartmentalization by faults and porosity variation. Targeted infill wells, lateral recompletions in cased wells, and horizontal wells are being considered on the basis of the reservoir characterization performed.

A Class Program workshop is planned for early 1998 to review the use and contributions of these and other seismic technologies (such as vertical seismic profiling and cross well tomographic surveys) in Class and other DOE supported projects.

Remotely measured data also include data gathered specifically at the wellbores using wireline logging and testing tools such as repeat formation testers. New tools are helping to determine reservoir architecture, fracturing, permeability, and remaining oil saturation in addition to the properties measured by more conventional tools. Class Program waterfloods are making good use of these technologies also in their optimization efforts:

Lomax Exploration Company, Class I, Monument Butte Unit, UT -- Use of FMI log to discern that fractures are ubiquitous throughout the reservoir interval. Pervasiveness of fracturing plus observations on lithologic heterogeneity led to important decisions concerning the waterflood potential of individual sedimentary units. MRI log run on 5 wells to determine movable oil and water. In a well with no potential by conventional logs, MRI showed good porosity and perm. Completion and flow testing proved an oil bearing zone.

"HARD" DATA
(Continued)

City of Long Beach, Class III, Wilmington Field, CA -- Wells in this hot, heavy oil pilot are being logged through casing for ROS with calibrated pulsed acoustic tool for design of recompletions (SPE 29655). Short and ultra-short radius horizontal recompletion techniques are also being evaluated.

A comprehensive workshop covering the use of wireline technologies in Class Program and other DOE-supported projects is being planned for early fall 1997.

Analysis of rock and fluid samples also provides important information. Analysis of proposed injection water should be a part of this consideration. Analyses should include determinations of rock-fluid compatibility and injected fluid compatibility with reservoir fluids. Relative permeability measurements and laboratory core floods using reservoir rocks and fluids with the proposed injection water should be performed at reservoir conditions of pressure and temperature, if possible. Injection water chemistry at prevailing reservoir temperatures and pressures may cause dissolution or precipitation of minerals at either injectors or producers. Either of these circumstances may result in irreversible formation damage (SPE 19666, SPE/DOE 35394). Essentially all of the Class Program waterflood projects are paying close attention to these considerations.

In one California project, not only the composition but the physical state of the injected fluid is being tested for possible detrimental effects on reservoir pore systems:

City of Long Beach, Class III, Wilmington Field, CA -- Advanced reservoir characterization and laboratory analysis of the interaction between reservoir rocks and steam are being performed prior to implementing a water- alternating-steam process (WASP) pilot demonstration.

Analog Data

- Similar Reservoirs
- Outcrops
  - University of Tulsa — Class I
  - University of Texas BEG — Class III
- Modern Environments

ANALOG DATA

"Soft" or analog data can make substantial contributions to the evolving "concept" of a reservoir, both on the scale of gross reservoir architecture and on the scale of interwell heterogeneities. Analog sources include examination of similar reservoirs, with reservoirs nearby in the same basin and play being perhaps the best models. Outcrops of depositionally and/or diagenetically and/or tectonically similar formations are also good contributors to reservoir information, if properly interpreted.

University of Tulsa. Class I, Glenn Pool Field, OK -- Outcrop studies of the producing formation aided in predicting large scale architecture and the types, scales, vertical successions, and relative orientation of sedimentary bodies located between wells in their analog subsurface reservoir.

University of Texas BEG, Class III, Geraldine Ford and West Ford Fields, TX -- Reservoir architecture derived from outcrops is being combined with 3-D seismic data and other subsurface information to design geologically optimized producer and injector well patterns for an anticipated polymer flood or CO2 flood.

Modern environment depositional analogs are a good source in many instances of information on sedimentary architecture as well as the expected type and scale of depositional heterogeneities to expect between wells.

Historical and Performance Data

- Production / Injection / Pressure
  - Fina — Class II
  - Wilmington Field (SPE 19847, 20064, 26082)
  - Lost Hills, Belridge, Midway-Sunset Fields (SPE 29625, 29626)
- Drilling / Completion / Stimulation

HISTORICAL AND PERFORMANCE DATA

Reservoir history can be an important and economical source of information for making the reservoir model "come together". The amount and kinds of fluids produced and the amount of fluids injected at different locations in the reservoir can go a long way toward predicting the continuity of the reservoir and the size and degree of separation of any compartments, especially when historical pressure data are also available. Knowing the completed intervals for each well as the reservoir evolved also helps determine which zones may have been inadequately swept by previous waterflood activities.

