SUPPORTING TECHNOLOGY FOR ENHANCED OIL RECOVERY

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FOR THERMAL PROCESSES

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**THE DEPARTMENT OF ENERGY
OF THE
UNITED STATES OF AMERICA
AND
THE MINISTRY OF ENERGY AND MINES
OF THE
REPUBLIC OF VENEZUELA**

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EIGHTH AMENDMENT AND EXTENSION TO
Annex IV--ENHANCED OIL RECOVERY THERMAL PROCESSES

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PREFACE

An agreement between the Department of Energy of the United States of America and the Ministry of Energy and Mines of the Republic of Venezuela to cooperate in Energy Research and Development was signed March 6, 1980. The object of cooperation under this DOE/MEMV Agreement was to promote a balanced exchange of energy technologies and to conduct joint projects in the areas of Petroleum, Solar Energy, Geothermal Energy, Hydroelectric Energy and Coal.

This agreement supported the Agreement for Scientific and Technological Cooperation between the two countries which was signed by the Secretary of State of the U.S.A. and the Minister of Foreign Relations of Venezuela on January 11, 1980.

The original DOE/MEMV Agreement was supplemented by six annexes to describe specifically the work to be done. Over the past fourteen years additional annexes have been signed, resulting in a total of fifteen annexes as of November 30, 1994. The Agreement has been extended to September 8, 1998. The annexes are:

- I. Characterization of Heavy Crude Oils.
- II. Supporting Research in the Area of Enhanced Oil Recovery.
- III. Evaluation of Past and Ongoing Enhanced Oil Recovery Projects in the U.S. and Venezuela.
- IV. Enhanced Oil Recovery Thermal Processes.
- V. Drilling, Coring and Telemetry.
- VI. Residual Oil Saturation.
- VII. Petroleum Products, Use and Evaluation.
- VIII. Coal Preparation, Combustion and Related Technology.
- IX. Subsidence Due to Fluid Withdrawal.
- X. On-Site Training of Petroleum Engineers.
- XI. Energy Conservation.
- XII. Geochemistry (Oil Generation, Migration and Accumulation).
- XIII. Microbial EOR.
- XIV. Exchange of Energy Related Personnel.
- XV. Oil Recovery Information and Technology Transfer.

Each of these annexes has a document describing the work to be done as part of the cooperation. Amendments and Extensions to the Annexes are provided for in the Agreement.

Currently, seven annexes are active (Annexes I, IV, X, XI, XIII, XIV, and XV); one annex is inactive (VIII); and seven annexes have been completed (Annexes II, III, V, VI, VII, IX, and XII).

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Appendix A. Full text of the "Eighth Amendment to Annex IV of the Implementing Agreement Between the Department of Energy of the United States of America and the Ministry of Energy and Mines of the Republic of Venezuela in the Area of Enhanced Oil Recovery Thermal Processes."

ABSTRACT

This report contains the results of efforts under the six tasks of the Eighth Amendment and Extension of Annex IV, Enhanced Oil Recovery Thermal Processes of the Venezuela/USA Agreement. The report is presented in sections (for each of the 6 tasks) and each section contains one or more reports prepared by various individuals or groups describing the results of efforts under each of the tasks.

A statement of each task, taken from the agreement, is presented on the first page of each section. The tasks are numbered 56 through 61. The first, second, third, fourth, fifth, sixth, seventh, and eighth reports on Annex IV, [Venezuela MEM/USA-DOE Fossil Energy Report IV-1, IV-3, IV-4, IV-5, IV-6, IV-7, and IV-8 (DOE/BETC/SP-83/15, DOE/BC-84/6/SP, DOE/BC-86/2/SP, DOE/BC-87/2/SP, DOE/BC-89/1/SP, DOE/BC-90/1/SP) DOE/BC-92/1/SP, DOE/BC-93/3/SP)] contain the results from the first 55 tasks. Those reports are dated April 1983, August 1984, March 1986, July 1987, November 1988, December 1989, October 1991, and February 1993 respectively.

Task 56 - DOE shall provide INTEVEP with results from the SUPRI heavy oil research program. This work deals with experimental determination of the flow mechanisms and analytical modeling of steam/foam systems, experiments on in-situ combustion and mathematical research on monitoring methods such as tracer and pressure transient testing. SUPRI will also communicate to INTEVEP the results of saturation determinations by Cat-Scan during laboratory experiments.

1.1 SOFTWARE FOR ANALYSIS AND INTERPRETATION OF CT DATA (Pascal Rondeu)

Software has been developed for interpretation, display and analysis of the data obtained from SUPRI EMI 5005 CT scanner. The two main programs will be described only briefly in this report because a complete technical report summarizing the progress to date and including source codes and user manuals will be submitted to the Department of Energy in the near future.

1.1.1 GENCODE : A CODE GENERATOR FOR PROCESSING CT IMAGES

1.1.1.1 Purpose of GenCode

GenCode is a software that reads a text file containing a GenCode program and generates a C code file that can be compiled into a Motif executable file useful to process CT images output. The GenCode syntax is a subset of the C grammar and introduces new data types such as the `ct_image` type that makes image manipulation easy. For best use the file generated by the GenCode program must be compiled with an object file provided. This enables the user to obtain a stand alone Motif application that does the calculation specified in the GenCode program as well as prompts for the calculation parameters. The input/output is described in the figure below.

1.1.1.2. The GenCode Grammar

Data Types are limited to five elementary types: `int`, `double`, `temp_int`, `temp_double`, `ct_image`. A variable name starts with a letter and is followed by an eventually empty sequence of letter, digits or underscore.

There is a special variable called **result** which can be either of type `int` or `double` and which must be present. This variable is not considered as a calculation parameter but is used to store the result of the calculation. Each time the **result** variable is assigned in the GenCode program, it is written in the result file of the calculation in the C code file.

Each variable of type `ct_image` is an input parameter for the calculation procedure and therefore a file name that represents the CT image is prompted to the user when the

resulting program is executed. CT images can be considered as 320*320 matrices of short (2 bytes) integers. When using a `ct_image` variable in a GenCode program the user can apply to it all of the operation (+, -, *, pow, etc..) like it was any other elementary data type. The GenCode program will take care of generating the loop that reads the image data. Each time at least one `ct_image` variable is used (using GenCode without specifying `ct_images` doesn't make sense) a region of interest is associated as a parameter of the calculation procedure. This region of interest is asked at run time. It defines the portion of the CT image for which the calculations are done. To specify the whole picture the region of interest needs to be (0, 0, 319, 319).

1.1.1.3 Program Organization

A GenCode program is a single procedure, therefore there is no procedure declaration. The program is made up of three sections: the declaration section, the condition section and the statement section.

The Declaration Section

This section contains a list of variable declarations including the special variable **result** of type int or double. All variables of type int, double or `ct_image` are parameters to the calculation procedure. All variables of types `temp_int` and `temp_double` are temporary variables. GenCode checks that all variables have a different name and that no variable has the name of a registered function.

The Condition Section

This section can be omitted. If not empty, it contains a list of conditions for the calculation to take place. Each condition starts with the keyword **cond** and is followed by a conditional expression. In the C code file generated by GenCode, if the conditional expression is false then the statement section is not executed. The test is done for each value of the CT images used. Although the section is working, the language does not offer any alternative value for the **result** variable. This can create result files of unpredictable size. The problem will be corrected in a future version. For now it is advised that conditions use the if-else statement from the statement section.

The Statement Section

This section is a list of statements describing the calculation procedure. A statement can either be of the following forms:

- an assignment of the *result* variable or a temporary variable. The syntax is:
 `variable_name = expression;`
- an if-else statement. The syntax for such statement is:
 `if (conditional expression)
 { statement_list }
 else { statement_list }`
- an empty statement: a semicolon (;). It can be used to specify an empty statement list in an if-else statement.

The conditional operators allowed are : ==, !=, >, <, >= and <=. Each operation can compare two expressions.

A regular expression can be any of the following:

- a registered function call. Note that this version of GenCode does not allow to call any user defined function from the GenCode program,
- a variable,
- an integer or double precision constant,
- an expression between '(' and ')'
- an operation between expression. The operators available are: +, -, *, and /,

1.1.1.4 Future Work on Gen Code

- Transform condition statement into an if-else.
- Allow multiple variable declarations on a single line.
- Allow comments to be inserted.
- Allow multiple result files to be generated.
- Create an if_ only statement.
- Allow multiple conditions in an if statement.
- Increase syntax checking in syntax analyzer.
- Allow user defined function calls

1.1.2. CATSOFT: A POST-PROCESSING AND DISPLAY APPLICATION

1.1.2.1. Overview of Catsoft

The Catsoft application enables one to post-process CT images made with the EMI 5005 scanner or images generated by the application itself. The main features of this X Window menu driven application are:

- Display CT images or images generated by the application.
- Display individual CT values or values from a user defined image region of interest.
- Display histogram of values of a region of interest of an image.
- Display values on an xy chart of a linear region of interest of an image.
- Zoom-in images for better display.
- Change the number of colors used as well as the range of values displayed.
- Perform standard calculations between CT files.
- Change the format of a data file to export it to another application.
- Allow calculations and format change to be done in series using input files.
- Interpolate linearly between specified scans for 3D reconstruction display.
- Compress/uncompress, tar and extract files.
- Launch application or edit text files.

1.1.2.2 Requirements: Hardware and Software

To run Catsoft you need a color X server connected to the X client running the application. The server and client are often the same machine. To fully use the application capabilities the server should have 120 contiguous spare cells in its color map. If it's not the case, a message appears in the main window when the application starts. The server must be equipped with a mouse, only the left button is used.

Although the application can run without any particular environment variable, two variables are necessary to use the on-line help and the user defined options and user defined experiment values. To use the on-line help, the application needs to know where the help file is. The directory containing it can be specified using the variable CATSOFT_HELP. If this variable is not specified the application will look in the current directory. If the help file cannot be found or opened, a message appears in the main window when the application starts. When starting the application looks for two files called cs_options and cs_experiment. These files can be in any reachable directory. For the application to read them, use the environment variable CATSOFT_DIR. If this variable is not specified the application will look in the current directory for these files. If they can not be found or opened a message appears in the main window when the application starts. To set an environment variable use the setenv command.

For example: setenv CATSOFT_DIR /home/pete/pascal/CATSOFT/.

To change the value of that variable just assign it to another value. To take away the variable from your current environment use the unsetenv command.

For example: unsetenv CATSOFT_DIR..

If the application is used often, it's a good idea to assign these variables in your file .cshrc. This file is read each time a shell is opened.

The cs Options File

The cs_options file is read when the application starts. It contains options values enabling the user to personalize the options for his needs. Some options can be accessed and changed from the application. A complete list of the options is given in the Catsoft user manual portion of the technical report mentioned above.

The cs Experiment File cs Experiment

The cs_experiment file is read when the application starts. It contains default experiment values. These values are used for file browsing, file output directory, or for calculations and conversion parameters. These values can be accessed or changed from the application, but not set as default from the application. The details of how to use these files are also in the report.

CatSoft Help File; i CatSoft Help

The help file must be called catSoft_help and is not supposed to be modified. However it might not be perfect, so the user may, at his own risk, add or correct a few things in. If the help is not in the current directory then use the environment variable CATSOFT_HELP to tell the application where it can be found.

At the start, all the standards X Window arguments such as -bg to change the background color can be used. The application main window is displayed (as shown on the next figure). It consist of text area and a menu bar on the top. The help menu is on the far right of the menu bar and can be accessed any time. When it starts, the application looks at the color map size and tries to allocate all the colors it could need. The result of this allocation is displayed. Then the application loads the help file, reads the cs_options and cs_experiment files. If an error is found a message is displayed, and the reason for it.

The main window text area displays all error messages and actions done by the application, and should be kept visible if the screen is large enough to do so, or consulted as often as possible. The menu bar enables one to access the different features of the application. If the application's main window is iconified all the windows from the application will be also.

In the report, there is a description of which features can be reached from the menu bar. The selection of menu items leads to dialog boxes that can be minimized or put behind other windows. The application keeps track of which dialog box is opened so if many boxes are opened it is easy to recall them by selecting the menu item again. The application then maximizes the dialog box and brings it up front. A menu item can be selected with the mouse or with the meta key combined with the underlined letter, of the menu title and then the menu item.

1.1.2.3. Displaying Images

To display a data file, select the Open item from the File menu. A standard file selection box appears and displays the files of the current directory. To select an image, click on the file name (the file name appears in the Selection text field), then click on the OK button or press return. File can also be selected with a double click on the filename. When a file is selected a display window is opened and the data is loaded, the mouse cursor is switched to a clock while the image data are loaded. If an error occurs a message appears in the main window and the display window is closed. The application tries to detect which format is your file. CT and RAW are easy to detect because they have a magic word. ASCII files have no magic word and the application may be confused if you select a bad ASCII file. To close the file selection box, click the Cancel button. In the display window one may zoom on part of the image or perform histograms or other analyses.

Most of the application dialog boxes are connected to a common standard file selection box enabling one to browse through the file system. When selecting an existing filename it is possible to either type the filename in the text box or to click on the File Browser button and select a file with the file browser. When a File browser button is clicked, its corresponding text box changes its background in red. A text box entry with a red background receives the output of the file browser. The file browser is then displayed. Click on the file name to select and then click on the Select button; the selected file name appears in the linked text box. The file browser remains open until the end Selection button is pressed. To link the file browser to another text box, click on the File Browser button situated under the text box to be linked.

The image formation can be changed using the convert item from the File menu. The conversions available are: CT to PPM, CT to RAW, RAW to PPM, and ASCII to PPM. To learn more on the image format see Appendix 1 of the user manual portion of the report. Depending on the working mode option the conversions work either in batch or one at a time. When converting to a PPM file, it is important to visualize the data file to convert first as the conversion process uses the current options to convert data into RGB values. This program can also use the standard tar, compress, and uncompress utilities

1.1.2.4 Performing Calculations Using Data Files

The calculations available to date are: Porosity, two-phase saturations, three-phase saturations, addition, subtraction, density, and Z number Id. Depending on the working mode option, the calculations work either in batch or one at a time. For all calculations the output file is always the size of the ROI specified. As for the input files it is possible to specify input files of different types. The application checks that image sizes match the region of interest specified. All input files of raw or ASCII format must be the same size as the region of interest. When an input file of type CT EMI 5005 is specified, the calculation is done only on the region of interest specified. Files of different formats can be put as input for the same calculation as long as their sizes match with each other and the region of interest specified. It is therefore very important to define a good region of interest before performing calculations so that result files can be reused for later calculations.

1.1.2.5 Three-Dimensional Reconstruction Module

To use the 3D reconstruction module, an input file is needed (its format can be found in the report). The input file must be written carefully because it affects how the reconstruction looks. The spacing specified between files affects the size of the Z plane. To view the plane a model must first be loaded. To load a model select the Load 3D model item in the 3D model menu. A file selection dialog box opens. Select the input file and click OK. All the data specified in the input file is loaded into memory. It remains in memory until another model is loaded or the application exits. If CT files are specified in the input files, only the region of interest, which must also be specified, is loaded. There is a limit of 150 images that can be specified for one model. Once a model has been loaded the other items of the 3D model menu are accessible. To view a plane select the item in the menu. A display window appears with a horizontal scroll bar under the image area. This scroll bar enables one to scroll through the third plane. All the functions from the standard image window are available with the 3D model display window.

1.2 A STUDY OF END EFFECTS IN DISPLACEMENT EXPERIMENTS (Suhail Qadeer)

In this study displacement experiments and numerical simulations are being used to study the influence of end effects on the relative permeabilities calculated from data obtained in the laboratory. It was shown in last years report that the flow near the inlet and outlet end is hemispherical. It has also been shown that there are large saturation gradients in the core after a drainage displacement, even after high rate displacements. Relative permeabilities were calculated using both Johnson, Bossler and Naumann (JBN) and history matching technique using the data generated by the numerical simulations. The severity of the errors introduced by the underlying assumptions in these methods is obvious.

1.2.1 SIMULATIONS

As described in previous report (Brigham *et al.*, 1993) ECLIPSE, a commercial black oil simulator was used in this study. The simulations were conducted to understand the geometry of fluid flow inside the core. It has been shown that it was necessary to use 2D (r - z) grid to properly include the geometry of the end plugs, which have concentric-circular and radial grooves for fluid distribution. The details are given in the aforementioned SUPRI report. The capillary pressure and relative permeability curves used in these simulations are typical curves for Berea sand stone, which is strongly water wet. These curves are shown in Fig. 1.2.1. These simulations provided us insight into the mechanics of fluid flow inside the core. The pressure drop and the recovery data obtained from these simulations was used to calculate the relative permeabilities using the conventional method of JBN, and also by history matching. The curves obtained by these analyses are compared with the original curves to show the errors introduced by these methods of analysis. In subsequent sections the details of the calculation procedure is presented.

1.2.2 JBN ANALYSIS

Johnson *et al.* (1959) presented a method for calculating relative permeabilities from data obtained during displacement experiments. Their method assumes that the flow is linear and incompressible, and the flow rate is high enough that the capillary forces can be neglected. To calculate the relative permeabilities, the pressure drop across the core, ΔP , and the cumulative recovery, W_p , are measured during the displacement process. From the pressure drop data the relative injectivity, I_r , is calculated using:

$$I_r = \frac{U/\Delta P}{U_s/\Delta P_s}$$

where U is the instantaneous velocity and U_s is the velocity at the start of the injection. Similarly, ΔP and ΔP_s are the pressure drop at corresponding time and at the start of displacement.

The cumulative recovery, W_p , is used to calculate the average saturation, S_{av} , and the fractional flow at the outlet face, f_{o2} , by

$$S_{av} = S_{init} + \frac{W_p}{V_p}$$

and

$$f_{o2} = \frac{dS_{av}}{dW_i}$$

where V_p is the pore volume and W_i is the cumulative pore volumes of fluid injected. Now relative permeability to oil, k_{ro} , is calculated by:

$$k_{ro} = \frac{f_{o2}}{\frac{d(\frac{1}{W_i f_r})}{d(\frac{1}{W_i})}}$$

and the corresponding saturation, S_2 , is given by:

$$S_2 = S_{av} + W_i f_{o2}$$

Finally the water relative permeability is calculated by:

$$k_{rw} = \frac{1 - f_o}{f_o} * \frac{\mu_w}{\mu_o} * k_{ro}$$

1.2.3 HISTORY MATCHING

The history matching method for calculating relative permeabilities was first proposed by Archer and Wong (1973). In this method parametric forms of the relative permeability curves are used. The parameters are varied either manually or by some automatic technique like the Levenberg-Marquardt method (Press *et al.*, 1992) until an objective function is minimized. The advantage of this method is that any numerical or analytical method can be used to model the displacement process, including the capillary forces. Although to date only linear models have been used in this method. In our study we have used both 1D and 2D numerical models which include the end plug as an integral part of the simulation model. The objective function which we want to minimize is given by:

$$J = \sum_{n=1}^{ndata} \left[\frac{\Delta P_{obs} - \Delta P_{calc}}{\Delta P_{max}} \right]^2 + \sum_{n=1}^{ndata} \left[\frac{R_{obs} - R_{calc}}{R_t} \right]^2$$

where ΔP_{obs} and ΔP_{calc} are the observed and calculated pressure drops, and R_{obs} and R_{calc} are the observed and calculated recoveries. ΔP_{max} is the maximum pressure drop and R_t is the total recovery from the displacement.

In this study we have used the Levenberg-Marquardt method to minimize the objective function. In the Levenberg-Marquardt method the search direction, S , is given by:

$$S(\vec{X}^k) = -[H^k + \lambda^k I]^{-1} \nabla J(\vec{X}^k)$$

where, I is the identity matrix, λ is the Marquardt's parameter, and, H is the Hessian matrix. The element of the Hessian matrix in the i^{th} row and j^{th} column is given by:

$$h_{ij} = \frac{\delta^2 J}{\delta x_i \delta x_j}$$

where x_i and x_j are the i^{th} and j^{th} elements of the parameter vector, X . The Marquardt parameter controls the direction and step length in the new search direction. For a large value of λ this method approaches the steepest decent method and for very small values it is equivalent to the Gauss--Newton method. By properly controlling the value of λ it can be assured that the rate of minimization is reasonable in all cases.

The following parametric form of the relative permeability curves is used in this study:

$$k_r = k_{re} * \exp(A * S_s^{-\alpha})$$

where:

$$S_s = \frac{S_w - S_{wc}}{1.0 - S_{or} - S_w}$$

The parameters allowed to vary are k_{re} , A , α and S_{wc} . It should be noted that there are, in total, four curves to be matched. Two for the drainage and two for the imbibition. It has been observed, from both experiments and simulations, that the core has a uniform saturation distribution at the end of imbibition displacements. It is therefore assumed that the irreducible oil saturation, S_{or} , and the end point wetting phase permeability, K_{wor} , can be calculated directly, and therefore these two are not included in the history match procedure.

1.2.4 RESULTS AND DISCUSSION

The relative permeability curves calculated by the JBN method from the simulated data for a viscosity ratio of one are shown in Figs. 1.2.2 - 1.2.5.

As explained in previous reports there are large saturation gradients at the end of the drainage displacement process. As a result the saturation profiles during the imbibition displacement do not monotonically decrease towards the outlet end. This results in large errors at lower water saturations as shown in Figs. 1.2.2 and 1.2.4. As the saturation profile inside the core becomes more monotonic the errors are reduced. A surprising observation is that the lower rate displacement has less error in the non-wetting phase relative permeabilities. This is probably caused by the fact that the wetting phase imbibes farther into the core because of the capillary forces, thus causing the saturation profile to be more nearly monotonic.

The results from the drainage displacements are shown in Figs. 1.2.3 and 1.2.5. These displacements give better results because the viscous forces dominate the capillary forces and the effect of the saturation gradient inside the core is reduced. As the wetting phase saturation decreases, the capillary forces increase, and the error in the calculated relative permeability curves increases.

The JBN analysis results for viscosity ratio of five are shown in Figs. 1.2.6 - 1.2.9. The errors are somewhat smaller in this case but the general trends are the same.

1.2.5 FUTURE PLAN

The history matching package has been developed and is being evaluated. This method will be used to investigate the errors introduced by neglecting the hemispherical nature of flow path near the inlet and outlet ends. After validating the procedures this method will be used to find out the differences in the relative permeabilities obtained by using the 1D and 2D flow model. In the end the effects of errors in the capillary pressure curves will be investigated.

Figure 1.2.1 Capillary pressure and relative permeability curves used in the numerical Simulations.

Figure 1.2.2 Relative permeabilities calculated by JBN method.
(Imbibition, flow rate = 8.0 cc/min., V.R. = 1.0)

Figure 1.2.3 Relative permeabilities calculated by JBN method.
(Drainage, flow rate = 8.0 cc/min., V.R. = 1.0)

Figure 1.2.4 Relative permeabilities calculated by JBN method.
(Imbibition, Flow rate = 2.0 cc/min., V.R. = 1.0)

Figure 1.2.5 Relative permeabilities calculated by JBN method.
(Drainage, flow rate = 2.0 cc/min., V.R. = 1.0)

Figure 1.2.6 Relative permeabilities calculated by JBN method.
(Imbibition, flow rate = 8.0 cc/min., V.R. = 5.0)

Figure 1.2.7 Relative permeabilities calculated by JBN method.
(Drainage, flow rate = 8.0 cc/min., V.R. = 5.0)

Figure 1.2.8 Relative permeabilities calculated by JBN method.
(Imbibition, flow rate = 2.0 cc/min., V.R. = 5.0)

Figure 1.2.9 Relative permeabilities calculated by JBN method.
(Drainage, flow rate = 2.0 cc/min., V.R. = 5.0)

1.3 STEAM-WATER RELATIVE PERMEABILITY (Mark Meeks)

Steam-water relative permeability is a topic of practical importance for modeling multiphase flow in enhanced oil recovery and geothermal projects. However, it is not a well-understood phenomenon. To gather background information on theory as well as published experimental and history-matching data, a literature review was conducted by searching the following data bases: EI Compendex; Enviro/Energy Line; Geo Ref; and Math Sci. These data bases yielded information primarily on studies appearing since 1987. To locate earlier studies a secondary bibliography was compiled from references listed in the primary works. This proved to be a fruitful approach, locating many pertinent works not located by the computer-assisted search.

1.3.1 LITERATURE REVIEW

The literature review showed that although preliminary studies in this area began as early as the 1950s, there still remains fundamental disagreement over the values for relative permeability versus water saturation curves and over the physical processes of fluid movement and heat transfer. The lack of agreement in experimentally determined values has led to the widespread usage of estimated values in computer simulation studies. A large part of the controversy stems from the difficulties arising in obtaining reliable saturation profiles of heterogeneous media. We hope that the acquisition of a new CT scanner capable of producing high-resolution images will enable us to establish accurate, reliable saturation profiles ultimately leading to more accurate multiphase flow models.

One of the first key studies to appear was by Arihara (1974), who was unable to determine saturation. Instead, he measured the temperature profile through the boiling region of a synthetic sandstone core to obtain fluid properties, enthalpy, and pressure throughout the two-phase region. Then he utilized equations for steady, single-component, two-phase, nonisothermal adiabatic flow together with a calculated relative permeability ratio and a water-oil permeability vs. water saturation curve to derive a water saturation for each steam or water relative permeability. A disadvantage to his approach is that the oil-water permeability ratio may not necessarily be transferable to a steam-water system.

Trimble and Menzie (1975) developed relative permeability curves for Boise and Berea sandstone cores. However, their assumption that liquid and vapor velocities were identical probably skewed the results when they calculated water saturation from steam quality. Chen (1976) scored a major advance by directly measuring water saturation with a capacitance probe for a synthetic consolidated sandstone core, assuming a nearly linear relationship between the capacitance probe signal and water content. His results contrasted markedly with those of Trimble and Menzie.

Several interesting attempts to circumvent the issue of saturation profiles followed. Instead of focusing on core samples, attention was shifted to the macroscopic level of geothermal field data from the Wairakei field of New Zealand. Grant (1977) calculated permeability reduction factors by making the assumption that the driving pressure gradient and temperature were not affected by the producing enthalpy change. After correlating liquid water flow rates with discharge enthalpy he was able to conclude, with what he admitted was a degree of uncertainty, that steam-water flow in a fractured medium differed from flow in a porous medium. Further, he theorized that steam-water flow in a fractured rock does not involve the interference between the two phases as occurs in a porous rock.

Horne (1978) continued research in this area by examining wellhead pressure change with time and utilizing downhole temperatures and fluid properties. He was able to derive a relative permeability curve ignoring the immobile water in the field. Thus, his curves were not relative permeability curves in the conventional sense. His flowing water saturation were really flowing liquid mass fractions, not resident volumetric water saturation. Despite further refinements by Shinohara (1978) these attempts to conduct analysis on the macrolevel did not produce satisfactory permeability curves.

Counsil (1979) employed Chen's technique of measuring water saturation with a capacitance probe to obtain steam-water relative permeabilities from steady-state two-phase, nonisothermal bench-scale flow experiments. Additionally, he obtained nitrogen-water relative permeabilities for a synthetic sandstone core under transient conditions. They concluded that for high water saturation, the external gas drive (nitrogen-water) gas relative permeabilities were different from those of the internal gas drive (steam-water) system.

Monsalve *et al.* (1984) investigated the effects of surfactants upon steam-water systems, noting that the residual steam saturation increases with increasing surfactant concentration so that the relative permeabilities to steam are shifted while the general shape of the curves remains unchanged. They concluded that, contrary to previous studies on gas-liquid systems, the relative permeability to water increased with increasing surfactant concentration rather than holding constant.

Sanchez and Schechter (1987) argued that errors in the measurement of steam quality by Monsalve *et al.* prevented exact comparisons with gas-water systems. Furthermore, Sanchez *et al.* maintained that the large differences between Counsil's steam-water and gas-water relative permeabilities were due to vaporization from pressure drop along the core and to problems with the calculation of heat transfer. Their experiment, carefully designed to minimize heat losses with adiabatic two-phase flow in an unconsolidated Ottawa sand pack, concluded that steam permeability can be accurately represented by gas permeability for two-phase flow. Instead of relying on a simple mass balance, liquid saturations were measured by analyzing the output of a 10-microliter pulse input of NaCl-36 through an HPLC sample injector.

To address the issue of whether steam-water permeabilities should be viewed in terms of a noncondensable gas-water model or a condensing phase model, Parlar and Yortsos (1987) drew upon percolation theory to describe capillary condensation and evaporation processes obtained in previous studies. They concluded that primary imbibition curves behave in accordance with the flow patterns of immiscible fluids, while the primary drainage curve, surprisingly, begins at zero residual vapor saturation with the corresponding liquid relative permeability remaining normal for a wetting phase in immiscible flow. Capillary pressure curves were obtained with the standard features of immiscible fluids except that residual saturation became very small for any phase. Apart from these considerations their results generally supported the idea that steam-water relative permeability could be approximated by studying immiscible gas-liquid flow regimes.

Closmann and Vinegar (1988) addressed the need to find a more accurate way of measuring liquid saturation by making CT scans of liquid saturation of natural cores at each equilibrium point. This approach allowed them to measure steam-water relative permeabilities in-situ for cores which were at steam-driven oil residual saturation. New techniques were introduced for calculating steam permeability from pressure data and from inlet and outlet temperatures. Their analysis revealed steam relative permeabilities close to values in the literature for gas flow through porous media. Water relative permeabilities were somewhat below values in the literature.

Sedgwick and Miles-Dixon (1988) developed three X-ray imaging methods for investigating multiphase flow through oil sands: (1) a single beam technique to directly measure bitumen and water saturation; (2) X-ray xeroradiography, producing high-contrast two-dimensional images of internal core structure and fluid distributions; and (3) CT scans with a complete three-dimensional imaging capability.

Oak *et al.* (1990) performed X-ray scans of two- and three-phase flow in fired Berea sandstone in a steady-state regime, paying special attention to saturation histories.

In summarizing the results of the literature search we can see two main approaches to the study of steam-water relative permeability:

- (1) a model based on adiabatic "boiling" flow with water as the sole chemical component moving in liquid and vapor phases, and;
- (2) the isothermal immiscible "gas-drive" flow using nitrogen and water.

The more recent studies have suggested that when heat losses are properly controlled the two approaches can yield roughly equivalent relative permeability data. If these studies are correct, then gas-drive flow models with no mass transfer should provide reliable data which can be substituted in the absence of data on steam-water relative permeability.

1.3.2 FUTURE WORK

We hope to obtain reliable permeability curves useful in resolving this issue. At present we are advancing from the literature review stage of our investigation into preliminary design of the coreholder for a sample of Berea sandstone. One consideration is the selection of the material for the coreholder. Efforts are underway to choose a plastic or composite material with proper insulating qualities capable of withstanding reservoir temperature and pressure conditions. Optimal size, flow rates, and heat properties are being determined by the Computer Modeling Group's Steam and Additive Reservoir Simulator (STARS, Version 4.0.1). Key factors, which we wish to be conscious of, include heat loss effects, gravity segregation, pressure drop, temperature profiles, slippage and Klinkenberg effects, scaling factors, heat pipe effects, stratification, capillary end effects, salinity of water, and steam quality.

1.4 CT IMAGING OF TWO-PHASE (OIL/WATER) FLOW IN FRACTURED POROUS MEDIA (Richard Hughes)

1.4.1 INTRODUCTION

Knowledge advancement in the area of two-phase flow in fractured porous media has largely been done through numerical simulation studies. Numerical researchers perform fine grid simulations to determine the relative effects of various parameters to develop better ways to represent the physical flow processes in dual porosity simulators. Most of the time these studies have relied on the sparse experimental data in the literature (Mattax and Kyte, 1962; Kleppe and Morse, 1974; Kazemi and Merrill, 1979) to verify their models.

The Mattax and Kyte data and the Kleppe and Morse data were obtained similarly. A solid core was placed in a core holder with spacers along the sides of the core. The gaps were initially filled with oil and were displaced by water being injected from below. Oil recovery and ratios were reported vs time. The Kleppe and Morse experiments could measure saturations via resistivity measurements, but these data were not reported. Mattax and Kyte performed additional imbibition tests using two cores with all faces sealed but one. The two cores were mated with spacers between the open faces. The mated cores were then immersed in water, and oil recovery and ratios were reported.

Kazemi and Merrill utilized cores cut in half for their experiments. Water was injected only into the fracture and displacement tests were run at various rates. Fine grid simulations were then used to match the recovery and data on rate vs pore volume injected. Matrix capillary pressure was the matching parameter that was adjusted, since it was noted that at low rates, imbibition dominates the flow. Successful matches were obtained at capillary pressures very close to the ones obtained on a whole core of the same material. Fracture capillary pressure was assumed to be "essentially zero." All but one of their tests were run with zero initial water saturation. Reported water-oil ratio values had substantial fluctuations with increasing pore volumes injected, which did not occur in their test with an initial water saturation.

Recent experimental work has concentrated on understanding the physical processes going on when the primary flow mechanism is gravity drainage (Horie *et al*, 1988; Firoozabadi and Hauge, 1990; Labastie, 1990; Firoozabadi and Markeset, 1992). In all of these experiments, stacked cores containing oil were displaced with air. Production rates were monitored and average block saturations were measured. The authors argue that matrix blocks are not isolated from each other as stated in many of the dual porosity model formulations, but must have some capillary continuity to obtain the observed performance. Capillary pressures in the fracture as high as 40 psi are reported (Firoozabadi and Hauge, 1990).

As the discussion above indicates, a more fundamental study of two-phase flow in fractured media is needed. Work sponsored under this program was initiated by Guzman and Aziz (1993) to study two-phase flow in fractured porous media. The initial purpose for this work was to attempt to measure relative permeabilities in the fracture. An experiment was designed to measure saturation distributions in two cores of identical material. One core would be a control, while the other would be cut in half and propped open with inert material to simulate a fracture. Oil and water would be injected into the cores at varying rates. Saturations would be measured by computerized tomographic (CT) scanning the core at various stages of the injection process. Fine grid simulations

would then be used to history match the experimental results. Fine grid simulations were performed to help in the design of the experimental procedure. An experiment was built but, unfortunately, problems which developed during single phase injection testing, precluded obtaining any useful results.

The proposed research will continue along the same lines as the Guzman and Aziz study plans. Detailed measurements of pressure, rate and saturation distribution, as the tests are being performed, will be recorded and attempts will be made to measure phase distribution inside the fracture. This research should result in a much better handle on the physical processes that occur when two-phases flow in a fractured system.

1.4.2 EXPERIMENTAL SET-UP AND PLANNED WORK

The experimental design of Guzman and Aziz will be utilized, with slight modifications due to simulation work conducted as part of their design.

Two cores made of Boise sandstone will be used in the experiments. One core will be compact and the other will be cut in half and propped open with Teflon material to simulate a fracture. Cyclohexane and brine doped with NaBr will be the two fluids used. The cores will be imbibed with the brine to 100% saturation and absolute permeability measurements will be performed. In addition, the cores will be scanned to ensure complete saturation and to obtain the attenuation coefficient for the doped brine. The cores will be drained to connate saturation with cyclohexane. Flow experiments with various water cuts and rates will be performed, and as the experiments are run, the cores will be scanned at points adjacent to six pressure transducers. Oil rate, total flow rate, and pressure will be measured and logged using electronic balances, and the pressure transducers connected to a data logger. Figure 1.4.1 shows the experimental setup.

