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TOPICAL REPORT

FEASIBILITY STUDY TO MODIFY THE DOE STEAMFLOOD AND CO_2 (MISCIBLE) FLOOD PREDICTIVE MODELS RESPECTIVELY TO INCLUDE LIGHT OIL STEAMFLOODING AND IMMISCIBLE GAS DRIVE

BY

W. D. Henline, M. A. Young, and J. T. Nguyen

Work Performed for the
U. S. Department of Energy
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FOREWORD

This report is fulfillment of Milestones A of Tasks 3 and 4 (Project BE2B) to report on the feasibility of updating the DOE predictive simulation codes to include new EOR processes not included in the current capability. The need to perform these code modifications is based on an assessment of both EOR potential for prospective processes and an examination of the numerics and model-governing equations for each specific case. A statement of work, schedule of tasks, and manpower requirements are specified in the report. This report recommends that the code modification project be implemented in the remainder of FY85.

INTRODUCTION

The Department of Energy (DOE) currently maintains a suite of simplified, predictive computer models for enhanced oil recovery (EOR) processes for use in reservoir EOR screening analysis and economic feasibility calculations. As valuable planning tools, these codes should have as broad a capability as possible. EOR processes which can now be evaluated include heavy oil steam drive, polymer flooding, micellar polymer flooding, in situ combustion, and CO_2 miscible flooding. Among the known available EOR processes, light oil steamflooding, steam soak, immiscible gas drive, and microbial EOR (MEOR) have not been addressed by the DOE predictive models. To consider including modeling capability for any of these requires additional knowledge of the ultimate EOR production potential for each process, as well as the technical feasibility of effecting the code improvements necessary. Based on common knowledge of current EOR field practice, MEOR is eliminated from further consideration, since it has not been fully demonstrated at field scale. The DOE has recently received a new cyclic steam stimulation (steam soak) code from Venezuela, therefore this process will also be excluded from consideration. The following sections discuss process EOR potential, necessary code improvement steps, and project manpower and scheduling for including light oil steamflooding and immiscible gas drive in DOE's predictive models. Inclusion of reservoir dip angle in the CO_2 miscible model is also discussed.

EOR POTENTIAL OF NEW PROCESSES

The primary reason for considering the development of new predictive capability is to screen appropriate domestic proven oil reserves and determine estimates of economically feasible, incremental oil production by specific EOR processes. A significant incentive is, therefore, the maximum amount of current oil remaining in place in those reservoirs which would qualify (based on pre-selected screening criteria) for the given EOR process. To obtain this information, a computer search of the NPC data base was performed by the Bartlesville Project Office (BPO) to find those domestic reservoirs which qualify for immiscible gas drive and light oil steamflooding. The following screening criteria were applied.

Light Oil Steamflooding

Oil Viscosity $\geq$ 100 cp
Oil saturation porosity product $\geq$ 0.1
Payzone thickness $\geq$ 20 ft.

Immiscible Gas Drive

API gravity ≅ 14
Pressure (psi) ≥ 850
Depth (ft) ≥ 1400

As a result of this screening, 78 reservoirs initially qualified for light oil steamflooding while 715 reservoirs satisfied the immiscible gas screen. Not all of these fields can be counted as candidates for EOR, since some were already being subjected to some tertiary method. By comparing the screened reservoirs against all known current EOR projects, these active projects were removed from the light oil steamflood and immiscible gas EOR potential. Tables 1 and 2 list the respective reservoirs on a state-by state basis together with original oil in place (OOIP).

