Fourth SPE Comparative Solution Project: Comparison of Steam Injection Simulators

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Summary. Three related steam injection problems are presented along with simulation results for them obtained from six organizations. The problems selected for comparison were intended to exercise many of the features of thermal models that are of practical and theoretical interest. The first problem deals with three cycles of cyclic steam injection and the other two problems deal with steam displacement in an inverted nine-spot pattern. The first two problems are of "black-oil" type and the third of compositional type. Complete data are presented for these problems. The comparison of solutions indicates good agreement for most of the results of importance in field operations.

Introduction

Validation of reservoir simulators for complex recovery processes is a particularly difficult problem because analytical solutions are available under only a few limiting conditions. While good agreement between the results from different simulators for the same problem does not ensure validity of any of the results, a lack of agreement does give cause for some concern. Such comparisons can also be useful in the development of new models and in optimizing the performance of existing reservoir simulators.

This is the fourth in a series of simulation problems for which results from a number of commercial simulators have been obtained and reported in the SPE literature. The first such study was organized and conducted by Odeh[1] on the simulation of a three-dimensional (3D), two-phase, black-oil case. Seven companies participated in that project. This was followed by a comparative solution project developed by the program committee for the 1982 SPE Reservoir Simulation Symposium in New Orleans. The problem selected was a three-phase, single-well radial cross-section coning problem. Eleven companies participated in this study. Chappelear and Nolen[2] were responsible for organizing this study and for reporting the results at the symposium. A similar approach was adopted by the program committee for the 1983 SPE Reservoir Simulation Symposium in San Francisco. In this case, the problem selected was to study gas cycling in a rich-gas retrograde condensate reservoir. In the first part of the study, the participants matched their phase-behavior packages to the data supplied, and in the second part they considered two options for the depletion of the reservoir. This study required a 3D, three-phase, multicomponent compositional model. Nine companies participated in this study. Kenyon and Behie[3] organized the project and reported the results at the symposium.

The enthusiastic response of industry and the academic community to the three problems encouraged the program committee for the 1985 SPE Reservoir Simulation Symposium to continue the tradition and to develop a set of problems suitable for the comparison of steam injection models. We were given the task of organizing this project.

The objective of this paper is to present selected results submitted by the participants in this project with a minimum of commentary. It is worth emphasizing that the type of comparison presented here and in previous reports[1-3] is different from other kinds of comparisons discussed in the literature (e.g., Refs. 4 and 5). In the SPE comparisons, the problems are designed by one or more knowledgeable people, and model results are provided directly by those who have built or acquired suitable models. This is different from a study where the person doing the comparison develops new software using published descriptions of several models. It is possible—although we have tried to minimize this—that some of the differences in the results compared here could be a result of different interpretations of the problem, while differences in a comparison of the type discussed in Ref. 4 may be caused by differences in the interpretation of the published procedures. Furthermore, the models used in our comparison are all commercial in nature. Some of these models have been in existence for several years and others are new.

Problem Statement

We have selected three related but independent problems for the comparison of steam injection models: (1) cyclic steam injection in a nondistillable oil reservoir with a two-dimensional (2D) radial cross-sectional grid, (2) nondistillable oil displacement by steam in an inverted nine-spot pattern by considering one-eighth of the full pattern (see Fig. 1), and (3) displacement of an oil consisting of two volatile components and one nonvolatile component in the same pattern as Problem 2. The oil properties were the same in the first two problems. The participants had the option to submit results for one, two, or all three problems. In addition we invited optional runs. A complete statement of the problems as offered to the participants is contained in Appendix A. (We have deleted the section on reporting requirements to save space.)

The problems were selected to exercise features of the models that are important in practical applications; they do not necessarily represent real field situations. In particular, we wanted to see the influence of grid orientation on the results of the steam displacement problems. The inverted nine-spot appeared to us to be ideal for this purpose.

Six companies (see Appendix B) participated in the project with only three submitting results for the compositional case (Problem 3). Four of the other companies contacted indicated an interest in the project during the early stages but were unable to provide results for the comparison for a variety of reasons. In addition to providing numerical results, the participants were also asked to describe their model briefly and to answer a number of questions about the model. These descriptions with only minor editorial changes are given in the next section.

Description of Models Used

Arco Oil and Gas Co. Arco used Scientific Software-Intercomp's (SSI's) THERM model described later.