Capillary pressure data from Sanyal (1971) was used for the design simulation studies. Late in the work, Guzman began measuring capillary pressure data from the block used for the cores. The data was significantly different from Sanyal's work and will need to be verified in this continuing study. Relative permeabilities for the matrix used in the design simulations was obtained from Purcell's formulas. The accuracy of calculating relative permeability from capillary pressure data will be evaluated with the compact core experiments.

Additionally, Guzman and Aziz had problems in their experiments with coreholder failures. As a result, the coreholder will need to be redesigned. Guzman initiated some preliminary work and additional ideas have been discussed. The experimental apparatus will also need to be rebuilt.

EXPERIMENT SETUP

Figure 1.4.1 Experiment set-up.

2.1 KINETICS OF IN-SITU COMBUSTION (Daulat Mamora)

A technical report titled "Kinetics of In-Situ Combustion," SUPRI TR 91 by Daulat Mamora , Henry J. Ramey, Jr., William E. Brigham and Louis M. Castanier was published in May 1993. The following is an abstract of this report.

Oxidation kinetic experiments with various crude oil types show two reaction peaks at about 250°C (482°F) and 400°C (725°F). These experiments lead to the conclusion that the fuel during high temperature oxidation is an oxygenated hydrocarbon.

A new oxidation reaction model has been developed which includes two partially-overlapping reactions: namely, low-temperature oxidation followed by high-temperature oxidation. For the fuel oxidation reaction, the new model includes the effects of sand grain size and the atomic hydrogen-carbon (H/C) and oxygen-carbon (O/C) ratios of the fuel. Results based on the new model are in good agreement with the experimental data.

Methods have been developed to calculate the atomic H/C and O/C ratios. These methods consider the oxygen reactions are different in kinetic and combustion tube experiments. A new experimental technique or method of analysis will be required to obtain kinetic parameters for oxidation reactions encountered in combustion tube experiments and field operations.

2.2 CATALYTIC EFFECTS OF METALLIC ADDITIVES IN IN-SITU COMBUSTION (Vivek K. Agrawal)

2.2.1 ABSTRACT

In-situ combustion is classed among the most energy efficient improved oil recovery methods available today. However, a chief constraint limiting practical application of in-situ combustion is the amount of fuel formation in the reservoir matrix ahead of the combustion front. If sufficient fuel is not deposited, as in the case of high gravity oils, the combustion front will not sustain itself. Conversely, if fuel deposition is in excess, as in the case of low gravity oils, the rate of advance of the front tends to be slow, which leads to a high demand for air to sustain combustion.

It is desired to find substances which have a catalytic effect on the kinetics of oxidation processes in in-situ combustion. There are many factors affecting the catalysis of such reactions, among which are primarily; the composition and concentration of the catalyst, surface area of the catalyst available for combustion reactions, and the temperature. Therefore, if the amount of fuel deposition ahead of the combustion zone can be controlled by the addition of a suitable quantity of catalyst, we can make this method of thermal recovery practically feasible over a broader range of field conditions.

Kinetics of crude oil oxidation reactions involved in in-situ combustion have been widely investigated. Measurements of kinetic parameters have been achieved by oxidizing crude oil in packed beds under a programmed heating schedule and by subsequently analyzing the effluent gases (Bousaid and Ramey, 1968; Weijdemans, 1968; Burger and Sahuquet, 1972; Dabbous and Fulton, 1974; Fassihi, 1981). All these studies indicate that the overall oxidation mechanism of crude oils in porous media is the result of an overlap of several reactions that occur at different temperature ranges. These different reactions can be broadly classified into three categories :

1. Low-temperature oxidation reactions. These are heterogeneous and produce no carbon oxides.
2. Medium-temperature (fuel deposition) reactions, which are homogeneous and involve the oxidation of the products of distillation and pyrolysis.
3. High-temperature fuel combustion reactions, which are heterogeneous in nature, where oxygen reacts with the heavy coke-like residue deposited at lower temperatures.

Mamora *et al.* (1993) developed a better model based on only reactions. By using a hydrocarbon as fuel and taking oxygen into account, he managed a better fit of the experimental data.

Other studies (Shallcross, *et al.* 1991), reported results from kinetic runs performed on crude samples from Hamaca, Venezuela and Huntington Beach, California using aqueous solutions of metallic salts. It was discovered that the presence of nickel, copper and cadmium had little or no effect; however, iron, zinc, tin and aluminum increased the fuel concentrations in the Huntington Beach oil.

Although all these studies have provided qualitative information about the effects of soluble metallic additives on the kinetics of combustion reactions, we still need field related quantitative parameters, such as the amount of air needed to burn a unit volume of the reservoir, and the fuel concentration. It is still an important topic of research to address the quantitative description of the kinetics of in-situ combustion. The objective of this study will be to find parameters which will quantitatively predict the kinetics of an in-situ combustion for a given set of reservoir parameters and oil properties, and the nature of the catalyst used.

2.2.2 LITERATURE REVIEW

The amount of fuel deposited and the velocity of the combustion front are affected by the kinetics of the oxidation and pyrolysis reactions occurring in the porous reservoir matrix. A desirable catalyst, when introduced during in-situ combustion, will modify the amount of fuel deposited and also will alter the fuel. If such catalysts can be identified, and their effects on the combustion process quantified, then in-situ combustion would be feasible for a broader range of crudes and different reservoir matrices. The first study was carried out by Racz (1985). Subsequent work done at Stanford University by Baena *et al.* (1990) and Shallcross *et al.* (1991) indicated that the addition of water soluble metallic salts can change the kinetics of the combustion reactions. The kinetics studies conducted by Holt (1992) describe combustion runs done using two types of heavy oils, Huntington Beach oil and Hamaca Crude. The metallic additives tested were iron, tin and zinc; and they were all observed to improve combustion efficiency. The front velocities were also seen to increase by the addition of metallic salts. Holt also observed changes in H/C ratio of the fuel, heat of combustion, air requirements and density of the produced crude. One of the interesting effects of metallic additives was observed in a light Californian oil. The control run indicated that the combustion could not be propagated due to a lack of adequate fuel deposition; however, the addition of iron caused a dramatic difference with the front being sustained and propagated. The existing literature has so far not addressed the quantitative determination of the influence of metallic additives, and their impact on combustion parameters. As can be seen from the literature, there is also a need to find suitable additives that reduce the amount of fuel deposition, which is a problem in very heavy crudes, causing very large air requirements to sustain combustion.

2.2.3 EXPERIMENTAL APPARATUS

The experimental apparatus is being rebuilt and organized in the new Green Earth Sciences Research Building. It will continue to be the same for the most part, but some minor modifications will be incorporated as required. Following are the main features of the apparatus; details are available in the paper by Mamora *et al.* (1993)

The combustion tube is a 1 m long and 7.6 cm O.D. tube made of 316 stainless steel with 0.041 cm wall thickness. A thermowell is placed along the axis, allowing temperature measurements to be made anywhere along the tube. Two electrical heaters located at 10 cm from the top of the tube are used as igniters. The tube is placed vertically in a thermally insulated pressurized chamber which is externally insulated to reduce heat losses to the surroundings. Air injection is controlled by a mass flow meter. The produced fluids are collected via a separator and condenser. The gases are continuously monitored for the amount of oxygen, carbon monoxide and carbon dioxide produced. A gas chromatograph is used to check for traces of other gases present in the effluent stream. All the measurements, data logging and analyses are controlled by a microcomputer interfaced

with the apparatus (Fig. 2.2.1). Software routines were developed by Mamora *et al.* (1993) to facilitate data analysis on the microcomputer.

A mix of sand, fire clay, oil and water containing a known concentration of metallic additive is packed into a tube. The tube is then preheated to about 60°C to simulate reservoir temperatures by using external heaters. Nitrogen is injected and the igniter is turned on. When the temperature of the igniter reaches about 315°C, air injection is started and nitrogen shut off. The start of combustion is indicated by the gas combustion at the outlet. The igniter is shut off when the combustion becomes stable and the front begins to propagate downwards. At the end of the run, the combustion is quenched by returning to nitrogen injection and the air supply is shut off. This is typically done at 90 cm from the top to avoid damage to the bottom flange.

2.2.4 RESEARCH OBJECTIVES AND METHODOLOGY

The objectives of this study are as follows:

1. Understand the reaction mechanisms involved with the addition of metallic additives.
2. Quantify parameters that affect the combustion reactions (amount of additives, effect of ions, etc.).
3. Try to find suitable additives that lower fuel deposition.
4. Experiment with simple cores (sand plus fixed amount of clays).
5. Use known oil samples, existing laboratory equipment, and perform kinetic runs and combustion tube runs.

2.2.5 STATUS TO DATE

The status of the project is as follows:

1. We are completing review of literature
2. The equipment is in the process of being rebuilt and tested.
3. We expect to perform some calibration runs in the near future.

3.1 STUDY OF STEAM INJECTION IN FRACTURED SYSTEMS (M. Deniz Sumnu-Dindoruk)

3.1.1 INTRODUCTION

This report is a summary of the progress in 1993 for the research project, "Study of Matrix-Fracture Transfer in Steam Injection." The objective of this study is to develop a matrix-fracture transfer function for nonisothermal processes such as steam injection. The first task was to make fine grid simulations with a commercial simulator to determine the sensitivity of certain flow parameters and also to use the simulation runs to decide on the experimental design parameters. This task was completed. The second task was to build the fractured model and to perform steam injection experiments. Building and testing of the apparatus was completed and preliminary runs were made during this period.

The first part of this report consists of the numerical studies, both simulations and analytical heat transfer calculations. The second part is a summary of the experimental apparatus and procedures. Finally, the report concludes with the preliminary experiments and plans for future work.

3.1.2 NUMERICAL STUDIES

Simulation runs and heat transfer calculations are discussed in the following sections.

3.1.2.1 Simulation Runs

Simulation runs were continued to study the sensitivity of the flow process to the relative permeability of the matrix. Table 3.1.1 describes the runs. The initial runs were made by using a set of relative permeability curves typical of a sandstone. Figures 3.1.1a and 3.1.1b show the gas-oil and water-oil relative permeability curves used for the matrix in the initial runs. In this report, they will be referred as base case relative permeability curves.

To investigate the effect of the relative permeability of the matrix on the flow process, the relative permeability curves for Boise sandstone, measured by Saraf (1966), were used for the second sets of runs. Figures 3.1.2a and 3.1.2b show these curves. The recovery comparison for the two sets of data is shown in Fig. 3.1.3. There is a considerable difference between the two cases. The oil recovery is higher in Case 33 (base case) than Case 20p. However, the matrix water-oil capillary pressure curves were not the same for the two cases. To check whether the differences were due to the capillary pressures, the water-oil capillary pressure of the matrix was set to zero for the following two runs, Case 37 and Case 19 (base case). As seen in Fig. 3.1.4, oil recovery is the same for the two cases even though two different relative permeability sets were used. To investigate further, the same water-oil capillary pressure curves but differing relative permeability curves were used in Case 33 and Case 38. The oil recovery, again was the same for both cases (Fig. 3.1.5).

This set of runs confirmed our previous capillary pressure sensitivity studies. Water-oil capillary pressure of matrix was found to be the most important parameter for this flow process. The relative permeability of matrix was found to be less significant.

3.1.2.2 Heat Transfer Calculations

Transient one-dimensional heat transfer calculations were continued with differing boundary conditions and differing insulation layer combinations.

The equation to be solved is the one-dimensional transient heat conduction equation given by,

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha} \frac{\partial T}{\partial t} \quad (3.1.1)$$

where,

T = temperature, °C

x = distance, cm

t = time, sec

α = thermal diffusivity, cm²/sec

The dimensionless form of 3.1.1 was solved for the following six different cases.

Case 1: One-layer (infinite polysulfone), and constant temperature inner boundary condition.

Case 2: Two-layers (polysulfone and fiberfrax, constant temperature inner and outer boundary conditions).

Case 3: Two-layers (polysulfone and fiberfrax, convective inner and outer boundary conditions).

Case 4: Two-layers (polysulfone and infinite fiberfrax), constant temperature inner boundary condition.

Case 5: One-layer (polysulfone, convective outer boundary condition); constant temperature inner boundary condition.

Case 6: Three-layer (polysulfone, polycarbonate and fiberfrax), constant temperature inner and outer boundary conditions.

In all of these cases except Case 3 and Case 5 constant temperature inner and outer boundary conditions were used. The convective boundary conditions used in these cases can be written as,

$$\text{at } x = 0 \quad h_{f1}(T_s - T_1) = -k_1 \frac{\partial T_1}{\partial x} \quad (3.2.2)$$

$$\text{at } x = b' \quad h_{f2}(T_2 - T_\infty) = -k_2 \frac{\partial T_2}{\partial x} \quad (3.2.3)$$

where,

h_{f1} = convective heat transfer coefficient from the inner boundary of the system to the insulation, J/sec cm² °C.

h_{f2} = convective heat transfer coefficient from the insulation to the surroundings, J/sec cm² °C.

k_i = thermal conductivity of each insulating layer ($i = 1, 2$ or 3), joule/sec cm °C.

T_s = steam temperature, °C.

T = temperature, °C.

x = distance, cm

b = thickness of the insulation, cm.

The thicknesses of the polysulfone and fiberfrax layers were taken as 1.2 and 1.27 cm respectively. The method used in the solution of the transient heat conduction equation was LaPlace transformation and the solutions in LaPlace space were inverted by the Stehfest Algorithm (1970). Figure 3.1.6 shows the dimensionless temperature versus time at $x = 2$ cm and Fig. 3.1.7 shows the dimensionless cumulative heat loss at $x_D = 0$.

When we compared the two infinite medium cases, Case 1 and Case 4, it was observed that adding an additional layer of insulation to the system decreased the heat loss. The heat loss in Case 4 is less than in Case 1. Neither a change in the slope of the straight lines in cumulative heat loss plots (Fig. 3.1.7) nor the development of a plateau in temperature plots (Fig. 3.1.6) was observed, indicating that steady state never developed for infinite insulation thicknesses.

For the cases with finite insulation thickness, when we compare the 3-layer solution (Case 6) with the two-layer solution (Case 2), we observe that the heat loss is higher in the 3-layer case, which is unexpected. This is due to the thickness of the third layer, which was decreased in Case 6 to keep the total thickness constant for all cases.

The only differences between Case 2 and Case 3 are the inner and outer boundary conditions. Case 2 has constant temperature inner and outer boundaries, while Case 3 has a convective boundary condition at both boundaries. The heat loss was observed to be less in Case 3 than Case 2 since temperature changes are more gradual with convective boundary conditions due to the extra resistance from the film layer in convective heat transfer.

To check whether the convective boundary solution approaches the constant temperature boundary solution, a sensitivity study was performed on the Biot number. The dimensionless Biot number is given by,

$$Bio = \frac{h_f t_{ref}}{k} \quad (3.1.4)$$

where t_{ref} is the reference thickness for the system, cm

Since h_f for convective transfer from the core holder to the surrounding air is known more accurately, the Biot number was changed by varying h_f of the porous medium. Figure 3.1.8 shows the dimensionless cumulative heat flux versus time for different Biot numbers. There is a considerable difference between the constant temperature boundary solutions and convective boundary solutions for the cases where Biot numbers are small. For high Biot numbers, the convective boundary solution approaches the constant temperature solution. Biot number for a porous medium is generally greater than 100 (Crichlow, 1972), therefore we can assume that we can use constant temperature boundary conditions to model our experimental heat losses.

The above heat transfer calculations were performed to get a feel about the heat losses expected in the experiment. The preliminary experiments which will be discussed later, showed that actual heat losses were less than expected, and the process is more complicated than the simplified one-dimensional calculations.

3.1.3 EXPERIMENTAL APPARATUS

In this section, a detailed description of the core holder, its plumbing and the data acquisition system are discussed.

3.1.3.1 Core Holder

The core holder is made of a temperature resistant plastic, polysulfone. The selection of this particular plastic is based on its superior properties and on the experimental constraints. Polysulfone has a low thermal conductivity which is essential for controlling thermal energy losses. It can also handle high temperatures and our operating pressure (30 psig maximum). Furthermore, polysulfone's resistance to solvents makes cleaning of the model feasible. It also does not create artifacts on scanning. Thermal expansion of polysulfone is also low, which enables us to control the fracture aperture. However, this creates problems when plastic fittings having thermal expansion coefficients greater than polysulfone, like nylon, are used. The fittings can expand at elevated temperatures and can cause cracks in the polysulfone. To avoid this, problem fittings made of PEEK, which has a coefficient of thermal expansion lower than polysulfone, are used on the core holder. It is rectangular in shape and Boise sandstone of dimensions $20 \times 4 \times 10$ cm is placed inside it. Spacers (0.07 cm) made of polysulfone are put between the core and the core holder and the core simulates the fracture.

Front and back plates of the core holder are removable, and a high temperature silicone engine gasket is used to seal the core holder. Polycarbonate plates of 0.5 inch thickness are put on top of the polysulfone plates for extra strength. Twenty 3/8 in. OD bolts made of polycarbonate are used to squeeze the gasket and to seal the model. To avoid bulging of the plates under pressure, four aluminum slabs are assembled on the front and back plates. Figure 3.1.9 shows the front view of the core holder. Side and top-bottom views show the locations of the bolts and supporting plates in more detail (Figs. 3.1.10 and 3.1.11).

Twenty one thermocouples are placed in the core holder to measure the temperatures in both the core and the fracture. Figure 3.1.12 shows the thermocouple

locations. These are placed along the center plane of all the faces of the core holder, is to enable us to scan at both sides of the thermocouple fittings.

Two pressure taps are located at the top of the model (Fig. 3.1.11). These taps will be used as auxiliary wells during cleaning and saturation. There are four wells located at the corners of the core holder at the top. These can be used interchangeably for different injection-production schemes. During a steam injection run, one injector and one producer located diagonally are used. All of the four corner wells are vertical and perforated in such a way that we can inject to, and produce from, the fracture itself. The wells located at the top center plane of the model can produce from the center of the core (Fig. 3.1.11).

Four heat flux sensors are used on the model. One is placed on the top, and the remaining three are placed on the side faces of the core holder (Figs. 3.1.10 and 3.1.11).

Plates made of aluminum were manufactured to assemble the core holder on the scanner table with the help of the bolts and screws. Fire bricks will be placed on the top and bottom of the model and fiberfrax insulation will be cast around the core holder if needed. Fire bricks help eliminate scanning artifacts.

3.1.3.2 Pressure Measurement and Plumbing of the System

Four differential pressure transducers are used to measure the pressure drop along the system. One of the pressure transducers measures the inlet pressure, two measure the pressure at two ports in the core and the last one measures the pressure at the outlet of the model. The locations of the pressure transducers are shown in Fig. 3.1.13.

The pressure transducers should be calibrated prior to each run. To make the calibration process simple, plumbing is such that it is not necessary to remove the pressure transducers while calibrating. The plumbing diagram for the pressure transducers is shown in Fig. 3.1.14.

Two three-way ball valves are used for each pressure transducer. Valve A is connected either to the calibration line or to the pressure port. Valve B is either connected to Valve A or to a loop which applies a zero pressure drop on the transducer. The positive sides of the transducers are connected to the pressure ports and the negative sides are connected to the core outlet. The negative side of Transducer 4 is open to the atmosphere. This enables us to measure the absolute pressure at Pressure Port 4 from which the pressures at the other ports can be calculated.

During calibration, all of the A Valves are open to the calibration source. For applying zero pressure drop on the transducers, Valve B's are open to loop and for applying full scale pressure, Valve B's are open to Valve A's. During the experiment, Valve A's are open to the pressure ports. Two additional valves are used for the pressure. Transducers 2 and 3 to be able to switch the ports, from pressure measurement during an experiment, to production wells during cleaning and saturating the model.

3.1.3.3 Plumbing System for Injection-Production

Figure 3.1.15 shows the flow diagram for injection-production lines. Distilled water is pumped from a water reservoir through a Constametric pump (Pump 1) to a three way valve. This valve is used either to inject cold water directly to the model, or to

a steam generator. Steam from the steam generator is either injected to the model or to a bypass line. This bypass line is used to circulate steam until it is at the desired temperature and pressure. A four-way fitting enables us to measure the pressure and the temperature of the steam in the injection line. All the injection lines are 1/8 in. SS tubing up to the point where they enter the core holder. At that point they are converted to 1/16 in. tubing, and all the lines are covered with fiberfrax insulation.

Produced fluids from the model pass through a condenser and a backpressure regulator. Finally, the effluents are measured by balances.

3.1.3.4 Plumbing for Cleaning and Saturating the Model

Our simulations showed that we need to inject the cleaning fluid at the four corners of the model and produce from the center wells to properly clean the oil from the system. This same scheme should also be used for saturating the model (Fig. 3.1.16).

When saturating the model with oil, Pump 2 is used to pump oil to a three-way valve. This valve passes the oil into the model at four locations with tee fittings. When cleaning the model, either mineral spirits or isopropanol can be injected to the model through Pump 3. During the saturation and cleaning processes, the fluids are produced from the two pressure ports located in the core approximately 4 cm deep.

3.1.3.5 Electrical Connections and Data Acquisition System

Pressure, temperature, heat flux and oil/water production data are measured and recorded during an experiment. The signals from the pressure transducers are sent to the demodulators, from which the analog signals are sent through a cable to a data logger. System thermocouples and heat flux sensor thermocouples are connected to the data logger via thermocouple wires. Heat flux sensor outputs are connected to the same cable that carries the transducer signals through a terminal block located on the cart for the experiment. Output from the balances for oil and water production measurements are connected directly to the PC via two parallel ports. Software written in Quick Basic records and displays the data during the experiment.

3.1.4 PRELIMINARY EXPERIMENTS

To test the experimental apparatus, and to determine the steam injection rates needed to develop a steam zone within a reasonable time, and to analyze the heat losses, the preliminary experiments were done with different steam injection rates.

The core holder was assembled by applying the gasket and the gasket was allowed to set. In the meantime the core was cooked in the oven to deactivate the clays. Then the core was put inside the core holder with the spacers. Vacuum was applied but a leak was detected between the thermocouple wire and the ceramic insulator. The leaky thermocouple was replaced and the model was pressure checked.

Prior to the steam injection experiment, the model was vacuumed for several days. Then carbon dioxide was injected to the system, followed by vacuuming again. Then the model was saturated with deionized water with the help of a gravity head.

Since the custom made staged thermocouples leaked, we had to use only one thermocouple per fitting until they are repaired properly. Therefore the temperature was only measured at 13 points in the model. Fig. 3.1.17 shows the locations of the thermocouples used in the preliminary experiments. Four heat flux sensors were used, one at the top of the core holder and the remaining three at the sides. Heat flux Sensor 1 is at the top of the model (y-direction), Sensor 2 on the injection side face, and 3 and 4 are at the production side face of the model (x-direction). No fiberfrax insulation was put around the model except on the top for this set of experiments, so the heat flux sensors were attached directly to the polysulfone core holder.

Three injection rates were used: 2, 4 and 6 cc/min. The injection pressure of saturated steam was between 14-15 psig, corresponding to a steam injection temperature of 120°C. The production pressure was kept constant at 10-11 psig with a backpressure regulator.

The experiments showed that we were able to see the steam zone development even with the lowest rate used (2 cc/min). Figure 3.1.18 shows the temperature measurements by Thermocouple 13, which is the closest thermocouple to the injector in the fracture. It shows the steam temperature in the fracture. The temperature maps for the different rates used also confirmed the steam zone development also (Figs. 3.1.19a, 3.1.19b and 3.1.19c).

Heat losses from the core holder, recorded by the heat flux sensors for the 2 cc/min run, are given in Fig. 3.1.20. The heat loss from heat flux Sensor 2 is less than for 1 and 4 since it is located where the thickness of the polysulfone is much greater than for the others. The heat loss from the model is less than calculated by the simple models. Figure 3.1.20 shows the comparison between the one-dimensional heat loss calculated by analytical methods and the measured heat loss by heat flux Sensor 2, in the experiment at 2 cc/min rate. More elaborate heat transfer models will be studied to better model the experimental heat losses.

3.1.4.1 Conclusions

Conclusions from the preliminary experiments were as follows,

- The experimental apparatus worked well, the core holder was able to stand the temperature and pressure.
- We were able to see the steam zone development even at the lowest rate. Low rates are preferable for the future Cat scan measurements. Therefore we will use low rates in our next runs.
- Due to the fact that polysulfone has very low thermal conductivity, the heat losses were not as high as we have calculated, even though we did not use fiberfrax insulation around the model.

3.1.4.5 FUTURE WORK

For the next set of experiments, additional thermocouples will be added to the model and the model will be assembled on the scanner table. Saturation measurements

will be made in addition to temperature, pressure and heat flux data. Heat loss calculations will be modified to attempt to match the experimental heat losses.

Table 3.1.1
Description of the Simulation Runs

Case 33	$k_{rel} = k_{relbase}$ and $P_c = P_{cbase}$
Case 20p	$k_{rel} = k_{relboise}$ and $P_c = P_{cboise}$
Case 37	$k_{rel} = k_{relboise}$ and $P_c = 0$
Case 19	$k_{rel} = k_{relbase}$ and $P_c = 0$
Case 38	$k_{rel} = k_{relboise}$ and $P_c = P_{cbase}$

Figure 3.1.1. Base case gas-oil (a) and water-oil. (b) relative permeability curves for the matrix.

Figure 3.1.2 Gas-oil (a) and water-oil (b) relative permeability curves for Boise sandstone measured by Saraf (1966).

Figure 3.1.3 Comparison of oil recovery for different relative permeability sets (P_{cwoil} is not the same for the two cases).

Figure 3.1.4 Oil recovery comparison for different relative permeability sets ($P_{cwm} = 0$ for both cases).

Figure 3.1.5 Oil recovery comparison for different relative permeability sets (P_{cwoil} is the same for both cases).

Figure 3.1.6 Dimensionless temperature vs time for $x = 2.0$ cm.

Figure 3.1.7 Dimensionless cumulative heat loss at $x = 0$ versus time.

- 2-layer, polysulfone + ff, constant temp
- ◆····· 2-layer, polysulfone + ff, convection (bio=bio)
- ◆--- 2-layer, polysulfone + ff, convection (bio=10*bio)
- ♥--- 2-layer, polysulfone + ff, convection (bio=0.1*bio)
- ▲--- 2-layer, polysulfone + ff, convection (bio=0.01*bio)
- ▽— 2-layer, polysulfone + ff, convection (bio=100*bio)
- ∅--- 2-layer, polysulfone + ff, convection (bio=2*bio)

Figure 3.1.8 Dimensionless cumulative heat loss vs. time
(Biota number comparison).

Figure 3.1.9 Front view of the core holder.

2. The calculated heat balance showed a high heat-loss not only to over/underburden rock, but also through produced fluids. Of the cumulative heat injected up to the time of the study, 21% had been lost to over/underburden and 21% through produced fluids.
3. Predicted production schedules indicated that upto 43% of the oil in place (at steamflood initiation) would be recovered by the steamflood.

5.2.4 APPLICATIONS

1. Results indicate that steamflooding is a viable option for tertiary recovery from mature waterflooded reservoirs.
2. Produced fluids carry a large amount of the injected heat. It may be feasible to recover this by using a heat exchange process, to further reduce project costs.

5.2.5 TECHNICAL CONTRIBUTIONS

1. Mature waterflood projects can be converted to steamflooding with good recovery efficiency.
2. Simple analytical methods which can be carried out on a PC-based spreadsheet can provide quick and acceptable estimates of steamflood project performance before resorting to expensive and time-consuming numerical simulation.

Figure 3.1.10 Side view of the core holder.

Figure 3.1.11 Top and bottom views of the core holder.

Figure 3.1.12 Locations of the thermocouples.

Figure 3.1.13 Locations of the pressure transducers.

Figure 3.1.14 Plumbing for the pressure transducers.

INJECTION SIDE

PRODUCTION SIDE

Figure 3.1.15 Flow lines for injection-production system.

INJECTION SIDE

PRODUCTION SIDE

Figure 3.1.16 Flow lines for saturating and cleaning the model.

Figure 3.1.17 Locations of the thermocouples for the preliminary experiments.

Figure 3.1.18 Temperature vs. pore volume, steam injected at rate = 2 cc/min.

Figure 3.1.19 Temperature maps at (a) 2 cc/min, (b) 4 cc/min and (c) 6 cc/min.

Figure 3.1.20 Heat flux vs time for rate = 2 cc/min.

Figure 3.1.21 Comparison of heat flux between the analytical models and the measured experimental heat flux.

3.2 DISPLACEMENT STUDIES USING A THREE-DIMENSIONAL LABORATORY STEAM INJECTION MODEL (Bakul Sharma)

3.2.1. INTRODUCTION

The aim of this research project is to use the SUPRI 3D steam injection laboratory model to investigate the mechanisms of steam and steam foam recovery methods. Computer models of the same processes will be developed using STARS (Steam Additives Reservoir Simulator) compositional simulator, and the results thus obtained will be compared with the experimental ones.

Invented for medical purposes in 1972 (Haunsfield, 1972), CT scanners have been used adversely in petroleum engineering applications. They are a useful tool for insitu saturation, porosity determinations and investigation of core flood experiments. Most of the experiments in which CT scanners have been used to investigate the mechanisms of some EOR processes were carried out in linear models, leading to poor representation of gravity override and channeling. CT scanners were not used for applications with high temperature and pressure, as in the case of thermal recovery processes. Metallic core holders required for laboratory simulation of thermal EOR processes made it difficult to use x-ray absorption techniques. Demiral *et al.* (1992) designed and constructed a three dimensional laboratory model to measure temperature, pressure and heat loss data. The model was designed in a manner such that the construction material was not a limiting factor during scanning.

Demiral *et al.* (1992) carried out runs for water displacement using steam, steam foam without nitrogen, steam foam with nitrogen, and nitrogen foam alone. They made two-phase saturation measurements in the CT scanner. The same experiments will now be carried out for displacement of oil, with three-phase saturation measurements in the CT scanner.

3.2.2 OBJECTIVES

- (a) Making three-phase saturation measurements in the CT scanner.
- (b) Better understanding of the mechanisms of steamflood.
- (c) Better understanding of the surfactant steamflood mechanism.
- (d) Mathematical or numerical modeling of the processes.

3.2.3 EXPERIMENTAL SET-UP

The experimental set-up is shown in Fig. 3.2.1. The injection end has two liquid chromatography pumps to inject water or surfactant solution and to feed the steam generator with distilled water. One extra pump will be added for oil. The 3D steam model with dimensions of 20×20×7.5 cm simulates one quarter of a five spot pattern. Aluminum, Teflon and Fiberfrax have been used as supporting and insulating materials. A top cover helps to compress the sand to assure that there is no gas space above the pack. The injection well system allows injection of steam with a quality of 0 to 100% through the total depth of the well. Heat losses from five sides of the model are measured

using heat flux sensors. Temperature and pressure variation with time can be recorded at three different levels in the model at regular intervals along the flow direction. Sixteen center thermocouples are placed at a level of 3.810 cm from the bottom of the model. Nine top and nine bottom thermocouples are placed at 6.985 cm and 0.635 cm from the bottom. Sixteen pressure taps are located at the same locations as the center thermocouples. The model will be packed with unconsolidated 100 mesh sand. A back pressure regulator maintains constant pressure at the producing corner of the model. A cooler condenses the produced steam. A separator will be added to the cooler outlet for separating oil and water. Water and oil production at the outlet will also be measured.

The CT scanner presently available is an EMI 5005 x-ray scanner. This is a second generation machine allowing energy levels from 80 keV to 140 keV and a 320x320 pixels imaging capability. A modern Pickers 1200 Scanner has been purchased and will be operating by June 1994.

The model can be scanned at six different locations (through the 1.5 cm clearance between the thermocouples) during the experiments. The total scan time for six slices is around 12 minutes. The positioning table indicator is set at the proper distance for each slice location so that the same locations will be scanned each time.

3.2.4 NUMERICAL SIMULATION/PHYSICAL MODEL

The experimental results can be modeled using either numerical simulation or a mathematical model. The compositional thermal simulator, STARS, is available in the Petroleum Engineering departmental computers. We plan to use this simulator for modeling the experimental results.

STARS is a three-phase multi-component thermal steam additive simulator. Grid systems can be defined to be Cartesian, cylindrical or variable depth/thickness in either two or three dimensions. The adaptive implicit option selects the blocks to be solved implicitly in a dynamic manner, based on specific thresholds, or on matrix switching criteria. This option can result in a savings of one third to one half of the execution time. The bottomhole pressure and the block variables for the blocks where the wells are completed are solved fully implicitly. There is a facility for local grid refinement.

3.2.5 FUTURE PLAN

3.2.5.1 Experimental Procedure

- (a) The model will be packed with -100 mesh unconsolidated sand.
- (b) CO₂ will be used to displace the air.
- (c) The model will then be flushed with water to remove the CO₂ in the pores.
- (d) Oil will then be pumped into the system until no traces of water are found at the outlet.
- (e) For the steamflood runs, steam will be injected until oil production is negligible. Temperature, pressure, saturation, heat flux, and production measurements will be made during the flood history.

- (f) Similar measurements will be made for a surfactant steamflood, with surfactant slug introduced at the breakthrough of steam.
- (g) Experiments using steam foam with nitrogen will also be carried out in a similar fashion.

3.2.5.2 Numerical Simulation

A number of sensitivity studies will be made to optimize the grid pattern and number of grid blocks to be used for simulation. This work is planned, keeping in mind the differences observed in gravity override phenomena in the simulation study made by Joshi *et al.*, 1993, which compared with that obtained in the experimental study made by Demiral *et al.* for the same processes.

Results obtained by simulation will be compared with those obtained experimentally.

Figure 3.2.1 Schematic of the experimental setup.

3.3 PORE LEVEL VISUALIZATION OF FOAM/OIL FLOW IN A SANDSTONE REPLICA MICROMODEL (F. C. Woody)

3.3.1 OVERVIEW AND OBJECTIVES

Steam injection is the most widely used enhanced oil recovery technique and is particularly suited for heavy oil reservoirs, where other methods, such as waterflooding, often fail. The injected steam has a much lower density and viscosity than the oil and water it is attempting to displace. This results in severe gravity over-ride and channeling through high permeability zones, leaving the bottom of the formation and low permeability zones unswept. Foams have been used as a method of mobility control in steam floods, mitigating the problems of channeling and over-ride and resulting in an efficient displacement.

At present the basic phenomena by which foam flooding works is not known. In particular, it is unclear under what circumstances injected surfactant forms a stable foam and how it reacts with the oil phase. What is lacking is a quantitative description of foam flooding based on a knowledge of the pore level processes by which the oil is displaced. This understanding can be used to develop a mathematical model of foam flooding that can be used to predict performance at the field scale.

In this project, we will study the pore level processes in foam flooding in a replica sandstone micromodel. The micromodel is an exact representation of a slice through a Berea sandstone etched onto a silicon wafer. It honors the microscopic heterogeneity of the rock, but, being two dimensional, loses some of the continuity of a three dimensional sample.