Decline curves, Hall plots, and a wide variety of other graphic techniques as well as material/pattern balancing techniques can provide useful insights.

Fina Oil and Chemical Company, Class II, North Robertson Unit, TX -- A unique use of decline curves and their integration with numerous other data sources helped to define infill targets in this project.

In the Wilmington Field Long Beach Unit, plots such as log(WOR) vs cum oil and (1/WOR)/WOR vs cum water injected and use of techniques for allocating oil and water production by layer have aided waterflood optimization by making possible gross production maps, oil production maps, water cut maps, injection streamline maps, and pattern performance maps (SPE 19847, 20064, 26082).

In many California reservoirs (particularly those in diatomites) -- e.g., Lost Hills, Belridge, Midway-Sunset -- waterflooding must replace voidage caused by production to avoid surface subsidence and possible wellbore and formation damage (SPE 29625, 29626).

Access to detailed history of drilling practices, completion practices, stimulation practices, and general operational procedures helps anticipate not only the paths that fluids may have taken in the reservoir in the past, but also the changes that development and operational activities may have had on the reservoir over its lifetime. In some instances these changes may be profound as in the instance of injection for long periods of time at pressures in excess of reservoir formation parting pressures, which can lead to direct communication between injection and producing wells.

Well Test Data

- Pressure Transient Test
- Interwell Tracer Tests
- Injectivity Tests / Injection Surveys
  - Inglewood Field (SPE 20044)
  - Elk Hills Field (SPE 29654)

WELL TEST DATA

Tests performed at the wellbores can give insight into the size of reservoir compartments, the interconnectivity of any such compartments, and the general ease of fluid flow in the reservoir and, in particular, between specific wells.

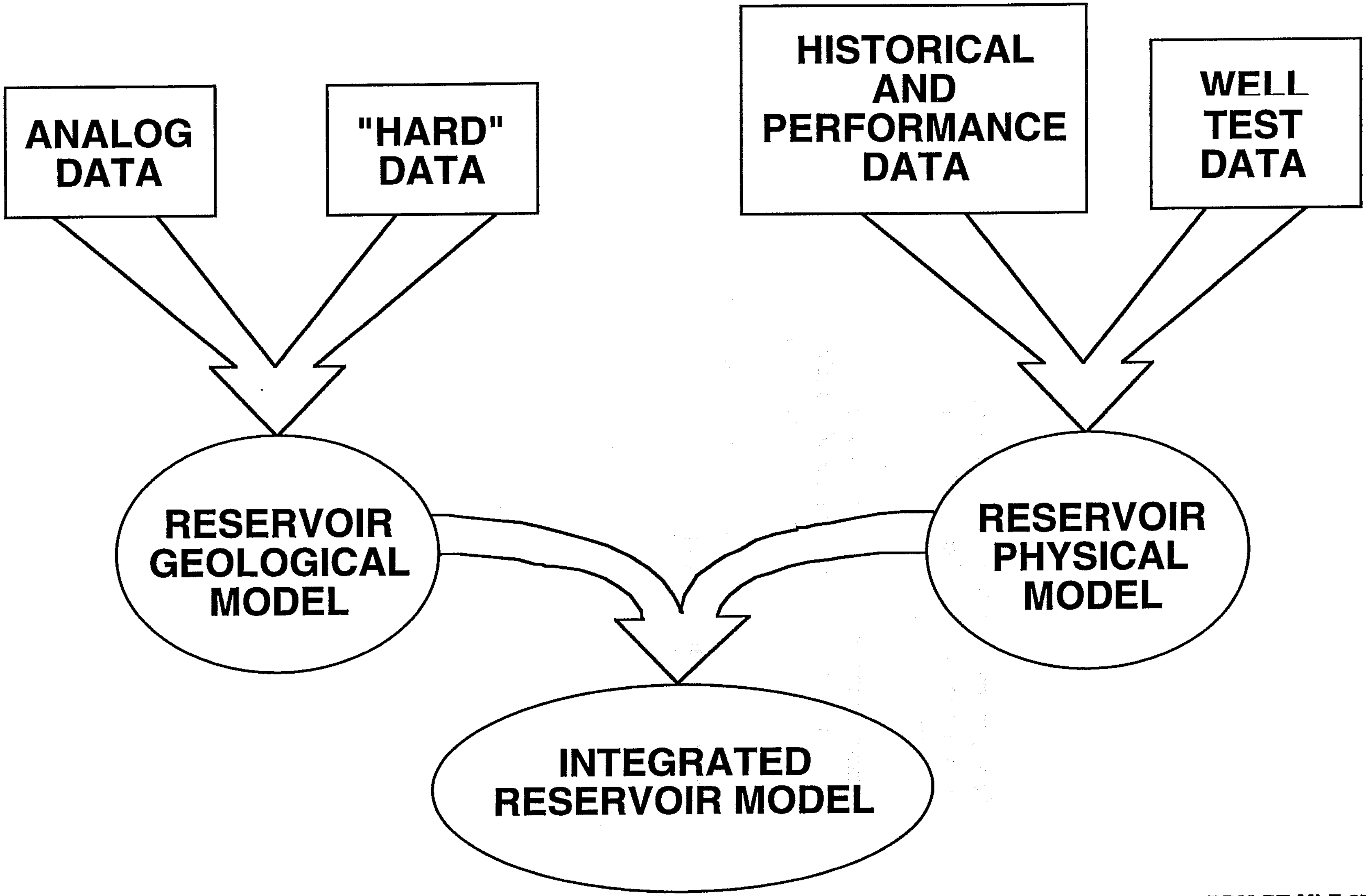
Pressure transient tests and interwell tracer tests have been commonly used in Class Program projects. Tracer tests can also include single well tracer surveys to chemically measure remaining oil saturation in the vicinity of a wellbore.