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**Now with Technology Development Group

Chevron Oil Field Research Co. Chevron's steamflood simulator is a fully implicit, fully compositional, finite-difference model. It can handle water and "n_c" user-specified hydrocarbon components. The hydrocarbon components may partition into the oleic and the vapor phases. The water component may partition into the aqueous and the vapor phases.

The mathematical model consists of $(2n_c+6)$ constitutive equations for every block. These equations are consolidated into (n_c+1) mass-balance equations and one energy-balance equation. The primary variables are water saturation, oil saturation or pressure, temperature, and (n_c-1) liquid mole fractions. Oil saturation is a primary variable for the three-phase case, but pressure is a primary variable for the two-phase case.

The transmissibilities are calculated as the product of a saturation-dependent term with a saturation-independent term. The saturation-dependent term is evaluated at the upstream node, the saturation-independent term is taken as an average of the neighboring block properties. A fully implicit 11-point method is used to reduce grid-orientation effects for uniform grids. The areal flow is based on the Yanosik and McCracken formula.[6] The well equations are fully implicit. No backflow is allowed in the production wells.

Timestep selection is based on Jensen's[7] method. The global iteration uses Newton's method. The linear equations were solved by Gaussian elimination for this project, although preconditioned conjugate-gradient-like methods are also available in the simulator.

Computer Modeling Group (CMG). ISCOM[8] is a fully implicit four-phase (oil, water, gas, and solid) multicomponent finite-difference thermal simulator. Model equations are formed from component mass and energy balances that account for accumulation, vaporization/condensation, injection/production, chemical reactions, heat conduction, heat loss, and the flow of mass and energy. Interblock flow is calculated by use of single-point upstream fluid mobility and enthalpy applied to a five-point block-centered finite-difference scheme on Cartesian, radial, variable-thickness, and specific curvilinear grids. To advance one timestep, Newton's iterative method is applied to residuals of the coupled nonlinear balance equations. Derivatives are obtained by numerical differentiation. The matrix equations are solved with either direct D4 Gaussian elimination or one of a suite of incomplete LU factorization iterative methods accelerated by orthomin[9] and preconditioned by the combinative[10] procedure. Each well generates a fully implicit constraint equation that is coupled[11] directly to and solved simultaneously with the reservoir balance equations. Layer allocation in production wells takes into account phase mobilities, phase densities, layer thickness, and fluid head in both reservoir and wellbore.

Model features include the accommodation of any number of oil, gas, or solid components, timestep selection that can control time truncation error,[12] steam-injection-well heat loss and pressure drop calculations, rigorous three-phase flash to surface conditions for production wells, and an advanced property package.

The use of a five-point operator for the grid in Problem 2A (see Appendix A) results in severe grid-orientation effects. The model unrealistically predicts steam breakthrough at the far well (one-eighth producer) first. A small capillary pressure was included to introduce the minimum amount of dispersion that would damp out incipient numerical fingers. Straight-line capillary pressure curves were used, and the endpoint (i.e., maximum) values were 7 psi [48 kPa] for the liquid/gas system and 5 psi [34 kPa] for the oil/water system. These values are well within acceptable limits. Because the gridblocks are so large (about 30 ft [9 m]), this amount of capillary pressure has little effect on front thickness. Rerunning Problem 1A with the capillary pressure present produced results little different from the run with no capillary pressure.

Mobil R&D Corp. THERMS is Mobil's in-house three-phase, 3D thermal model, which is designed primarily to simulate in-situ combustion, steam, and hot waterflooding.[13]

THERMS is a fully implicit model with options for five- and nine-point finite-difference operators. The nine-point scheme described by Shah's[14] Eqs. 7 and 8 was used to calculate diagonal and parallel transmissibilities. The reservoir flow equations are coupled with well equations, and resulting nonlinear equations are solved by a Newton-Raphson scheme. THERMS has two methods for the solution of linear system of equations: direct Gaussian elimination method, which is specifically designed to handle a variable number of unknowns per gridblock, and an iterative solution package that uses a modified preconditioned conjugate-gradient method. The direct method with D4 ordering was used for the runs for this project.