A novel micromodel fabrication technique has been pioneered at Stanford (Hornbrook *et al.*, 1991, 1992). A high quality photograph of the rock section is digitized. The digital image is manipulated slightly to ensure that there are continuous pathways through the section. The image, which is approximately 500 mm across, is replicated many times to fill an area 5 cm squared. This image is reproduced as a chrome on glass mask. The grains are opaque and the pores are transparent. A coating of photoresist is placed on a silicon wafer. Ultraviolet light shines through the mask onto the wafer. The light kills the photoresist, so after exposure the flow path image exists as clean silicon for the pores, and silicon still coated with photoresist for the grains. A dry etch technique is then used to create the network of pores and grains onto the wafer. The maximum etch depth is between 5 and 30 mm and is controlled by the thickness of photoresist on the wafer. After etching, a glass plate is placed over the wafer by anodic bonding. Two inlet ports and one outlet port are then put in place at opposing corners of the model. Three ports are needed to perform three phase flow experiments where the capillary pressure differences between gas and water and between oil and gas can be controlled independently. Several similar micromodels will be constructed so that the experiments can be run through micromodels with exactly the same pore structure, which enables exact comparisons of the results from different experiments to be made. The manufacturing process is shown schematically in Fig. 3.3.1 and the experimental set-up is shown in Fig. 3.3.2.

Preliminary experiments of foam flow in such micromodels have already been performed on one type of oil and with one surfactant concentration (Hornbrook *et al.*, 1991, 1992). We plan to perform many more experiments on a wide range of oils and

surfactants to assess the circumstances in which foam flooding is effective and to find the pore level processes by which high oil recoveries can be achieved. We will also vary the foam injection procedure, since this can have a dramatic effect on recovery, particularly for the displacement of residual oil.

The observed displacement processes can be coded into a numerical network model. This simulator represents the pore space as an array of pore spaces connected by narrower throats. The position of the fluids is controlled by capillary forces and so it is possible theoretically to compute the capillary pressures at which different displacement events will occur. These predictions can be compared with the observed processes. From simulations of systems containing hundreds of thousands of pores, mesoscopic or averaged properties of the flow can be computed. It is these properties that are used in conventional transport models to predict oil recovery at the field scale. The simulator can be used to predict capillary pressure and relative permeability under different flow conditions, for different foam systems and for different types of pore structure. In particular, the simulator will be used to estimate the residual oil saturation in the presence of foam and the effect of oil and surfactant properties on recovery. The model can be tuned on the experimental data until it can reliably predict the pore scale events seen in the micromodel. The model will test whether or not the conventional characterization of multiphase flow based on saturation dependent relative permeabilities and capillary pressures adequately describes the full range of phenomena seen in foam flow. The final result will be a pore level tool that can reliably predict the averaged displacement properties under a wide range of circumstances and which is not dependent on a particular functional form of the averaged parameters.

3.3.2 EXPERIMENTAL APPARATUS

In addition to the silica micromodels, oils and surfactants, several other pieces of equipment are needed. The principal pieces of equipment required are a high quality reflected light microscope, a video camera, a cassette recorder and a television monitor. The experimental set-up is shown schematically in Fig. 3.3.2.

A new Canon microscope has been purchased for the visualization. It is a reflected light microscope, which when connected to a video monitor, allows pore level processes to be observed, recorded and analyzed.

The television monitor employed is a high definition color model. It will permit the viewing and analysis of the experiment and the analysis of pore level displacement processes.

Figure 3.3.1 Schematic of the manufacture of a silicon etched micromodel.

Figure 3.3.2 Experimental apparatus schematic (after Hornbrook, 1992).

5.1 STEAM DRIVE OPTIMIZATION (A. Garg)

5.1.1 ABSTRACT

Steam drive is employed in heavy oil reservoirs to improve oil mobility by reducing the viscosity of reservoir fluids and provides the additional benefit of producing a hydrocarbon rich vapor phase. The light components are condensed at the condensation front and produced as lower viscosity crude oil. Thus steam drive can be a more efficient and successful method of heavy oil recovery. Though there have been many steam drive pilots and some large-scale operations, an optimization of the steam injection process has not been researched.

The objective of this research is to determine an optimal injection schedule to maximize steam utilization and recovery. This objective is achieved by applying economic conditions on steam drive production performance calculations. The primary steps are:

- 1) choosing a representative steam-drive model to convert heat injection into oil production
- 2) developing an economic model to relate injection and handling costs with gross production revenue
- 3) optimizing the economic function using a multi-variable, non-linear optimization technique

Optimization is used to maximize profit by adjusting the initial conditions of injection rate (w_t), steam quality (f_{st}), and steam pressure (P_s). Therefore, the main efforts have been toward developing accurate oil production rate, steam injection costs and water handling costs as functions of these three parameters.

5.1.2 LITERATURE REVIEW

Several processes for steam drive modeling have been proposed; each incorporate various physical effects. The fraction of heat injected to that remaining in the reservoir is termed heat efficiency and is independent of the model applied, because calculations are made on a per unit basis. However, to predict recovery, models to represent the steam-swept zone are necessary.

There are frontal-advance models where the steam front is vertical and uniformly propagates through the reservoir as injection continues. Marx and Langenheim (1959) relate this definition to a step function temperature profile such that the temperature behind the front is at a constant elevated temperature equal to the steam injection temperature and the reservoir is at the initial temperature ahead of the steam front. Growth of the heated zone is limited only by vertical conductive heat losses.

Hearn (1969) uses the Marx and Langenheim model, however, he includes latent heat and sensible heat transfer at later times. Therefore, the Hearn model produces a smaller steam zone than Marx and Langenheim for equivalent heat injected, because of additional heat losses.

The fundamental deficiency in the above two models is the neglect of gravity override and convective heat transport. Mandl and Volek (1969) consider the heat transport into the oil/water region ahead of the steam front to have a significant effect on the production process. Mandl and Volek include convective heat transport into the region between the condensation front and the production well as an effect on steam zone growth. As long as the latent heat injection rate is greater than the rate of its consumption, heat loss occurring solely from vertical conduction is valid. Yet, at a critical time, t_c , the heat flow in the reservoir is controlled by convection within the reservoir as opposed to conduction to the surrounding strata. Mandl and Volek's contribution was in calculating critical time as a function of the reservoir thickness, temperature and steam quality, then averaging two boundary conditions and solving analytically to estimate steam zone volume.

Myhill and Stegemeier (1978) follow the basic assumptions of earlier models of constant thermal properties, vertical temperature isosurfaces and constant steam injection rate. Honoring both conductive heat transfer to cap and base rock and convective heat transfer within the productive interval, Myhill and Stegemeier used a mathematical model to predict oil/steam ratios. The oil/steam ratio is calculated assuming oil produced is equal to the steam zone volume multiplied by the change in oil saturation. To calculate steam zone volume, they modified the Mandl and Volek equations by using sensible heat fraction of the wet steam as the interpolating factor on the upper and lower bounds.

Acknowledging that a discrete temperature profile has been a constant assumption in previous models, Willman, et. al. (1961) compare a steam drive mechanism to a hot waterflood and conclude that temperature profiles are more distinct with steam injection. They also show that greater recovery is experienced with steam because of distillation, viscosity reduction and oil swelling effects.

The models discussed by Hearn, Mandl and Volek and Myhill and Stegemeier all included additional heat loss effects beyond the fundamental Marx and Langenheim model, however, fail to consider gravity override. Gravity override is a process where steam tends to flow along the top of the reservoir due to a low density fluid being injected into a high density, highly viscous crude. With an increasing oil viscosity, steam will tend to bypass the oil and eventually, this leads to a high temperature zone overlaying the oil zone.

Work conducted by Van Lookren (1983) provides insight about the strong effect of gravity forces on the steam zone's shape. The basic steam zone shape is governed by the value of a dimensionless group of parameters as functions of viscosity, steam quality, density and reservoir thickness. The detailed calculation methods presented are applicable to linear or radial steam drives. The definition of a pseudo-mobility function used in steam zone shape calculations encounters problems at high viscosities. The slope of the front becomes negative at high viscosities, which is unlikely. Van Lookren's work then is most applicable to lower viscosity reservoirs.

Vogel (1984) considered the gravity override phenomenon to be the dominant flow mechanism and generated a horizontal steam front model that progressed downward through the reservoir, sweeping oil from top to bottom. This model, however, is dependent on the relative effects of viscous forces and gravity forces and may not be representative of a thin reservoir where viscous forces dominate.

Gajdica, et. al. (1990) eases the assumptions required to develop an accurate steam zone shape and developed a semi-analytical model that also includes thermal

expansion and compressibility effects. This semi-analytical model was used to estimate the locations of steam and water fronts and calculate the average phase saturations in each zone, and thus the recovery history.

5.1.3 PROGRAMMING THEORY

The program to optimize steam injection has been developed in three stages. The first stage involves programming a representative model to estimate oil and water production performance for adjustable steam injection rates. The second stage relates oil production and steam injection to a revenue and cost schedule for the project. Finally, the third stage applies a nonlinear optimization technique to an objective function based on maximizing profits. A flow diagram representing the current algorithm is shown in Fig. 5.1.1.

5.2.3.1 Steam Performance Model

In steam recovery, efficient heat utilization is ideal to achieve the maximum temperature of oil and quantity of produced fluid. Some of the heat injected is lost through produced fluids and by conduction to strata. Marx and Langenheim considered hot fluid injection into a well at a constant rate and constant temperature. Though the Marx and Langenheim heat loss calculations can be applied to any thermal recovery process, the assumption of uniform temperature in the heated zone equal to the temperature of the injected fluid makes the results more applicable to steam drive processes.

Marx and Langenheim assume that heat losses from a horizontal reservoir are by vertical conduction into adjacent formations. This model is used to calculate cumulative heat injected, heat losses and heat remaining in the reservoir. The calculations come from a heat balance of the system. The traditional application has been to estimate the areal extent of the equivalent heated zone with a constant injection rate; however, Ramey (1959) extended the application to variable injection rates by use of superposition calculations. This corrected areal sweep equation is applicable to any areal geometry and develops area swept as a function of time.

To predict production performance, it is necessary to calculate cumulative oil produced by assuming that the volume of the steam zone is equivalent to the volume of oil displaced. Cumulative oil production can then be translated into oil production rate and a percentage decline is assigned to the production schedule. Holding the total (oil and water) production rate constant, an associated increasing water production schedule is developed. As the Marx and Langenheim heat loss calculation is being utilized, steam zone volume is calculated assuming a vertical steam front. However, this steam zone volume calculation can be modified to incorporate gravity override effects as modeled by other papers in the literature survey. Variation in residual oil saturations within the steam zone that would result from the distillation process of light hydrocarbons have been neglected. Laboratory core experiments would be necessary to quantify the amounts of distillation occurring during heat injection. However, these effects would tend to increase oil recovery, and the resulting production calculations would be moderately conservative.

5.1.3.2 Economics Model

The economics model to be used is based on estimating discounted net revenue. Profit for a proposed steam drive reservoir is a function of the gross revenue less the associated costs. Gross revenue is directly calculated for the current market value of oil multiplied by the oil production. A constant oil price is an input, however, if necessary, oil price can be input as a function of time. The associated costs are steam injection costs and produced water handling costs. Each of these cost terms are reduced to functions of injection rate, steam quality, steam temperature and steam pressure. Based on a discount rate, each year's cash flow is adjusted to a net present value and summed to achieve a discounted net revenue for the lifetime of the project.

5.1.3.3 Optimization Method

The economics model provides a profit equation that is dependent on three parameters: (1) steam injection as water equivalent, (2) steam quality, and (3) steam temperature. These parameters are the optimizing variables necessary to maximize profit. Several methods of optimization are available and are applied depending on the objective function's format. In this situation, profit is the optimizing objective function and since profit is defined incorporating cost schedules, a nonconstrained optimization technique can be applied. Since three parameters are to be optimized simultaneously, a multi-variable analysis is performed. The majority of methods for optimization are iterative, yet, are only useful if the sequence of estimates converges rapidly for the objective function described. For this problem, the Gauss-Newton method of optimization is applicable. Gauss-Newton is a method that uses the sum of squares to optimize a multi-variable, non-linear objective function. If the objective is properly defined to eliminate the need for variable constraints, it is preferable to use methods such as Gauss-Newton. Constrained methods of optimization are available if it becomes necessary to define the limits of optimizing variables.

5.1.4 RESULTS AND WORK REMAINING

The program with steam performance and economic evaluation calculations has been tested with preliminary models to verify the consistency of results. All production streams and revenue calculations appear to uphold the theories discussed. The performance calculations were run with a constant injection rate and a variable injection rate and compared to examples presented by Prats (1982).

The Gauss-Newton optimization technique is a standard algorithm used in a variety of areas. If the objective function is properly defined, convergence to an optimal input array should be produced. Once the optimization has been incorporated into the existing program, results will be tested on field data available from the Kern River and Wilmington steam floods.

Figure 5.1.1 Flow diagram.

5.2 RESERVOIR ENGINEERING EVALUATION OF WILMINGTON STEAMFLOOD (Sameer Joshi)

5.2.1 INTRODUCTION

A new research project was started in September 1993. The research work deals with the economics of thermal recovery processes and extend the previous work of Ramage and Ramey (1986). It deals essentially with the application of Monte Carlo simulation techniques for estimating uncertainty in the input variables used in economic calculations for thermal recovery. The method will be applied to actual field projects for which data has been published. An application has been made to Union Pacific Resources Co. (UPRC), Ft. Worth, Texas for permission to use data relating to their Wilmington steamflood project in Long Beach, California (Lim *et al.*, 1993). It is expected that permission will shortly be granted to use the data as a field example for this research project.

In 1993, a field project dealing with the Wilmington steamflood of UPRC was done. This steamflood project is being carried out in a previously waterflooded reservoir, which makes it extremely interesting from the economic viewpoint. An engineering study which determined an overall energy balance for the steamflood project was designed and carried out. A performance prediction and evaluation study was also done. All calculations were carried out using available analytical methods using a PC based spreadsheet program, without use of any numerical simulator. This work will be presented at the SUPRI-A Annual Industrial Affiliates meeting, 1994 and has also been submitted for publication at professional meetings (Joshi *et al.*, 1994). The main features of the work are summarized below.

5.2.2. DESCRIPTION OF WORK

The Wilmington Steamflood (Lim, *et al.*, 1993) of Union Pacific Resources Co. (UPRC) at Long Beach, CA was initiated in 1989, in a reservoir which had previously undergone waterflooding. Average initial reservoir oil saturation, at start of the steamflood, was 35%.

Field production data were studied, using available analytical methods, to derive an overall energy balance for the steamflood, calculate the steamflood capture efficiency and predict further steamflood performance under different projected operating scenarios. Predicted production schedules from the model were history-matched with the actual production data.

All steamflood calculations were carried out using a PC-based spreadsheet program. Volumetric calculations were done on a Silicon Graphics™ workstation.

5.2.3. RESULTS, OBSERVATIONS AND CONCLUSIONS

1. The capture efficiency of the Wilmington steamflood was calculated at 60%. This is an acceptable value for a steamflood and considered significant, taking into account the fact that the reservoir had previously been waterflooded to a low oil saturation of 35%.

Task 57 - INTEVEP, shall provide DOE with information on the Steam with Additives: field and laboratory research. The research is to reach conclusions about the economic applicability of these additives in increasing the efficiency of the cyclic steam injection and to identify production mechanisms.

**STEAM INJECTION WITH SOLVENT. NUMERICAL SIMULATION OF
LABORATORY TESTS**

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ABSTRACT

In Venezuela during recent years, gasoil has been evaluated as an additive to increase the steam injection process efficiency. The results of laboratory and field tests have shown a significant improvement in the production behavior. Despite these experiences, it is necessary to complement the information with results obtained from numerical simulation studies in order to know injection parameters effects, such as gasoil concentration, schemes and rates of injection, temperatures, etc. and also some mechanisms involved in the process.

In this work, the results achieved in the numerical simulation of displacement test with steam and gasoil are presented. A fully implicit 2-D thermal, three-phase compositional simulator was used to obtain all the data presented in this paper.

The numerical simulation results show a similar oil production performance to those obtained in the displacement tests with injection of gasoil and steam simultaneously. These results indicate rise of the production rate when the solvent concentration increases. They also reveal that the solvent co-injection scheme improves the productivity in relation to the gasoil pre-injection at low temperature. However, when gasoil is pre-injected at higher temperature the oil production performance is similar to the co-injection scheme performance. This can attribute to the favorable temperature effect on the diffusion mechanisms. On the other hand, an increase of the gasoil injection rate causes a productivity reduction.

INTRODUCTION

The heavy oil production in Venezuela has been associated to the steam injection processes and mainly to cyclic steam injection. However, the process efficiency can be enhanced by using different additives¹ such as foaming agents, gases, and solvents^{2,3}, specially the gasoil⁴, the best performing additives in the field tests carried out up to date.

Laboratory tests with a 9 °API Cerro Negro Crude have indicated that injecting steam with small amounts of gasoil as low as 5 % with respect to the initial crude in a sandpack, can substantially increase the oil recovery while high concentrations might conduct to channelling problems. Also, the injection schemes evaluation showed a better production behavior under the co-injection steam-solvent scheme.

Nonetheless, to achieve a better understanding of the process and to detect the existing laboratory limitations and the long periods required for each test, it is necessary to integrate the laboratory

evaluation with a numerical simulation study to extend the scope of the process analysis and to confirm and complement the laboratory results.

For these reasons the objective of this work is to determine the most favorable process injection conditions and to evaluate some potential mechanisms acting in the steam-solvent injection process through numerical simulation using on the STARS simulator.

NUMERICAL SIMULATION-MODEL DESCRIPTION

The results of steam injection processes with gasoil were obtained by means of the numerical simulation of laboratory tests. A bidimensional, multiphase and compositional numerical model capable of simulating thermal process was used. The laboratory cell was represented by a cartesian grid with 15 blocks in horizontal direction and 5 blocks in vertical direction. The laboratory cell had the following dimensions: 31 cm of length and 3.78 cms of width.

As indicated in Fig.1. the injector and the producer wells are located at both ends of the cell. The simulator was used considering three components and three phases: water (aqueous and gaseous), dead oil (oleic) and gasoil (oleic and gaseous).

A validation of the simulation model was accomplished by comparing with results of three laboratory displacement test performed with steam, steam plus gasoil pre-injection and steam plus solvent co-injection. Fig 2. shows the observed and calculated results (history match of the oil production) for the three tests using the relative permeability curve for the water oil system and the restrictions in the fluid production rates as adjusting parameters.

STUDY OF THE INJECTION PARAMETERS

Considering that it is possible to establish some variables in the field such as amount of solvent, scheme injection, temperature, and solvent injection rate it is convenient to evaluate these variables through laboratory tests and numerical simulation in order to identify those conditions that favor, the oil production behavior in the steam/solvent injection process.

Therefore, to knowing the effect of these variables and combining the results obtained from laboratory tests conducted previously would allow to understand the process of steam injection with gasoil.

Following, it will be found the description of each sensibility analysis made in this numerical simulation along with the discussion of the results obtained.

Evaluation Conditions

The established injection parameters used in the simulation runs are grounded on experimental data from steam/solvent displacement tests described by Bruzual⁴. Total injection rate of 4 cc/min was

kept constant for each run. The injected gasoil volume is referred to the initial weight of crude and the injection of gasoil is applied during a given period.

Co-injection scheme consisted in the simultaneous injection of steam and gasoil until the estimated amount of solvent is reached and subsequently the steam alone is injected to complete 4 porous volumes.

In the pre-injection scheme a previous injection of a desired gasoil volume at a reference temperature or at cell temperature is performed. Once the required volume is injected, then steam alone is injected until 4.0 porous volumes are reached.

The selected operational parameters used in the numerical simulation were the following:

Total injected volume	398.4 cc
Injection temperature:	
Co-injection	254°C
Pre-injection	25°C
Steam Quality	0.8
Injection pressure	600 psi

Steam/Solvent Injection Rate: 4 cc/min

Gasoil Injection Rate (Pre-injection): 1 cc/min

Amount of gasoil (% initial crude mass): 2, 5, 10 and 20.%

Effect of the Solvent Amount

In Fig. 3 the effect of varying the amount of injected solvent from 2 to 20 % of the crude oil initial mass in the cell can be observed. While the amount of injected solvent is increased, the recovery of the oil also increases. However, the behavior of the crude recovery as function of the amount of gasoil shows a maximum efficiency at nearly 5% of the gasoil.(Fig.4) This behavior is similar to that observed in laboratory tests.

In previous work, Ziritt and Burger,⁵ Alikhan and Farouq Ali,⁶ Farouq Ali and Abad,⁷ found that the oil recovery depends on the additive slug size.

Effect of the Solvent Injection Scheme.

When comparing the co-injection and pre-injection schemes for 5 % and 10 % of gasoil and steam without gasoil (Fig. 5a and Fig. 5b), it can be observed that the solvent injection scheme affects oil production in a steam with solvent injection process. When gasoil is co-injected, an improvement of the injection profile yields a greater crude recovery as far as the effect of solvent remains. In the

case of the pre-injection, it can also be observed an improvement in the crude recovery, but it is less in comparison to the co-injection case.

The latter results in the solvent co-injection scheme are attributed to the solvent entering along with the steam at the temperature of 254°C, allowing a better mixture with the crude and permitting a higher efficiency of fluid displacement. However, in solvent pre-injection, the gasoil enters at lower temperature (25°C), favoring the creation of channels which do not permit a good crude sweeping. Fig.6a and Fig.6b shows the remaining crude saturation during solvent co-injection at a given time.

These results allow to infer that the solvent injection scheme is highly important in the steam injection process. Shu and Hartman³ confirmed this results in their work.

Effect of the solvent injection temperature.

A sensibility analysis of the gasoil pre-injection temperature was made at two different cell temperature (90 °C and 150 °C). The results of these runs are shown in Fig.7. It can be observed a better production behavior when the solvent injection temperature is elevated. Heating and pre-injecting the gasoil allow to reach a production behavior similar to that obtained with the co-injection scheme. The temperature increase allows a better mixture and diffusion of the solvent in the crude and consequently a better efficiency is achieved in the fluid displacements.

Effect of gasoil injection rate.

In addition, the effect of solvent injection rate on the oil recovery was studied. It was observed that the oil recovery performance for pre-injection scheme is independent from solvent rate, however, a certain degree of dependence in the co-injection scheme was evidenced.(Fig.8). This effect was studied keeping a total fluid rate of 4 cc/min and injecting 1 cc/min of solvent and 3cc/min of steam in a first run and 3cc/mm of solvent and 1cc/min of steam in a second run. The results indicate that the oil recovery decreases at higher solvent rate. It might be due to gasoil fingering, conducting to a poor sweep efficiency.

CONCLUSIONS

The increase of gasoil concentration improves the oil production. However, it can be observed that the process is more efficient for gasoil concentrations around 5%, remaining almost invariable for higher gasoil concentrations.

The co-injection scheme allows to improve the oil productivity more than the pre-injection scheme.

When the gasoil temperature is increased for pre-injection scheme, then the oil production performance is similar to that of the co-injection scheme performance.

An increase of the gasoil injection rate for con-injection scheme causes the oil production reduction.

NOMENCLATURE

2-D	= Two -dimensional
CUMOIL	= Accumulate oil
CO-INJ 1cc	= Co-injection 10%, gasoil rate 1 cc/min.
CO-INJ 3cc	= Co-injection 10%, gasoil rate 3 cc/min.
kcoi2	= Co-injection 2%
kcoi5	= Co-injection 5%
kcoi10	= Co-injection 10%
kcoi20	= Co-injection 20%
kpre5,25oC	= Pre-injection 5% at 25 oC
MOL FRAC	.= Gasoil mol fraction, oleic phase GASOIL
PRE-INJ 25oC	= Pre-injection 10% at 25 oC
PRE-INJ 90oC	= Pre-injection 10% at 90 oC
PRE-INJ 150oC	= Pre-injection 10% at 25 oC
PV	= Fraction of pore volumen
STEAM	= Steam injection without solvent
TEST 1	= Laboratory test 1: co-injection 10%
TEST 2	= Laboratory test 2: pre-injection 10%

REFERENCES

1. Stone, T. and Ivory, J. : "An examination of steam-CO₂ processes", JCPT, (May-Jun. 1987), 64-61.
2. Farouq, A. S. M., and Snyder, S. G. : "Miscible Thermal Methods applied to a Two-Dimensional, Vertical Tar Sand Pack, with Restricted Fluid Entry", JCPT, (Oct.-Dec. 1973) , 64-61.
3. SHU, W. R, and HARTMAN, K. J. : "Effect of Solvent on Steam Recovery of Heavy Oil" SPE 14223, presented at the 60th Annual Technical Conference of SPE, Las Vegas, NV (Sept. 1985) , 22-25.
4. Bruzual, G. J. "Estudio de la Inyección de Vapor con Solvente para la Recuperación de petróleo", Tesis UDO-INTEVEP, Los Teques, Venezuela (Jun. 1990).
5. Ziritt, J. L. and Burger, J. " Combined Steam and Solvent Injection", 1st International Conference on the Future of Heavy Crude And Tar sands", UNITAR (Feb. 7-17, 1982) Caracas, Venezuela, 760-772.
6. Alikhan, A.A. and Farouq, A. S. M.,: "Heavy Oil Recovery by Steam-Driven Hydrocarbon slugs from Linear Porous Media", SPE 5109, presented at the 49th Annual Fall Mtg. of SPE, Houston, Texas, (Oct.-Dec. 1974) .
7. Farouq, A. S. M., and Abad, B. : "Bitumen Recovery from Oil Sands, using Solvent in conjunction with Steam" JCPT, (Jul.-Sept., 1976) , 80-90.

Tabla 1
Cell Characteristics

Length of Cell (cm)	31.0
Width of cell (cms)	3.8
Initial Temperature (oC)	90.0
Initial Pressure (psi)	600.0
Permeability (mD)	1202.0
Porosity (%)	28.6
Initial water Saturation (%)	6.2
Initial Oil Saturation (%)	93.8
Oil Gravity (	1.0122
Gasoil Gravity	0.8762

Fig.1 Grid used in the simulation

Fig.2 Model calibration. Co-injection and Pre-injection of steam with 10% of gasoil

Fig. 3 Gasoil amount effect. Co-injection Scheme

Fig. 4. Optimum Gasoil amount

Fig. 5 a Injection scheme effect - 5% of gasoil.

Fig. 5 b Injection scheme effect- 10% of gasoil

Fig. 6a Oil saturation behavior during co-injection scheme.5% of gasoil

Fig. 6b Oil saturation behavior during pre-injection scheme. 5% of gasoil

Fig. 7 Temperature effect in pre-injection scheme. 10% .of gasoil

Fig. 8 Solvent rate injected effect
Co-injection scheme. 10% .of gasoil

**STUDY ON ROCK AND FLUIDS INTERACTIONS AND THE EMULSION
BEHAVIOR FOR THE TIA JUANA CRUDE/SODIUM SILICATE SOLUTION
SYSTEM AT HIGH TEMPERATURE**

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ABSTRACT

Searching for increases of the oil recovery in steam injection processes, different kinds of additives have been under evaluation either at the laboratory or at the field in heavy oil areas in Venezuela. Among these additives, the alkaline solutions show some advantages associated to their potentiality for natural surfactants production from reactions with the acidic components of the crude oil and consequently for interfacial tension reduction of the system which may contribute to additional oil recovery in addition to the steam thermal effects.

Injection of alkaline solutions before the steam might conduct to favorable conditions for greater crude mobility in those zones not contacted by the steam in previous stimulation steps. Also, an additional reduction of the crude saturation could be achieved in those zones already invaded by the steam. Both phenomena could contribute to increase the crude recovery.

Not only the reactions of the alkalis with the crude organic acids are associated to the alkali solution injection, but also their interactions with the porous medium and the formation water, could be favored by the typically high temperature of the steam injection process. The severity of these reactions depend on the type of alkali applied, the crude characteristics and the mineral composition of the formation. For this reason, the application of an alkaline solution in a steam injection project, implies a laboratory evaluation of the reservoir rock/fluid interactions and the study of the emulsion behavior, among other aspects.

In this work, the results obtained from the evaluation of the different reactions occurring at high temperature between the sodium silicate and crude with high acid number from Tia Juana area, at the East Coast of Lake of Maracaibo, are presented. The results show an interfacial tension reduction in three orders of magnitude, caused by the presence of tensoactive compounds such as sodium naphthenates, observed in the aqueous phase through infrared analysis. The analyses performed before and after the rock reaction with the silicate solution during 10 days of exposure at 260 °C did not show important dissolution effects. It can be remarked that in spite of the significative reduction in kaolinite and increments in smectite, the low percentage of clay (11%) in the rock and the high crystallinity of the smectite, severe problems in the formation are not expected. Finally, the characterization of the emulsions formed at different sodium silicate concentrations, water/crude oil ratios and shear rates, indicate that in general, external crude phase emulsions are yielded at low water/oil ratio (10/90) due fundamentally to volumetric factors. The results achieved correspond to a first phase of an integral study on alkaline solution injection in the steam injection process and they might support the planning of future field steam injection tests incorporating alkaline solutions.

INTRODUCTION

With the purpose of increasing the efficiency of the steam injection process either by reactivation or by generation of additional oil recovery mechanisms, several types of additives including solvents and foaming agents have been evaluated and used. The use of these additives is aimed at counteracting or eliminating negative effects associated to some physical phenomena such as gravity override, heavy fractions deposition and also to heterogeneities in the formation.

Substances, like the alkalis (sodium hydroxide, sodium carbonate) have been tested as additives to the steam injection under the premises that they can react with acidic compounds present in the crudes, especially those with high acid number, producing tensoactive species which could yield spontaneous crude / water system emulsifying, thus thus reducing the interfacial tension and favoring the mobility and wettability. However they may also react with the formation sand, which is one of the factors affecting the alkali consumption [1-6].

Based on their properties, the effects of alkaline solutions injection previous to the steam injection, should be evaluated considering the formation of low viscosity emulsions by in-situ saponification reactions, seeking a higher fluid mobility throughout the producing sand and consequently increasing the sweep efficiency. Also, it is necessary to study the alkaline solution interactions with the formation fluids and the rocks because they can produce negative effects for the steam process due to the possibility of reactions which might conduct to either rock dissolution or insoluble compounds precipitation, increasing or reducing the formation permeability, and influencing the production behavior.

In this work, the results from a preliminary laboratory study on the interactions among reservoir fluids (crude and water), formation sand and sodium silicate solutions are presented. This evaluation was carried out as an initial phase of an integral study on alkaline solutions injection to withstand field tests in heavy oil areas at Western Venezuela.

EXPERIMENTAL DEVELOPMENT

The scope of the study includes the evaluation of all possible interactions occurring in the formation, through experiments out of the porous medium and observation of the production behavior through displacement tests. Because some wells of the Tia Juana area are potential candidates for alkali injection, representative fluid samples of this area were used in the experiments.

The main characteristics of the reservoir fluids and sand, the experimental conditions, and also the laboratory experiences are described in this section.

Fluids and Sand Characteristics

Crude oil samples collected at the Tia Juana Flow Station F-6 were used and its main characteristics are shown in table 1. Production water samples taken after a first steam injection cycle and reference water with high calcium and magnesium cations content were selected and their compositions are indicated in table 2. The alkali solution was prepared with sodium silicate ($\text{Na}_2\text{SiO}_3 \cdot 9\text{H}_2\text{O}$) varying the concentration between 0 and 10,000 ppm. The characteristics of the formation sand of the Tia Juana area can be observed in table 3.

Rocks and Fluids Interactions

Interfacial Tension Behavior and Spontaneous Emulsification

An important and indicative parameter for detecting saponification reactions that could be occurring between the sodium silicate and the crude oil acidics components is the interfacial tension at different conditions for the system under study. The interfacial tension values allow the definition of the low and ultralow interfacial tension ranges. For this reason, interfacial tension measurements were performed at 25, 60 and 80 °C at alkali concentrations varying between 0 and 15000 ppm, using a spinning drop interfacial tensiometer. To verify these interfacial tension results, a set of bottle tests was prepared with Tia Juana Crude/sodium silicate solution system varying the alkali concentration from 0 to 15000 ppm at different temperatures (25, 60 and 80 °C). The spontaneous emulsification phenomenon was evaluated by observing physical changes in each system as function of time.

Crude Oil - Sodium Silicate Reactions.

To verify the formation of tensoactive species from the sodium silicate solution-crude oil reactions at high temperatures, a mixture of these two fluids with a crude/alkali ratio of 1/10 was heated at 260 °C (steam temperature) during 10 days, and subsequently, the aqueous phase was separated and the pH was measured. Then, through infrared and N.M.R analyses, the organic species produced from the saponification reactions were characterized.

Rock/Alkaline Solutions Interactions. Temperature Effect.

One of the aspects requiring more attention in the alkaline solution injection processes is the alkaline solution/rock interactions because these can be detrimental to the process, due to the silica

dissolution, causing negative preferential channels for the displacement. Also, an excessive alkali consumption can be observed with a reduction of the effective amount for a desirable reaction with the crude. Normally, the alkali-rock reactions are favored by high temperatures associated to steam injection processes, either during or after each injection cycle.

The temperature effect was evaluated by determining the silica concentration in solution, before and after a ten (10) days exposure of the alkali-sand system at 40 and 260 °C, which correspond to the original reservoir and the saturation steam temperature at 700 psi, respectively.

Rock/Formation Water/Alkaline Solution Interactions. Divalent Ions Effects.

As in any injection process using a different fluid than formation water, the sodium silicate solution and formation water compatibility must be studied. For this purpose, two water samples with different composition were selected to determine the divalent cations influence on the generation and precipitation of insoluble species, which can cause formation plugging.

A production water with a representative composition corresponding to a first steam injection cycle, and a reference production water with a greater calcium and magnesium ions content, were selected for this study.

Rock/Formation Water/Alkaline Solution/ Crude Oil Interactions. Crude Presence Effect.

The presence of crude oil can influence in some ways the reactions occurrence in the reservoir, by reducing the contact area between alkaline solution and the rock, and/or the formation water, that consequently favors the desirable crude-alkali reactions.

In general, the interactions among different phases were evaluated by determining the concentrations of silicate and calcium in solution for the different systems, before and after being exposed to a temperature of 260 °C, during 10 days. These experiences were performed with a 1500 ppm sodium silicate solution concentration. After each reaction, the rock sample composition was determined by X-ray diffraction analysis for evaluating possible changes with respect to the original composition.

Emulsion Characterization.

Alkali injection in the steam process can lead to a non uniform distribution of the fluids and the alkali concentration at the wells adjacencies. Parameters such as water/oil ratios and shear rate in

some specific zones are determinative for the emulsion characteristics. Consequently, a study oriented to identify the conditions conducting to unfavorable characteristics for the fluid flow in the porous medium should be developed. The emulsion characterization was made through measurements of the variables mentioned as follows:

Type of Emulsion

A qualitative determination of the type of emulsion was accomplished through solubility tests, adding a drop of emulsion into 100 ml of water and observing if the drop is dissolved. In case of dissolution, the emulsion was classified as Oil in Water emulsion or Water in Oil Emulsion if the drop remained indissolved.

Emulsion Viscosity

The viscosity is determined right after the emulsion formation, using a rotational viscometer at 60°C. Also, viscosity is measured at different pressures and temperatures through a Hoake RV-2 high pressures viscometer.