Spinner and temperature surveys performed on injection wells tell where and in what volume fluids are being injected. Similar surveys in production wells identify where fluids are entering the wellbore.

In the Inglewood Field in California, an index was designed to summarize profile surveys with a single number for ease of comparison between wells (SPE 20044).

In the Elk Hills Main Body "B" reservoir a video camera was used along with openhole logs, production logs, and production tests to identify swept and unswept layers (SPE 29654).

Construction of Integrated Reservoir Model



BDM-PT-MLF-97-3024

CONSTRUCTING AN INTEGRATED RESERVOIR MODEL

If you have noticed one thing to this point, I hope it has been this: No one tool or technique serves to give us the complete reservoir picture; only carefully integrated interpretations from a variety of sources gives us the "best" picture.

All Class Program waterflood optimization projects have involved integrated reservoir characterization, but some are notable for their high degree of success in this area:

University of Tulsa, Class I, Glenn Pool Field, OK -- Highly integrated reservoir characterization including cross well tomography, resistivity imaging logs (to identify bypassed zones), and geostatistical realizations yielded a recompletion strategy resulting in a 200% increase in oil production from the pilot area.

Fina Oil and Chemical Company, Class II, North Robertson Unit, TX -- Another extremely highly integrated study combining cross well seismic, borehole imaging logging, core-log modeling, well tests, and geostatistics that is seeking to optimize waterflood by targeted infill drilling and recompletions.

University of Kansas, Class II, Schaben Field, KS -- Geologic, digital log and production data were entered into a database management and analysis system for use in identifying areas of unrecovered mobile oil. Three new wells drilled in favorable areas for data collection have boosted reservoir production by 20%.

ARCO Western Energy, Class III, Yowlumne Field, CA -- Highly integrated reservoir characterization, including advanced logging techniques such as FMI, were used to identify edge-of-fan fractured and uncontacted targets for slant well drilling.

The logical question at this point is, "Why all the fuss over a model of the reservoir?" The answer is that this model serves as the basis for prediction of what happens to fluids in the reservoir, both what has happened and what will happen. Used as a basis for simulation modeling of reservoir performance the "reality" of the reservoir model can be tested by attempting to match past produced fluid histories (using historical well geometries, schedules, and completions). A match indicates an appropriate reservoir model which can then be used to create "what if" scenarios with various well and completion geometries and various injection/withdrawal schedules to predict and optimize future waterflood performance.

A wide variety of commercial simulators suitable for waterflood optimization are available as well as the publicly available BOAST, a PC-based, three phase, three dimensional black oil simulator developed by and available through the Department of Energy. Versions of this simulator are also available to handle slant and horizontal wells and to address profile modification as well. The Polymer/Waterflood Predictive Model employs an analytical approach to model polymer flood applications.