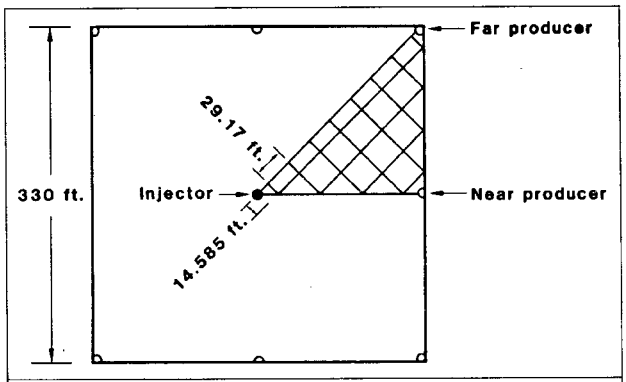

Fig. 1—Element of symmetry used in the simulation of steam injection in an inverted nine-spot (Problems 2A and 3A).

Société Nationale Elf Aquitaine. Elf's model[15] is based on the water component, oil component, and energy conservation equations. When gas phase exists, the relationship between the pressure and the temperature is also used.

For each gridblock at every timestep, the fully implicit equations of conservation are solved by the Newton-Raphson method. The flows are calculated with harmonic averaging for transmissivities and upstream weighting for densities, enthalpies, relative permeabilities, and viscosities. In the horizontal layers, a nine-point scheme is used that is similar to that of Yanosik and McCracken.[6] The diagonal flows are implicit, and their derivatives are used in the Jacobian matrix. The diagonal coefficient chosen for the steamdrive problem (Problem 2A) is not one-sixth (Yanosik-McCracken) but one-fifth.

The matrix equations are solved by a direct band Gaussian elimination for the results presented, but an ILU iterative method is also implemented in the simulator. For the injection well, the bottomhole pressure (BHP) is calculated to satisfy the flow-rate constraint. The energy injected corresponds to the saturated steam energy at this pressure. When flow rate is constrained, the production well is fully coupled to the reservoir by inclusion of the BHP in the unknowns. In all cases, a unique average density is used for calculating the well pressure at each layer, which determines the allocation of production between layers and phases.

Scientific Software-Intercomp. SSI's THERM is a 3D generalized numerical simulation model applicable to design and analysis of projects involving steam (or hot water) flooding and cyclic stimulation and in-situ combustion. The model accounts for capillary, gravitational, and viscous forces active in three-phase fluid flow, heat conduction within the formation, and heat loss to the overburden and underlying rocks. The generalized formulation allows any number of user-specified components and component distributions among the phases, thus allowing study of light-oil distillation, emulsion phenomena, and injection of foam, CO_2, and/or N_2, along with steam.

The finite-difference formulation is fully implicit, including upstream-weighted interblock flow and injection/production well terms.[16] An implicit BHP feature adds stability and preserves user-specified rates and constraints (e.g., maximum steam production rate). Each well may be vertical, deviated, or horizontal and may include several "branches" feeding a single pump/wellbore. Production is allocated to layers implicitly in all variables—pressure, temperature, compositions, and phase saturations. Global Newton-Raphson iterations are constrained by maximum changes in variables over the iteration, while automatic timestep size is determined by maximum changes over the timestep.

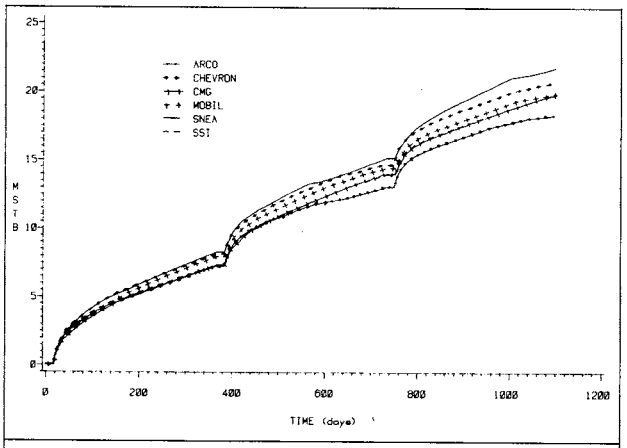

Fig. 2—Problem 1: cumulative oil production.

