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SUPRI HEAVY OIL RESEARCH PROGRAM

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PROJECT 1: FLOW PROPERTY STUDIES

To assess the influence of different reservoir conditions (temperature and pressure) on the absolute and relative permeability to oil and water and on capillary pressure.

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:

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

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:

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

where:

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

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.

PROJECT 2: IN-SITU COMBUSTION

To evaluate the effect of different reservoir parameters on the in-situ combustion process. This project includes the study of the kinetics of the reactions.

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; Weijdem, 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.

Figure 2.2.1 Schematic diagram of kinetic and combustion tube apparatus.

PROJECT 3: STEAM WITH ADDITIVES

To develop and understand the mechanisms of the process using commercially available surfactants for reduction of gravity override and channeling of steam.

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 $P_c = P_{cbase}$

(a)

(b)

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_{cwom} is not the same for the two cases).

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

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

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

- CASE 1, 1-layer, polysulfone inf.
- CASE 2, 2-layer, polysulfone + fiberfrax
- ▲— CASE 3, 2-layer, polysulfone + fiberfrax, conv.
- +— CASE 4, 2-layer, polysulfone + inf. fiberfrax
- ◆— CASE 5, 1-layer, polysulfone, conv.
- CASE 6, 3-layer, polysulfone, polycy. and fiberfrax

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

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

Figure 3.1.9 Front view of the core holder.

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).

PROJECT 4: RESERVOIR DEFINITION

To develop and improve techniques of formation evaluation such as tracer tests and pressure transient tests.

There are no students presently working on this project.

PROJECT 5: FIELD SUPPORT SERVICES

To provide technical support for design and monitoring of DOE sponsored or industry initiated field projects.

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%.

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.

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