Waterflood Optimization

- Technical Aspects
  (Reservoir Characterization Models)
  - Identifying the target
  - Getting the best well geometry
  - Optimizing operational procedures and technologies
- Business Aspects
  - Resources
  - Teamwork
  - Environmental
- Conclusions

WATERFLOOD OPTIMIZATION

I think by now I have impressed upon you the importance of reservoir characterization to waterflood optimization. Obviously it is much more important than it was at the primary production stage for most reservoirs. And not surprisingly, the role played by reservoir characterization will become even more important as recovery beyond waterflood is considered.

Let's return to our original outline and look at the technical aspects of waterflood optimization a bit more closely.

Identifying the Target

- How Big is It?

  (this justifies all subsequent efforts)

- Where is It Located?

  (may focus on a limited portion of the reservoir)

IDENTIFYING THE TARGET

Step one, how big is the recovery target? This certainly will take some degree of reservoir characterization to determine, and this step is all-important, because the size of the target is the economic constraint under which all subsequent efforts toward waterflood optimization must be justified.

Of course, having a good idea where the sizable target or targets are located is important too. This effort will also require some reservoir characterization, perhaps no more than was already performed for the step above. Note here that it is not necessary to do a detailed study of the entire reservoir; a small portion of the reservoir may be addressed at a time.

Waterflood Optimization

- Technical Aspects
  (Reservoir Characterization Models)
  - Identifying the target
  - Getting the best well geometry
  - Optimizing operational procedures and technologies
- Business Aspects
  - Resources
  - Teamwork
  - Environmental
- Conclusions

WATERFLOOD OPTIMIZATION

Getting the best geometrical arrangement of injection and production points is the next critical step. This is a three-dimensional problem involving both areal and vertical considerations.

Getting the Best Well Geometry (Pattern or Areal Optimization)

- "What if?" Conversion Scenarios
  - Elk Hills (SPE 21759)
  - Wilmington Field (SPE 26094)
  - Inglewood Field (SPE 21987)
- Targeting Infill Locations
  - University of Kansas — Class I
  - Diversified — Class I
  - Fina — Class II
  - Luff — Class II
  - University of Texas BEG — Class III
  - Strata — Class III

GETTING THE BEST WELL GEOMETRY
(Areal Component)

First, let's look at the horizontal or areal component, more specifically at well patterns.

One logical approach may be to use the integrated reservoir model we have built in conjunction with some type of simulation (either a conventional simulator, a streamtube simulator, or other approach) to make decisions on conversions of existing wells to or from injection to increase recovery. (This must, of course, be done under the constraints imposed by the condition of existing wellbore equipment and the location, condition, and capacities of existing surface equipment/facilities.)

The Elk Hills Main Body "B" reservoir in California was found to be layered, resulting in a large amount of bypassed oil using the existing peripheral waterflood pattern (SPE 21759).

At the Long Beach Unit in the Wilmington Field, reservoir simulations played a critical role in evaluating numerous "what if" injection/production pattern scenarios to re-optimize placement and volume of injection to recover remaining bypassed reserves (SPE 26094).

At North Vickers East in the Inglewood Field waterflood, a hybrid streamtube technique, involving fractal assignment of properties to a vertical cross section and an areal streamtube for prediction, was employed for waterflood hindcasting (SPE 21897).

More important perhaps than exclusively using existing wells is the evaluation of recovering new oil from infill locations. In the past, infill drilling was done largely on a geometric or pattern basis. This approach assumes reservoir regularity, when, in fact, there aren't any such beasts. Some locations may be good for infill, others not. Using our integrated reservoir characterization model, which in many cases will include a geostatistical prediction of interwell-scale heterogeneity that may or may not be constrained by "hard" data, we can predict through simulation which infill locations are likely to be economic. Class program projects that are making a specific point of targeting infill wells include: **University of Kansas Class I, Diversified Operating Corporation Class I, Fina Oil and Chemical Company Class II, Luff Exploration Company Class II, University of Texas BEG Class III, and Strata Production Company Class III.**

Getting the Best Well Geometry (Conformance or Vertical Optimization

- Mobility vs Temperature of Heavy Oil
- Mobility Control / Profile Modification
  - Hot Water / Steam (SPE 18574, 29665)
  - City of Long Beach — Class III
- Polymers (Straight Chain / Crosslinked)
  - University of Kansas — Class I
  - Dos Quadras Field (SPE 20060)
  - Midway-Sunset Field (Petr. Eng. Int'l. 1/92)

GETTING THE BEST WELL GEOMETRY
(Vertical Component)

Now let's look at getting the best vertical arrangement of injection and production points. We can call this conformance optimization or vertical optimization.