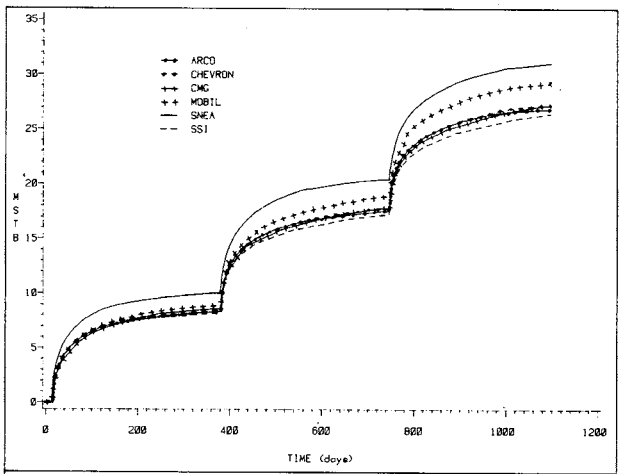

Fig. 3—Problem 1: cumulative water production.

The model's optional nine-point difference scheme[6,17] reduces grid-orientation effects associated with the conventional five-point scheme.[18,19] The matrix equations are solved by the reduced bandwidth direct D4 method[20] or by the ASAP iterative method.[21] Grid size and geometry are automatically calculated internally for parallel or diagonal grids[18] for minimal symmetrical elements of five-, seven-, and nine-spot patterns[22]; associated well productivity indices are internally calculated in accordance with Peaceman's[23] work.

Productivity/Injectivity Index

The productivity/injectivity index for Phase l and Layer k may be defined by

$$q_{l,k}=J_k\frac{k_{rl}}{\mu_l}(p_{l,k}-p_{w,k}), \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where

$q_{l,k}$ = the injection or production rate,
k_{rl}/μ_l = the effective mobility,
$p_{w,k}$ = the well pressure, and
$p_{l,k}$ = the pressure of Phase l in the adjacent reservoir block.

The expression for the PI for Layer k is

$$J_k=0.001127\theta\frac{2\pi}{\alpha}(hk)_k; \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

in SI units,

$$J_k=2.5988\times10^{-5}\theta\frac{2\pi}{\alpha}(hk)_k,$$

where $(hk)_k$ is the permeability-pay-thickness product for Layer k. The coefficient α and k_{rl}/μ_l were calculated in various ways for the two types of problems considered.

Chevron.

$\alpha = \ln(r_e/r_w)-0.5$,
r_e = radius to the center of first block for Problem 1,
$r_e = \sqrt{\Delta x\Delta y/\pi}$ for Problems 2 and 3 (this yields a $J=5.053$ for the far producer, top layer),
k_{rl}/μ_l = actual mobility of the phase for a production well,
k_{rl} = 1 for the injection well,
μ_l = average viscosity of the injected fluid for injection well,
$\Delta x=\Delta y$ = 29.17 ft [8.89 m], and
θ = well fraction.

CMG. Same as Chevron except for the differences indicated:

$\alpha = \ln(r_e/r_w)$,
$r_e = 0.249\sqrt{(\Delta x^2+\Delta y^2)/\pi}$ for Problems 2 and 3, and
k_{rl}/μ_l = total block mobility for injection well.

Mobil. Same as CMG except for the differences indicated: r_e was calculated by Peaceman's[23] method for Problem 2, $k_{rl}=1$ for

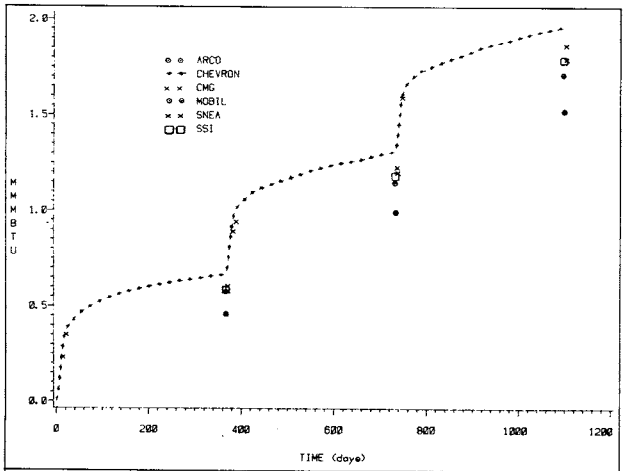

Fig. 4—Problem 1: cumulative heat loss.