Drop size distribution and emulsion stability.

Measurements of the average drop size and drop size distribution were performed only on the oil in water emulsions with the particles analyzer Malvern 3600. The variation of the drop size and its distribution over the time for different alkali concentrations and water-oil ratios, including the presence of sand, were studied.

To complement the previous results and to establish the conditions and zones of maximum system stability, the emulsion coalesced volumes were measured at different times for samples placed in calibrated tubes.

In general, the emulsions were prepared for water/oil ratios from 10/90 to 70/30 and alkali concentration between 0 and 7000 ppm, applying shear rates of 120 and 1200 rpm at 60 °C. The temperature effect on the emulsion stability was evaluated by keeping them at 25 and 60 °C during 60 days.

RESULTS AND DISCUSSION

The emulsions were prepared for water/oil ratios from 10/90 to 70/30 and alkali concentration between 0 and 7000 ppm, applying shear rates of 120 and 1200 rpm at 60 °C. The temperature effect on the emulsion stability was evaluated by keeping them at 25 and 60 °C during 60 days.

Rock and Fluid Interactions.

Interfacial Tension Behavior and Spontaneous Emulsifications

In Figure 1 the interfacial tension behavior for sodium silicate solutions/Tia Juana crude system at 25, 60 and 80 °C is illustrated. In this figure three zones can be distinguished. One corresponding to alkali concentrations lower than 1000 ppm, where an important reduction of the interfacial tension from initial values above 15 dynes-cm in absence of silicate was observed as consequence of the progressive formation of tensoactive species. The second zone is characterized by ultralow interfacial tension values due to the presence of a greater amount of tensoactive compounds capable of producing a larger interfacial area. Finally, above certain alkali concentrations, increments of the interfacial tension are observed which can be attributed to sodium carboxilate precipitation as an excess of sodium silicate in the system is achieved [7].

Regarding the temperature effect, lower interfacial tension values are obtained at higher temperatures. Additionally, the concentration range associated to the ultralow interfacial tension, become extended as the temperature increases, which favors the reactions. This interfacial tension behavior was validated through the spontaneous emulsification tests with the Tia Juana Crude Oil/Silicate Solution systems. The qualitative results at 25, 60 and 80 °C after 24 hours are illustrated in Figures 2a, 2b and 2c. It can be observed that the silicate concentration range, where the spontaneous emulsification proceeds, is greater at 60 and 80 °C. These results are in concordance with the temperature effect found in the interfacial tension evaluation. The influence of the formation water on the tensoactive generation was evaluated at 60 °C and it is illustrated in figure 2d. comparing the results obtained with distillate water (Fig. 2b) and the formation water tests (Fig. 2d). It is observed a spontaneous emulsifying range displacement towards higher silicate concentrations in presence of formation water and also a reduction of this range is obtained. This phenomenon can be associated to a reduction of the hydroxyl ions concentration by precipitation as calcium and magnesium hydroxides and/or silicates, lowering the formation rate of tensoactive species.

Crude/Alkaline Solution Reaction

The crude/silicate solution interactions were evaluated from the results of the reaction at high temperature (260 °C) during 10 days. The aqueous phase analysis indicated a solution pH reduction

from 11.25 to 10.48, because of the consumption of hydroxyl ions by the organic acids in the crude. Also, sodium naphthenate presence in the aqueous phase was determined through infrared analysis and their formation is attributed to the reactions between the organic acids and the sodium silicate, causing the interfacial tension reductions already mentioned [8].

Rock/alkaline solution interactions. Temperature Effect

Frequently, the reactions between the rock and the alkalis are favored by the high temperatures in the steam injected wells, which normally are above the initial reservoir temperature during and after each injection cycle. The temperature effect was evaluated through variations of the silica and calcium concentrations before and after 10 days of exposure time of the formation sand/silicate solution system at temperatures of 40 and 260 °C.

The pH values and silica and calcium concentrations changes at both temperatures are shown in Table 4 and Figure 3. In general, it can be observed that more severe changes in this parameter are produced at higher temperatures, due to a greater clay dissolution, mainly kaolinite and calcite. This effect can be associated to an important increase of the reaction rate.

The mineralogical changes by the temperature effects in the total rock and the clayish fraction are shown in Table 5, which includes both the original composition and the resulting composition from the alkali-rock reactions at 260 and 40 °C. The results indicate a reduction in the total rock clay content at both temperatures. Additionally, important changes in the clay fraction composition were observed at 260 °C, specially in the kaolinite and smectite content.

These changes are visualized by the diffractograms shown in Figure 4. It can be observed that the kaolinite corresponding peaks almost disappear at 260 °C and the smectite corresponding peaks drastically increase. At 40 °C, minor changes are observed. It can be mentioned that microscopy analysis indicate a higher smectite crystallinity after the reactions at high temperature, which can confer a greater rock resistance for next high temperature processes, such as cyclic steam injection .

Sodium Silicate Solution Influence at High Temperature

Performing a comparative evaluation of the steam and the silicate solution effect on the rock, two experiences were carried out under the same temperature conditions and reaction time, trying to simulate both the pH prevalent values in steam injection and silicate injection processes. The measured silica and calcium concentrations before and after the reactions (Figure 5) indicated a more extensive dissolution of both species under similar pH values (Table 6) as in the steam injection

process. This might indicate that the silicate solution reduce the reaction strength with the sand at these temperatures, so it can be inferred that any damage caused by the silicate solution could be smaller than the damage caused by conventional steam injection.

On the other hand, despite similar modifications of the total clay content in both experiences (Table 7), significative changes in some of the clay types were observed in absence of silicate.

It shall be remarked the important increment of the illite and smectite content in the reaction with water, while the kaolinite practically disappears.

Effect of Divalent Cations

As mentioned, to evaluate the formation water influence on the sand/silicate solution interactions, two samples with different compositions (Table 2) were selected. The pH variations and also the silica and calcium concentration changes are shown in Table 8 and Figure 6. It can be noticed that a silica and calcium concentration increment is generated by the presence of divalent cations in the formation water, which can be attributed to a larger amount of ions sodium from the silicate solution and the formation water, favoring the ion exchange with the calcium on the clay surface and silica from the quartz. Furthermore, the solution pH is reduced as consequence of the reaction between hydrogen and hydroxyl ions on the clay surfaces and by precipitation with calcium ions.

No important modifications of the total rock and the specific clay contents by effect of the formation water were observed (Table 9). This could indicate a more important effect of the temperature on the clays transformation as compared with the formation water composition.

Effect of the Crude Presence

It is also important to know about the rock-fluid interactions as the crude oil is incorporated to the studied systems, for a complete evaluation of all simultaneous interactions among the phases involved in the actual process. Results presented in Figure 7 show that silicate/sand interactions in presence of formation water are reduced in crude presence, as it is indicated by a lower silica and calcium dissolution. This behavior is favorable for the process because the interactions with the rock are reduced, increasing the alkali/crude interactions.

With regard to the total rock, not important changes were observed because of the effect of crude presence .

Emulsion Characterization

Following, the results obtained from the emulsion characterization, thus, emulsion type, droplet diameter distribution, viscosity, and stability are discussed.

Type of Emulsion

Microscope observations and solubility tests were performed to determine emulsion types under the established alkali concentration and water/oil ratios (WOR). These results indicated that below a sodium silicate concentration of 1000 ppm and WOR greater than 20/80, only dispersions were observed, these concentrations are not high enough for tensoactives production and emulsion formation. Water in oil emulsions (W/O) are yield for water/oil ratios smaller than 20/80 and for any alkali concentration, prevailing the volumetric factor over the physico-chemical phenomenon. Oil in water emulsions (O/W) are obtained for water/oil ratios higher than 20/80 and alkali concentrations greater than 1000 ppm.

Drop Size Distribution and Emulsion Stability

The droplet diameter and the emulsion stability behavior of the Tia Juana crude/sodium silicate solution system is represented in Figure 8, which shows the droplet diameter variation as function of the alkali concentration. In general, at low alkali concentrations (less than 1000 ppm) the largest droplet diameters, characteristics of dispersions, are prevalent. For a concentration range between 1000 and 5000 ppm the droplet diameter decreases significantly, being the reduction more abrupt for low water/oil ratios.

For higher concentrations range between 5000 and 7000 ppm, the smallest droplet diameter are predominant and remain practically constant in this range. These results are in concordance with the stability behavior observed through the phase separation tests. At low silicate concentrations a faster drops coalescence, attributed to greater drop diameters, is obtained. As the concentration increases the coalescence rate decreases and it can be observed that at higher water/oil ratios any phase separation is associated to phase sedimentation caused by an aqueous phase excess, instead of the coalescence mechanism. According to the average particle diameter and size distribution, the emulsion stability is not significantly influenced by the temperature.

Emulsion Viscosity

The effect of the water/oil ratio and the alkali concentration on the emulsion viscosity is shown in Figures 9 and 10. Figure 9 indicates that for a given water/oil ratio the viscosity is not affected by

the silicate concentration, for values above 1000 ppm. As illustrated in Figure 10, for any alkali concentration, the viscosity suffers an abrupt reduction as the water/oil ratios increase from 10/90 to 70/30.

As mentioned before for water/oil ratios around 10/90, water in oil emulsions are formed, reaching viscosity values, greater than the original crude oil viscosity. At water/oil ratios larger than 10/90, oil in water emulsions, characterized by viscosities as low as 6 cPs, are prevalent.

In Figure 11, the emulsion characteristics for the Tia Juana crude oil/alkali solution system as function of Na_2SiO_3 concentration and water/oil ratio are summarized. Three main zones can be distinguished, one dispersion zone for alkali concentrations below 1000 ppm and water/oil ratios higher than 20/80, a water in oil emulsion (W/O) zone characterized by high viscosities, within the range of water/oil ratios below 20/80 and for any alkali concentration value, and finally, an oil in water emulsion (O/W) zone for water/oil ratios larger than 20/80 and the whole range of concentration is characterized by a wide range of low viscosity values.

CONCLUSIONS

An important interfacial tension reduction is observed after sodium silicate/crude reactions occur. As the temperature increases, the sodium silicate concentration range associated to the ultralow interfacial tension become extended.

Temperature increments favor sand dissolution, while the crude oil presence reduces this effect.

Although modifications in the clayish fraction were observed, severe problems in the formation are not expected due to the low clay content in the sand (11%).

For water/oil ratios as low as 10/90 water in oil emulsions are formed. Oil in water emulsions with low viscosity are obtained within a wide range of alkali concentrations and water/oil ratios.

These results indicate the high probability for obtaining emulsions with high mobility. However, at low water/oil ratio there is the possibility to obtain water in oil emulsions with high viscosity.

This study shows the importance of evaluating the interactions between the sodium silicate solutions and the reservoir fluids and rocks as well as the emulsion characterization among other aspects, before undertaking any field application.

REFERENCES

1. Rudin J. and Wasan D. T., 1992, "Mechanisms for lowering of interfacial tension in alkali/acidic oil systems. Experimental studies". Colloids Surfaces, V.68, 67.
2. Cooke C. E., Williams R. E. and Kolodzie P. A., Dic. 1994, "Oil recovery by alkaline waterflooding" . J. Pet. Tech., 1365.
3. Chiwetetelu, C. I., Hornof, V. and Neale G., Jul-Ag 1989, "Interaction of aqueous caustic with acidic oils", J. Can. Pet. Tech., V28, No 4, 71.
4. Isaacs C. E. and Smolek K. F., April 1983, " Interfacial tension behavior of Athabasca bitumen/aqueous surfactant systems". The Canadian Journal of Chemical Engineering, V61, 233.
5. Wang J., Li Y. and Zhang J., August 1991, "Study of enhanced heavy oil recovery by hot caustic flooding", 5th UNITAR International Conference on Heavy Crude And Tar Sands, V3, 419.
6. Johnson, C. E., January 1976, "Status of caustic and emulsion methods", J. Pet. Tech., 85
7. Gutierrez, X., 1983, "Estudio de las Variables y Parámetros Fisicoquímicos que Contribuyen a la Formacion y Estabilizacion de Emulsiones de Bitumen Cerro Negro en Agua Alcalinizada con Na_2CO_3 ". Tesis Doctoral, Universidad Central de Venezuela.
8. Manrique E.J., Villalba M., Mendez Z. and Der Sarkissian J., February 1994, "The Effect of Crude Oil Composition on Phase-Rock Interaction: Implications on Formation Damage in the Enhanced Recovery of Heavy Oil". SPE Intl. Symposium on Formation Damage Control . SPE 27391 .

Table 1
Tia Juana Flow Station F-6

API Gravity:	12 °
Acid number:	4.5 mg KOH/gr. crude
Viscosity 60 °C:	1300 cP
Density 60 °C:	0.94976

Table 2
Formation Water Composition (ppm)

Ion	Well LL-4145	Reference
CO ₃ ⁼	< 10	-
Ca ⁺⁺	1.73	39
HCO ₃ ⁻	128	69
Mg ⁺⁺	0.33	155

Table 3
Rock Composition of the Tia Juana Area Sand

Component	Weight %
Quartz	87
Mineral Clays	11
Calcite	2
Total	100

Table 4
pH variation in the aqueous phase before and after reactions.

Temperature °C	pH (initial)	pH (final)
260	11.25	8.11
40	11.25	9.88

Table 5
Effect of Temperature on Rock Composition Variations.

	TOTAL	ROCK			CLAYISH	FRACTION	
	Quartz	Clays	Calcite	Kaolinite	Illite	Smectite	Chlorite
Original	87	11	2	42	11	47	-
260 °C	95	5	-	11	16	68	2
40 °C	95	5	-	29	19	52	-

Table 6
pH variation in the aqueous phase before and after reactions.

	pH (initial)	pH (final)
Na ₂ SiO ₃	11.25	8.11
Water	6.99	9.88

Table 7
Effect of Solution pH on Rock Composition

	TOTAL	ROCK			CLAYISH	FRACTION	
	Quartz	Clays	Calcite	Kaolinite	Illite	Smectite	Chlorite
Original	87	11	2	42	11	47	-
Na ₂ SiO ₃	95	5	-	11	16	68	2
Water	95	5	-	3	21	72	4

Table 8
pH variation in the aqueous phase before and after reactions.

	pH (initial)	pH (final)
Na ₂ SiO ₃	11.25	8.11
Na ₂ SiO ₃ /4145	11.02	8.13
Na ₂ SiO ₃ /Ref.	10.45	8.00

Table 9
Effect of the Formation Water Composition on Rock Composition

	TOTAL	ROCK			CLAYISH	FRACTION	
	Quartz	Clays	Calcite	Kaolinite	Illite	Smectite	Chlorite
Original	87	11	2	42	11	47	-
Na ₂ SiO ₃	95	5	-	11	16	68	2
Na ₂ SiO ₃ /4145	93	7	-	9	15	72	5
Na ₂ SiO ₃ /Ref.	90	10	-	10	16	68	4

Fig.1 Interfacial Tension Behavior. Temperature Effect. Tia Juana Crude/Sodium Silicate System

Fig. 2 Spontaneous Emulsification. Temperature and Formation Water Effect. Time reaction: 24 h
2a. Distilled Water. Temperature= 25 °C

Fig. 2 Spontaneous Emulsification. Temperature and Formation Water Effect. Time reaction: 24 h
2b. Distillated Water. Temperature= 60 °C

Fig. 2 Spontaneous Emulsification. Temperature and Formation Water Effect. Time reaction: 24 h
2c. Distillated Water. Temperature= 80 °C

Fig. 2 Spontaneous Emulsification. Temperature and Formation Water Effect. Time reaction: 24 h
2d. Formation Water. Temperature= 60 °C

Fig. 3 Effect of the Temperature on Silica and Calcium Dissolution

ORIGINAL SAND

Fig. 4 Rock Diffractograms for Different Temperatures

Fig. 5 Effect of Solution pH on Silica and Calcium Dissolution

FIG. 6 Effect the Formation Water on Silica and Calcium Dissolution

FIG. 7 Effect of the Crude Presence on Silica and Calcium Dissolution

Fig. 8 Droplet Diameter as Function of Sodium Silicate Concentration

Fig. 9: Effect of the Alkali Concentration on the Emulsion Viscosity. Temperature= 60 °C, Shear rate= 1200 rpm

Fig. 10: Effect of the Water/Oil Ratios on the Emulsion Viscosity. Temperature= 60 °C, Shear rate= 1200 rpm

Fig. 11: Emulsion Characteristicsa for the Tia Juana Crude/Alkali Solution System as Function of Na_2SiO_3 Concentration and Water/Oil Ratio

THE EFFECT OF CRUDE OIL COMPOSITION ON AQUEOUS PHASE-ROCK
INTERACTION: IMPLICATIONS ON FORMATION DAMAGE IN THE ENHANCED
RECOVERY OF HEAVY OIL

By
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INTEVEP, S.A.

THE EFFECT OF CRUDE OIL COMPOSITION ON AQUEOUS PHASE-ROCK INTERACTION: IMPLICATIONS ON FORMATION DAMAGE IN THE ENHANCED RECOVERY OF HEAVY OIL¹

E. Manrique, M. Villalba, Z. Méndez, J. Der Sarkissian

ABSTRACT

Aqueous fluids are shown to interact strongly with sandstones at elevated temperatures and have been reported to produce formation damage related to dissolution and precipitation of minerals. But the presence of crude oil, along with the crude-oil type, may affect the rate and amount of this chemical interaction. Additionally, if the crude oil has small but important amounts of organics acids (> 2 mg KOH/g oil), these can react with the alkaline solutions to produce "in-situ" surface active compounds. These surfactants can be adsorbed on rock surfaces and alter the wettability of reservoirs rocks.

An experimental study was conducted to examine and predict the effect of crude oil composition on in-situ surfactant production and to evaluate the potential formation damage on friable sandstones of heavy crude oil reservoir — Western Venezuela. The tests were carried out at relatively high temperatures (200°C) of system mineral/crude oil/aqueous fluids and the system crude oil/aqueous fluids. Minerals, crude oils and solutions were analyzed by different analytical techniques before and after reaction took place.

The results from this investigation showed that pH and presence and type of crude oil affect the dissolution of minerals. Experimental evidence suggested a strong reduction of the interfacial tension after the reaction of acidic crude oils with alkaline solutions. NMR, IR and GC/MS analysis indicate the presence of organic compounds in the aqueous phase.

INTRODUCTION

During the recovery processes with steam injection of heavy oil, chemical reactions that play an important role in the mechanisms of production of a reservoir, have been reported. These reactions, under high temperature and pressure conditions may affect the mineral matrix (dissolution and precipitation of minerals) and the crude oil (cracking of some components).

Several researchers have reported the importance of evaluating the effects that the crude oil composition and the presence of minerals may have over the alteration of the crude oil properties [1], in-situ formation of stable emulsions [2,3] and rock wettability [4,5].

¹ This work was presented in the "SPE International Symposium on Formation Damage Control" (SPE Paper 27391). Lafayette, Louisiana; 9–10 Feb., 1994.

Others [6–9] have directed their investigations towards the study of dissolution and precipitation of minerals, and how this phenomenon affects permeability and porosity of a formation. All these studies have led to important knowledge for the design of more efficient recovery processes and for the control of the formation damages.

This study is based on the determination of the effects of the presence of organic compounds in the aqueous phase, over dissolution and precipitation of minerals in a formation. Its purpose is to evaluate the possibility of generating natural surfactants in Boscan Field sandstones, with heavy crude oils from reservoirs where steam injection recovery processes have produced satisfactory results and some organic compounds with superficial activity in the aqueous phase have been determined. Those compounds are responsible of generating a significant reduction of the interfacial tension of the environment. Besides, these experiments may present relevant information about the alteration of the crude oil properties, which may occur during a determined recovery process.

EXPERIMENTAL

For the experiments, 3 kinds of heavy crude oil were used. Their properties are presented in Table 1. Boscan crude oil (A), which belongs to the formation to be evaluated and where the steam injection process did not present satisfactory results. Crude oils B (Eastern Venezuela) and C (Western Venezuela), from reservoirs where the generation of natural surfactants during the process of steam injection is evident.

Mineralogical composition of the sands used in this study (Boscan Field sandstones) is mainly quartz (75–80%), feldspar (10–15%) and clays (5–10%).

The study of the systems crude/aqueous phase (water and sodium hydroxide) and mineral/crude/aqueous phase in steady state, was done in stainless steel microreactors, grade TP-316 (ASTM A-269). These reactors were placed in an oven, during 20 days, at a constant temperature of 200°C. The reaction conditions are described in Table 2.

Once the reactions of the systems crude/aqueous phases are finished, aqueous and organic fractions are isolated in separating funnels with a capacity of 250 ml. The pH and the sulfate concentration in the solution are determined. Besides, iron concentration in this fraction is determined by Atomic Absorption (AA), to evaluate the possible reactivity of the reactor walls. One part of this solution is acidified with hydrochloric acid (HCl, 1N) to pH=1 and then it is extracted with ethyl acetate. The solvent of the extracted organic phase is evaporated, and the remaining is analyzed by Infrared (IR), Nuclear Magnetic Resonance (NMR) and Mass Spectrometry (MS and MS/FAB) to determine the nature of the organic compound present in this phase. In the case where an organic compound mixture is seen in the extract of ethyl acetate, an esterification of the fraction is made to be analyzed by Gas Chromatography and Mass Spectrometry (GC/MS). All the crude oils and each one of its fractions (SARA) are characterized by pyrolysis (FID), simulated distillation and Thermal Chromatography (TC). Saturate and aromatic fractions

of each crude oil are characterized by GC/MS. Through these techniques, changes in crude oil and in each fraction (SARA) after reacting, can be evidenced.

For the case of the reactions in the presence of Boscan sandstones, reacted mixtures are separated by vacuum filtration, using a porous plate filter. Crude saturated sandstones are washed with toluene and dried in an oven at a constant temperature of 80°C, during 45 minutes. Crude oil dissolved in toluene is filtered to separate sand residues, and then it is dried with magnesium sulfate. Finally, after evaporating the solvent at a normal temperature, the separation of each one of the crude oil fractions (SARA) is made. After the solutions react, pH and the concentrations of aluminum, silicon and potassium (AA) are determined, these are a product of the mineral dissolution. The sulfate concentration resulting from the oxidation of sulfur compounds is also determined. Solids are characterized by X-Ray Diffraction (XRD), Thermal Chromatography/Mass Spectrometry (TC/MS) and by Scanning Electron Microscopy, joined with Energy Dispersive Spectroscopy (SEM/EDS). Characterization of the organic compounds present in the aqueous phase as well as the crudes and each of its fractions (SARA), is similar to the one made in the crude/aqueous phase systems.

Besides, interfacial tensions are determined to the crude/aqueous phase before and after they react. For the cases of low tensions (< 1 mN/m) a spinning drop tensiometer is used. For higher tensions (> 1 mN/m) a hanging ring method (Nouy ring method) is used. These measurements are made at 50°C and the heavy crude oils are dissolved at 10% and at 40% in toluene (according to the crude weight) for the cases of the measures in the spinning drop tensiometer and hanging ring, respectively.

EXPERIMENTAL RESULTS AND DISCUSSIONS

Crude/aqueous phase systems

The pH changes seen during the reactions among the different crudes with water and a solution of NaOH (3000 ppm) are presented in Table 3. Besides, sulfate concentrations found in the aqueous phases, after reacting, as a product of the oxidation of sulfur compounds present in the reaction environment, are reported. It is seen that for crude oils with a higher content of sulfur, a higher concentration of sulfates in the aqueous phases are determined, specially during the reactions with NaOH.

Except for the reaction water-crude oil A, in all the aqueous phases, after reacting, the presence of organic compounds, was determined. They are responsible of generating a reduction of the interfacial tension to lower values (20 to 10 mN/m), due to the low concentration of organics present in water, and ultra low values (10^{-2} to 10^{-4} mN/m) for the cases of the reactions with sodium hydroxide. It is important to say that in the solutions obtained after the reaction among the NaOH with crude oils A and B, foam formations are noticed in the aqueous phase, which present a high stability, while in the reaction with the crude C a stable emulsion of crude oil in water is obtained. Figure 1 shows the Infrared spectrum of the organic phase present in the solution obtained after the reaction between NaOH and crude oil B

(non-aromatic carboxylic acids), while Figure 2 presents the organic phase obtained in the solution after the reaction water-crude oil C (aromatic carboxylic acids)

Regarding the pH of the solutions, after reacting, a reduction of them (pH) for the reactions with NaOH, is observed. This shows alkali consumption, due to the interactions occurred with specific acidic compounds that are present in the crude oils. Nevertheless, this tendency was not seen during the reactions made with water. This could be because of the low concentration, properties and the kind of organic species present in the aqueous phases, after reacting with the different crude oils.

Mineral/crude/aqueous phase systems

Table 4 shows the changes in the pH and the aluminum, silicon and potassium concentrations, which came from the minerals dissolution happened during the reactions of the Boscan sandstones, with water in the presence of different crude oils. Besides, concentrations of sulfates present in the aqueous phase can be observed. Just as for the crude/aqueous phase reaction systems, a higher concentration of sulfate, while reactions are made with crude oil with higher content of sulfur, is evidenced.

It could be observed that interactions happening in the reaction system (mineral-crude-water) generate a reduction of the pH of the aqueous phases after reacting, no matter the kind of crude oil, although the analysis made over these solutions by Atomic Absorption show the importance of the kind of crude over dissolution of minerals in this formation. Analysis made over the sands by XRD (Table 5) show a higher consumption of clays, in the presence of crude oils A and C, than the reactions with crude B. Additionally, through the Scanning Electron Microscopy (SEM/EDS) it is observed that, during the reaction with crude oil A a higher precipitation of amorphous minerals over the surfaces of these sands occurs.

After reacting, in none of the aqueous phases the presence of organic compounds was determined. That is why there is no evidence of important reductions in the interfacial tensions (crude-water), before and after reacting, specially for the case of the reaction with the crude A. This indicates that mineralogical composition of the Boscan sandstones inhibits the transference of organic compounds towards the aqueous phase; the contrary of what was observed during the reactions of the crude oils B and C with water, under the same reaction conditions. Nevertheless, these sands act like natural catalysts that reduce the viscosity of B and C crude oils. This suggests that under the studied reaction conditions, Boscan sandstones have lost their catalytic activity over the crude oil (A) of the same formation. Figures 3 and 4 shows the reduction of the viscosity of crude oil C and the change observed in the saturate fraction from this crude (after reacting with water and Boscan sandstones), through the analysis of simulated distillation of crudes and gas chromatography, respectively. This enrichment observed in hydrocarbons C_8 — C_{10} comes from the cracking of the resins of this crude oil, according to the analysis made by pyrolysis FID over each one of the SARA fractions of the same.

As for the effect of the initial pH in mineral-crude-aqueous phase reaction system, Table 4 shows the pH changes and the aluminum, potassium, silicon and sulfate concentrations, produced during the reactions

of Boscan sandstones, with the different crudes, in the presence of NaOH. The sulfate concentrations present in the solution, increase with respect to the reactions made with distilled water, just as it happened in the crude-aqueous phase systems (Table 3), even though it was in superior concentrations due to the presence of these sands. It is evident that during these reactions with the different crude oils, high concentrations of sodium sulfate in solution are produced. Figure 5 shows the infrared spectrum of the aqueous phase obtained after the reaction mineral-NaOH-crude B, which is characteristic of the spectrum of the sodium sulfate [10].

It can be observed that interactions occurred in these reaction systems, in an alkaline environment, cause a reduction of the pH of the aqueous phases, after reacting, and where a higher pH reduction is obtained in the reaction with crude oil A. Just as it was observed during reactions in water, with NaOH the effect of the kind of crude oil over the dissolution of Boscan sandstones could be evidenced; nevertheless, it should be noted that aluminum and potassium concentrations, unlike silicon in the aqueous phase, drastically decrease in relation with the ones determined after reacting with water. This suggests that mineral dissolution (clays and feldspars) in NaOH could be reduced in relation with the one observed in water, due to the chemical reactions between the alkali and the acid compounds present in the crude oils, generating surfactants in the aqueous phase. Additionally, in the analysis of the solids by electrophoretic mobility and TC/MS the adsorption of organic compounds onto rock surface, is evidenced. Figure 6 shows a TC/MS spectrum of the non-aromatic carboxylic acids desorbed from the Boscan sandstones after the reaction with NaOH and crude oil B.

Analysis made by XRD show that the consumption of clays during reactions with NaOH is lower while the acid number of the crude oil grows, and as the same time, these consumption is lower that the one observed during reactions with water; except for the reaction with crude oil A (Table 5). Besides, in the analysis by SEM/EDS the precipitation of sodium sulfate (Figure 7) and amorphous aluminosilicates during reaction, in the presence of Boscan crude (A), is evidenced. This low clay consumption, in the presence of NaOH shows that organic-inorganic interactions (crude-alkali) play an important role in mineral dissolution during secondary and tertiary recovery processes. Nevertheless, additional studies are required to determine, with further details, the phenomena that happen in this kind of systems, including the evaluation of temperature effects, reaction time, and specially, the type of alkali, among others.

It is important to point out that for reactions with the crude oils B and C the presence of organic compounds in the aqueous phase is evidenced. The presence of Boscan sandstones inhibits in some way, due to competition, the alkali consumption of the crude. Therefore, the interfacial tension (1 to 3 mN/m), does not reach the ultra low values observed in the crude/NaOH reactions (10^{-4} mN/m). Figure 8 shows an Infrared spectrum obtained from the extract of ethyl acetate, of the aqueous phase after reacting with Boscan sandstones, in the presence of crude oil B. It can be observed that this spectrum is similar to the one obtained in the reaction system NaOH-crude oil B (Fig. 1). Besides, the reduction of the viscosity of the crude oils B and C, after reacting with NaOH was determined, just as observed in the case of water reactions.

CONCLUSIONS

The presence of organic species dissolved in aqueous phase, play an important role in the dissolution of mineral during recovery oil processes; nevertheless, these effects can vary significantly from one reservoir to another, due to the differences in mineralogy, kind of crude and reaction conditions.

Generation of organic species soluble in aqueous phase after reacting are characteristic, and are related with the properties of each crude oil.

Organic compounds present in the aqueous phase or generated during a determined recovery process, have an important influence in the mineral-crude-aqueous phase interaction system and probably these interactions are interdependent in all the phases of the system.

The presence of organic anions in the aqueous phase reduces the precipitation of new minerals at the conditions studied.

This kind of studies can contribute to the planning and development of improved recovery strategies of crudes which in turn will reduce formation damages.

REFERENCES

1. Monin, J.C. and Audibert, A. "Thermal Cracking of Heavy-Oil/Mineral Matrix Systems." SPE Reservoir Eng. (Nov., 1988), pp. 1243.
2. Schechter, R. S., Jones, G. D., Hayes, M., Cayias, J. L. and Wade, W. H. "Spontaneous Emulsification — A Possible Mechanism for Enhanced Oil Recovery." SPE 5562, presented at the 50th Annual Fall Meeting of SPE/AIME, Dallas, Texas, Sept. 28–Oct. 1, 1975.
3. Bennion, D. B., Chan, M. Y. S., Sarioglu, G., Courtnage, D., Wansleebe, J. and Hirata, T. "The In-Situ Formation of Bitumen-Water-Stable Emulsions in Porous Media During Thermal Stimulation." SPE 25802, presented at the International Thermal Operations Symposium, Bakersfield, CA, February 8–10, 1993.
4. Bennion, D. B., Thomas, F. B. and Sheppard, D. A. "Formation Damage Due to Mineral Alteration and Wettability Changes During Hot Water and Steam Injection in Clay-Bearing Sandstones Reservoirs." SPE 23783, presented at the SPE Intl. Symp. on Formation Damage Control, Lafayette, LA, February 26–27, 1992.

5. Wolcott, J. M., Groves, Jr. F. R. and Hyo-Gule, Lee. "Investigation of Crude-Oil/Mineral Interactions: Influence of Oil Chemistry On Wettability Alteration." SPE 25194, presented at the SPE Intl. Symposium on Oilfield Chemistry, New Orleans, LA, March 2-5, 1993.
6. Mohnot, S. M. and Bae, J. H. "A Study of Mineral-Alkali Reactions: Part II." SPE 13576, presented at the International Symposium on Oilfield and Geothermal Chemistry, Phoenix, Arizona, April 9-11, 1985.
7. Cheng, K.H. "Chemical Consumption During Alkaline Flooding: A Comparative Evaluation." SPE/DOE 14944, presented at the SPE/DOE Fifth Symposium on Enhanced Oil Recovery, Tulsa, OK, April, 20-23, 1986.
8. Mohnot, S. M., Bae, J. H. and Foley, W. L. "A Study of Mineral/Alkali Reactions." SPE Reservoir Eng. (Nov. 1987), pp. 653.
9. Chakrabarty, T., Bridge, D. A., Stark, S. C. and Longo, J. M. "The Role of Mineral Reactions in the Thermal Recovery of Bitumen." Paper No. CIM 92-43, presented at the Cim 1992 Annual Technical Conference, Calgary, June 7-10, 1992.
10. "An Infrared Spectroscopy Atlas for the Coatings Industry." ISBN No. 0-934010-00-5. 1980. pp. 525.

TABLE 1. Crude Oil properties.

Crude Oils	API	Sulfur (% w)	Acid Number (mg KOH/g crude)	S	A	R	A
(A)	8.6	4.231	1.2 - 1.4	29.3	24.7	21.6	21.5
(B)	9.1	3.440	2.0 - 2.5	32.1	30.0	16.2	11.8
(C)	10.4	2.607	4.5 - 5.2	44.3	36.8	9.0	13.0

TABLE 2. Experimental conditions.

Experiments	Amounts of reactants (g)			Time (days)	Temp. (°C)	Pressure (psi)
	Crude Oil	Aqueous phase	Mineral			
Crude/aqueous phase	20	45	-	20	200	300-450
Mineral/crude/aqueous phase	20	45	20			

TABLE 3. Analysis of solutions after the Crude Oil/Aqueous phase reactions.

Crude Oil	Aqueous phase	pH _i	pH _f	[SO ₄ ²⁻] (ppm)
A	H ₂ O	6.12	6.07	2.3
B			5.68	1.2
C			6.52	1.7
A	NaOH	12.67	10.83	37.9
B			10.67	19.3
C			10.95	13.9

[Fe] < 0.1 ppm

TABLE 4. Analysis of solutions after the Mineral/Crude Oil/Aqueous phase reactions.

Crude Oil	Aqueous phase	pH _i	pH _f	[Si] (ppm)	[Al] (ppm)	[K] (ppm)	[SO ₄ ²⁻] (ppm)
A	H ₂ O	6.12	3.73	7	46	260	1855
B			3.48	47	6	346	1694
C			3.35	4	37	212	1635
A	NaOH	12.67	6.52	136	< 0.5	54	4087
B			7.90	117		77	4027
C			7.99	135		25	3814

[Fe] < 0.1 ppm

TABLE 5. Clay content before and after reactions (XRD).

Crude Oil	Clay contents (%)		
	Before reaction	After the reaction with H ₂ O	After the reaction with NaOH
A	10	2	3
B		5	6
C		4	7

Fig. 1. Infrared spectrum of the non-aromatic carboxylic acids presents in the aqueous phase after the reaction of crude B with NaOH.