TABLE 1. - Light oil reservoirs suitable for steam drive

	State	Number of Reservoirs	OOIP MMSTB
	AR	3	475
	CA	17	8202
	IL	1	19
	KS	1	61
	LA	22	1880
	OK	1	17
	TX	20	2494
TOTAL		65	13148

TABLE 2. - Reservoirs suitable for immiscible gas flooding

	State	Number of reservoirs	OOIP, MMSTB
	AK	2	26160
	AL	1	78
	AR	15	2475
	CA	114	39254
	CO	2	42
	FL	2	77
	IL	10	1622
	KS	18	2823
	KY	2	129
	LA	17	2252
	MS	18	1498
	MT	4	579
	NM	7	1147
	OK	15	3252
	TX	87	12967
	UT	2	26
	WV	6	110
	WY	32	3565
TOTAL		354	98056

Based on these numbers and a presumption of an ultimate residual oil saturation of 35 percent after waterflood, an estimate of the maximum recoverable oil by each process is:

Light Oil Steamflooding	4,602 MMSTB
Immiscible Gas Flooding	34,320 MMSTB

These numbers are meant only as order-of-magnitude values and are not to be used as representations of the actual EOR potentials for each process. As such they do indicate a considerable incentive for developing a predictive simulation capability for both light oil steamflooding and immiscible gas drive. The codes can be used to perform more detailed oil recovery and economic analyses for each reservoir. These results can then properly define the economic EOR potential for each process. From the standpoint of these processes the recovery and economic analysis will provide information to compare with processes that can compete in application to the same reservoirs. Light oil steamflooding essentially would be applied to the same oil as the miscible/polymer process and cannot be considered as adding additional reserves over and above what would be provided by micellar/polymer flooding technology. Also, comparative economics should be determined to see if economic differences occur between immiscible flooding with N_2 versus CO_2.

The conclusion from this section is that, from the standpoint of ultimate oil reserves for process application, there is sufficient incentive to develop predictive code improvements to describe light oil steamflooding and immiscible gas drive. Aspects of the technical feasibility of doing this will be considered next.

TECHNICAL FEASIBILITY FOR PREDICTIVE CODE IMPROVEMENTS

To include the capability to simulate light oil steamflooding and immiscible gas into the DOE codes, a decision has been made to utilize the code structures currently in place. Thus the DOE steam predictive code would be modified to account for the steam-oil distillation occurring in a light oil steam drive. Immiscible gas (N_2 and CO_2) behavior would be accounted for by modifying the DOE CO_2 miscible gas predictive code. A brief technical review of each of these codes along with the suggested modifications is presented here.

MODIFICATIONS TO THE STEAMFLOOD PREDICTIVE MODEL

The steamflood predictive model developed for the DOE by Scientific Software-Intercomp is essentially a variable volume "tank" model in which the tank volume is defined by the radial extent of the advancing oil and steam/hot water banks. The rate of this frontal advance is governed by solution of the appropriate thermal energy and fractional flow governing equations. Listed below is a synopsis of the equations and assumptions used in the current (black oil) steamflood predictive model.

Total Energy Balance on Tank (Reservoir)

$$\frac{d}{dt}\left(\overline{\rho_s C_{ps}}\, V_s T_s\right) + \frac{d}{dt}\left(\overline{\rho_L C_{pL}}\, V_L T_L\right) = H_I - \frac{d}{dt}\int_0^t \left(\overline{\rho_s C_{ps}}\, T_s \frac{\partial V_s}{\partial t'}\right) dt' - \frac{d}{dt}\int_0^t \left(\overline{\rho_L C_{pL}}\, T_L\right)\frac{\partial V_L}{\partial t'}\, dt',$$

where
ρ_s = steam (vapor) density
C_{ps} = steam (vapor) heat capacity
V_s = steam zone volume
T_s = steam zone temperature
ρ_L = hot liquid bank density
C_{pL} = hot liquid bank heat capacity
V_L = hot liquid bank volume
T_L = hot liquid bank temperature
H_I = total enthalpy injection rate at the injection well

Component Material Balances

Steam: (in the steam zone)

$$M_I = (2\pi R_s) h_n (f_{w,s}\rho_{w,s} + f_{s,s}\rho_{s,s}) v_s$$

where

$$f_{i,j} = \frac{\lambda_{r,ij}}{\sum_i \lambda_{r,ij}} = f_{i,j}\,(S_{ij},\, S^o_{ij}\quad)$$