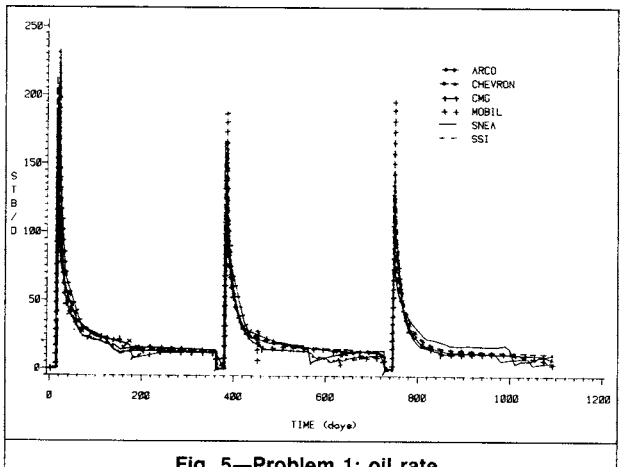

Fig. 5—Problem 1: oil rate.

TABLE 1—TIME FOR 10 STB/D OF STEAM RATE FOR PROBLEM 2A

	Near Producer (days)	Far Producer (days)
Arco	336	2,245
Chevron	411*	1,543*
CMG	539	1,398
Mobil	257	1,583
Elf	381	1,454
SSI	487*	1,497*

*Estimated from adjacent timesteps.

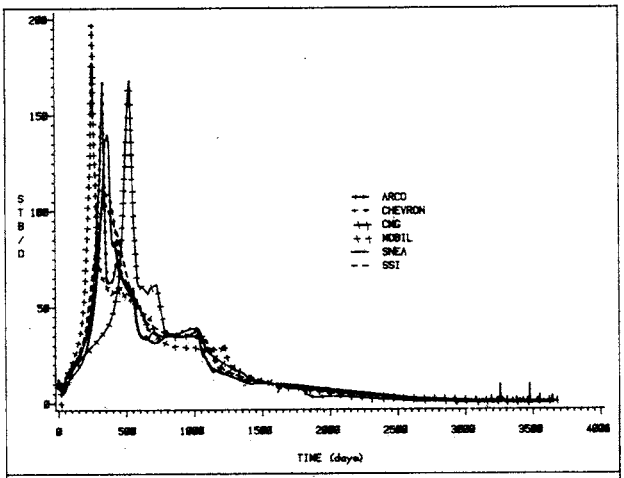

Fig. 6—Problem 2: oil rate for near producer (full-well basis).

the injection well, and μ_I=actual phase viscosity for the injection well.

ELF. Same as CMG except for the differences indicated: r_e=radius to the outer boundary of the first block for Problem 1 and r_e=0.2 Δx (Peaceman's method) for Problem 2.

SSI and Arco. α was the same as CMG for Problem 1, but α was calculated numerically as explained by Coats and Ramesh[19] for Problems 2 and 3. (This yields a J=6.41 for the far producer, top layer.) $k_{rI}/\mu_I = k_{rgro}/\mu_s$ for injection well (μ_s=steam vapor viscosity).

The participants calculated the center of the first block for Problem 1 in several ways. This caused a variation in r_e of 0.94 to 2.13 ft [0.29 to 0.65 m].

Calculation of Three-Phase Relative Permeability. All participants used some form of Stone's[24] second model to calculate oil relative permeability in the three-phase system. Chevron smoothed the function so that as $k_{ro}\to 0$, $\partial k_{ro}/\partial S_o \to 0$ also. CMG, Mobil, and SSI used the normalized form given by Aziz and Settari[25] and Coats.[26] Elf (SNEA in figures) used the modification of Stone's formula presented by Dietrich and Bondor.[27] Each participant used the same approach for all the solutions submitted by that participant.

Results

Problem 1. All the results presented are for Problem 1A. For this cyclic steam case, the block boundaries were specified and participants located the gridpoints within blocks. Arco used logarithmic mean; Chevron and SSI located the gridpoints at the centroid of cells; CMG used arithmetic mean; and Elf and Mobil used geometric mean.