Fig. 2. Infrared spectrum of the aromatic carboxylic acids presents in the aqueous phase after the reaction of crude C with water.

Fig. 3. Simulated distillation of crude C before and after the reaction with Boscan sandstones in water.

Fig. 4. Gas chromatograms of the saturate fractions (crude C) before and after the reactions with water and with sandstones in water.

Fig. 5. Infrared spectrum of sodium sulfate generated during the reaction of crude B with NaOH.

Fig. 6. TC/MS spectrum of the non-aromatic carboxylic acids desorbed from Boscan sandstones after the reaction with crude B and NaOH.

Fig. 7. SEM micrograph showing the precipitation of sodium sulfate during the reaction of crude A with NaOH.

Fig. 8. Infrared spectrum of the aromatic carboxylic acids presents in the aqueous phase after the reaction of crude B with Boscan sandstones in NaOH.

Task 58 - DOE shall provide INTEVEP with information from research performed by NIPER on light oil ($>20^\circ$ API gravity) steamflooding. The research will include results from a titanium high-temperature, high-pressure steamflood model for determination of in situ dynamic saturation changes during steamflooding using existing NIPER capability in X-ray CT scanning. The saturation profiles, together with temperature, pressure, and electrical conductivity profiles, can then be employed to calibrate the numerical simulators for predictive purposes of steamflooding. Emphasis of the steamfloods will be on oil-wet dolomitic reservoirs that contain high pour point waxy crudes.

LIGHT OIL STEAMFLOOD RESEARCH—SOFTWARE FOR LABORATORY AUTOMATION OF A HIGH-PRESSURE, HIGH-TEMPERATURE STEAMFLOOD LABORATORY

by
David K. Olsen and Syed M. Mahmood

ABSTRACT

The report presents the results of Task 58 research conducted as part of the Annex IV, a Thermal Oil Production Research agreement between the U.S. Department of Energy and the Venezuelan Ministry of Energy and Mines. The National Institute for Petroleum and Energy Research (NIPER) conducts this research under DOE's thermal light oil research program, whose goal is to improve the understanding of light oil production using steam and to help accelerate development and expansion of the resource base recoverable by thermal methods.

NIPER's light-oil thermal research program has two major components: field support for the light oil steamflood being conducted by DOE in the Upper and Lower Shannon Sandstone at the Naval Petroleum Reserve No. 3 (NPR-3), Teapot Dome Field, Wyoming, and laboratory steamflood research. The laboratory research involves construction of a high-pressure high-temperature steamflood laboratory, automation of the laboratory [development of the supervisory control and data acquisition (SCADA) software program, LabWARDEN 2.0], and analysis of the potential for thermal recovery of high pour point crudes from sucrosic dolomitic reservoirs. The report emphasizes the laboratory automation software and its capabilities.

LabWARDEN 2.0 is a menu-driven, user-friendly, general-purpose SCADA program for data acquisition/control/analysis/presentation for laboratory automation. Its features include: run-time system setup and reconfiguration; built-in constraints to eliminate operator errors; real-time graphic display of current and previous data with editing and smoothing; data export to other applications for report generation or animation such as automatic 3-D rotation of data; pictorial display of test status for quick troubleshooting; error and out-of-range audio/video warnings for designated users on a computer network; automatic resetting of instrument(s) to rectify minor problems; and automatic shutdown in emergencies when the operator does not respond. LabWARDEN was developed in anticipation that it would be used in NIPER's high-pressure, high-temperature laboratory and other laboratories where test requirements frequently change.

This work at National Institute for Petroleum and Energy Research was supported by the U.S. Department of Energy under both cooperative agreement DE-FC22-83FE60149 with IIT Research Institute and contract DE-AC22-94PC91008 with BDM-Oklahoma, Inc.

INTRODUCTION

This paper describes research activities defined by Task 58 as part of the Annex IV agreement on Thermal Oil Production Research between the U.S. Department of Energy and the Venezuelan Ministry of Energy and Mines. This research is part of DOE's thermal light oil research program at NIPER, which has the primary objective to maximize the economic producibility of the U.S. oil resources by overcoming technical, environmental and economic constraints that currently limit production. The thermal light oil research program seeks to improve the understanding of light oil production using steam and to use this understanding for accelerating development and expansion of the resource base recoverable using this production technology.

The thermal light oil program has essentially two research components: support for the light oil steamflood field being conducted by the U.S. Department of Energy at NPR-3, Teapot Dome Field, Wyoming, and a laboratory research component. This Task 58 report references an assessment of the NPR-3 light oil steamflood, reported in the literature. NIPER has used pressure, temperature, and analysis of produced fluids in the laboratory to study steam displacement of various crudes, gravity override, fingering, and steam diversion. Stanford University Petroleum Research Institute has shown that determination of in situ saturation by methods like X-ray CT are required to study steam diversion with surfactants (foam). Pressure/temperature data alone were not sufficient to differentiate the diverting agent from steam. After a 1991 review of industrial laboratory steamflood capabilities, a titanium steamflood physical model that included the potential for X-ray CT scanning and simultaneous measurement of temperature, pressure, and electrical conductivity was constructed. The model was designed to operate at representative field temperatures and pressures (550° F and 1,000 to 1,500 psi), a significant increase over previous laboratory operating conditions (max of 450° F and 450 psi). This necessitated rebuilding the laboratory, upgrading facilities, and improved experimental control. Due to health and safety concerns for operating a high-pressure, high-temperature laboratory, and the lack of a suitable location and funding for construction, modifications of the NIPER laboratory have been delayed. Thus the research described in Task 58 has not been undertaken, and the scope of work under Task 58 had to be modified. Construction of a new laboratory has been approved for 1995. In anticipation of a high-pressure, high-temperature laboratory, Task 58 was modified to include the automation of the laboratory [development of a supervisory control and data acquisition (SCADA) software program, LabWARDEN 2.0] and the testing of laboratory subassemblies for use in the steamflood laboratory. This Task 58 report emphasizes the development and capabilities of LabWARDEN 2.0, a SCADA package.

An assessment of the resource base defined as high pour point oil is being conducted but is not complete. The research is aimed at determining if the high pour point Penn grade oils (which command a premium price as lubricating feedstocks) that occur in the sucrosic dolomites of the southern Appalachian Basin could be economically recovered by steam. Current recovery by primary production and limited waterflooding is less than 20%. Production is from stripper wells (<10 B/D) with most wells producing <2 B/D.

RESULTS AND DISCUSSION

Steamflood at Naval Petroleum Reserve No. 3 (NPR-3)

Background

The U.S. DOE operates a marginally economic light oil (32° API gravity) steamflood at NPR-3 that produced 851 B/D, or 44% of the total field production in fiscal year 1993 as shown in Table 58-1 (NPR, 1993; Olsen et al., 1992). The operation, shown schematically in Figure 58-1, tests thermal oil production technology in a very heterogeneous, faulted and highly fractured, shallow (350 to 500 ft), tight (average 63 mD, air permeability) area within two zones referred to as Upper and Lower Shannon sandstone. Reservoir parameters and an estimation of the Shannon's resource are listed in Table 58-2. Steam was used to preheat the reservoir for an in situ combustion pilot conducted in the early 1980s (Sarathi et al., 1994). The in situ combustion pilot was not expanded due to the high volume of air leakage through the fracture system, and the combustion front failed to adequately propagate (inability of the combustion to jump the fractures) combined with the marginal economics caused by the downturn in oil prices in 1986. A pilot steamflood was conducted in 1986 and based on favorable results has been expanded to commercial scale (1992) using five 50 MM Btu/hr steam generators, each steaming approximately 30 acres at a time (10 to 12 injectors and 18 to 20 producing wells/generator). The steamflood flood targets recovery of a fraction of the 144 million barrel resource in the Shannon. Based on the outcome of the field experiments being conducted on a pattern basis, operating procedures for the development of the remainder of the field will be revised.

The low permeability, heterogeneous nature of the reservoir dictated that unconventional steamflood operations be undertaken. These operations have been summarized in SPE paper 25786 (Olsen et al., 1992). Viscosity reduction is the principal recovery mechanism of heavy oil from the unconsolidated heavy oil reservoirs of California (Sarathi and Olsen, 1992; Wu, 1977; Willman et al., 1961). However, the mechanisms for recovery of light oil by steam from the fractured Shannon reservoir include a combination of reservoir repressurization, drainage of the oil from the matrix into the fractures, movement of the steam from the fractures into the rock matrix (displacement). Within the matrix blocks, steam distillation, thermal expansion of the fluid, and dry heat distillation (convection) are included (Olsen et al., 1992).

Analysis of Operations

In June 1994 recommendations were made by the Rocky Mountain Oilfield Testing Center Steamflood Project Team (of which BDM-Oklahoma is a member, along with industrial, academia, DOE, and the field contractor, FD Services) to increase the steam quality to 80 while maintaining the same injection rate for pattern 5A. This increase in steam quality has resulted in additional oil production, but at a higher cost (additional gas to increase the steam quality from 52 to 80). Although the steamflood operates on a commercial scale, behavior of patterns are being evaluated because performance of individual wells is so unpredictable due to the very heterogeneous nature of the low permeability, highly fractured Shannon reservoir. Modifying operations (completion techniques, adjusting steam quality, injection rate, injection pressure, and tailout) are being undertaken to determine the best (most economic) mode of operation.

Tailout is defined as any of the following processes: reduction in steam quality at the same rate, reduction in rate but the same steam quality, water alternate steam, or shut in of the steam injectors. The very heterogeneous nature of the reservoir and the lack of numerical simulators (which can simulate the known geology and operations) mandates that the steamflood be considered as experimental pattern tests. The lessons learned from the Shannon steamflood may be applicable to other low permeability, light oil resources such as the Monterey Shale in California (with billions of barrels of oil) or other pressure-depleted, shallow light oil reservoirs of the Midcontinent or Appalachian Basin.

Steam was initially used to preheat the reservoir to initiate an in situ combustion pilot in 1984. Since the initial steamflood pilots in 1986, two approaches for steam injection have been used. The initial approach injected 80 quality steam (80% steam and 20% water) as measured at the discharge of the steam generator and injected significantly above fracture pressure, which resulted in oil production peaking followed by rapid decline. To reduce costs, the mode of injection was changed in 1993. Steam quality and injection rate were reduced in three patterns (between 47% and 60%, quality steam was injected at or below fracture pressure). Lower quality steam results in significantly less heat being injected into the reservoir. This greatly reduces the cost of gas to fire steam generators.

BDM-Oklahoma, DOE at NPR-3, and FD Services are analyzing field performance and preparing an updated SPE paper for presentation at the SPE/CIM Thermal Operations Symposium scheduled for June 1995 in Calgary, Canada. Depending upon which mechanism(s) of oil production dominate, this low-heat approach may result in better sweep (hot waterflood) and more oil production, but it may also result in adverse economics (lower oil production, lower or negative cashflow because of extended project life, or greater heat loss to the surrounding formations). Loss of oil production is weighed against the much lower cost of steam generation (purchase of less gas to fire steam generators) and lower expense for operations (less water for disposal, fewer pump repairs, lower chemical costs, and less manpower for maintenance). Integration of the cost versus time curve and the oil sales (\$) vs. time curve are being compared. The history of each pattern is complex in that the geological environment is different and oil prices (income) and gas prices (expense) have been dynamic. It is still too early to tell if operation with lower quality steam will adversely affect operations since oil production (although low) is being maintained. With the addition of data from the fourth quarter of FY 1994 operation, the trends in cost of operation should be clearly visible.

BDM-Oklahoma's analysis of pattern data shows the negative impact on oil production caused by implementation of some published steam tailout techniques used in heavy oil steamfloods. The tailout of steam is critical to this marginal steamflood. The operator is trying to determine when and how to scavenge heat and reduce the expense for gas to fire the generators in the Shannon steamflood patterns when nearing the end of their economic life. Field operations were altered by the operator soon after detection of the adverse performance of some of the tailout techniques.

X-Ray Scannable Titanium Steamflood Model

NIPER has used pressure, temperature, and analysis of produced fluids to study steam displacement of various crudes, gravity override, fingering of steam through the formation, and steam diversion. Stanford University Petroleum Research Institute has shown that determination of in situ saturation by methods like X-ray CT are required to study steam diversion with surfactants (foam). Pressure/temperature data alone were not sufficient to differentiate the diverting agent from steam. After a 1991 review of industrial laboratory steamflood capabilities, a titanium steamflood physical model (shown in Figure 58-2) was constructed that included the potential for X-ray CT scanning and simultaneous measurement of temperature, pressure, and electrical conductivity. The model was designed to operate at representative field temperature and pressure, a significant increase over previous laboratory operating conditions. This necessitated rebuilding the laboratory, upgrading facilities, and improving experimental control.

X-ray CT measurements were conducted on a prototype titanium model that balanced wall thickness (a thicker titanium pressure vessel wall absorbs more X-rays and requires a higher energy to penetrate) with pressure requirements for the confining vessel. NIPER's X-ray CT scanner is a Somatom 2, a medical X-ray CT scanner, that normally operates at 80 to 110 Kev. This energy level provides adequate resolution of density to determine fluid saturation in corefloods at low pressure with composites or thin wall metal tube to confine fluids. NIPER conducted a series of experiments using the Somatom 2 to determine minimum wall thickness for the titanium model that would provide acceptable resolution and still maintain a 3:1 safety factor for the titanium vessel (rated at working pressure of 1,500 psi and limited in operating temperature by the internal insulation to 530° F). The titanium tube prototype was systematically machined to a thinner wall thickness, packed with quartz sand, filled with water and air, and rescanned. To be within the safety limits of the metal (accounting for the pressure and temperature ports) minimum wall thickness was determined to be 0.20 inches and would require a minimum X-ray energies of 105 Kev and 140 Kev for adequate image resolution. According to the X-ray tube manufacturer, operating at this energy level will greatly reduce the life of the \$25,000 X-ray tube in Somatom 2 to a few hundred scans, which may be inadequate to complete a full steamflood test. Consequently, using the Somatom 2 scanner was deemed inadequate for imaging the titanium steamflood model.

Laboratory Automation Software—LabWARDEN

Operating the titanium steamflood model (with or without methods to determine changes in saturation within the sandpack) required an updated computer data acquisition control system. As part of the reconstruction of the steamflood laboratory and in anticipation of being able to operate at higher temperatures and pressures, a general purpose laboratory/pilot plant data acquisition/control/analysis/presentation software, LabWARDEN, was developed. The software, LabWARDEN 1.0, a data acquisition & control (DAC) program, was developed to operate on a Macintosh computer and has been used in NIPER's X-ray CT and high-pressure laboratories, and a number of petroleum laboratories since its release in 1993. It is based on National Instrument's LabVIEW 2® language, an object-oriented (OO) dataflow graphical language. LabWARDEN 1.0 software has been described in a two-volume DOE Fossil Energy report that includes the executable code (Mahmood and Olsen, 1993a, b).

Due to the significant advances made in National Instrument's newly released LabVIEW 3[®] language, major revisions of LabWARDEN 1.0 were undertaken to upgrade it to a Supervisory Control and Data Acquisition (SCADA) software package. LabWARDEN 2.0 software now operates on Macintosh, PC, and Sun computers. Our goals in developing this more advanced version of LabWARDEN were to permit a higher level of safe operation, provide greater control of NIPER's high-pressure, high-temperature steamflood laboratory and to develop software that would allow easy adaptation (modification) by others for automation of their system. Specifically LabWARDEN 2.0 is (1) a simple yet powerful automation program that is inexpensive, flexible, easy to use/modify, and capable of monitoring test progress and taking corrective actions automatically when needed; (2) an effective program that does not require a computer workstation for effective utilization; (3) a program that allows interaction with other major software packages to enhance its capabilities, e.g., to automatically open spreadsheets and databases such as Microsoft Excel[®] or Fox Base[®], to transfer data in its preferred format and to plot this data; and (4) a program that allows real-time access to the input and output data so that system setup can be changed and reports can be generated in real time.

LabWARDEN 2.0 is intended for automating systems consisting of several hundred sensors and instruments with electronic control features. For simple systems such as a coreflood with pump, a pressure transducer and fraction collector, LabWARDEN is an overdesign. LabVIEW can easily be formatted with the three drivers to operate the control/data acquisition system. (LabWARDEN can easily be formatted to control this system but was designed to operate more complex facilities.) For simple systems, such as the previous example, system-specific line code programs (even LabWARDEN 1.0) may be adequate and be more cost effective than a SCADA package. System-specific programs are developed to automate a fixed instrumental setup under repetitive operation in which changes are rarely made. For larger and more complex programs, the data input/output displays become cluttered and difficult to decipher. A change in instrumental setup or operational features requires reprogramming and retesting, preferably by the same programmer who originally wrote the program.

Commercial automation packages are favorable, even at a premium price, for very large and demanding systems. Professionally written and thoroughly field-tested/updated, they offer ease of use, greater functionality, and higher reliability; thus these packages are used in the majority of industrial applications. These packages allow for the building of additional applications by reconfiguring parameters with minimal programming by the user. LabWARDEN 2.0 serves the automation needs of systems lying between small scale (a few automation tasks which can be directly programmed) and very large systems (hundreds of automation tasks where time and control are of critical nature, e.g., avionics, which are best served by a commercial SCADA package). LabWARDEN 2.0 offers flexibility because the source code can readily be modified using LabVIEW 3's intuitive yet powerful graphical object-oriented dataflow environment.

Update and Release Notes on LabWARDEN Version 2.0

LabWARDEN 2.0 was tested on Macintosh and PC computers. This SCADA package was developed to improve the safety features, capabilities of the software's automation/control/analysis/presentation features and reliability. LabWARDEN's simple and

intuitive Graphical User Interface (GUI), sequencing, constraining, auto-reset, and remote operation features can be used to reduce operator errors and quickly handle abnormal conditions.

A summary of the LabWARDEN 2.0 and its capabilities were presented at the 1994 SPE Computer Conference. The SPE paper "New Advances in Laboratory Automation Programming" (Mahmood and Olsen, 1994) provides a background in object-oriented programming (OOP), a comparison of various SCADA packages, and a description of LabWARDEN 2.0 capabilities. In FY 1994 the cabling and driver programs (software component controllers) were updated for the following components: Scanivalve pressure sampling system, Mettler balances, Anafaze measurement and control units (a proportional, integral, derivative, PID controller), electrical relays for solenoid valves, ISCO high-pressure pumps (on/off and rate), backpressure regulators, heaters, pressure transducers, thermocouples, flowmeters, tank levels, and hydraulically operated pistons for the titanium steamflood model. Each component is being assembled and tested (100 psi and ambient temperature) with the software where the subcomponents are modular (carts and racks) in anticipation of using the complete system in the laboratory in 1995.

LabWARDEN 2.0 OOP structure (programming style) relies on inheritance and data encapsulation that allows complex assemblies (code) to be developed from repeated use of relatively simple objects (i.e., set of functions, procedures, data, type definitions, arithmetic and/or other operations). OOP permits modules (an independent program segment, like a subroutine) to be written with little knowledge of the code in another module. Modules can be reassembled and replaced without reassembling the entire code. The programs OOP graphical computer language permits easier and faster adaptation than the typical line-code languages such as FORTRAN. The programs look like logic flow diagrams, electrical circuitry, or process layout rather than typical syntax line codes. LabWARDEN offers significant advantages over custom-made programs when flexibility and/or networking is desired, since it is easy to reconfigure during run time and to interact among several remote locations and different types of computer running this program. Since the background of each user is different, hands-on use of LabWARDEN 2.0 to control some of the components (e.g., pumps, valves, etc.) in the sample format of the steamflood laboratory provides for the extensive capabilities of this program. More details of the structure and use of the programming environment, LabVIEW 3.0 can be found in National Instruments User's Manuals and video tape classes (National Instruments, 1993a, b). LabWARDEN 2.0 is currently available in Beta version. Unlike LabWARDEN 1.0, it has not been extensively tested for operating pressurized equipment and does not have a supporting operating manual. Upgrades are only anticipated for BDM-Oklahoma's use in the steamflood laboratory.

The new features in LabWARDEN 2.0 include:

1. Cross-platform compatibility between Macintosh, PC, and Sun computers.
2. Generic ASCII file structure that allows Microsoft Excel[®] or similar software to be used to build or modify applications.
3. Multiple applications can be saved and used alternately.

4. Point-and-click strategy to access, edit, and control all instruments individually or by configuration (e.g., groupwise).
5. Relocatable and independent menus to access all needed functions simultaneously without navigating between facilities.
6. Animated control panel that can be further edited and customized as desired.
7. No reconfiguration required for repetitive runs. The last run's attributes are saved and used as default settings.
8. Standard file dialog boxes to find and select files more conveniently.
9. Error warnings for individual items are shown by blinking icons. The last few error warnings can be viewed by pointing-and-clicking on the icon.

LabWARDEN 2.0 can be used in five ways: pull down or point and click to activate menus (Figure 58-3), from a spreadsheet list of attributes (Figure 58-4), via customized schematics (e.g., Figure 58-5), generic displays or within LabVIEW. From the computer, the attributes of each piece of equipment is constrained and listed [e.g., pump cannot be turned on until a downstream valve is opened or, if programmed, the pump will turn on and slowly increase pressure to a predetermined pressure (physically this requires a pressure transducer between valve and pump) at which time the valve will open and the pump will increase speed to pump at preset flow rate]. The home menus of LabWARDEN and two of its facilities are shown in Figure 58-3. An example of programming from a spreadsheet template file such as Microsoft Excel[®] is shown in Figure 58-4. The electronic board is specified as well as the driver attributes controlling an item. In the third line of Figure 58-4, CT pump No. 7 is connected to channel 0, driver 0 and is assigned an item number (a unique identifying number for the piece of equipment). The maximum (20) and minimum (10) flow rates (ml/min) can be set, as well as high (18 ml/min) and low (12 ml/min) flow rate alarms.

A simplified flow schematic of NIPER's high-pressure, high-temperature steamflood laboratory is shown graphically in Figure 58-5. Pumps can be actuated by clicking on the pump icon and the parameters for flow rate can be set (higher or lower flow rate) from the window of the schematic. In the schematic, two of the pumps (darkened icons) are set at 0.01 and 10 ml/min, respectively. The pump operating at 10 ml/min has an open (darkened icon) valve downstream. The third pump connected to the gas source (light icon) is inactivated (off and at 0 ml/min). The steam heater is "ON" but has the valve downstream (light icon) is shown closed. In this configuration an error message is generated because you cannot pump fluid into the steam generator and have a downstream valve that is closed. If the operator did not respond to the error message, the system progresses to predefined shutdown. Since the program has a temperature scale on the steam generator and its temperature is set for 78°F, it appears that the steam generator has just been turned on and will activate an error message as soon as sufficient pressure is detected. The pressure of 340 psi on the back pressure regulator (BPR) is due to the lower pump which is filling the system at 10 ml/min. Pumping out of the tank on the lower left cannot proceed for long because the tank is empty and shows "0" fluid. This will generate an error message and alert the operator that the tank is empty and corrective action needs to be taken or the system will execute a predefined shutdown sequence.

LabWARDEN also allows the use of a generic display of items (equipment such as a pump, electrically operated valve, float control, etc., each with its unique equipment number) as shown in Figure 58-6. When the icon for the item number is activated the attributes for the item are shown and can be set. Conflicts between equipment (e.g., trying to pump fluid past a closed valve) are addressed through a series of computer-prompted questions when attributes are being assigned (entered into the computer).

Although each of these displays looks different, they interact and are supported in the background by a hierarchy of programming, as shown in Figure 58-7 for a small segment of the NIPER MAIN FACILITY PANEL. Several levels within the program are illustrated. All panels and supporting block diagrams can be generated by the user from the electronic copy of the program. However, printing a complete set of individual panels and supporting block diagrams from the electronic copy of the program may require several days because of the size of the files and the time required on most laser printers. Viewing the electronic copy of LabWARDEN is preferred because the panels and wiring diagrams lose some clarity and detail (the color-coded visual effects) in converting figures into black and white copies for inclusion in this report. The multiple programming methods (pull down, spreadsheet, schematic, generic displays or writing the program in LabVIEW 3.0) within LabWARDEN 2.0 allow users with different levels of programming experience to develop a customized automation system for their specific laboratory.

Main Features of LabWARDEN 2.0

LabWARDEN is a completely integrated package including data acquisition, data analysis, presentation-quality graphics and tables, process control, process monitoring, constraining sequencing, alarms, remote networking, and interapplication communication (IAC). The open architecture of LabWARDEN 2.0 allows further extension of software using LabVIEW graphical language.

LabWARDEN allows run time review and redefinition of data and settings. It provides multiple choices and options for data display. The same data input/output terminals can be used for many instruments. LabWARDEN uses a point and click at the icons (pictorial representation of an item) strategy to select one or more instruments for displaying data. For example, one could choose to display up- and downstream pressures on a single waveform chart for comparison. Then the temperature in the specimen can be displayed on an intensity chart to see thermal front movement. It is also possible to display current data along with one or more previous readings, e.g., to see how fast upstream pressure is building up in comparison to the last test. An instrument's icon with an error condition would blink until the operator clicked on it to read the problem.

More specifically, the LabWARDEN program provides the following features:

1. allows the user to select any number of instruments and specify their parameters for a particular run. The selection can be made during run time, or a previous run instrument configuration can be chosen prior to a run. The devices/instruments can be added/deleted/reset anytime during a run;

2. allows the user to set various sequences (such as startup and shutdown sequence) so that instruments can be reset in proper order;
3. provides a way to monitor instruments so that the user is informed if values go out of a user-specified range;
4. eliminates operator errors by setting constraints so that an instrument cannot be reset if other instruments are not in acceptable states;
5. allows the user to automatically rectify minor problems by specifying what to do if an instrument's value changes abruptly or falls into a warning range, e.g., automatically reset one or more devices to a specified percentage of their current value;
6. allows the user to automatically handle emergencies by specifying an emergency response sequence so that if an instrument(s) value(s) fall outside the acceptable range, or if there is an abrupt change, the devices can be automatically reset to safe operating conditions in an orderly fashion;
7. provides easy access and editing to current and previous data with advanced graphic features; and
8. provides a visual display of the status of a test in progress for quick troubleshooting.

Technical Requirements for Using LabWARDEN 2.0

Users must acquire a licensed version of National Instruments' LabVIEW 3.0 software to legally execute LabWARDEN 2.0. LabVIEW 3.0 requires 5 megabytes of RAM, but 8 megabytes is recommended when running LabWARDEN 2.0. Installation of the total package, which is only needed if further development is intended, requires 24 megabytes of hard disk space. LabWARDEN 2.0 requires 10 megabytes of hard disk space. Each driver, on the average, requires an additional 150 kilobytes of disk space.

Users need to load the driver programs for communicating with unique instruments. These driver programs serve as liaison between a computer and an instrument and incorporate the attributes of the instrument, the cabling, and attributes of the electronic board within the computer as shown in Figure 58-8. LabWARDEN package includes several driver programs as examples (Table 58-3 and Figure 58-9). LabVIEW libraries also contain many driver programs, and more driver programs are available from third-party consulting/software development companies and growing number of user groups. It is very likely that one could find and reuse a preexisting driver. If an instrument communicates in a unique command language for which a driver does not exist, a new program can be written or modified in a few hours (average time for experienced users). LabWARDEN's package contains templates for writing and modifying a driver program. Inexperienced users should seek help for developing a driver program. Limited guidance is provided in the appendix for startup and presentation of results as shown in Figures 58-10 and 58-11. National Instruments provides technical support by telephone, fax, mail or e-mail as part of the LabVIEW software package.

SUMMARY

This report contains two parts: an overview with references to the SPE papers that have been written on the marginal light oil steamflood being conducted by DOE at Teapot Dome Field, Wyoming, and a description of some of the attributes of LabWARDEN 2.0, a SCADA package developed for the automation of NIPER's steamflood laboratory.

The steamflood tests the use of steam to recover 32° API gravity from a highly fractured shallow tight sandstone reservoir. The lessons learned from the steamflood may be applicable to some of the old Midcontinent or Appalachian Basin oil fields or the large Monterey Shale deposit of California.

LabWARDEN 2.0 is available as a Beta copy for use on Macintosh, PC, and Sun computers and will not be supported by further documentation (operators guide). The best method of investigating what LabWARDEN 2.0 can do is to invest the time in a hands-on evaluation of the SCADA package. The program is highly versatile and many of the features can be used in different ways to configure an automation/data collection system for a specific laboratory application where test requirements frequently change. LabWARDEN 2.0 uses the language and platform developed in LabVIEW to accelerate development of an automation/data collection system for a specific application.

REFERENCES

- Mahmood, S. M. and D. K. Olsen, 1993a. *NIPER LabWARDEN, Vol. 1 The Description and LabVIEW® Executable Code of a General Purpose Laboratory Automation Program*. U. S. Department of Energy Report, NIPER-689, September.
- Mahmood, S. M. and D. K. Olsen, 1993b. *NIPER LabWARDEN, Vol. 2, Descriptive Panels and Diagrams for NIPER LabWARDEN Software*. U. S. Department of Energy Report, NIPER-689, DE94000126, September.
- Mahmood, S. M. and D. K. Olsen, 1994. Recent Advances in Laboratory Automation Programming, SPE paper 28231, presented at the Petroleum Computer Conference, Dallas, TX, July 31- August 3.
- National Instruments, 1993a. *LabVIEW for Macintosh, Users Manual*, National Instruments Part Number 320591-01, August.
- National Instruments, 1993b. *LabVIEW for Windows User Manual*, National Instruments Part Number 320534-01, December.
- Naval Petroleum and Oil Shale Reserves, 1991. *Annual Report of Operations Fiscal Year 1991*, U.S. Dept. of Energy Report DOE/FE-0254P.
- Naval Petroleum and Oil Shale Reserves, 1992. *Annual Report of Operations Fiscal Year 1992*, U.S. Dept. of Energy Report DOE/FE-9271.
- Naval Petroleum and Oil Shale Reserves, 1993. *Annual Report of Operations Fiscal Year 1993*, U.S. Dept. of Energy Report DOE/FE-0300.

- Olsen, D. K., P. S. Sarathi, M. L. Hendricks, R. K. Schulte and L. A. Giangiacomo, 1993. Case History of Steam Injection Operations at Naval Petroleum Reserve No. 3, Teapot Dome Field, Wyoming: A Shallow Heterogeneous Light-Oil Reservoir, SPE paper 25786, presented at the International Thermal Operations Symposium, Bakersfield, CA, February 8-10.
- Sarathi, P. S., D. K. Olsen and C. Ray Williams, 1994. Naval Petroleum Reserve No. 3, (NPR-3), Teapot Dome Field, Wyoming: Case History of the In Situ Combustion Pilot Operation, proceedings of the DOE/NIPER Symposium on In Situ Combustion, April 21-22, 1994, U. S. Department of Energy Report NIPER- 02990-94, April.
- Sarathi, P. S. and D. K. Olsen, 1992. Practical Aspects of Steam Injection Processes—A Handbook for Independent Operators, U.S. Dept. of Energy Report NIPER-580 (DE92001070).
- Willman, B. T., V. V. Valleroy, G. W. Runberg, A. J. Cornelius and L. W. Powers, 1961. Laboratory Studies of Oil Recovery by Steam Injection. J. Pet. Tech., v. 13, No. 7, July, pp. 681-690.
- Wu, C. H., 1977. A Critical Review of Steamflood Mechanisms, SPE paper 6550, presented at the SPE Annual California Regional Meeting, Bakersfield, CA, April 13-15.

Table 58-1 FY 1991-93 NPR-3 Production¹

ZONE	Crude Oil (BOPD)			Natural Gas (MCF/Year)		
	FY91	FY92	FY93	FY91	FY92	FY93
Shannon						
Primary	467	417	382	0	0	3,513
Av. Prod/Well, bbl		1.4	1.6			
Steamflood	786	934	851	0	0	0
Av. Prod/Well, bbl		5.1	4.7			
Steele Shale	255	274	179	13,319	16,983	2,609
Niobrara Shale	162	176	127	1,865	5,439	1,467
2nd Wall Creek	403	313	311	2,909,455	2,496,158	2,166,711
3rd Wall Creek	22	26	20	0	0	0
Muddy Sand	12	99	23	272,765	270,249	107,106
Dakota	3	4	3	1,474	608	0
Lakota	5	3	1	11,515	19,998	9,485
Tensleep	131	99	92	0	0	0
TOTAL	2,246	2,345	1,989	3,210,393	2,809,435	2,290,891

¹ See reference Naval Petroleum and Oil Shale Reserves Annual Reports FY 1991, 1992, 1993.

Table 58-2 Shannon Reservoir Properties and Steamflood Resource

	Thickness, ft	Porosity, %	Permeability, mD	Oil saturation, %	Water saturation, %
Upper Shannon					
Bar Margin	10.0	20.1	65	60	35
Interbar	5.3	19.0	33	60	35
Bioturbated Shelf	32.0	16.7	4	45	50
Lower Shannon					
Interbar	3.5	20.2	18	55	40
Bioturbated Shelf	21.4	17.8	3.5	45	50
Original bottomhole pressure (est.), psi (kPa)					340 (2,344)
Present bottomhole pressure, psi (kPa)					5 to 50 (34-344)
Gas-oil ratio, scf/stb (stdm ³ /stock-tank m ³)					32 (5.7)
Reservoir temperature, F (C)					65 (18)
Oil viscosity, 65 F, 18 C					10 cP
Oil viscosity, 250 F, 121 C					12 cP
Oil viscosity, 400 F, 204 C					0.412 cP
Thermal conductivity of reservoir before steamflood				0.975 BTU/ft-hr/ F (1.687 W/m-hr-K)	
Thermal heat capacity of reservoir before steamflood				31.6 BTU/ft ³ / F (2.2 x 10 ³ KJ/m ³ K)	
Upper and Lower Shannon Steamflood, acres (ha)					768 (311)
Upper and Lower Shannon Steamflood, OIP, bbl (m ³)					34,300,000 (5,450,000)
Upper Shannon Steamflood (single bench), acres (ha)					280 (113)
Upper Shannon Steamflood (single bench), OIP, bbl (m ³)					8,300,000 (1,320,000)
Nonfloodable Shannon, acres (ha)					2,452 (992)
Nonfloodable Shannon, OIP, bbl (m ³)					93,400,000 (14,800,000)
Primary Shannon, bbl(m ³)					8,000,000(1,370,000)
Total Shannon, acres (ha)					3,500 (1,416)
Total Shannon, OIP, bbl (m ³)					144,000,000 (22,900,000)

Table 58-3 List of Drivers Developed for High-Temperature, High-Pressure Steamflood Laboratory

DRIVER NAME	TYPE	SAMPLE USE
ANALOG INPUT EXAMPLE	Analog Input	Reads Thermocouples
DIGITAL OUTPUT EXAMPLE	Digital Output	Controls Pump Rate
INDIC. POWER MONTR	Analog Input	Monitors Power Supply
INDC. RS232 DBPR100	Serial Input	Monitors Electronic Backpressure
INDIC. SCANIVALVE	Serial & GPIB I/O	Monitors and Controls Scanivalve
MULTIPLE SCANIVALVE	Serial & GPIB I/O	Monitors and Controls Scanivalve
POWER MONITOR	Analog Output	Controls Power Backup Charger/Battery
RS232 DBPR100	Serial Output	Controls Electronic Backpressure Regulator
RS232 METTLER PJ15	Serial I/O	Monitors and Controls Mettler Balance
RS232 METTLER PJ6	Serial I/O	Monitors and Controls Mettler Balance
RS232 PAROSCIENTIFIC	Serial I/O	Monitors and Controls Electric Pressure Gauge
SLOPE/CURVATURE FINDER	Computational	Detects Abrupt Changes in Parameters
SOLENOID ON/OFF EXAMPLE	Analog Output	Turns Pump On/Off
TIMED ON/OFF EXAMPLE	Clock/Timer	Turns Instruments On/Off at Set Point
TIMER EXAMPLE	Clock/Timer	Turns Instruments On/Off at Multiple Set Points
NIPER DIAGNOSTIC	Computational	Detects Failure and Abnormal Conditions

Figure 58-1 Schematic of Shannon Steamflood at NPR-3

Figure 58-2 Schematic of Titanium Steamflood Pressure Vessel

Figure 58-3 The Home Menus of LabWARDEN and Two of its Facilities

LabWARDEN IPanel Configs														
	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	Parameter ->	Board	Channel	Driver	Item	Cutoff	Cutoff	Warn.	Warn.	Cutoff	Cutoff	Warn.	Warn.	Auto
2	NAME	No.	No.	No.	No.	Max	Min	Max	Min	Accel.	Decel.	Accel.	Decel.	Actions
3	CT pump	7	0	0	0	20	10	18	12	0	0	0	0	
4	Pressure Gauge	0	0	0	1	1000	100	900	200	0	0	0	0	
5	surf temp	0	0	0	3	800	400	700	500	0	0	0	0	
6	surfactant tank	0	0	0	7	300	100	250	150	0	0	0	0	
7	surf feed tank	0	0	0	8	700	300	600	400	0	0	0	0	
8	oven temp	0	0	0	11	200	160	180	170	0	0	0	0	
9	cooler	0	0	0	12	500	100	450	150	0	0	0	0	L;18:999.00:H;
10	Inlet press	0	0	0	14	600	200	500	300	0	0	0	0	
11	Outlet press	0	0	0	15	1000	200	900	300	0	0	0	0	
12	press1	0	0	0	17	500	100	400	200	0	0	0	0	
13	press2	0	0	0	20	450	400	425	410	0	0	0	0	
14	press3	0	0	0	21	100	30	90	40	0	0	0	0	
15														

Figure 58-4 A Copy of LW IPanel Configs Template File. Each application built in LabWARDEN has its own copy of this file to store all the parameters.