First, in California reservoirs, waterfloods are often successful in heavy oil reservoirs. This success is made possible by the fact that these particular reservoirs are either deep or are located in areas of high geothermal gradient which means the reservoir is hot. Hot, heavy oil has mobility characteristics more in line with lighter oils at lower temperatures. Vertical conformance problems are usually not insurmountable under these conditions.

In controlling mobility, however, several additional considerations are typical of or unique to California reservoirs also.

Thick gross pay intervals in many California turbidite (Class III) reservoirs lead to poor vertical sweep efficiencies, more permeable zones thieving the lion's share of injected water.

There is some indication that hot water flood followed by steam flood may perform better than steamflood alone (SPE 18754) possibly due simply to gravity effects. Reversing the order may cause collapse of the steam zone leading to poor recovery, but the jury is still out on this as some apparent successes have been reported (SPE 29665). The analogy here would be to a conventional WAG process for improving sweep under CO_2 flood.

City of Long Beach, Class III, Wilmington Field, CA -- A water-alternating-steam process (WASP) is being considered in this pilot demonstration to improve sweep efficiency over past steam flood.

Use of polymers, both straight chain (for routine mobility problems) and crosslinked (for severe problems as in the case of fractures) are in common usage to improve vertical conformance.

University of Kansas, Class I, Savonburg Field, KS -- In this project a combination of polymer flooding and infill drilling is expected to yield an additional 363,000 BO.

A polymer flood initiated in the California Dos Cuadras Field (a peripheral waterflood) had experienced no polymer breakthrough 3yrs after flood start (SPE 20060).

A phenolic resin plugback technique was used in the Midway-Sunset Field to successfully isolate water producing zones. The technique paid out in just 120 days (Petroleum Engineer International, 1/92).

Getting the Best Well Geometry (Conformance or Vertical Optimization)

- Microbial
  - Hughes Eastern — Class I
- Selective Recompletions
  - University of Tulsa — Class I
- Horizontal Wells / Completions
  - Strata — Class III
  - City of Long Beach — Class III
  - Wilmington Field (OGJ 4/10/95)
  - Yowlumne Field (SPE 24910)

GETTING THE BEST WELL GEOMETRY
(Vertical Component)
(Continued)

Microbial techniques have also been successfully applied to modify vertical profiles.

Hughes Eastern Corporation, Class I, North Blowhorn Creek Field, AL -- Injection of inorganic nutrients to feed and encourage growth of indigenous microbes for fluid diversion in this fractured reservoir has shown success. In test patterns 8 of 15 production wells show increased production, 2 of 4 injection wells show increased injection pressure.

Of course, a common way to handle vertical conformance problems, especially if stimulation has not resulted in cross flow behind pipe, is simple recompletion of wells. One Class Program project in particular has found this approach to be especially effective:

University of Tulsa, Class I, Glenn Pool Field, OK -- Reservoir characterization showed that recompletions to address bypassed oil zones would be economically preferable to drilling a horizontal well to improve recovery in this pilot study. A production increase of 200% was realized.

The ultimate in achieving vertical conformance is the drilling of a horizontal well, a horizontal leg or lateral, or performing horizontal completions. Good use of these new technologies has been or will be made in the following Class Program waterflood optimization projects:

City of Long Beach, Class III, Wilmington Field, CA -- Wells identified with sufficient remaining oil saturation will be recompleted using short and ultra-short radius horizontal laterals.

Strata Production Company, Class III, Nash Draw Field, NM -- A number of advanced reservoir characterization techniques such as 3-D seismic, VSP, MRI logs, well tests, and geostatistical approaches were used to optimally locate 2 horizontal injection wells drilled from the same central location.

In the Yowlumne Field waterflood in California, a 2,200 ft lateral horizontal well achieved conformance within a thin sand interval not economically developable using vertical wells and produced at a rate of more than 3 times that of vertical wells in the same area of the field (SPE 24910).

Nine horizontal wells were drilled in the Long Beach Unit of the Wilmington Field; two were drilled with coiled tubing (Oil & Gas Journal, 4/10/95).