Cumulative heat loss at the end of first cycle varied from 465 to 666 MMBtu [491 to 703 GJ]. During this time, 3,406 MMBtu [3594 GJ] of heat was injected. Similar results were obtained for other cycles. Maximum historical material-balance errors reported ranged from 7 to 37 STB [1 to 6 stock-tank m^3] of oil and 93 to 350 STB [15 to 56 stock-tank m^3] of water, and the cumulative material-balance errors ranged from 12 to 44 STB [2 to 7 stock-tank m^3] of oil and 50 to 350 STB [8 to 56 stock-tank m^3] of water. Only three of the participants provided this information. The calculated original water in place ranged from 413,196 to 421,330 STB [65 693 to 66 986 stock-tank m^3] and oil in place from 498,325 to 506,780 STB [79 227 to 80 572 stock-tank m^3].

Figs. 2 and 3 show a comparison of cumulative oil and water production, and Fig. 4 shows total heat loss, all as a function of time. In addition, Fig. 5 shows oil rate.

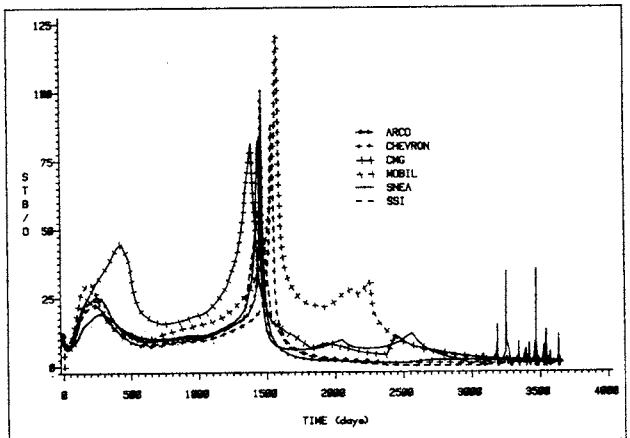

Fig. 7—Problem 2: oil rate for far producer (full-well basis).

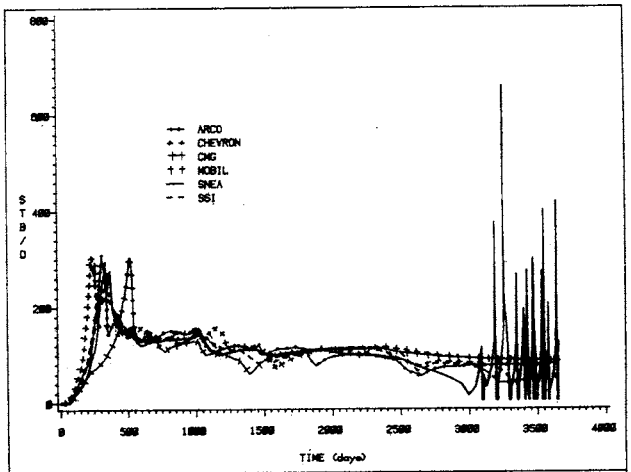

Fig. 8—Problem 2: water rate for near producer (full-well basis).

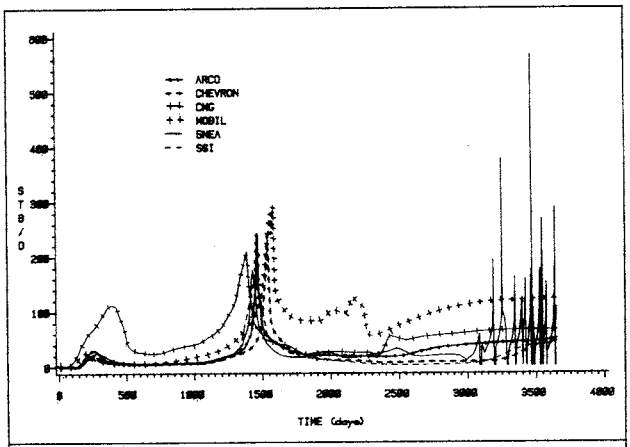

Fig. 9—Problem 2: water rate for far producer (full-well basis).

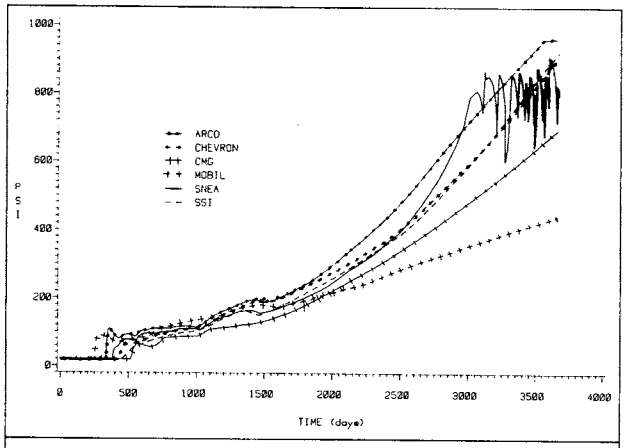

Fig. 10—Problem 2: BHP for near producer.