Figure 58-5 A Simplified Example of a Customized Display Facility Built in LabWARDEN for a High-Pressure, High-Temperature Thermal Laboratory

SECONDS LAPSED SINCE LAST UPDATE					342	UNFLAG	DONE
ITEM 0	ITEM 1	ITEM 2	ITEM 3	ITEM 4	ITEM 5	ITEM 6	
250.00	135.23	455.00	753.00	127.00	875.00	354.00	
ITEM 7	ITEM 8	ITEM 9	ITEM 10	ITEM 11	ITEM 12	ITEM 13	
936.00	675.00	250.00	250.00	250.00	250.00	250.00	
ITEM 14	ITEM 15	ITEM 16	ITEM 17	ITEM 18	ITEM 19	ITEM 20	
250.00	250.00	250.00	250.00	250.00	250.00	250.00	
ITEM 21	ITEM 22	ITEM 23	ITEM 24	ITEM 25	ITEM 26	ITEM 27	
250.00	250.00	250.00	250.00	250.00	250.00	250.00	
Blinking Interval: 10			SET TO UPDATE IN: 5 SECONDS				

Figure 58-6 The "LabWARDEN Display Facility," a Generic Display Facility Readily Used by Any Application in LabWARDEN.

The diagram illustrates the NIPER Sort Emergency Panel, which is a sub-panel of the Main Facility Panel. The Main Facility Panel is shown at the top, featuring a large display area and a control panel with various buttons and indicators. The NIPER Sort Emergency Panel is shown below, with a control panel that includes a 'SET VALUE' field, 'ACTIVATE' and 'ONLY WITH' buttons, and a 'SIMULATION' button. The diagram also shows the internal logic of the NIPER Sort Emergency Panel, including a 'NIPER SORT EMERGENCY' block and a 'NIPER SORT EMERGENCY' block. The diagram is labeled 'DIAGRAM FOR SORT EMERGENCY PANEL'.

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Figure 58-8 The Drivers and Software Developed is Only Part of the Automation of Equipment. The Boards are the Bridges Between Equipment and Computer.

Figure 58-9 Front Panel of "Library of Indicator Drivers"

Figure 58-10 Sample Plot of Data Exported from LabWARDEN into Microsoft Excel for 3-D Display of Data (Axis are not labeled.)

Figure 58-11 Sample display of data of pressure gradient (psi) versus time (seconds) from the series of 28 pressure transducers inside of the titanium steamflood model as pressure is slowly bled off at one of the endcaps.

APPENDIX

LabWARDEN 2.0 Operation

The best way to preview the software other than by using it is to detail the steps involved in performing some important functions. The following is a sample of the step-by-step procedure for selected operations in LabWARDEN. All the procedures describe below assume that you have already clicked on the LabWARDEN icon, which opens the LabWARDEN menu for further action (Figure 58-3). The HELP window is always available from this menu or can be installed as an optional pull down window. The HELP window supplements this very cursory introduction to LabWARDEN 2.0.

Configure LabWARDEN for a Steamflood Laboratory

1. If you have run a similar test before, skip this step.

If this is the first time you are running this test, you may have to load the instrument driver programs which were not previously loaded in LabWARDEN. To load drivers, press CONFIGURE NEW SETUP button (Figure 58-3), which will open a dialog. Press LOAD DRIVERS button in the dialog box to open the control and indicator driver files.

- (a) Select LIBRARY OF INDICATOR DRIVERS VI and press +F to show its diagram (Fig. 58-9).
- (b) View each frame to see if the needed driver already exists for your instrument. If it does, skip to step 2. You do not need to load the driver again. In any event, note the frame number in which an instrument's driver resides for later reference.
- (c) Go to the last frame.
- (d) +Click anywhere on the border of the last frame and select the DUPLICATE FRAME option from the pop-up menu.
- (e) In this newly created frame, +Click anywhere on the icon inside the box and successively select REPLACE and VI... from the two pop-up cascading menus. This will open a file dialog box. Search the various folders to locate the Driver VI's name and double click on it. This will replace the icon in the newly created frame with the icon of the driver. Note the frame number for this driver.
- (f) Load more drivers if desirable using steps b through e. When all the drivers are loaded, save and close the VI.

(Note: The driver programs are provided by vendors and/or are available from the LabVIEW libraries. If you can not find a suitable driver, develop one yourself or with the help of National Instrument's Technical Staff, who can also refer you to a user group or consultant).

2. Find and click on LW IPanel Configs Template file. The template will have column headings. Type in the name of each read-only instrument and its required attributes (Figure 58-4), then name and save the file. Note that the Driver No. is the frame number in which the driver is loaded in Library of Indicator Drivers VI. This file can be opened and edited in many commercial programs including TeachText.
3. Follow steps 1 and 2 above for control instruments. Use the same procedure except that this time load drivers in Library of Control Drivers VI in step 1 and open LW CPanel Configs Template file in step 2.

The successful completion of the above three steps will configure LabWARDEN for your system. Notice that there is only one way to accomplish this. The system could also be configured from within LabWARDEN using the data acquisition module or the display module. The data acquisition module allows for entering data in the FORM format where the user fills in the blanks or updates default values. The display module enables point and click on the pictorial icon to select each instrument one by one to enter its data, or its own tables are used for convenient data editing.

Run Automation for a Steam-Foam Test

1. Press RUN AUTOMATION button on LabWARDEN main menu (Figure 58-3a).
2. A dialog box will appear showing the names and the last modification date of the configuration files used in the last run. Press OK if the run is being repeated. If this is a different run than the last run, press SELECT NEW FILE button which will open the file dialog box with the default folders file. Select the desired configuration files (which you are expected to have already created in section A above).

The successful completion of steps 1 and 2 will begin the automation process. The AUTOMATION MENU BAR (Fig. 58-3b) will appear. If the configuration contains a startup sequence, the control instruments will begin to reset in the defined order. The reset of any instrument when it is waiting for countdown can be canceled, or the startup of all the remaining instruments can be canceled at any time. If there is an error during startup, it will be displayed in a dialog box.

The data is written in generic ASCII Files as soon as it is read, and it can be accessed immediately through any commercial software that can handle TEXT format. An example of data display in Microsoft Excel is shown in Figure 58-10. This figure is a plot of the temperature response from three thermocouples, S1 to S3 over a 20-minute time period. The heating and cooling of each of the thermocouples could be displayed as a table or schematically as shown in Figure 58-10. The data can also be examined at any time using LabWARDEN facilities.

Anytime during a run, the instruments can be reset by clicking on the MANUAL RESET button on the AUTOMATION MENU BAR. This opens a window very similar to the display facility window (Figure 58-6). An instrument can be reset through this window by

pointing and clicking on the icon and typing in the new control value in the pop up box that appears. Alternatively, a set of instruments can be reset by changing their values within the icon and pressing the GO RESET NOW button.

Review the Test Status During a Test

Press the TEST STATUS button on the AUTOMATION MENU BAR (Figure 58-3b). This will open a display VI such as NIPER DISPLAY FACILITY (Figure 58-5) or LabWARDEN DISPLAY FACILITY (Figure 58-6). The NIPER DISPLAY FACILITY has been animated and changes its icons according to the status of an instrument, besides displaying numeric value of the data. The instruments which have experienced system or test errors (such as communication or limit error) will have blinking icons. Clicking on a blinking icon will display the error for the instrument. Clicking on the UNFLAG button will save the errors in the error log file with date and time stamp, e.g., LW ERRORS ON 4/25/94; 8.38 AM followed by instrument name and error message. Only the five latest errors for each instrument are kept in buffer, the rest are logged in the file and can be viewed anytime using TeachText or other commercial word-processing software.

Review Test Data

The data from a recent test in progress or one of the previous tests can be plotted with a variety of options, or it can be exported to a commercial spreadsheet or graphic program. The set of instruments for which data is to be displayed can be selected by pointing and clicking on the instrument icons. This allows for comparison between two or more instruments or between data from a recent test versus previous tests. An example of data automatically exported and plotted in Microsoft Excel® is shown in Figure 58-10. The following session is an example of graphing data in LabWARDEN:

1. Press REVIEW EX-DATA button on the LabWARDEN main menu bar (Figure 58-3a). It will open up the menu bar for the LabWARDEN GRAPHIC FACILITY (Figure 58-3c). Select REVIEW EX-PLOT opening a window similar to that shown in Figure 58-11 (shading depicts actual color program display).
2. Select the type of plot. An X-Y graph is the most common option.
3. Select a run number to display. The LAST RUN# display shows the number of run in the current file.

Develop a Custom-Made Pictorial Representation of the System

Pictorial representation is entirely optional. It does not add functionality to the automation process, but it does make its operations simpler and more comprehensible. It can truly display every aspect of information by pointing and clicking on the desired instrument(s) icon, or by viewing the process in entirety. The pictorial representation gives a better feeling of the status of the test. Figure 58-5 is a customized pictorial display of NIPER's high-pressure, high-temperature thermal laboratory under construction.

The generic display facility shown in Figure 58-6 can be used readily by any user and does not require modification. To animate a generic display facility for a specific test configuration, the following steps are required. These steps involve copying the pictures from Canvas[®] or other drawing programs and pasting them into the generic facility:

1. In Canvas or a similar program, sketch an outline of the process. Then draw or copy icons for various instruments. For animated displays, more than one copy of the instrument is needed to depict different instrument status; e.g., a pump may require two—a grey colored one for OFF position and a red color one for ON position.
2. Copy each icon one by one from the sketch to the clipboard and paste it into its corresponding icon and frame number; e.g., the icon for the ON position of a pump, item no. 3 in the system, is pasted into the Name 2 icon, frame 1 (presuming that the frame 0 was assigned to the OFF position). After pasting all the frames for this item, give it a suitable name; e.g., SURFACTANT INJECTION GROUP.
3. After copying the icons for all instruments, delete any excess icons from the generic display.
4. Copy and paste the remaining outline pictures (the nonanimated ones, e.g., pipes, tees, etc.) one by one into the free space in the generic display.
5. Rearrange the pictures and icons according to the original outline in Canvas to depict the process.

Steps 1 through 5 will make the generic display into a custom-made display similar to the one shown in Figure 58-5. There is no reprogramming involved. One could save many custom-made displays for different processes and recall the one needed for the current test.

Task 59 - INTEVEP shall provide DOE with information on the Modelling of Thermal Processes. The effort will include the use of any refinements and dominant decomposition techniques in order to enhance modelling capabilities of steam processes.

DOE/MEMV AGREEMENT, ANNEX IV

**IMPROVEMENTS IN THERMAL RESERVOIR
SIMULATION. Formulation for a Hybrid Grid Refinement**

Pedro Vaca

June 1994

SUMMARY

In this report we present the results obtained in Task 59 of the DOE/MEMV Agreement, Annex IV, regarding the improvements on simulation of thermal processes. Specifically we present the improvements obtained by the implementation of the capability of Local Grid Refinement (LGR) in a thermal reservoir simulator. Even if the improvement involves cartesian refinement as well as radial, our attention will be put on the radial one. All the features regarding cartesian refinement are implicitly contained in the description of the radial.

Unless the properties of the fine grid are assigned by the user, they are inherited from the coarse "father" block, most of them with no change (porosity, heat capacity, saturations, etc.) The only two properties needed of special treatment are permeabilities and thermal conductivities. Both properties need to be modified from the coarse rectangular "father" block to the fine radial "son" blocks, depending on the medium anisotropy and the "father" geometry.

The connections of the fine grid with the coarse neighbors are also described, applying recent published methods as well as original procedures when the coarse "father" block is non-square.

We also present the results of the application of these improvements to some theoretical and practical cases.

1. INTRODUCTION

In order to be able to make exhaustive studies on the effects of thermal processes on the production, in cases of heavy and extraheavy oil reservoirs, it is necessary to have thermal simulation tools more capable than the ones we have today. Among the required capabilities, there are two of high importance: the possibility of making complex simulations, with high number of cells and wells, and the one of being able to simulate injection and production wells of any type: vertical, horizontal, or slanted.

To face the handicaps we have now for doing these types of simulations, we made some improvements to a comercial thermal simulator, specially incorporating a new formulation for LGR, which will allow to have fine grids in regions selected by the user (for example, around the wells) and coarse grid in the rest of the reservoir. This formulation was integrated with the "domain decomposition" technique, so that we will be able to make reservoir simulations not only at high scale, but also at high speed.

The LGR formulation here implemented considers two options for the user:

- Cartesian refinement, which can be convenient when applied to reservoir regions of special characteristics, such as faults, localized heterogeneities, slanted or horizontal wells, etc.
- Radial (or hybrid) refinement, applied to a square or rectangular block, more appropriate to zones where the phenomenon is supposed to be radial or quasi-radial, specially around the vertical wells (and maybe also around the horizontal wells if the gravitational effects are considered negligible).

In this report we present the formulation corresponding to the second option, i.e., the design and implementation of radial refinement around a vertical well, located in a rectangular coarse gridblock.

Several people have written about this issue, but here we will mainly use ideas from PhD Theses of Pedrosa O. [1] and Nacul E. [2]. In both authors we can find methodologies to construct the fine grid and to connect it with the coarse grid. But in both cases only the

case of square coarse gridblocks is treated. We also handle the case of rectangular coarse gridblocks to be refined with a radial fine grid.

2. THE "DOMAIN DECOMPOSITION" TECHNIQUE

2.1 General concept

The simulations of fluid flow in porous media in some cases must be of such a magnitude that the job turns to be, if not impossible, at least too inefficient. The mathematical techniques of domain decomposition allow to solve such problems in an efficient way, dividing the total domain (the total reservoir) into smaller subdomains or regions (see Fig. 1), in which the problem is solved independently, and then all domains are put together (in some mathematical way), so that finally we obtain the solution to the global problem.

Fig. 1. Illustration of the domain decomposition technique.

This technique is very flexible and its multiple variants allow the subdomains to be overlapped, embedded, or separate. They even allow to apply different discretization schemes in each domain or even different models, if the problem suggests that way (see Ewing [3]).

The technique looks ideal for cases in which LGR is used, because in these cases each refined region can be treated as a different domain and the coarse initial grid as one more subdomain. That is the improvement we want in our simulators: to have the capability of refining the regions around the wells, while the rest of the reservoir is maintained with the original coarse grid.

It can also be observed the advantage this technique provides when using parallel computers: each subdomain could be solved in one different processor simultaneously, saving significant cpu time when obtaining the global solution.

Additional details on this technique and different ways of applying it can be seen in the Ewing's paper, as well as in other numerous sources, as in the "Proceedings" of technical events about this topic. Several of these technical events are held each year around the world, among them the "International Conference on Domain Decomposition Methods for Partial Differential Equations".

2.2 The FAC Method

When discretizing the differential equations that describe the fluid flow in the reservoir, a system of non-linear difference equations arises, which is generally solved using the Newton method or some of its variants. Many researchers have used this same method to solve the systems arising when LGR option is applied. Many others have used the domain decomposition technique, but still applied to the systems of linear equations derived from the linearization of the non-linear equations (algebraic domain decomposition) [4].

Nevertheless, one more powerful and efficient approach consists in applying the domain decomposition technique directly to the non-linear problem, using the Newtonian iterations only in the subdomains [5]. One version of this procedure is the algorithm developed by McCormick [6] and known as the FAC Method (Fast Adaptive Composite Grid). This is the algorithm used in our simulator. It is briefly described as follows:

- At each coarse timestep, an estimated initial value $U(0)$ is taken for the solution in the total domain (composite grid = coarse + fine grids) and a residual $R(0)$ is calculated for this first estimation:

$$R(0) = F - LG(U(0)) \quad (1)$$

where F is the vector of time non-dependent elements (the right hand side) and LG is the difference operator for total domain, such that, if U is the solution of the system, then

$$F - LG(U) = 0 \quad (2)$$

- For the first subdomain (the coarse grid, for example), the corresponding $u(0)$ and $r(0)$ are taken. Then

$$f = r(0) + L_s(u(0)) \quad (3)$$

is calculated, where L_s is the LG operator restricted to the first subdomain.

- Then, for this first subdomain, it is solved:

$$L_s(u(1)) = f \quad (4)$$

- The solution in the total domain is corrected:

$$U(1) = U(0) + I(u(1) - u(0)) \quad (5)$$

where I is an operator mapping the solution from one subdomain to the total domain.

- The same procedure continues with the second subdomain, then third, fourth, and so on, until convergence is obtained in all subdomains and the total domain.

3. LGR APPLYING DOMAIN DECOMPOSITION

One of the typical cases in which the domain decomposition technique is applied, is that of local grid refinement (LGR). In this case, the total domain is the set of all cells or blocks, coarse and fine. Each refined region, as well as the coarse grid, represents one subdomain.

In general, at least in the area of reservoir simulation, the refinements are defined using cartesian or radial grids. In the former case the only complicated thing is how to manage the connection of the fine grids (son grids) with the coarse grid (father grid) and how to use the special border conditions to solve the systems in the refined zones.

The use of radial grids to refine rectangular blocks implies, apart from the problems just mentioned, others having to do with grids construction, properties assignement to the cells of these grids, (especially permeabilities and thermal conductivities), and border connections, more complex in these cases than in the cartesian refinements.

In this report only the radial refinement is treated. The cartesian one is explained in an analogous manner, with the simplifications due to the equality (at a minor scale) in the grid characteristics.

Fig. 2. Connection of fine cartesian grid with "father" grid.

4. RADIAL REFINEMENT IN CARTESIAN GRIDS

While in the case of cartesian refinement the refined region can be constituted by several blocks in each direction, in the case of radial refinement only the wellblocks can be refined, so the refined region is constituted by only one block. If the well is completed in more than one layer, each layer can be refined in the same fashion, as we explain soon. The connections between layers is performed in the usual way (as in the cartesian case). From here we will only refer to the case of radial horizontal refinement of a cartesian block with a vertical well in it.

4.1 Case of square gridblocks horizontally isotropic

For square block cases, the radial grid is constructed in such a way that its most external circle R_N has an area equal to that of the cartesian square block being refined, i.e.,

$$R_N = \frac{\Delta x}{\sqrt{\pi}} \quad (6)$$

where Δx is the side length of the square being refined.

Starting from this value (and possibly others such as the well radius, the first block center, etc.), the rest of the block radii are calculated exponentially from the center to the outer radius. In the angular direction, only 1 block of 360 degrees, 4 of 90 or 8 of 45 are permitted (Fig. 3, a and b).

The fine grid inherits all properties regarding rocks and fluids from the “father” block, except permeabilities and heat conductivities, which must be modified according to procedures further explained. Optionally, the user could assign different properties to these fine gridblocks if the necessary information is available, but the most general case is the first one.

Given that in the case of square isotropic blocks the permeabilities are equal in the horizontal plane, the radial fine grid inherits this same value for its blocks, in radial

as well as in angular direction. Same thing happens to the heat conductivities. In the vertical direction, the values of the “father” block can be inherited or other values given by the user can be assigned.

Fig. 3. Radial refinement of a square gridblock.

4.2 Case of square gridblocks horizontally anisotropic

In this second case, the radial fine grid is constructed identically as in the first case, but the permeabilities in radial and angular directions must be calculated in a special way. Thermal conductivities are also calculated exactly in the same manner as the permeabilities.

- If we have only one angular block (360 degrees), the angular permeability has no meaning. But the radial permeability is calculated as:

$$k_R = \sqrt{k_x k_y} \quad (7)$$

where k_x and k_y are the permeabilities in X and Y directions, respectively.

When working with 4 or 8 angular blocks, we must first calculate the permeability in diagonal direction (45 degrees with the horizontal), which is given by:

$$k_D = 0.5k_x + 0.5k_y \quad (8)$$

Then, supposing that permeability varies linearly from its value in horizontal direction to its value in diagonal direction, we can finally have the following expressions.

- If we have 4 angular blocks (Fig. 3a):

+ R Direction:

$$k_R = 0.75k_x + 0.25k_y, \quad \text{Regions 1 and 3} \quad (9)$$

$$k_R = 0.25k_x + 0.75k_y, \quad \text{Regions 2 and 4} \quad (10)$$

+ θ Direction:

$$k_\theta = 0.25k_x + 0.75k_y, \quad \text{Regions 1 and 3} \quad (11)$$

$$k_\theta = 0.75k_x + 0.25k_y, \quad \text{Regions 2 and 4} \quad (12)$$

- If we have 8 angular blocks (Fig. 3b):

+ R Direction:

$$k_R = k_x, \quad \text{Regions 1 and 5} \quad (13)$$

$$k_R = k_y, \quad \text{Regions 3 and 7} \quad (14)$$

$$k_R = 0.50k_x + 0.50k_y, \quad \text{Regions 2, 4, 6 and 8} \quad (15)$$

+ θ Direction:

$$k_\theta = k_y, \quad \text{Regions 1 and 5} \quad (16)$$

$$k_\theta = k_x, \quad \text{Regions 3 and 7} \quad (17)$$

$$k_\theta = 0.5k_x + 0.5k_y, \quad \text{Regions 2, 4, 6 and 8} \quad (18)$$

Thermal conductivities are assigned in the same way.

4.3 Case of rectangular gridblocks

In this third case, the most general one, we first transform the rectangle into an equivalent square, as it is described below. Then, once having the square, we proceed as in the case before. In a more detailed manner, the procedure is as follows:

Let Δx , Δy be the side dimensions of the rectangular wellblock we want radially refined (see Fig. 4).

First we define the constant

$$\beta = \sqrt{\frac{\Delta x}{\Delta y}} \quad (19)$$

Then we define the transformation

$$F(x, y) = \left(\frac{1}{\beta}x, \beta y\right) \quad (20)$$

F transforms the rectangle into a square (Fig. 5) of same area, and side given by:

$$\Delta X_N = \sqrt{\Delta x \Delta y} \quad (21)$$

Fig. 4. Rectangular gridblock to be radially refined.

(the F inverse is $F^{-1}(x, y) = (\beta x, \frac{1}{\beta} y)$).

Now the grid is designed as in the cases before, but, in order to have a square really equivalent to the original rectangle, i.e., so that the simulation results are identical in both cases, it is necessary to modify the permeabilities and thermal conductivities so that the transmissibilities are equal in both cases, which is what guarantees equal results.

In the formula of the transmissibility in X direction, for example, Δy appears multiplying and Δx dividing. According to the F transformation, equation (31), Δx in the rectangle is transformed into $\frac{1}{\beta} \Delta x$ and Δy into $\beta \Delta y$. So, the transmissibility in X direction is multiplied by β^2 . (Similarly, the transmissibility in Y direction is divided by β^2). In order that the transmissibilities remain identical to them of the rectangle, we must transform k_x

Fig. 5. F Transformation.

in the rectangle into $\frac{1}{\beta^2}k_x$ in the square, and k_y into β^2k_y . Now it is possible to assign the properties to the radial gridblocks following the same reasoning as in the Section before.

- If we define only 4 angles of 90 degrees each one (Fig. 3a):

+ R Direction:

$$k_R = 0.75 \frac{1}{\beta^2} k_x + 0.25 \beta^2 k_y, \quad \text{Regions 1 and 3} \quad (22)$$

$$k_R = 0.25 \frac{1}{\beta^2} k_x + 0.75 \beta^2 k_y, \quad \text{Regions 2 and 4} \quad (23)$$

+ θ Direction:

$$k_\theta = 0.25 \frac{1}{\beta^2} k_x + 0.75 \beta^2 k_y, \quad \text{Regions 1 and 3} \quad (24)$$

$$k_{\theta} = 0.75 \frac{1}{\beta^2} k_x + 0.25 \beta^2 k_y, \quad \text{Regions 2 and 4} \quad (25)$$

- If we have 8 angular blocks (Fig. 3b):

+ R Direction:

$$k_R = \frac{1}{\beta^2} k_x, \quad \text{Regions 1 and 5} \quad (26)$$

$$k_R = \beta^2 k_y, \quad \text{Regions 3 and 7} \quad (27)$$

$$k_R = 0.5 \frac{1}{\beta^2} k_x + 0.5 \beta^2 k_y, \quad \text{Regions 2, 4, 6 and 8} \quad (28)$$

+ θ Direction:

$$k_{\theta} = \beta^2 k_y, \quad \text{Regions 1 and 5} \quad (29)$$

$$k_{\theta} = \frac{1}{\beta^2} k_x, \quad \text{Regions 3 and 7} \quad (30)$$

$$k_{\theta} = k_R, \quad \text{Regions 2, 4, 6, 8} \quad (31)$$

Thermal conductivities are assigned in an analogous manner, after having applied the same transformations as to the permeabilities, in order to have the same values in thermal conductivities in the rectangular block as well as in the square one.

5. CONNECTION TO THE “FATHER” GRID

Without losing generality, it will only be considered the connection in X direction, positive sense (right side). The connections with the other 3 adjacent blocks are analogous.

From analogous reasons, only the general case of rectangular gridblocks with arbitrary permeability values will be considered. Cases of square blocks are reduced to this general case taken $\beta = 1$.

5.1 Case of 4 angular blocks

We first consider this case because, after understanding it, the case of only one angular block is very easy to understand.

Fig. 6 shows the complexity of this connection, totally different from the case of cartesian refinement, where we always work with rectangular gridblocks, in the coarse grid as well as in the fine one. In the case of radial refinement we have to connect one rectangular coarse gridblock (in the “father” grid) to one “irregular” gridblock (in the fine grid).

Observing Fig. 6 again, it can be seen that the boundary irregular block, beyond being approximated by a radial block belonging to the fine grid, it can also be approximated by a rectangular block (with dashed sides and center x_B).

For the purpose of the connection to the rectangular coarse gridblock, this last approximation is preferable because in the boundary it is reasonable to consider the flux still linear. Anyway, other possible types of approximation don't give us very different results (see Appendix A).

The accumulation term of this block has the same expression as any other and it does not deserve any special consideration. So, we will only consider the flux terms.

To better understand the flux behavior in the boundary, we take the F inverse, F^{-1} , and apply it to the square block and to the circles in the fine grid. With this procedure

Fig. 6. Boundary connections.

we get the result shown in Fig. 7, i.e., the same Fig. 4 with some eclipses inside.

To calculate the flux between block Ω_c (the refined block with dimensions identified now as ΔX_c , ΔY_c and ΔZ_c) and Ω_{c+} (the adjacent coarse gridblock, with dimensions identified as ΔX_{c+} , ΔY_c y ΔZ_c), we take a control volume $\Omega_{c+\frac{1}{2}}$ in the boundary (the dashed block in Fig. 7) and apply the usual integral:

$$\iiint_{\Omega_{c+\frac{1}{2}}} \frac{w_{J,x}}{k_x M_J} d\Omega = - \iiint_{\Omega_{c+\frac{1}{2}}} \frac{\partial \Phi_J}{\partial x} d\Omega \quad (32)$$

where $w_{J,x}$ is the flux of phase J in X direction, M_J is the relative permeability of phase J divided by the viscosity of phase J , and Φ_J is the potential of phase J .

Fig. 7. Result from applying F^{-1} to Fig. 6.

We now approximate the right hand side of (32) by:

$$-\iiint_{\Omega_{c+\frac{1}{2}}} \frac{\partial \Phi_J}{\partial x} d\Omega \cong -\Delta Z_c \Delta Y_c [P(\vec{x}_{c+}, t^{n+1}) - P(\vec{x}_B, t^{n+1})] \quad (33)$$

where $\vec{x}_{c+}$ is the center of Ω_{c+} block, $\vec{x}_B$ is the grid point of the irregular block, and P represents the pressure in each block.

The left hand side is approximated by

$$\iiint_{\Omega_{c+\frac{1}{2}}} \frac{w_{J,x}}{k_x M_J} d\Omega \cong \frac{w_{J,x,c+\frac{1}{2}}}{(k_x M_J)_{c+\frac{1}{2}}} V_{\Omega_{c+\frac{1}{2}}} \quad (34)$$

where $w_{J,x,c+\frac{1}{2}}$ is the x component of flux in the $\Omega_c - \Omega_{c+}$ boundary, $(k_x M_J)_{c+\frac{1}{2}}$ is the mobility of phase J in the boundary (estimated as an average of the mobility of phase J in X direction inside the volume $\Omega_{c+\frac{1}{2}}$), and $V_{\Omega_{c+\frac{1}{2}}}$ is the control volume calculated as:

$$V_{\Omega_{c+\frac{1}{2}}} = \frac{\Delta X_c \Delta Y_c \Delta Z_c}{2} + \left[\frac{\Delta X_c \Delta Y_c}{4} - \frac{\pi R_B^2}{4} \right] \Delta Z_c \quad (35)$$

where R_B is the grid point radius of the irregular boundary block in Fig. 6 (F preserves the areas). We could similarly take the area of the eclipse with boundary $\bar{R}_B = F^{-1}(R_B)$ obtaining same result, but it is simpler to take the radius R_B in Fig. 6.

Combining equations (33), (34) and (35) we obtain:

$$w_{J,x,c+\frac{1}{2}} = - \frac{P(\vec{x}_{c+}, t^{n+1}) - P(\vec{x}_B, t^{n+1})}{\frac{\Delta X_{c+}}{2} + \left[\frac{\Delta X_c}{4} - \frac{\pi R_B^2}{4 \Delta Y_c} \right]} (k_x M_J)_{c+\frac{1}{2}} \quad (36)$$

The grid point radius of the boundary radial block, R_B , (see Fig. 6), can be selected in several ways. In the simulator we are modifying, for example, the user has three different options. For the connection to the coarse grid, the option selected was the one locating the radius in such a way that it divides the block into two areally equal sectors. In this case it is easy to see that:

$$R_B = \sqrt{\frac{\Delta X_c \Delta Y_c (\alpha^2 + 1)}{2\pi\alpha^2}} \quad (37)$$

$$(\alpha = \frac{R_N}{R_{N-1}})$$

which converts the second term in the denominator of (36) into

$$\frac{\Delta X_c}{4} - \frac{\pi R_B^2}{4 \Delta Y_c} = \frac{\Delta X_c (\alpha^2 - 1)}{8 \alpha^2} \quad (38)$$

Substituting this value into equation (36) we obtain that the transmissibility between the irregular block and the adjacent one in the coarse grid is:

$$T_{b_x} = \frac{\Delta Y_c \Delta Z_c}{\frac{\Delta X_{c+}}{2k_{x_{c+}}} + \frac{\Delta X_c(\alpha^2 - 1)}{8\alpha^2 k_{x_c}}} \quad (39)$$

supposing in this definite formula that k_{x_c} and $k_{x_{c+}}$ could be different.

T_{b_y} is calculated in the same way.

If in Fig. 6 the irregular boundary block is approximated by a rectangle of equal area and dimensions $L \times \Delta X_N$, it is found that $\frac{L}{2}$ has the expression:

$$\frac{L}{2} = \frac{\Delta X_N(\alpha^2 - 1)}{8\alpha^2} \quad (40)$$

But $F^{-1}(L) = \beta L$. So,

$$F^{-1}\left(\frac{L}{2}\right) = \sqrt{\frac{\Delta X_c}{\Delta Y_c}} \frac{\sqrt{\Delta X_c \Delta Y_c}(\alpha^2 - 1)}{8\alpha^2} \quad (41)$$

$$= \frac{\Delta X_c(\alpha^2 - 1)}{8\alpha^2} \quad (42)$$

the same expression as the obtained in equation (38). So, in the formula (39) we have the same result if we substitute the second term of the denominator by the expression $\frac{L}{(2k_{x_c})}$.

These last results show that taking the control volume as the addition of the semiareas of the two adjacent blocks multiplied by ΔZ_c , is equivalent to approximating the irregular block by a rectangle with sides $\frac{\Delta X_N(\alpha^2 - 1)}{4\alpha^2} \times \Delta X_N$ in the square block of Fig. 6, or with sides $\frac{\Delta X_c(\alpha^2 - 1)}{4\alpha^2} \times \Delta Y_c$ in the original rectangular block (Fig. 7). Of course,

to get the same results in both cases we must take the right permeabilities (and thermal conductivities) in each case, i.e., $\frac{1}{\beta^2}k_x$ in the first and k_x in the second.

5.2 Case of 1 angular block (360 degrees)

We treat this case in the same fashion as the case before. We suppose that we have 4 (imaginary) angular blocks defined as before and make all the calculations in the same way.

5.3 Case of 8 angular blocks

For the case of 8 angular blocks the procedure is similar to the case of 4 angular blocks, but now we must connect 3 fine gridblocks to one coarse gridblock in each side of the refined coarse gridblock. Fig. 8 illustrates the connection problem in this case.

From symmetry reasons, the irregular fine blocks located in the diagonals must be approximated by square blocks. (This approximation must be made on the coarse block transformed by F, in the case of non-square refined gridblocks). The blocks in the direction of the cartesian axes (blocks 1, 3, 5, 7 of Fig. 8) are approximated by rectangles.