Operations Optimization

- How Much Water Injected? Where? What Kind?
- Quality / Formation Compatibilty)
  - University of Kanas — Class I
- Altered Produced Fluid Streams (Lift and Facilities)
  - Lost Hills Field (SPE 29636)
  - Beta Field (SPE 29508)
- Surveillance / Monitoring
  - Inglewood (SPE 18816)

OPERATIONS OPTIMIZATION

Changing production and injection geometries will lead to the necessity for additional decisions concerning: How much water? Where? and What kind/condition of water? (Problems may include contaminants such as solids, dissolved solids, gases [particularly O2], carryover oil, and microbes, as well as potential incompatibility with reservoir temperature and/or pressure conditions.)

We have already mentioned water compatibility studies as important. They may again become important later in waterflood history as new and different parts of the reservoir are subjected to waterflood or as produced waters are considered for reinjection in different parts of the reservoir.

University of Kansas Class I, Savonburg and Stewart fields, KS -- In this project, operators designed an air flotation unit for injection water cleanup to remove solids and carryover oil. In continuing work under the Advanced Classwork Program they have maximized design and operational factors to maintain injectivity and further lessen the need for periodic well cleanup.

Lomax Exploration Company, Class I, Monument Butte Unit, UT -- Successful implementation of waterflood was achieved in a highly paraffinic, heterogeneous, and low permeability reservoir against the "conventional wisdom".

Changing patterns of injection and production will also affect production streams (hopefully). Different fluids and relative and absolute fluid volumes are likely to be produced. Lift mechanisms and surface facilities must be able to accommodate these changes.

In the Lost Hills Field California waterflood, evaluation of the ability of pump-off controllers to reduce power consumption, reduce well failure frequency, increase production, and gather pertinent data on waterflood performance for further optimization was performed. The study involved a pilot study, well selection, equipment selection, and lease operator buy-in issues (SPE 29636).

In the Beta Field (offshore Long Beach) heavy oil produced by electric submersible pumps was accompanied by increasing water cuts as the flood progressed. This resulted in problems that were addressed by changes in design and operation of the pumps and by finding alternate lift methods in some instances (SPE 29508).

A third important aspect of operations optimization is continued collection of performance information for future optimization and ultimately for implementation of improved recovery methods beyond waterflood. This involves continual or regular periodic review of production and injection data as discussed previously (being always on the lookout for anomalous performances signifying more study is needed!) and review of the successes/failures of various treatment and stimulation approaches.

OPERATIONS OPTIMIZATION
(Continued)

Review of past acid treatments in the Inglewood waterflood in the LA Basin allowed design optimization for treatment of $CaCO_3$ scale, asphaltenes and paraffins, migrating clays and fines, and drilling and completion fluid damage (SPE 18816).

Waterflood Optimization

- Technical Aspects
  (Reservoir Characterization Models)
  - Identifying the target
  - Getting the best well geometry
  - Optimizing operational procedures and technologies
- Business Aspects
  - Resources
  - Teamwork
  - Environmental
- Conclusions

WATERFLOOD OPTIMIZATION

Although the treatment we will give the business aspects of waterflood optimization is much more cursory, they are just as important as the technical aspects we have spent so much time discussing.

Business Aspects of Waterflood Optimization

- Approach Controlled by Available Resources
- Teamwork and Communication
  - City of Long Beach — Class III (SPE 29911)
- Environmental
  - 5% to 20% of wellhead price = compliance

BUSINESS ASPECTS OF WATERFLOOD OPTIMIZATION

First, we have to acknowledge the fact that our approach to waterflood optimization is going to be strongly influenced by the resources available. That is, (1) the availability of capital to invest in reservoir characterization and implementation of any new wells, equipment, etc. (The size of the improved recovery target can help leverage this resource factor to some extent!), (2) the availability of the required manpower and skills to perform the necessary tasks, and (3) the familiarity with technologies necessary to select the best of those available to apply to the reservoir situation.

Keep in mind that the entire reservoir does not have to be considered at once! Pilot implementations are a good practical approach when risk taking is a factor. (However, what is risky for one organization may be routine for another.)

I have tried to emphasize how important it is to develop a reservoir model that is mutually supported by all the available data. This can't be accomplished by having all your professional people (i.e., geoscientists, reservoir engineers, operations engineers, etc.) working on the reservoir in a relay fashion, each doing his job and then turning the project over to the next professional group. A team approach likened to that of a basketball team (with professionals comparing ideas and working consistently toward a common goal) rather than a relay team approach is necessary to make the pieces come together efficiently; in fact the pieces may not come together at all if this isn't done.