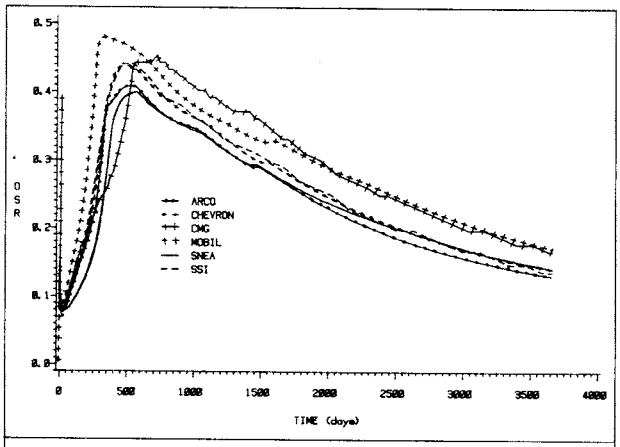

Fig. 12—Problem 2: cumulative OSR for the full pattern.

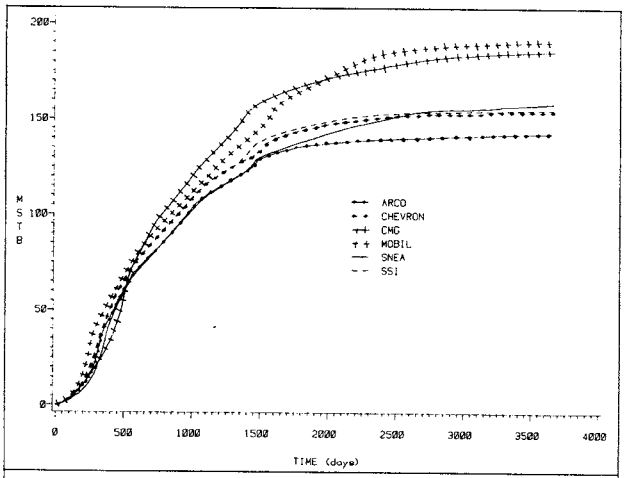

Fig. 11—Problem 2: cumulative oil production for the full pattern.

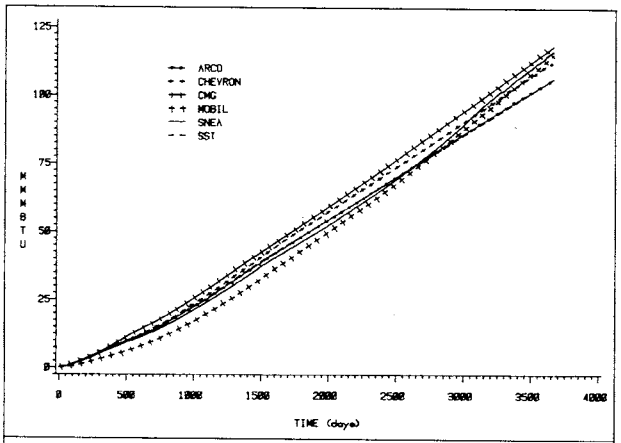

Fig. 13—Problem 2: cumulative heat loss for the full pattern.

TABLE 2—TIME FOR 10 STB/D OF STEAM RATE FOR PROBLEM 3A

	Near Producer (days)	Far Producer (days)
Chevron	556*	965*
CMG	580	998
SSI	604*	966*

*Estimated from adjacent timesteps.

Problem 2. Five of the six participants used the grid shown in Fig. 1 (Problem 2A); Mobil used a square area equal to one-half the full pattern area with two injectors (one-quarter each) and three producers (one full, two one-quarter). There are three full producers per injector in this pattern. There was little difference in the calculated materials in place for the problem. The maximum historical and cumulative material-balance error reported for oil was 129 STB [21 stock-tank m^3].