Subsidiary Conditions

$$f_{o,s} = 0 \quad , \; S_{o,s} = S^{o}_{o,s}$$

$$\sum_i f_{i,j} = 1$$

Here,

$f_{i,j}$ = fractional flow of species i in zone j.
v_i = frontal velocity of zone i (superficial)
R_i = frontal radius of zone i
h_n = net reservoir thickness
$\lambda_{r,ij}$ = relative mobility of species j in zone i
S_{ij} = saturation of species i in zone j
M_I = mass flowrate of injected steam

Adiabatic Assumptions

$$(\rho_s C_{ps}) v_s \frac{dT}{dt} = v_s\{(f_{w,s}\rho_{w,s}C_{pw}+f_{s,s}\rho_{s,s}C_{ps}) \frac{dT}{dt} + f_{s,s}\rho_{s,s}\Delta H_v\}$$

where

$$v^f_s = \frac{dR_s}{dt}$$

These equations will permit calculation of steam zone saturations and v^f_s

Oil: (mass conservation must be applied at hot water/steam "shock" front)

$$\rho_{o,s}v_{\phi s}f_{o,s}-\rho_{o,s}S_{o,s}v^f_s = \rho_{o,w}v_{\phi w}f_{o,w}-\rho_{o,w}S_{o,w}v^f_s$$

(Buckley-Leverett result or <u>quasi-static assumption</u>)

Water: (at steam/hot water "front")

$$(\rho_{s,s}f_{s,s}+\rho_{w,s}f_{w,s})v_{\phi s}-(\rho_{s,s}S_{s,s}+\rho_{w,s}S_{w,s})v^f_s = \rho_{w,w}v_{\phi w}f_{w,w}-\rho_{w,w}S_{w,w}v^f_s$$

here

$$v_{\phi j} = \frac{v_j}{\phi}$$

ϕ = porosity

*These mass balances provide <u>liquid water and oil</u> saturations in the <u>hot liquid bank</u> as well as

$$v^f_s = \frac{dR_w}{dt}$$

Derived Quantitites

Saturations in the hot liquid bank and cold liquid bank as well as the cold liquid bank frontal velocity

$$v_c^f = \frac{dR_c}{dt}$$

can be determined directly from the above solutions by the application of frontal mass balances.

System Closure

To complete the system of equations, resulting in calculation of bank volumes and temperatures, an energy balance (adiabatic assumption) on the hot liquid bank is needed.

$$\frac{d}{dt}(\overline{\rho_L C_{pL}}\, V_L T_L) = (\rho_{w,w} f_{w,w} C_{pw} + \rho_{o,w} f_{o,w} C_{po}) V_w (2\pi R_s h_n) \frac{dT_L}{dt}$$

$$- \frac{d}{dt} \int_0^t (\overline{\rho_L C_{pL} T_L}\, \frac{\partial V_L}{\partial t'}) dt'$$

In order to successfully model the behavior of "light oil" containing reservoirs undergoing steamflooding, the simulator must account for the associated vapor/liquid equilibrium effects. Since light crude oils (and some heavy crudes) contain a significant fraction of low boiling hydrocarbon components, the elevated temperatures produced by steaming will cause selective vaporization (distillation) of these compounds to the vapor (steam) phase. To account for this in a process simulator, the methodology for determining this phase equilibration and its effect on phase fractional flows must be included. These inclusions can be made most appropriately under the following assumptions.

Thermodynamic Assumptions

1. Ideal oil solutions
2. Oil insoluble in liquid water phase
3. Vapor-liquid equilibrium distributions can be obtained from fugacities determined from an appropriate equation of state.