For a much more in-depth discussion of the importance and functionality of a team approach see the excellent review in "Integrated Petroleum Reservoir Management, a Team Approach" by Abdus Satter and Ganesh Thakur (PennWell Books, 1994).

City of Long Beach, Class III, Wilmington Field, CA -- In this waterflood project, both reservoir development and reservoir operations teams were formed, each with authority to make reservoir financial decisions. A financial information system was designed for the reservoir to aid the teams in their decision making processes. Other characteristics of the teams (discussed in SPE 29911) include: teams share common incentives, teams set and review their goals and the achievement of those goals, calculated risk taking is rewarded (thus encouraging wide experimentation), computerized surveillance tools were developed and are being used to make optimization of the waterflood a constant and speedy process.

Environmental considerations are extremely important in California. I think you know what the business influence of these considerations is better than I. They include considerations such as requirements for disposal of produced fluids at licensed, monitored sites, and numerous technical hurtles relating to underground injection, surface activities, and emissions from surface facilities. Population pressure has indeed played a large role in petroleum economics of the state as a whole, but in some areas in particular. Taken as a whole, from 5 to 20% of the wellhead price must be allotted to regulatory compliance, and the cost is expected to rise, especially as air quality standards become more restrictive (6th UNITAR International Conference, 1995).

Conclusions for Waterflood Optimization

- Reservoir Knowledge is a Prime Requirement
- An Integrated (Team) Approach is Necessary
- New Technologies Make a Proactive Approach Possible
- California Reservoirs are Good Candidates for Waterflood Optimization
- Class Projects are Great Technology Sources for Waterflood Optimization

CONCLUSIONS FOR WFO

Waterflood optimization requires a team effort, a knowledge of the reservoir, familiarity with technologies available, and an awareness of relevant business aspects.

This is what reservoir management is all about -- (we'll say more about this in a later talk this afternoon.)

New technologies and ideas/approaches make a proactive approach viable (potentially profitable) in almost any reservoir.

California reservoirs now being waterflooded, in spite of some of their idiosyncrasies and special environmental considerations, are good candidates for waterflood optimization. Waterflood works; so will waterflood optimization if consideration is given to the factors we have talked about here this afternoon.

DOE's Field Demonstration Program projects, the Class Program waterflood optimization projects in particular, are really good sources for learning about selection and implementation of waterflood optimization technologies. Be sure to watch for information to be released shortly on technology oriented workshops from DOE Programs coming up over the next few months.

The following slide lists the Class Program projects that involve optimization of existing waterfloods.

Waterflood Optimization Technologies From Class Program Projects

CLASS I

Diversified
Lomax
University of Tulsa
University of Kansas
Hughes Eastern

CLASS II

Laguna
Luff
Fina
University of Kansas

CLASS III

City of Long Beach (#1)
City of Long Beach (#2)
University of Texas BEG
ARCO Western
Strata

SELECTED REFERENCES

SPE 18754, C-W Shen, 1989, "Hot Waterfloods Prior to and Following Steamfloods"

SPE 18816, G.P. Dayvault and D.E. Patterson, 1989, "Solvent and Acid Stimulation Increase Production in Los Angeles Basin Waterflood"

SPE 19666, R.C. Hager and W.E. Hermance, 1989, "The Effects of Waterflooding on Reservoir Properties and Producing Operations: Applications for Geochemical Modeling"

SPE 19847, S.J. Lyjek, 1989, "Simple Performance Plots Used in Rate-Time Determination and Waterflood Analysis"

SPE 20044, G.P. Dayvault, 1990, "Injection Profile Control in a Multizone Los Angeles Basin Waterflood"

SPE 20060, H.T. Dovan and R.D Hutchins, 1990, "Dos Cuadras Offshore Polymer Flood"

SPE 20064, K.K. Lo, H.R. Warner Jr., and J.B. Johnson, 1990, "A Study of Post-Breakthrough Characteristics of Waterfloods"

SPE 21759, N. Ezekwe, S. Smith, and M. Wilson, 1991, "Performance of a Peripheral Waterflood Project in the Main Body 'B' Reservoirs (Stevens) at the Elk Hills Oil Field, California"