The area of all these approximant blocks, square or rectangular, is the same, because in both cases we are approximating radial blocks of equal area. Such an area can be calculated by:

$$A = \frac{\pi(R_N^2 - R_{N-1}^2)}{8} \quad (43)$$

So, the side of the approximant blocks in the diagonals is:

$$D = \sqrt{A} \quad (44)$$

Once we obtain these dimensions, it is easy to see that the dimensions of the intermediate rectangle are (see Fig. 8):

$$L_y = \Delta X_N - 2D \quad (45)$$

Fig. 8. Boundary connections (case of 8 angular blocks).

$$L_x = \frac{A}{\Delta X_N - 2D} \quad (46)$$

Now, applying F^{-1} to these dimensions in order to have the original rectangle, we obtain Fig. 9, i.e., the dimensions in X direction become multiplied by β and the dimensions in Y direction, divided by that same value. With these dimensions, and maintaining the permeability in the original values, we can calculate the transmissibility between each one of these blocks and the adjacent one in the coarse grid.

Thermal transmissibilities are calculated in the same way, substituting permeabilities by thermal conductivities.

Fig. 9. Result of applying F^{-1} to Fig 8.

6. COMMENTS ON RESULTS OF SOME APPLICATIONS

We tested this formulation with some simple cases and applied it to one field case.

About the test cases we can make the following comments:

- Grids with local grid refinement (LGR) (no matter if rectangular or radial) in the wellblocks drive to same results as fine grids having all blocks about as fine as the refined wellblocks.
- Same grids with no LGR in the wellblocks do not represent gas saturation, water saturation and temperature as well as fine grids, driving to incorrect production rates, mainly at the beginning of production stage.
- Saving in execution time for refined grids (compared to fine grids) increases with number of wells. This saving, due also to the application of the “domain decomposition” technique, could be so significant that for studies with a high number of wells the simulation could not be possible unless using LGR.

About the field case we can say:

- Using LGR, very good results have been found in matching pressure and production history with a reasonable cpu time consumption.
- BPH is much better represented using LGR than using coarse blocks. Match in this variable can not be correctly done using coarse grids.
- Pressure behavior in observation wells (no injection or production) can be correctly represented without using LGR in their wellblocks.
- Big cycling steam injection projects can now be simulated, using LGR combined with “domain decomposition” techniques, with very good representation of the phenomenon around the wells and similar accuracy in representing the interwell

phenomena, such as the production and pressure behavior in one well when injecting in another one, for example.

7. CONCLUSIONS

- The use of the “domain decomposition” numerical technique, applied to reservoir simulation, is highly profitable because it allows to carry out big and complex studies with very low CPU expenses, compared to the CPU time necessary without using this technique.
- The “domain decomposition” technique is specially useful in cases of grid refinement applied to reservoir regions where the changes are sharp and localized, in space as well as in time (in wellblocks, for example). In these cases, both space and time are “decomposed” giving additional advantages to this technique.
- The radial refinement in the wellblocks can be more advantageous than the rectangular, because the flux around the wells tends to be radial and in this case a radial grid fits the flux better than a cartesian grid. Even if those blocks are not square, it is possible to design a radial refinement with the same quality in accuracy as for the case of square blocks.
- In cases of anisotropic reservoirs, it is necessary to make certain approximations which, correctly made, allow to obtain results of same quality as those obtained in isotropic cases.
- With these improvements, thermal simulations of similar magnitude as the ones carried out with black oil simulators can now be performed.

REFERENCES

1. PEDROSA; O.A., AZIZ; K. Use of Hybrid Grid in Reservoir Simulation, paper SPE 13507. Middle East Technical Conference., Bahrain; March, 1985.
2. NACUL; E.C. Use of Domain Decomposition and Local Grid Refinement in Reservoir Simulation PhD Thesis, Stanford University, 1991.
3. EWING; R.E. A survey of domain decomposition techniques and their implementation. *Adv. Water Resources*, vol(13, No. 3): 117-125. 1990.
4. EWING; R.E., LAZAROV; R.D., VASSILEVSKI; P.S. Local Refinement Techniques for Elliptic Problems on Cell-centered Grids *Numerische Mathematik*, vol(59(5)): 431 - 455 1991.
5. SCOTT; L. Solution of the Difference Equations using Nonlinear FAC. Manuscript.
6. MACCORMICK; S.F. Fast adaptive composite grid (FAC) methods. Defect Correction Methods BÄHMER; K., STETTER; H.J. (Ed.). Vienna; Springer-Verlag, 115-121 p. 1984.

APPENDIX A. CONTROL VOLUME IN THE FINE GRID / COARSE GRID BOUNDARY

In Section 5 of this paper, where interblock transmissibilities at boundaries between fine and coarse grids are calculated, the control volume taken was formed by adding half of the volume of both connected blocks. The radius R_B was taken in such a way that it divided the irregular block into two halves of same volume.

Nevertheless R_B could be taken according to other criteria. In this Annex we examine the influence of some of these criteria on the transmissibility calculation.

For a more specific and simplified analysis of this issue, let's suppose that $\Delta X_c = \Delta X_{c+}$, $k_x = k_y$ and that fluid properties are equal in the connected blocks. Then the flux equation (36) can be written as:

$$w_{J,x,c+\frac{1}{2}} = -\frac{\Delta P}{\left[\frac{3\Delta X}{4} - \frac{\pi R_B^2}{4\Delta Y}\right]}(k_x M_J)_{c+\frac{1}{2}} \quad (\text{A.1})$$

Depending on the different locations of the gridpoint in the irregular boundary block, the following results are obtained:

1. R_B defined as in (37). The flux equation gives:

$$w_{J,x,c+\frac{1}{2}} = -\frac{\Delta P}{\Delta X \left(\frac{5\alpha^2-1}{8\alpha^2}\right)}(k_x M_J)_{c+\frac{1}{2}} \quad (\text{A.2})$$

(remember that $\alpha = \frac{R_N}{R_{N-1}}$)

2. R_B defined as

$$R_B = \frac{R_N - R_{N-1}}{\ln\left(\frac{R_N}{R_{N-1}}\right)} \quad (\text{A.3})$$

In this case the flux equation gives:

$$w_{J,x,c+\frac{1}{2}} = -\frac{\Delta P}{\Delta X \left(\frac{3\alpha^2(\ln\alpha)^2 - (\alpha-1)^2}{4\alpha^2(\ln\alpha)^2} \right)} (k_x M_J)_{c+\frac{1}{2}} \quad (\text{A.4})$$

3. R_B defined according to Pedrosa [1]

$$R_B = R_{N-1} \exp\left[\frac{\alpha^2}{\alpha^2 - 1} \ln\alpha - \frac{1}{2}\right] \quad (\text{A.5})$$

In this third case the flux equation gives:

$$w_{J,x,c+\frac{1}{2}} = -\frac{\Delta P}{\Delta X \left(\frac{3\alpha^2 - [\exp(\frac{\alpha^2}{\alpha^2-1} \ln\alpha - \frac{1}{2})]^2}{4\alpha^2} \right)} (k_x M_J)_{c+\frac{1}{2}}. \quad (\text{A.6})$$

Compare now the factors multiplying ΔX in the denominator of the flux equation. Let F_1 , F_2 and F_3 the factors of equations (A.2), (A.4) and (A.6), respectively. Table 1 shows the values of these factors for several values of α .

	$\alpha \rightarrow 1$	$\alpha = 2$	$\alpha = 3$	$\alpha = 4$	$\alpha = 5$	$\alpha \rightarrow \infty$
F_1	0.5	0.594	0.611	0.617	0.620	0.625
F_2	0.5	0.620	0.656	0.677	0.688	0.750
F_3	0.5	0.604	0.629	0.639	0.645	0.658

TABLE A.1. Comparison of F_1 , F_2 and F_3 for several values of α .

It can be observed that the differences are small, specially between F_1 and F_3 . The value of F_2 when $\alpha \rightarrow \infty$ is not realistic, because the limit of 0.75 would be equivalent to take the grid point just in the block inner radius, which does not look acceptable. So, if the values of F_1 and F_3 are accepted as more realistic, the difference between both factors for

the different values of α is little significant, which indicates that their associated formulae to calculate R_B are equally acceptable, in the usual ranges of α .

Nevertheless, if we would like the grid point of the rectangle approximant the irregular block to coincide with the one of the radial block belonging to the fine grid, the first way of calculating R_B makes impossible this objective, while the second and third ones makes it possible for values of α of 2.01 and 3.27 (approximating to two decimal figures). In conclusion, for small values of α (between 2 and 5, the usual values), anyone of the three methods looks acceptable, given that the differences in the three factors are less than 7%.

Task 60 - DOE shall provide INTEVEP with information on electrical conductivity imaging using cross-borehole and surface-to-borehole electromagnetic tomography conducted by Lawrence Livermore National Laboratory. Such information is useful in oil field characterization i.e. tracing of oil sands) and in process monitoring (steam soak or drive monitoring). The information will consist of instrumentation design, data collection schemes, software for providing conductivity images and results of field surveys.

Crosshole EM for Oil Field Characterization and EOR Monitoring: Field Examples

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Abstract

During the past several years research efforts in reservoir characterization and process monitoring using the electromagnetic (EM) induction method have progressed from theoretical models through field trials. In this report we describe the application of the (EM) method to water and steamflood monitoring and discuss some experimental work involving propagating EM fields through steel well-casing.

We applied crosshole and surface-to-borehole (EM) imaging to reservoir characterization and steam flood monitoring in the Lost Hills oil field in central California. Steam was injected into three stacked, eastward-dipping, unconsolidated oil sands within the upper 200 m. The steam plume was expected to develop as an ellipse aligned with the regional northwest-southeast strike. EM measurements were made from two fiberglass-cased observation wells straddling the steam injector on a northeast-southwest profile. Field data were collected before the initiation of a steam drive to map the distribution of the oil sands and then 6 months after the steam was injected to monitor the progress of the steam chest. Resistivity images derived from the initial EM data clearly delineate the distribution and dipping structure on the target oil sands. Difference images from data collected before and after steam flooding indicate that the steam chest has developed only in the deeper oil sands, leaving the upper, richer oil sand largely untouched.

The EM system was also utilized in a waterflood monitoring project at the U.C. Richmond Field Station test facility. For this test we injected a slug of salt water and applied the borehole-to-surface array to determine if the body could be detected by deploying instruments in a single well and at the ground surface. Preliminary results showed that an anomaly due to an injected saltwater plume could be easily detected but less easily isolated from the effects of surface geological and cultural noise. These data will be interpreted in the next several months.

A three year experiment to study the effect of steel well casing on crosshole EM was initiated in 1994. The experiment consists of lab-scale measurements to determine the properties of the casing, a series of EM measurements within the casing to determine the effect of signal propagation and a series of crosshole surveys to determine if the casing and formation effects are easily separable.

1. Introduction

During past five years at Lawrence Livermore National Laboratory (LLNL), we have applied the EM induction method to the problem of thermal front tracking during enhanced oil recovery (EOR) operations (Wilt et al, 1991). During this past year we have also turned our attention to the larger, but related, problem of petroleum reservoir characterization.

As in the past this research is a collaborative effort. The main focus of our activities at LLNL is hardware development, field measurement, and geological interpretation of the results. We are therefore dependent on others for theoretical and software development, geological information and working sites to test field systems. Our closest collaborators are Lawrence Berkeley Laboratory (LBL) for theory and software development, Schlumberger-Doll Research

(SDR) for hardware and software development and Mobil Exploration and Production for field site access and geological information. This interdependency serves to make our research dollars stretch further and allows us to complete the tasks in a timely manner.

In this paper we discuss results from recent applications of EM technology to the Mobil Lost Hills #3 oil field and at our test facility in Richmond California. We also discuss some preliminary results from a multi-year experiment for measuring electromagnetic fields in steel well casing.

2. Applying borehole-to-surface EM for water flood monitoring

In many oil field and environmental problems only one borehole is available for geophysical measurements. In an oil field this may be one of several widely spaced observation wells; in an environmental spill area this may be the initial monitoring well. It is important to make use of this well to determine the electrical resistivity distribution beginning at the wellbore and extending outwards. This may help determine the direction of steam flood migration or the movement of an underground spill. One technique that utilizes a single well is the borehole-to-surface array (BTS), where an EM transmitter is located in the borehole and data are collected on the surface. The method allows for multicomponent measurements along any surface profile; we can therefore focus the subsurface investigation without requiring an additional well. The disadvantage is that the data are less sensitive to the subsurface resistivity than the crosshole array due to the increased source-receiver separation; the array is also more sensitive to the effect of surface geological and cultural noise.

To test the applicability of this method to waterflood monitoring we designed a test at our Richmond Field Station facility. This experiment consisted of injecting a slug of salt water into a shallow aquifer and collecting borehole-to-surface EM data before and after injection. We also collected crosshole EM data at the same frequency as the BTS data using boreholes along the same profiles. The crosshole data will be used to supplement the BTS measurements for improved inversion resolution and for comparison with the BTS data. We will apply numerical inversion to both data sets determine the in-situ resistivity distribution and the direction of salt water migration.

The measurements consist of deploying a borehole transmitter in the injection well and several other observation holes and collecting horizontal and vertical component magnetic fields on the surface on a densely sampled grid (Figure 1). To ensure that measurements were repeatable a series of temporary stations was established and outfitted with small pipes for placement of the surface detectors. A complete survey was done before and after salt water injection. The baseline data for this experiment were collected in December, 1993 and the saltwater was injected over Christmas. Post injection data were collected during the last week of December, 1993 and January, 1994. Early analysis of these data showed significant distortion due to leakage current from the transmitter. This was subsequently repaired and new data were collected in March before salt water withdrawal. A final data set was collected in April, after salt water withdrawal.

The data, in general, were of excellent quality. The average repeatability error was one or two percent. The EM anomaly, although only half of the size of the crosshole anomaly, was easily discernible, and it is likely that these data can be used for imaging the subsurface plume. Indications of cultural and external noise in the data set persisted even after considerable effort to reduce these effects.

In Figure 2 we show baseline vertical field magnitudes and differences, in percent, between data collected before and after saltwater injection. The field data, which are plotted below the surface receivers in Figure 2a, show a smooth continuous amplitude distribution with

Figure 1. Base map for the Richmond Field station water flood experiment

Figure 2a) Borehole-to-Surface EM field data and **b)** observed percent differences before and after salt water flood for profile NW-SE.

the field steadily decreasing with distance from the source borehole. The difference plot (Figure 2b) indicates several zones where the field changed after the injection of salt water; the most prominent are the horizontal bands located at a depth of 30 m, between stations 15 and 50 and between stations -45 and -5. Forward modeling shows that these differences are due to the salt water slug. Preliminary indications are that the causative body is a roughly horizontal feature offset to the north of the injection well.

The plot also shows two vertically oriented anomalies; one near the borehole INJ1 and the other at -55. Experience indicates that this type of anomaly is due to a surficial body or some external source of noise. The central anomaly, near the injection borehole, is likely due to residual current leakage in the transmitter tool or the supply cable. Although heroic steps were taken to minimize this leakage some residual current could be measured and this clearly affects data at stations close to the source well. The second anomaly, near -55, is probably due to a grounded metallic fence used in an earlier biological experiment. Although we removed much of this structure prior to measurement some of the effects remain.

Since the plot in Figure 2b presents the difference in fields, we should expect that the effect of current leakage or a grounded fence would be the same for both surveys and therefore subtract to zero when a difference is taken. This unfortunately was not the case because the near surface resistivity changed (due to rainfall) between the measurement times. It therefore affected the EM coupling to the surface features. This type of variation in geological and cultural noise is the rule, however, and not the exception. It is our challenge to engineer the measurement system to be insensitive to this.

Even with the above effects the data set is of excellent quality and is suitable for inversion. Interpretation of these data is presently underway as part of the Ph.D. thesis for U.C. student Hung-Wen Tseng. He will initially apply some simple two-dimensional models and later interpret the data with a three-dimensional code that he is developing.

3. Reservoir Characterization and Steam Flood Monitoring at Lost Hills #3

Mobil Exploration and Production, U.S. has operated several EOR projects in central California for a number of years; We are applying EM technology at their Lost Hills lease as a pilot test to monitor a new steam flood. Two fiberglass-cased observation wells were drilled along a northeast-southwest profile straddling a steam injector (Figure 3). The wells were drilled for the combined purposes of crosshole EM surveys and repeated temperature and induction (resistivity) logging. Steam was injected at depths of 65, 90, and 120 m into upper, middle, and lower members of a heavy oil sand. The steam injection is expected to follow the natural northwest-southeast regional strike, with the plume developing as an ellipse with the major axis aligned with the natural fractures. The monitoring wells are positioned orthogonal to the regional strike direction so that the crosshole EM data roughly follows the assumption of two-dimensional rectangular geometry.

In Figure 3 we show a cross-section derived from borehole induction logs in this section of the field. The higher resistivity intervals (10-100 ohm-m) typically represent oil sands, the lower resistivity units (1-6 ohm-m) are confining silts and shales. The target sands extend from 60 to 120 m in three separate intervals. The upper sand is the thickest and most continuous of the three. It begins at a depth of 60 m, has a thickness of up to 20 m, and it dips gently eastward at about 6°. The middle and lower members are thinner and less continuous. The middle member is 3-6 m thick and lies at a depth of approximately 90 m. This unit seems to pinch-out near 35W and water-out somewhere between 35E and borehole 4034. The lower unit, which lies at about 110 m, is continuous throughout this portion of the field and dips eastward at about 8°. The water table lies at a depth of 160 m, just below the bottom of the wells.

Figure 3. Base map for the Lost Hills EM study.

Figure 4. Induction resistivity logs along profile A'-A" at Lost Hills.

EM Field Surveys

We utilized both crosshole and surface-to-borehole arrays for the Lost Hills project. With the surface-to-borehole array a loop transmitter is situated on the surface and measurements are made in the boreholes. This differs from the borehole-to-surface array, discussed above, where the transmitter is located within the borehole. The surface-to-borehole array is preferred in deeper applications because a surface deployed loop transmitter is much more powerful than a borehole source, and this power is necessary for data collection at depths more than 100m.

Crosshole and surface-to-borehole EM data were collected in November 1993 and April 1994, before the onset of cyclic steaming and after the initial 6 months of steaming. Surface-to-borehole EM data were collected along profile A'-A", using 10-x-10-m surface loop transmitters. The surface loops are spaced along profile A'-A", at 10- to 20-m intervals, to a maximum distance of 125 m from the receiver borehole, 35E. For each transmitter, magnetic field data were collected at 6-m intervals at depths from 10 to 140 m using frequencies of 1 and 5 kHz. Individual surface-to-borehole profiles typically required about 1 hour; the collection of 16 profiles on line A-A' required 2 days for both frequencies.

Crosshole EM data were collected at two frequencies, 5 and 20 kHz at depths between 30 and 130 m using boreholes 35W and 35E. Receivers were spaced 4 or 8 m apart in borehole 35E, and EM data were collected continuously as the transmitter moved between 130 and 30 m in borehole 35W. A typical crosshole profile required approximately 1 hour to measure; the entire survey, which consisted of 18 profiles, required 2 field days to complete for each frequency.

Surface-to-Borehole Results

Two sample surface-to-borehole data profiles are shown below together with the fit from a one-dimensional model in Figure 5. The profile shows the EM field amplitudes as a function of depth in borehole 35E using a surface loop transmitter located 65 m from the well. The one-dimensional model is made by initially assuming that the earth consists of 11 layers of equal resistivity, each having a thickness of 10 m, overlying a halfspace of the same resistivity. The resistivity of the layers (but not the thicknesses) are then adjusted by the inversion code until the observed and calculated data matched. A similar plot is produced from each of the 16 loop transmitter sites.

In general, the surface-to-borehole data quality was excellent, with most individual profiles repeating over time to several percent. The difference in the observed amplitudes in Figure 5 indicates that the data collected in April, 1994 has a lower amplitude than the November 1993 data at lower depths. This is consistent with a reduced resistivity at depth which is the expected effect due to steam injection (Ranganayaki et al., 1990; Mansure and Meldau, 1990). Unfortunately not all of the data profiles consistently show this trend; we also observe a 2-3 percent scatter in most of the readings at depth. At present, these data are inadequate to map the steam chest; as the steam flood develops further over time we expect it to be more visible to surface-to-borehole measurements. For the three transmitter sites adjacent to the steam injection well 5035, the 1-kHz data are quite noisy and the 5-kHz data show obvious signal contamination. This may be related to current channeling or grounding along nearby steam pipes and well casings.

An approximate resistivity distribution along A-A" can be made by plotting the individual layered models beneath the transmitter loops and piecing together the one-dimensional interpretations into a pseudo two-dimensional cross section (Figure 6). The resolution of the section is low, and the "noise" is high, but the position and depth of upper oil sand seem to match the known locations as determined by the borehole induction logs in wells 5035 and 35W. The

Figure 5. Surface-to-borehole data for a profile 65 m from the receiver borehole 35E.

Figure 6. Pieced-together one-dimensional inversion of surface-to-borehole data along A-A.

one-dimensional interpretation is much less accurate in the lower oil sands, however; the section seems to lose resolution at depth.

The pieced-together cross section as shown above is clearly an intermediate step in the interpretation of surface-to-borehole data. At present it is not practical to apply existing two- and three-dimensional inversions to the surface-to-borehole data due to the large numerical meshes required. We expect that this will change as new computational tools are developed and existing codes expanded and adapted.

Crosshole EM Results

We show a sample crosshole EM profile collected at 5 kHz in Figure 7. The profile is measured using a fixed receiver located within the upper oil sand at a depth of 60 m and a continuously moving transmitter with measurements made at 1-m intervals. At first glance, the amplitude data reflect the relative positions of the source and receiver coils; the fields become larger as the source and receiver coils approach the same level and fall off in proportion to the borehole tool separation. The phase data are considerably more sensitive to the resistivity distribution. For example, the magnitude of the phase data is higher within the higher resistivity oil strata, but it shows pronounced rotation in the lower resistivity shale beds above and below the oil sands. The crosshole field data repeat to approximately 2 percent; we use this figure as a lower bound in estimating data uncertainty during interpretation. Notice that the data profiles show a significant change after steam injection, especially for transmitter depths below 70m. The amplitude declines by more than 20 percent and the phase decreases by almost 40 degrees; these are well outside the error estimates of two percent and 1 degree respectively.

In Figure 8 we show the 5-kHz amplitude and phase data in contoured form for surveys collected before and after steam injection. The axes of the contour plot represent the transmitter and receiver positions; the observed data are plotted at coordinates corresponding to their measurement position. In this figure all of the field profiles can be examined on the same plot, and the data from the two surveys can be directly compared. In general, the contour plots have the same characteristics as the individual profiles; that is, the amplitude data reflect the geometric spacing between borehole tools while the phase data are higher in the higher resistivity oil sands between 60 and 110 m. Notice that while the data collected in 1993 and 1994 are remarkably similar for tool depths above 60 m, they are quite different below this. The data collected in April 1994 show a systematic reduction in both amplitude and phase at depths from 60 to 120 m compared to the November 1993 measurements. A maximum of more than 25 percent difference in the field amplitude is observed together with more than 40 degree change in the measured phase. We attribute this to decreases in electrical resistivity due to the steam flooding. The observed difference in the crosshole data is considerably greater than the surface-to-borehole observations. This is primarily due to the closer proximity of the crosshole tools to the steamed zone.

Crosshole field data are interpreted using numerical models that fit the EM fields to a two-dimensional resistivity distribution. We use a rectangular mesh two-dimensional code developed at Schlumberger-Doll Research (Torres-Verdin and Habashy, 1993). This code uses an approximation that, linearizes the field relationships, to speed the calculation. This approximation speeds the calculation by more than a factor of 5 while still retaining the required accuracy of a few percent. A typical data inversion still requires more than 12 hours for the two-dimensional solution on a fast computer workstation using a mesh of some 500 cells.

We show the subsurface resistivity distribution between boreholes 35E and 35W before and after steam injection in Figure 9. The darker section in the images represent higher resistivity zones associated with heavy-oil sands; the lighter areas are lower resistivity silts and confining shale beds of 1-8 ohm-meters, with an average value of 3 ohm-m. The water table lies at a depth

Figure 7. Sample crosshole EM data profile collected between boreholes 35W and 35E.

Figure 8. Combined 5-kHz crosshole data set (a) before and (b) after steam injection.

of 130 m. The initial image indicates that the upper oil sand is a 20 m thick unit that dips gently eastward. Figure 9 indicates that the middle and lower sands are thinner and more discontinuous between the wells. The initial image, which is consistent with borehole logs, also shows the upper and lower confining silts to be low-resistivity units.

The two images shown in Figure 9 are visibly different only at depths below 70 m in the center of the image. In this portion of Figure 9, the EM data indicate that the resistivity has decreased significantly due to the steam injection. In all other parts of the image, the before and after resistivities are similar.

In Figure 10 we show a difference image made by subtracting the two previous images. The image shows resistivity decreases more than 35 percent in the region surrounding the injection hole at depths below 80 m. This indicates that a substantial steam chest has formed in the middle and lower sands, and almost none of the steam has gone into the upper oil sand. Since there is considerable steam injection in the upper perforated zone, this implies that there is some connection between the upper and lower oil sands via natural or man-made fractures. Note that the difference plot also indicates that the steam chest is following the stratigraphic dip.

The upper oil sand is clearly having some difficulty accepting steam, at least in the initial phase of steam flooding. This may be explained by the higher oil saturation in this upper unit and the lower pressures that may be applied at the shallower depth. We expect this unit will also develop a substantial steam chest, but it will require more time. We plan to collect EM data in these wells every 4 to 6 months within the next year, and we will focus the measurements on this particular region.

3. EM measurements through steel well-casing

In Figure 11 we show some experimental EM data collected at the South Belridge oil field in central California in an observation well; the borehole is steel-cased from the surface to a depth of 150m but fiberglass cased below this. The data were collected, at a frequency of 540 Hz, using the surface-to-borehole array with a loop source situated above the measurement borehole. The plot shows that amplitude decreases with depth until the receiver reaches a depth of 150m, where it increases by a factor of 1000 as the coil emerges from the steel casing. The plot shows both the problem and promise of working in steel casing. The problem is that the signal is greatly attenuated, especially at high frequencies. For example, these results indicate that it will probably not be possible to collect EM data through casing at frequencies much above 500 Hz; this limits the resolution. However, in spite of the attenuation, the fields are well behaved within the casing and it may be possible to remove the casing effect by a simple arithmetic correction.

A project to understand EM propagation through steel-casing was initiated in 1994 through the LBL/LLNL industrial sponsors consortium. The goals of the experiment are to determine the limits and applications for crosswell EM surveys through steel well casing. The work consists of three parts. First the properties of the casing will be determined from EM measurements. Next the fields from a borehole transmitter will be measured through segmented steel casing. Finally a set of crosshole measurements will be made in fiberglass cased boreholes and a second set with steel pipe inserts in the same wells to determine if the casing effect may be easily removed.

Initial work for this two-year project has begun. The measurements will be the responsibility of U.C. student Bing Wong under the direction of Professor Alex Becker.

Figure 9. Resistivity images from crosshole EM before and after 6 months of steam injection.

Figure 10. Difference image derived from subtracting the two images in Figure 9.

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References

- Mansure, A. J., and Meldau, R. F., 1990, Steam-zone electrical; characteristics for geodiagnostic evaluation of steamflood performance, *Soc Pet Eng. Formation Evaluation*, September, 241–247.
- Ranganayaki, R. P., Akturk, S. E., and Fryer, S. M., 1990, Formation resistivity variation due to steam flooding: a log study: *Geophysics*, **57**, 488–494.
- Torres-Verdin, C., and Habashy, T., 1993, An Approach to Nonlinear Inversion with Application to Crosswell EM Tomography, Extended Abstracts Society of Exploration Geophysicists Annual Meeting, Washington, DC. PP 351-354.
- Wilt, M. J., Morrison, H. F., Becker, A., and Lee K. H., 1991, *Cross-borehole and Surface-to-Borehole Electromagnetic Induction for Reservoir Characterization*, DOE report DOE/BC/91002253.

Figure 11 Surface-to-borehole EM data in a partially steel-cased well at the South Belridge oil field.

Task 61 - INTEVEP shall provide DOE with information from laboratory work and field research on H₂S generation in thermal processes and production on steam stimulated wells.

H₂S GENERATION IN STEAM PROCESS

By

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ABSTRACT

The production of hydrogen sulfide (H_2S) in the conditions of steam injection processes (200 - 300 °C), has been well documented by the performance of both field and laboratory tests. This is the case of the steam drive project in M-6 (Lagunillas), at the Bolívar Coast of Maracaibo Lake, Venezuela, and in other areas in which cyclic steam injection has been performed.

In most of the studies carried out up to date, crudes having different API gravities, as well as reconstituted reservoir sands and core samples, have been employed in order to simulate the conditions in which aquathermolytic reactions occur. For all these studies, static reactors (autoclaves), in which the required reaction times are in the order of days and months, were employed. This work presents the results of an experimental research, aimed at studying the aquathermolytic reactions using a dynamic reactor in which changes are more pronounced and reaction times shorter.

Obtained results show the variation in the concentrations of gases generated during the reaction, specifically H_2S , in terms of temperature and displacement times, in the designed system. By means of these data the kinetic parameters showing variable reaction orders between 1 and 0.2 were obtained. Likewise, the Arrhenius equation made it possible to determine values of the activation energy, oscillating from 23.7 to 73.9 Kcal/g-mol.

Additionally, a field work measuring the H_2S concentration in twelve wells recently injected with steam, is reported. The most important conclusion of said work is that, during cyclic steam injection processes, the maximum H_2S concentration is produced during the first fifteen days of the opening of the well to production. Subsequently, this concentration decreases to values similar to those observed in a cool well.

1. INTRODUCTION AND OBJECTIVES

The injection of steam into oil reservoirs is a common technique for improving the production of heavy and viscous crude oils. Very often a change in the composition of oil and gas may be observed during steam injection processes, both cyclic and drive. In general, corrosive gases, such as H₂S and CO₂, are produced in increased quantities. Especially H₂S in high concentrations, causes many production problems, thus, special precautions and safety regulations have to be adhered to.

It was shown that an increase in H₂S, CO₂, etc. depends strongly on the temperature of the steam injected. Furthermore, it was possible to prove that gases evolved during steam processes are originated from a decomposition of crude oil components.

Obtained results show that bitumen samples undergo aquathermolysis, in presence or absence of reservoir sand. These results with reconstituted sands are similar to those obtained with whole core samples, both in static and dynamic tests. In the dynamic tests, however, changes are more pronounced in shorter reaction times.

Based on these findings and observations, the problems and objectives of the present task, have been defined into three broad areas:

1. Laboratory physical simulation of the aquathermolysis reactions that occur during the steam injection process. This includes a laboratory experiment design at different flow rates and temperatures, employing a dynamic system.

2. Identify some kinetic parameters as function of H₂S generation data.
3. Study the H₂S production in steam stimulated wells. This includes the design of a sampling program in the field, which allows to establish a correlation of the following data: injection cycles, steam injected, production time, etc.

In this study the aquathermolytic activity of bitumen and sand from the Hamaca area reservoir, East of Venezuela, was measured. It was also necessary to identify some kinetic parameters in function of H₂S generation data, employing an elementary mechanism and deducing the respective kinetic equation. Simultaneously, determinations of H₂S production from twelve wells, four cycles in the same area, were performed.

2. LITERATURE REVIEWED

Hyne [1,2] used the term aquathermolysis to describe the reactions occurring in the 200 - 300 °C temperature range, which may include acid polymerization, organosulphur compounds cleavage due to reaction with water, gas release from both the fluids and rock matrix, water gas shift reaction, and hydrodesulphurization. Other authors [3,4,5] have studied the thermal visbreaking of heavy oils and bitumens in the 260 - 325 °C temperature range. These reactions, however, are not very important at temperatures below 280 °C, and they may actually be suppressed in this range by the presence of water.

In their previous experimental works Hyne [1,2] and Vilorio [6,7], have studied the aquathermolytic activity of Canadian and Venezuelan oil/bitumen, under a variety of conditions using static autoclaves. They have shown that significant chemical reactions occur between the oil sand and water in the 200 - 300 °C temperature range, whereby both oil and the porous matrix undergo aquathermolysis. The primary sand reaction appears to involve mineral carbonate producing varying amounts of CO₂, while the heavy oil/bitumen undergoes competitive chemical transformations that affect the final viscosity. It is also possible to have decomposition of carboxyl compounds in the oil.

One characteristic of the preceding work was that the reaction times were long, in the order of days and even months. This may have been due to the use of static cells where diffusion controlled steps may have been present. Therefore, in this work we studied in detail the aquathermolytic activity of the Hamaca bitumen by dynamic experiments over a broad range of temperature and different injection rates.

The dynamic tests were carried out by displacing bitumen contained in a sand packed tube with steam. Since the time to displace a tube pore volume was too short, if compared to typical reaction times, the displaced products were recirculated in a way similar to the operation of a tubular reactor with recycle. Bitumen and gas properties were measured after a prescribed total residence time in the tube. Gas composition in function of pore volume or

reaction time, deserves special attention in this work, so as to determine the reaction rate and some kinetic parameters of the global reaction.

3. EXPERIMENTAL EQUIPMENT

The dynamic experiments were performed in a special apparatus shown in Figure 1, which was discussed in a previous paper [8]. It consisted of a 5 cm (2 in) I.D. displacement core holder, placed inside a thermostatic oven ; two piston furnished cylinders of 1000 cm³ total capacity , connected to the core holder through a spiral shaped stainless steel tubing , which was preheated outside the oven with a heating jacket . The spiral tubing allowed enough residence time to let the fluids reach thermal equilibrium with the oven, before entering the displacement cell. The rest of the apparatus was made up of an injection pump , a water reservoir and metering balance , to measure the volume of fluids injected into the system, a back pressure valve, gas sampling valves , manometers and thermocouples , all connected with stainless steel tubing and fittings, as shown in the above Figure.

Gas analyses were performed by gas chromatography with a Carle CG-S-50 apparatus, which allowed the determination of hydrogen, hydrogen sulfide, carbon dioxide, carbon monoxide, methane and other hydrocarbons up to C₆.

4. EXPERIMENTAL PROCEDURE

The experiments were started by packing the displacement cell with reconstituted sand from the Hamaca reservoir. These sands were obtained from whole core samples by extracting

with toluene, drying with hot air, and sifting. The packed cell was initially saturated with water, and later displaced with dehydrated stock tank crude. The crude's saturated cell was then placed inside the thermostatic oven, connected to the system, and heated to the desired temperature. A known amount of bitumen and water was poured in one of the injection cylinders, so as to maintain the crude/water ratio to 1.08. This number was identified as the best crude/water ratio to produce high volumes of generated gas in this system. After setting the back pressure valve to the desired value, and turning the heating jacket on, we began injecting the contents of this cylinder into the displacement cell, collecting the displaced fluids in the other injection cylinder.

When all the fluids of the first cylinder had passed through the core holder and had been collected in the second cylinder, the experiment was carried out displacing then in the reverse direction. This cycle was repeated as often as necessary, sampling the gas phase through the corresponding sampling valves.