Transport (fractional flow) Assumptions and Modification

1. The steam zone now has significant partial pressure of hydrocarbon components, requiring modification of the fractional flow governing equations.
2. Fractional flow treatment will be modified by assuming local thermodynamic equilibrium exists between the steam and hot liquid banks. Thus one can write:

$$f_{s,s}\rho_{s,s} = \sum_i f_{i,s}\rho_{i,s}$$

i = species i
Subscript (s) refers to steam zone or steam vapor

$f_{i,j}$ = fractional flow of species i in zone j

$\rho_{i,j}$ = mass density of species i in zone j.

also

$$f_{i,s} = f(S_{i,s}, S_{j,s}; \; ---)$$

where

$S_{i,s}$ are <u>saturations</u> of species i in the steam zone.

<u>Hydrocarbon Steam Zone Saturation Calculations</u>

Phase species distributions are determined from species K-values, i.e.,

$$K_i^{(s)} = \frac{S_{i,s}}{S_{i,L}} = K_p \frac{Y_{i,s}}{X_{i,L}},$$

where

K_p = a proportionality constant

X & Y are mole fractions.

Now,

$$\frac{Y_{i,s}}{X_{i,L}}, = \frac{\phi_i^L}{\phi_i^s}$$

where ϕ_i^j are determined from the <u>Peng-Robinson</u> equation of state.

Thus

$$\ln\phi_i = (RT)^{-1} \int_0^p \left[\left(\frac{\partial V}{\partial n_i}\right)_{T,p,m_j} - \frac{RT}{p'}\right] dp,'$$

and

$$p = \frac{RT}{v-b} - \frac{a(T)}{V(V+b) + b(V-b)}.$$

a(T) and b are compositionally and temperature dependent parameters characteristic of the crude oil system in question. These alterations and inclusions in the steam predictive code can be performed in a straightforward manner, however, significant re-programming will be involved to build a thermodynamics package for K-values.

CODE MODIFICATIONS FOR IMMISCIBLE GAS DRIVE

The DOE now has a functional algorithm to estimate performance of reservoirs undergoing miscible CO_2 flooding. This model, developed by Scientific Software-Intercomp, makes use of the non-linear method of characteristics to numerically solve the fractional flow equations. These take the form,

$$\frac{\partial C_i}{\partial t_D} + \frac{\partial F_i}{\partial X_D} = 0 \quad i = 1, 2, ---, N \text{ species}$$

$$C_i = \sum_j C_{ij} S_j \quad j = 1, 2, ---, 1 \text{ phases}$$

$$F_i = \sum_i C_{ij} f_j,$$

where C_{ij} = concentration of species i in phase j

S_j = saturation of phase j.

In a reservoir with no slope or inclination (dip)

$$f_j = \frac{\lambda_j}{\sum_j \lambda_j}.$$

In the present model, this is assumed to be the case. Inclusion of a dip angle will modify the fractional flow treatment as follows:

$$f_j = \frac{\left(1 + \frac{g \sin\Theta}{\Delta P} \rho_j\right)\lambda_j}{\sum_j \lambda_j + \frac{g \sin\Theta}{\Delta P} \sum_j \rho_j \lambda_j}$$

Modifications proposed here will include adopting the formulation with dip angle. Additional definitions used here are,

$$t_D = \int_0^t \frac{q_I(t')\, dt'}{V_p}$$

V_p = total pore volume

$X_p = x/L$

L = reservoir "length" or "radius"

$q_I(t)$ = total volumetric fluid injection rate.

The effects of unstable frontal displacement (fingering) are estimated in the CO_2 miscible solution by application of the Koval method (or Koval factor) to the fractional flow equations. Currently, solutions can be obtained with or without fingering. It is proposed to modify the algorithm to determine the onset of fingering through use of a threshold criterion. For example, a criterion due to Blackwell, et al.,* can be used to determine the mass flux beyond which fingering can occur. Here,

$$\left(\frac{q(r,t)}{2\pi rh}\right) \simeq \text{MIN} \left(\frac{k\Delta\rho}{\Delta\mu}\right)\sin\Theta,$$

$q(r,t)$ = local volumetric flowrate
r = radial position
h = reservoir thickness
k = total permeability
Θ = dip angle