SPE 21897, Shoeleh S. Di Julio, 1992, "North Vickers East Waterflood Performance Prediction with Fractal Geostatistics"

SPE 24910, A.W. Marino, and S.M. Shultz, 1992, "Case Study of Stevens Sand Horizontal Well"

SPE 26082, G.S. Woodling, P.J. Taylor, H.H. Sun, Q.N. Nguyen, and T.R. Brix, 1993, "Layered Waterflood Surveillance in a Mature Field: the Long Beach Unit"

SPE 26094, R.J. Skinner, L.C. Ames, and C.P. Henderson, 1993, "Using Reservoir Simulation to Evaluate Operating Strategies in the Long Beach Unit"

SPE 29508, D.E. Carpenter and A.A McCrea, 1995, "Beta Field History: Submersible Pumps in Heavy Crude"

SPE 29625, C.A. Wright, R.A. Conant, G.M. Golich, P.L. Bondor, A.S. Murer, and C.A. Dobie, 1995, "Hydraulic Fracture Orientation and Production/Injection Induced Reservoir Stress Changes in Diatomite Waterfloods"

SPE 29626, E.P. De Rouffignac, P.L. Bondor, J.M. Karanikas, and S, K. Hara, 1995, "Subsidence and Well Failure in the South Belridge Diatomite Field"

SPE 29636, A.C. Eckel, H.P. Abels, and R.A. Merritt, 1995, "Testing and Practically Applying Pump-Off Controllers in a Waterflood"

SPE 29654, M.G. Starcher, J.R. Murphy, P.D. Alexander, and J.L. Whittaker, 1995, "Video Camera Log Used for Water Isolation in the Main Body 'B' Pool, Elk Hills Field, Kern Co., California--Water and Oil Identification"

SPE 29655, D. Moos, S. Hara, C. Phillips, A. Hooks, and K. Tagbor, 1995, "Field Test of Acoustic Logs for Measuring Porosity and Oil Saturation in a Mature Waterflood in the Wilmington Field, CA"

SPE 29665, S.T. DeFrancisco, S.J. Sanford, and K.C. Hong, 1995, "Utilizing WASP and Hot Waterflood to Maximize the Value of a Thermally Mature Steam Drive in the West Coalinga Field"

SPE 29911, J.A. Leone, J.R. Hemphill, and G.S. Woodling, 1995, "Optimization of a Mature Waterflood in the Long Beach Unit: Government and Industry Joint Venture"

SPE/DOE 35394, C.J. Koh, P.C. Dagenais, D.C. Larson, and A.S. Murer, 1996, "Permeability Damage in Diatomite Due to In-Situ Silica Dissolution/Precipitation"

PennWell Books, Abdus Satter and Ganesh Thakur, 1994, "Integrated Petroleum reservoir management, a Team Approach"

Petroleum Engineer International, R. McNally, January 1992, "Petroleum Producers Reach for New Ideas"

Oil and Gas Journal, A.D. Koen, April 10, 1995, "Newest Technology Gives Lift to Aging Wilmington Production"

6th UNITAR International Conference on Heavy Crude and Tar Sands, D.K. Olsen and E.B. Ramzel, 1995, "State of Heavy Oil Production and Refining in California"

MORE CLASS PROGRAM PROJECT INFORMATION

In this presentation I have referred only to a small sampling of the tremendous amount of practical information on reservoir characterization, reservoir management, and technology implementation that is available from Class Program waterflood optimization projects. A good source of overview information on the Class Program projects is the *Class Project Summary Sheets*, a volume published by DOE containing brief descriptions and status information on all of the projects. Similar overview information can be downloaded from the National Petroleum Technology Office website homepage (www.npto.doe.gov) in the form of the CLEVER (**CL**ass **EV**aluation **E**xecutive **R**eport) database. The *Class Act*, a DOE-sponsored newsletter, highlights information on important project accomplishments and upcoming technology transfer events such as workshops, publications, and presentations. This and other DOE newsletters (e.g., *EYE On Environment* and *Inside Tech Transfer*) are also available at the website. Detailed project technical information may be obtained from interim project technical reports published by DOE and from numerous publications in professional journals. To obtain DOE publications relating to Class projects or for further information please contact:

Herb Tiedemann
National Petroleum Technology Office

Phone:	(918) 699 - 2000
Fax:	(918) 699 - 2005
E-mail:	htiedema@npto.doe.gov
Website:	www.npto.doe.gov