In this work it was assumed that the reaction of residence time of the whole system, was the residence time of the fluids in the core holder, averaged over all the fluids particles. In this case the reaction or residence time of a run, was given by:

$$Tr = N (Vc - Vm) /q,$$

where

N = number of displacements

Vc = Fluids' volume

Vm = Dead volume in the system, always constant

q = injection rate cm³/min.

4.1 DESIGN OF LABORATORY EXPERIMENTS

A set of experiences varying the rate of injection, as well as the system temperature, was performed, keeping constant the selected Hamaca sand reservoir, the tank crude, the fluid volumes, the number of displacing, and the crude/water ratio.

Injection rates or displacements of 2, 4 and 6 cm³/min, and temperatures between 200 - 290 °C were considered, simulating the typical temperatures of the steam injection processes.

4.2 FIELD SAMPLING PROGRAM

To determine the H₂S production levels in the Hamaca area, a first preselection based on the sedimentology and lithology of the area, was established trying to guarantee the fluid production from the same producing sands in the area, with similar grain diameters (1000 - 1900 microns), and basically constituted by quartz minerals and low clay contents.

Twelve wells were considered for sampling, three of which were cool producing, other three were under a first injection cycle, three in a second cycle, two in a third cycle, and one in a fourth cycle. The amounts of injected steam varied between 3500 - 5000 tons, and the production period between 1 and 1600 days at different cycles.

Gas samples were taken from the general test separators and previously dried before measuring the H₂S in the gas production at field, by using Drager tubes and through a Tracor/Atlas gas chromatograph, furnished with a sulfur selective detector.

5. RESULTS

5.1 EXPERIMENTAL RESULTS

Table 1 presents some physical and chemical characteristics of the Hamaca crude. Additionally, the mineralogical analysis of crude-free core samples is shown in Table 2.

Figures 2 to 7, present the gas production accumulation ($\text{cm}^3/100 \text{ g}$ of crude), in terms of reaction time at different displacement velocities. In these figures it can be observed how the concentration of the generated gases (H_2 , H_2S , CO_2 , CH_4 , C_2^+) increases in terms of temperature, and decreases as the displacement velocity increases; that is, the reaction time of the crude and the mineral matrix, become everytime shorter. This argument corresponds with the decrease of the chemical ability of the system under study - crude/matrix mineral/water - and is directly associated with the nature of both the crude and mineral matrix.

Table 3 shows the variation of the reaction order, with regard to temperature and displacement or contact velocity variations. Similarly, the production of gases in function of temperature and displacement velocity, is presented in Table 4. The concentration of each of these gases at 280 - 290 °C does not have any simple arithmetical relation with gas production at 240 - 260 °C. It may be inferred that catalytic and cracking and/or decomposition reactions of more complex compounds, begin to occur after 280 °C. This is the case of organosulfurated compounds, which can produce H_2S in specific conditions of temperature and nature of the medium.

Table 5 presents the calculated values of the preexponential factor and the activation energy in the 240 - 290 °C range, at different displacement velocities. Tests performed at 200 - 240 °C are not reported, since the volume of generated gases was very low, thus, hindering the performance of the respective composition analysis. However, the H_2S and CO_2 detected concentrations, employing Drager tubes, are not superior to 7 ppm.

5.2 ANALYSIS OF KINETIC RESULTS [9]

The differential method was employed in the analysis of the obtained data. This method directly analyzes the adjustment degree of the experimental data to the reaction velocity expression. The considered global chemical reaction can be expressed as follows:

1. Water steam (200- 300 °C)
2. Reservoir sand

In general terms, and in function of the concentration of H₂S, generated during the reaction, it was established an elemental mechanism having an H₂S production velocity proposed as:

$$V = d[\text{CBitumen}]/dt = V_{\text{H}_2\text{S}} = K (\text{CH}_2\text{S})^n$$

From the experimental data, velocity in several reaction times, as well as the values corresponding to concentration, were calculated.

Being CH₂S the independent variable, and applying logarithm, it results:

$$\ln V_{\text{H}_2\text{S}} = \ln K + n \ln \text{CH}_2\text{S}$$

From a logarithmic double graphic, a straight line of n slope and of Lnk intercept, is obtained when $\ln \text{CH}_2\text{S} = 0$.

The influence of temperatures on the rates of chemical reactions, is usually interpreted in terms of what is known as the

Arrhenius equation, according to which:

$$K = A \cdot \exp(-E_a/RT),$$

where

K = rate constant

A = preexponential factor (1/h)

E_a = activation energy (Kcal/g-mol)

R = gas constant

Velocity was calculated by means of numerical techniques, which allowed to approximate the function derivative to each time, by adjusting the straight line passing through five points at both right and left of the considered time. The kinetic parameters were estimated through least squares correlations.

Table 3 presents the reaction order values in function of both reaction temperature and displacement velocity. In general terms, the reaction order tends to decrease in function of temperature and displacement velocity.

If temperature is kept constant, variations of the reaction order, in terms of the displacement velocity, are very subtle in the 240 - 260 °C, variable orders from 1.03 to 2 cm³/min, and 0.60 to 6 cm³/min. However, between 280 - 290 °C the decrease of the reaction order is quite drastic, which may lead to think about the existence of a more complex kinetic mechanism than the proposed one.

Table 4 shows the values of the preexponential factor and those of the activation energy, calculated for the different

examined temperatures and displacement velocities. The low values reported by the preexponential factor and the activation energy, confirm the presence of a catalytic system. This can be understood from the collisions theory point of view, if we keep in mind that the A - factor represents the product of the number of collisions by a steric factor; then, this value should be lower in the presence of a catalyst, since the number of collisions among molecules sensible to decomposition is much higher than that of molecules with the active centers of a catalyst.

Therefore, it may be expected that when the displacement velocity increases, the activation energy increases also, and the preexponential factor decreases, as observed. In function of the magnitude of the activation energy found (23.7-59.1-73.9 Kcal/g-mol), it is possible to infer that the decomposition of more complex compounds takes place. If the mineralogical analysis performed on sand samples is thoroughly observed, it can be seen that an 8% is constituted by clays and a 6% by iron minerals in the form of sulfides, which, as it is known, catalyze decomposition reactions of molecules containing sulphur.

In a summary about kinetic-mechanistic studies in homogeneous phase, Martin [10] reveals average values of 40 Kcal for the decomposition of some thiols at 420 - 480 °C; 51 Kcal for some sulfides at 360 - 420 °C, and pressures of 4 psi. As regards disulfides, very little information is available; nevertheless, it is pertinent to compare the dissociation energy of an alkyl-S-S

-alkyl bond having 74 Kcal, with the highest value of the activation energy, calculated at the highest displacement velocity.

These experimental observations have not been previously reported and should allow to undertake a more intimate analysis of both the reaction and the mechanism by which it is produced. There is a variety of aspects to be considered within the quantitative analysis performed, such as the effect of temperature on the viscosity of the bitumen employed, which would favor the decomposition of compounds contained in the crude's heaviest fractions, as resins-asphaltenes; as well as the influence of changes in the medium's nature, mainly as regards the ionic force. These results have important implications for thermal recovery projects, since it is possible to incorporate a simple kinetic model, that allows to predict the magnitude order of gas production, such as H₂, H₂S, CO₂, etc., to a thermal simulator.

5.3 FIELD RESULTS

Table 6 shows the results of the analysis of the H₂S concentration, in terms of the days of well production and injection cycle. These results lead to infer that the high quantities of H₂S (1800 ppm - 1st day), are obtained on the first days of well production (1-15 days). After 300 days of production, these quantities decrease to H₂S concentrations similar to those

obtained in its cool production.

Figure 8 presents the H₂S production in terms of production time, which is independent from the injection cycle. When correlating the H₂S concentration and the crude's accumulated production, it can be observed that concentration shows a clear tendency of remaining constant after 120 days of production. Through Figure 9, it is possible to estimate the H₂S production in terms of the crude daily production, independently from the injection cycle in which it is present.

6. CONCLUSIONS

1. It is possible to perform a physical simulation of the aquathermolytic activity of different crude in dynamic conditions, and obtain in short reaction times, the reaction velocity of the catalytic transformations and its contribution to the global process.

2. The Hamaca bitumen suffers aquathermolytic reactions in ranges of 200 - 290 °C. From 280 °C on, catalytic, and specifically thermal (cracking/decomposition), reactions become more important in the process in which H₂, H₂S, CO₂, CH₄ and C₂+ are generated.

3. The compensation in the low values of the preexponential factor and those of the calculated activation energy, applying the Arrhenius equation, supposes the presence of a catalytic system, which is evidently conformed by the mineral matrix.

4. The H₂S production in wells recently injected with steam, in the Hamaca area, increases during the first days of production (1-15 days), reaching levels of 1800 ppm, and decreases after 300 days to cool production levels (10-30 ppm).

7. REFERENCES

1. Hyne, J.B. "Synopsis Report No. 50, Aquathermolysis", Alberta Oil Sands Technology And Research Authority, April 1986.
2. Hyne, J.; Clark, P.; Koo, J.; Greidanus, J.; Tyler, J.; and Verona D. "Aquathermolysis of Heavy Oils", Rev. Tec. INTEVEP, 2(1): 87-95 (1982).
3. Henderson, J.H.; Weber, L. "Physical Upgrading of Heavy Crude Oil by the Application of Heat", J. Can. Pet. Tech: 20-212 (Oct-dec 1965).
4. Shu, W.R.; Venkatesan, V.N. "Kinetics of Thermal Visbreaking of a Cold Lake Bitumen", J. Can. Pet. Tech.: 60-64 (March-April 1984).
5. Shu, W.R.; Hartman, K.J. "thermal Visbreaking of Heavy Oil During Steam Recovery Processes", SPE Res. Eng.: 474-482 (sept 1986).
6. Vilorio, A.; Parisi, S.; Borges, L.; "Generación de Sulfuro de Hidrógeno en Métodos Térmicos de Recuperación de Crudos" Rev. Tec. INTEVEP, 4(1): 47-53 (1984)
7. Vilorio, A.; Parisi, S.; Martínez, E.; Gimeika, A.; Sánchez, V. "Efecto de la Inyección de vapor sobre la calidad de un Crudo Extrapesado de la F.P.O." Rev. Tec. INTEVEP, 5(1): 67-72 (1985).
8. Rivas, O.R.; Campos, R.E.; Borges, L.G. "Experimental Evaluation of Transition Metals Salt Solutions as Additives in Steam Recovery Processes" SPE 18076 Presented at the 63rd Annual Technical Conference and Exhibition of the Society of Petroleum Engineers held in Houston, TX, October 2-5, 1988.
9. Jungers, J.C.; et. al. "Cinétique Chimique Appliquée" Société des Editions TECHNIP, 1979.
10. Martín, G.. "Estudios Mecánicos en Pirólisis de Compuestos Orgánicos de Azufre", Rev. Tec. INTEVEP, 8(2): 73-81 (1988).

8. ACKNOWLEDGMENTS

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PROPERTY	VALUE
%SULPHUR	3.83
MW (VPO)	559 +/- 13
°API A 60°F	9.2
SPEC. GRAVITY (SG)	1.0057
C (CONRADSON)	14.02
KINEMATIC VISC (cST)	
AT 140°F	4266
AT 210°F	263.2
DINAMIC VISC. AT 80°C	1217
SARA	
SAT	12.4
AROM	52
RESI	25.6
ASPHAL	10
ELEMENTAL ANALYSIS	
C	84.14
H2	10.46
Ni	120.68
V	572.57

TABLE 1. Characteristics of the Hamaca Stock Tanks Bitumen
Used in this Work

COMPOSITION (%P/P)	VALUE
QUARTZ	86
IRON MINERALS	
PYRITE	4
SIDERITE	2
CLAYS CONTENT	8
KAOLINITE/CHLORITE	67%
ILLITA/SMECTITE	33%

TABLE 2. Mineralogic Composition of Hamaca Sand Reservoir

Vd (cc/m)	Temperature			
	240°C	260°C	280°C	290°C
2	1.02	0.60	0.40	0.50
4	1.02	0.60	0.50	0.50
6	0.60	0.60	0.30	0.20

TABLE 3. Reaction order in Function of Temperature and Displacements Rates

	Vd (cc/m)		
	2	4	6
Ea (Kcal/g-mol)	23.7	59.6	73.9
A (1/h)	6.5 exp(-10)	6.3 exp(-24)	1.2 exp (-29)

TABLE 4. Activation Energy and Preexponential Factor at Different Displacements Rates

T (°C)	Vd = 2 cc / m				
	H2S	H2	CO2	CH4	Total
240	8.93	7.93	320.1	9.26	385.1
260	14.7	23.7	435.8	22.35	553.3
280	35.3	289.9	620.4	131.9	1292
290	64.1	414.9	668.2	194.5	1718
T (°C)	Vd = 4 cc / m				
	H2S	H2	CO2	CH4	Total
240	1.59	10.2	80.7	4.33	114.3
260	6.44	13.8	107.2	9.64	160.9
280	43.8	175.2	434.8	93.2	830.4
290	64.2	282.3	626.6	126.3	1198
T (°C)	Vd = 6 cc / m				
	H2S	H2	CO2	CH4	Total
240	0.41	2.83	22.9	1.55	37.7
260	4.98	27.2	88.2	9.93	152.4
280	22.3	79.6	153.2	34.6	327.8
290	43.4	181.2	264.3	85.6	628.2

TABLE 5. Gas Production at Different Temperature and Displacement Rate

CYCLE	Prod. Days	H2S conc, (ppm)	Nº Wells
0	100 - 500	5 - 20.	3
I	90 - 600	260 - 20	3
II	8 - 1600	600 - 20	3
III	900 - 1200	40 - 20	2
IV	1 - 180	1800 - 160	1

TABLE 6. H₂S Production on cyclic steam injection

Hamaca Area- (Bare 5)

FIG.1 EXPERIMENTAL EQUIPMENT (DYNAMIC SYSTEM)

GAS PRODUCTION ON DYNAMIC LAB SYSTEM.

GAS PRODUCTION ON DYNAMIC LAB-SYSTEM.

FIG.2. GAS PRODUCTION.

GAS PRODUCTION ON DYNAMIC LAB-SYSTEM.

GAS PRODUCTION ON DYNAMIC LAB-SYSTEM.

FIG.3. GAS PRODUCTION.

GAS PRODUCTION ON DYNAMIC LAB-SYSTEM

GAS PRODUCTION ON DYNAMIC LAB-SYSTEM.

FIG. 4. GAS PRODUCTION.

GAS PRODUCTION ON DYNAMIC LAB-SYSTEM.

GAS PRODUCTION ON DYNAMIC LAB-SYSTEM

FIG.5. GAS PRODUCTION.

GAS PRODUCTION ON DYNAMIC LAB-SYSTEM.

GAS PRODUCTION ON DYNAMIC LAB- SYSTEM.

FIG. 6. GAS PRODUCTION.

GAS PRODUCTION ON DYNAMIC LAB-SYSTEM.

GAS PRODUCTION ON DYNAMIC LAB-SYSTEM.

FIG.7. GAS PRODUCTION.

H2S PRODUCTION ON CYCLIC STEAM INJECTION

H2S PRODUCTION ON CYCLIC STEAM INJECTION

APPENDIX A

Full text of the "Eighth Amendment and Extension of
Implementing Agreement IV Between the Department of Energy
of the United States of America and the Ministry of Energy
and Mines of the Republic of Venezuela in the Area of
Enhanced Oil Recovery Thermal Processes."

EIGHTH AMENDMENT TO AND EXTENSION OF

IMPLEMENTING AGREEMENT NO. IV

BETWEEN

THE DEPARTMENT OF ENERGY OF THE UNITED STATES OF AMERICA

AND

THE MINISTRY OF ENERGY AND MINES OF THE REPUBLIC OF VENEZUELA

IN THE AREA OF

ENHANCED OIL RECOVERY THERMAL PROCESSES

WHEREAS, the United States Department of Energy (hereinafter referred to as DOE) and the Ministry of Energy and Mines of Venezuela (hereinafter referred to as MEMV) entered into an Agreement in the field of Energy Research and Development signed March 6, 1980 (hereinafter referred to as the Agreement);

WHEREAS, the Agreement has been extended to include the period through March 6, 1993;

WHEREAS, in furtherance of their mutual interests, DOE and MEMV on 29 September 1980, entered into Implementing Agreement IV for cooperation in the area of Enhanced Oil Recovery Thermal Processes (hereinafter referred to as the Implementing Agreement);

WHEREAS, DOE and MEMV have previously agreed to the First, Second, Third, Fourth, Fifth, Sixth, and Seventh Amendments to and Extensions of the Implementing Agreement;

WHEREAS, DOE and MEMV have discharged their principal obligations and duties under the Implementing Agreement and the First, Second, Third, Fourth, Fifth, Sixth, and Seventh Amendments and Extensions to their mutual satisfaction and benefit;

WHEREAS, DOE and MEMV now desire to further extend ongoing cooperative efforts and further desire to initiate and pursue new and additional cooperative activities;

WHEREAS, the need exists to increase the recovery efficiency of steam injection methods for the recovery of heavy oil, and the use of additives continues to be an attractive method of potentially increasing recovery efficiency;

WHEREAS, DOE and MEMV desire to cooperate in the application of in-situ combustion for the recovery of heavy oil;

WHEREAS, DOE and MEMV desire to further cooperative efforts on the understanding of the thermal processes and the reservoir and its fluids where these processes are conducted;

IT IS AGREED AS FOLLOWS:

ARTICLE 1

In accordance with Articles 5 and 7 of the Agreement, DOE and MEMV hereby further amend and extend the Implementing Agreement as hereinafter provided.

ARTICLE 2

Article 1 of the Implementing Agreement and all other articles and provisions not herein amended are extended as written. The Parties named hereafter are the same Parties identified in Article 1 of the Implementing Agreement.

ARTICLE 3

Article 2 of the Implementing Agreement is amended by adding the following Tasks 56 through 61:

Task 56 - DOE shall provide INTEVEP with results from the SUPRI heavy oil research program. This work deals with experimental determination of the flow mechanisms and analytical modelling of steam/foam systems, experiments on in-situ combustion and mathematical research on monitoring methods such as tracer and pressure transient testing. SUPRI will also communicate to INTEVEP the results of saturation determinations by Cat-Scan during laboratory experiments.

Task 57 - INTEVEP shall provide DOE with information on the Steam with Additives: field and laboratory research. The research is to reach conclusions about the economic applicability of these additives in increasing the efficiency of the cyclic steam injection and to identify production mechanisms.

Task 58 - DOE shall provide INTEVEP with information from research performed by NIPER on light oil, > 20 API gravity steamflooding. The research will include results from a Titanium high temperature high pressure steamflood model for determination of insitu dynamic saturation changes during steamflooding using existing NIPER capability in X-ray CT scanning. The saturation profiles, together with temperature, pressure, and electrical conductivity profiles, can then be employed to calibrate the numerical simulators for predictive purposes of steamflooding. Emphasis of the steamfloods will be on oil-wet dolomitic reservoirs that contain high pour point waxy crudes.

Task 59 - INTEVEP shall provide DOE with information on the Modelling of Thermal Processes. The effort will include the use of any refinements and dominant decomposition techniques in order to enhance modelling capabilities of steam processes.

Task 60 - DOE shall provide INTEVEP with information on electrical conductivity imaging using cross-borehole and surface-to-borehole electromagnetic tomography conducted by Lawrence Livermore National Laboratory. Such information is useful in oil field characterization (i.e. tracing of oil sands) and in process monitoring (steam soak or drive monitoring). The information will consist of instrumentation design, data collection schemes, software for providing conductivity images and results of field surveys.

Task 61 - INTEVEP shall provide DOE with information on H₂S Generation in Steam Processes: Laboratory and Field Research to provide laboratory data on H₂S generation in thermal processes and field monitoring of H₂S production on steam stimulated wells.

ARTICLE 4

The Implementing Agreement shall hereafter consist of the Implementing Agreement as amended by the First, Second, Third, Fourth, Fifth, Sixth, Seventh, and Eighth Amendments and Extensions.

ARTICLE 5

This Eighth Amendment and Extension shall become effective when signed by the DOE and MEMV Project Managers of Annex IV or their designated representatives. The Implementing Agreement, as amended, shall remain in effect until September 30, 1994, or until terminated by written notice as provided in Article 8 of the Implementing Agreement.

Done in Caracas, Venezuela and Bartlesville, Oklahoma.

On behalf of DOE

Project Mgr - Thomas Reid

September 30, 1992
Date

On behalf of INTEVEP

Project Mgr - Peter Colonos

9-30-1992
Date

APPENDIX B

Full text of the extension to the "Agreement Between the Department of Energy of the United States of America and the Ministry of Energy and Mines of the Republic of Venezuela in the Field of Energy Research and Development."

Signed on September 8, 1993 extending the Agreement for five years to September 7, 1998.

AGREEMENT
BETWEEN
THE DEPARTMENT OF ENERGY OF THE UNITED STATES OF AMERICA
AND
THE MINISTRY OF ENERGY AND MINES OF THE REPUBLIC OF VENEZUELA
IN THE FIELD OF ENERGY RESEARCH AND DEVELOPMENT

Whereas the Government of the United States of America and the Government of the Republic of Venezuela are Parties to an Agreement for Scientific and Technological Cooperation, with Annex, of December 8, 1990;

Whereas the United States Department of Energy (hereinafter "DOE") and the Ministry of Energy and Mines of the Republic of Venezuela (hereinafter "MEM") (hereinafter "the Parties") concluded an Agreement in the Field of Energy Research and Development of March 6, 1980, (hereinafter "the 1980 Agreement");

Whereas the Parties believe that the cooperative activities in the field of energy research and development undertaken pursuant to the 1980 Agreement were mutually beneficial to both Parties;

Whereas the Parties have a common interest in continuing certain Implementing Agreements under the 1980 Agreement and in undertaking new cooperative activities in the field of energy research by entering into a new Agreement;

Now therefore the Parties agree as follows:

ARTICLE I

The objective of cooperation under this Agreement is to continue, for the mutual benefit of the Parties, the balanced exchange of energy technology information related to petroleum, natural bitumen, solar energy, geothermal energy, hydroelectric energy, coal, and energy efficiency established by the 1980 Agreement and to conduct related joint research and development activities, which will be further defined in Project Annexes to this Agreement.

ARTICLE II

Cooperation under this Agreement may include, but is not limited to, the following:

1. Exchange of scientific and technical information, and results and methods of research and development on a periodic basis in a manner agreed to by the Joint Steering Committee (JSC) established by Article III;
2. Organization of seminars and other meetings on agreed topics of research and development in the areas enumerated in Article I in a manner agreed to by the JSC;
3. Survey visits by specialists to the energy research facilities of the other Party at the invitation of the host institution;
4. Exchange of materials, instruments, components, and equipment for testing;
5. Exchange of personnel for participation in agreed research, development, analysis, design and experimental activities;
6. Joint projects in the form of experiments, tests, design analysis, or other technical collaborative activity;
7. Joint funding of specific research and development projects which may be undertaken in connection with other qualified organizations or persons in a manner agreed to by the JSC; and
8. Other such forms of cooperation as may be jointly agreed in writing by the Parties and approved by the JSC.

ARTICLE III

1. A Joint Steering Committee (JSC) shall be established with each Party designating three officials to serve as Coordinators, to supervise the implementation of this Agreement. As mutually agreed, the JSC shall meet to evaluate all aspects of the cooperation under this Agreement. These meetings shall be held alternately in the United States and Venezuela.
 2. The JSC shall approve and monitor all cooperative activities to be carried out under this Agreement.
-

3. At its meetings, the JSC shall review and evaluate any newly proposed activities and the status of cooperation under this Agreement. The JSC also shall give appropriate guidance and direction to subcommittees and the project managers of activities established under this Agreement. If so requested, the JSC may give advice to the Parties regarding the progress and future of the cooperative activities established under this Agreement.
4. Each Party shall nominate one person to act on its behalf, during periods between meetings of the JSC, in all matters concerning cooperation under this Agreement.
5. The JSC shall, as necessary and appropriate, establish separate subcommittees in each of the following areas: petroleum, natural bitumen, solar energy, geothermal energy, hydroelectric energy, coal, and energy efficiency to facilitate implementation of projects which may be undertaken in those areas.

ARTICLE IV

1. Proposals for cooperation under this Agreement may be presented by either Party or its designated representatives to the JSC for its approval.
 2. Each cooperative activity which is approved by the JSC shall be described in writing in a Project Annex to this Agreement. Such Annexes shall contain detailed procedures for the implementation of the cooperative activity, including but not limited to the contributions by each Party (costs and cost-sharing), schedules, and responsibilities of each Party.
 3. No cooperative activity shall be undertaken by the Parties until a Project Annex has been concluded by the Parties.
 4. Each Project Annex concluded by the Parties thereof shall be subject to and refer to the provisions of this Agreement.
 5. The following Implementing Agreements, which were entered into pursuant to the 1980 Agreement shall continue to apply until work undertaken is completed subject to the terms and conditions of this Agreement, or until this Agreement expires or is terminated in accordance with Article XIII:
-

- A. Implementing Agreement I, Joint Characterization of Heavy Crude
- B. Implementing Agreement II, Cooperation Supporting Research at Universities, Government Energy Technology Centers, and National Laboratories
- C. Implementing Agreement III, Evaluate Past and Ongoing Enhanced Oil Recovery Projects in the United States and Venezuela
- D. Implementing Agreement IV, Enhanced Oil Recovery Thermal Process
- E. Implementing Agreement VIII, Coal Preparation, Combustion, and Related Analytical Technology at Universities, Government Energy Technology Centers, and National Laboratories
- F. Implementing Agreement X, On-Site Training of Petroleum Engineers
- G. Implementing Agreement XI, Energy Conservation
- H. Implementing Agreement XII, Geochemistry
- I. Implementing Agreement XIII, Microbial Enhanced Oil Recovery
- J. Implementing Agreement XIV, Exchange of Energy Related Personnel

ARTICLE V

The following provisions shall apply concerning exchanges of equipment pursuant to this Agreement:

1. By mutual agreement, a Party may provide equipment to be utilized in a joint activity. In such cases, the sending Party shall supply, as soon as possible, a detailed list of the equipment to be provided together with the relevant specifications and appropriate technical informational documentation related to the use, maintenance, and repair of the equipment.
 2. Title to the equipment and necessary spare parts supplied by the sending Party for use in joint activities shall remain in the sending Party, and the property shall be returned to the sending Party upon completion of the joint activity, unless otherwise agreed.
-

3. Equipment provided pursuant to this Agreement shall be brought into operation at the host establishment only by mutual agreement between the Parties.
4. The host establishment shall provide the necessary premises for the equipment, shall provide for utilities such as electric power, water, and gas, and normally shall provide materials to be tested, in accordance with the agreed technical requirements.
5. The responsibility and expenses for the transport of equipment and materials from the United States of America by plane or ship to an authorized port of entry in Venezuela convenient to the ultimate destination, and also responsibility for its safekeeping and insurance en route shall rest with DOE.
6. The responsibility and expenses for the transport of equipment and materials from Venezuela by plane or ship to an authorized port of entry in the United States of America convenient to the ultimate destination, and also responsibility for its safekeeping and insurance en route shall rest with MEM.
7. Equipment provided pursuant to this Agreement for use in joint activities shall be considered to be scientific, not having a commercial character, and each Party shall make its best effort to obtain duty free entry.

ARTICLE VI

The following provisions shall apply concerning exchanges of personnel under this Agreement:

1. Whenever an exchange of personnel is contemplated, each Party shall ensure the selection of adequate personnel with skills and competence necessary to conduct the activities planned under this Agreement. Each such exchange of personnel shall be mutually agreed in advance by an exchange of letters between the Parties, referencing this Agreement and its pertinent intellectual property provisions.
 2. Each Party shall be responsible for the salaries, insurance, and allowances to be paid to its staff or its contractors.
 3. Each Party shall pay for the travel and living expenses of its staff or its contractors when staying at the establishment of the host Party, unless otherwise agreed.
-

4. Each Party shall arrange for adequate accommodations for the other Party's staff or its contractors (and their families) on a mutually agreeable, reciprocal basis.
5. Each party shall provide all necessary assistance to the staff of the other Party or its contractors as regards administrative formalities.
6. The staff of each Party or its contractors shall conform to the general rules of work and safety regulations in force at the host establishment.

ARTICLE VII

1. The Parties shall ensure adequate and effective protection of intellectual property created or furnished under this Agreement and relevant annexes. The Parties agree to notify one another in a timely fashion of any inventions or copyrighted works arising under this Agreement and to seek protection for such intellectual property in a timely fashion. Rights to such intellectual property shall be allocated as provided in this Article.
2. SCOPE
 - A. This Article is applicable to all cooperative activities undertaken pursuant to this Agreement, except as otherwise specifically agreed by the Parties or their designees.
 - B. For purposes of this Agreement, "intellectual property" shall have the meaning found in Article 2 of the Convention Establishing the World Intellectual Property Organization, done at Stockholm, July 14, 1967.
 - C. This Article addresses the allocation of rights and interests between the Parties. Each Party shall ensure that the other Party can obtain the rights to intellectual property allocated in accordance with this Article by obtaining those rights from its own participants through contracts or other legal means, if necessary. This Article does not otherwise alter or prejudice the allocation between a Party and its nationals, which shall be determined by that Party's laws and practices.
 - D. Disputes concerning intellectual property arising under this Agreement should be resolved through discussions between the concerned participating institutions or, if

necessary, the Parties or their designees. Upon mutual agreement of the Parties, a dispute shall be submitted to an arbitral tribunal for binding arbitration in accordance with the applicable rules of international law. Unless the Parties or their designees agree otherwise in writing, the arbitration rules of UNCITRAL shall govern.

- E. Termination or expiration of the Agreement shall not affect rights or obligations under this Article.
- F. Cooperative activities will not be entered into where the purpose of the cooperative activity is to produce inventions in the following areas, or where there is a possibility of producing inventions in the following areas, until such time as inventions in these areas are considered patentable subject matter by both Parties:
 - 1. drinks and food products for humans and animals;
 - 2. medicines of all kinds; and
 - 3. pharmaceuticals and chemical preparations, reactions and compounds.

3. ALLOCATION OF RIGHTS

- A. Each Party shall be entitled to a non-exclusive, irrevocable, royalty-free license in all countries to translate, reproduce, and publicly distribute scientific and technical journal articles, reports, and books directly arising from cooperation under this Agreement. All publicly distributed copies of a copyrighted work prepared under this provision shall indicate the names of the authors of the work unless an author explicitly declines to be named.
- B. Rights to all forms of intellectual property, other than those rights described in Section VII.3.A. above, shall be allocated as follows:
 - 1. Visiting researchers, for example, scientists visiting in furtherance of their education, shall receive intellectual property rights under the policies of the host institution. In addition, each visiting researcher named as an inventor shall be entitled to national treatment with regard to awards, bonuses, benefits, or any other rewards, in accordance with the policies of the host institution.

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2. (a) For intellectual property created during joint research, for example, when the Parties, participating institutions, or participating personnel have agreed in advance on the scope work, each Party shall be entitled to all rights and interests in its own territory. Rights and interests in third countries will be determined in implementing arrangements. If research is not designated a "joint research" in the relevant implementing arrangement, rights to intellectual property arising from the research will be allocated in accordance with paragraph VII.3.B.1. In addition, each person named as an inventor shall be entitled to national treatment with regard to awards, bonuses, benefits, or any other rewards, in accordance with the policies of the host institution.
- (b) Notwithstanding paragraph VII.3.B.2.(a), if a type of intellectual property is available under the laws of one Party but not the other Party, the Party whose laws provide for this type of protection shall be entitled to all rights and interests worldwide. Persons named as inventors of the property shall nonetheless be entitled to awards, bonuses, benefits, or any other rewards as provided in paragraph VII.3.B.2.(a)

4. BUSINESS-CONFIDENTIAL INFORMATION

In the event that information identified in a timely fashion as business-confidential is furnished or created under this Agreement, each Party and its participants shall protect such information in accordance with applicable laws, regulations, and administrative practices. Information may be identified as "business-confidential" if a person having the information may derive an economic benefit from it or may obtain a competitive advantage over those who do not have it, or the information is not generally known or publicly available from other sources, and the owner has not previously made the information available without imposing in a timely manner an obligation to keep it confidential.

ARTICLE VIII

-
1. Unless otherwise agreed, all costs resulting from cooperation pursuant to this Agreement shall be the responsibility of the Party that incurs them.

2. Each Party shall conduct the activities provided for in this Agreement, and its Annexes subject to its applicable laws and regulations, and shall provide financial resources subject to the availability of appropriated funds.
3. Each Party shall use its best efforts to obtain all permits and licenses required by the applicable laws and regulations for the implementation of this Agreement and its Annexes.

ARTICLE IX

Both Parties agree that no information or equipment requiring protection in the interests of national defense or foreign relations of either Party and classified in accordance with the applicable national laws and regulations shall be provided under this Agreement. In the event that information or equipment which is known or believed to require such protection is identified in the course of cooperative activities undertaken pursuant to this Agreement, it shall be brought immediately to the attention of the appropriate officials and the Parties shall consult to identify appropriate security measures to be agreed upon by the Parties in writing and applied to this information and equipment and shall, if appropriate, amend this Agreement to incorporate such measures.

ARTICLE X

The transfer of unclassified export-controlled information or equipment between the Parties shall be in accordance with the relevant laws and regulations of each Party. If either Party deems it necessary, detailed provisions for the prevention of unauthorized transfer or retransfer of such information or equipment shall be incorporated into the contracts or implementing arrangements. Export-controlled information shall be marked to identify it as export-controlled and identify any restrictions on further use or transfer.

ARTICLE XI

All information or equipment transmitted by one Party to the other Party under this Agreement shall be appropriate and accurate to the best knowledge and belief of the transmitting Party, but the transmitting Party does not warrant the suitability of the information or equipment transmitted for any particular use or application by the receiving Party or by any third party. Information or equipment developed jointly by the Parties shall be appropriate and accurate to the best knowledge

and belief of both Parties. Neither Party warrants the accuracy of the jointly developed information or the appropriateness of equipment or its suitability for any particular use of application by either party or by any third party.

ARTICLE XII

All questions related to the interpretation or application of this Agreement shall be settled by the Parties by mutual agreement.

ARTICLE XIII

1. This Agreement shall enter into force upon signature by each Party and shall remain in force for five (5) years.
2. This Agreement may be amended or extended by mutual written agreement of the Parties. This Agreement may be terminated upon one (1) year's advance notification in writing by either Party. Such termination shall be without prejudice to any rights and interests which may have accrued under this Agreement to either Party up to the date of termination.
3. All joint efforts and experiments not completed at the expiration or termination of this Agreement may be continued until their completion under the terms of this Agreement.

Done at Caracas and Washington, in duplicate, in the English and Spanish languages, each text being equally authentic, this 8th day of September 1993.

FOR THE DEPARTMENT OF ENERGY
OF THE UNITED STATES OF
AMERICA

Signature

Jack S. Siegel
Acting Assistant Secretary
for Fossil Energy

Printed Name/Title

FOR THE MINISTRY OF ENERGY AND
MINES OF THE REPUBLIC OF
VENEZUELA

Signature

Rafael M. Guevara
General Director

Printed Name/Title