To modify this algorithm to account for the effects of immiscible gas drive, it is necessary to account for effects of vapor/liquid equilibrium. The CO_2 program now has routines which calculate the equilibrium distribution between two liquid phases (oleic and aqueous using liquid-liquid distribution coefficients. This program must be expanded to include vapor-liquid distribution coefficients (K-values). K-values will be estimated by using the Peng-Robinson or Redlich-Kwong equations of state for vapor phase fugacities. Aqueous phase solubilities of CO_2, N_2 or other "non-condensibles" will be estimated by a modified version of Henry's Law. Since significant regions of the reservoir will contain free vapor, the effects of vapor-phase override will also have to be included in the code modifications.

*Ref. Blackwell, R. J., et ##?al. Factors Influencing the Efficiency of Miscible Displacement. Petroleum Trans., AIME, v. 216, 1959, pp. 1-8.

PROJECT STATEMENT OF WORK, MANPOWER REQUIREMENTS AND SCHEDULE

STATEMENT OF WORK

Tasks outlined below are considered necessary to accomplish the predictive model modifications described earlier.

Modifications for Light Oil Steamflooding

Task 1: Development and Programming for Thermodynamics Package

It will be necessary to develop all required equations and data to permit application of the Peng-Robinson equation of state to some typical light crudes. Reference will have to be made to literature background for similar systems, and basic data (e.g. crude component boiling range characterizations and component interaction coefficients) assembled. Having done this, a Fortran subroutine(s) will be written to (in a fashion usable by the present code) calculate K-values. This subroutine will be meshed with the current liquid K-value routine, if that appears to be an efficient approach.

Task 2: Computer Program Update

The present steamflood algorithm will be updated to accept the new crude component species (fractional flow modifications) and thermodynamic variables. This will require expansion of the program array dimensionality as well as input and output capability to handle the additional data requirements.

Modification of the CO_2 (Miscible Flood) Predictive Code

Task 1: Include Modification for Gravity Effects

The fractional flow equations and associated solution subroutines will be modified to include gravity (reservoir dip angle) effects. Modified equations include the local pressure gradient explicitly, and this will require

Task 2: Develop Thermodynamics Package

Work similar to that outlined in Task 1 of the steamflood code modifications will be required here. Additional work will be required to mesh this new routine with the existing K-value subroutines.

Task 3: Computer Program Update

To accommodate new species (N_2 and other gases) the CO_2 program and dimensionality will have to be expanded. Also the input and output routine capabilities need to be modified and expanded to accommodate the additional component property and thermodynamic data requirements.

MANPOWER REQUIREMENTS

On a task-by-task basis, the following manpower requirements are estimated. These requirements, of course, must be factored into the calendar schedule of work.

Requirements for Steamflood Model Modifications

	Man-months
Task 1	1.5
Task 2	3.0
	4.5

Requirements for CO_2 (Miscible Flood) Model Improvements

	Man-months
Task 1	0.5
Task 2	0.5
Task 3	1.5
	2.5

Total program requirements, 7.0 man-months

Scheduling Work

Project: Steamflood

TASK	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Task 1.						XXXXX	XXXXXX					
Task 2.							XXXXX	XXXXXX	XXXXXX	XXXXX*		
Progress Reporting Requirements		AΔ	AΔ	AΔBΔ	AΔ	AΔ	AΔBΔ	AΔ	AΔ	AΔBΔ	AΔ	AΔCΔ[1]

Task No.	**Milestone**	**Description**
		* Test new steamflood predictive model.

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Scheduling Work

Project: CO_2

TASK	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Task 1.										XXXXXX		
Task 2.										XXXXX	XXX	
Task 3.										XXXXXX	XXXXXX	XXXX**
Progress Reporting Requirements		A∆	A∆	A∆B∆	A∆	A∆	A∆B∆	A∆	A∆	A∆B∆	A∆	A∆C∆[1]

Task No. Milestone	Description
	** Test new CO_2 predictive model.

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