Table 1 shows computed time for each of the producers to reach 10 STB/D [1.59 stock-tank m^3/d] of steam production. Figs. 6

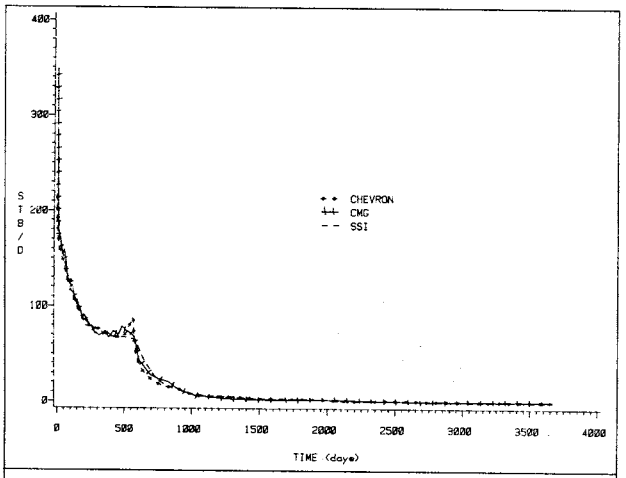

Fig. 14—Problem 3: oil rate for near producer (full-well basis).

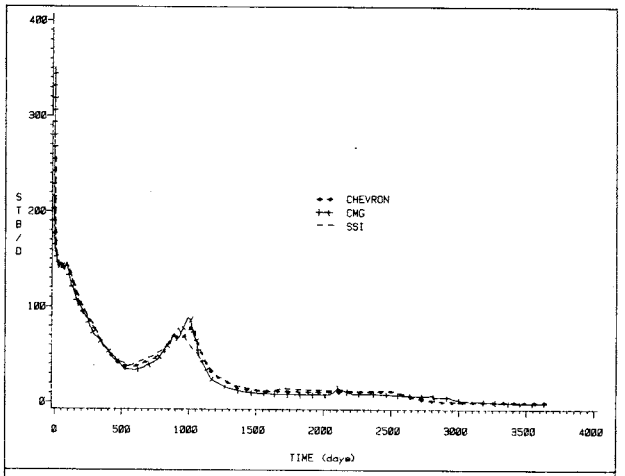

Fig. 15—Problem 3: oil rate for far producer (full-well basis).

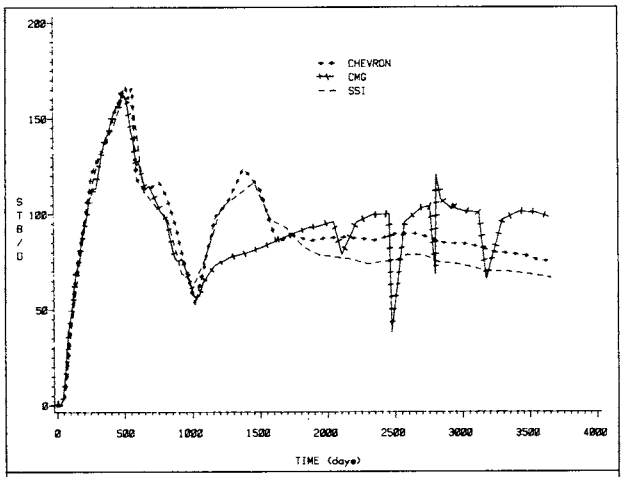

Fig. 16—Problem 3: water rate for near producer (full-well basis).

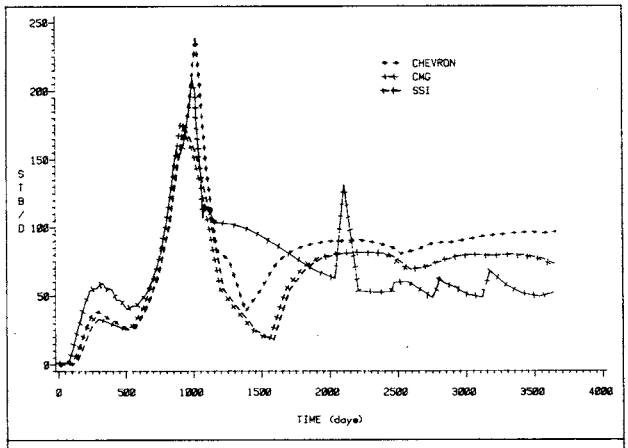

Fig. 17—Problem 3: water rate for far producer (full-well basis).

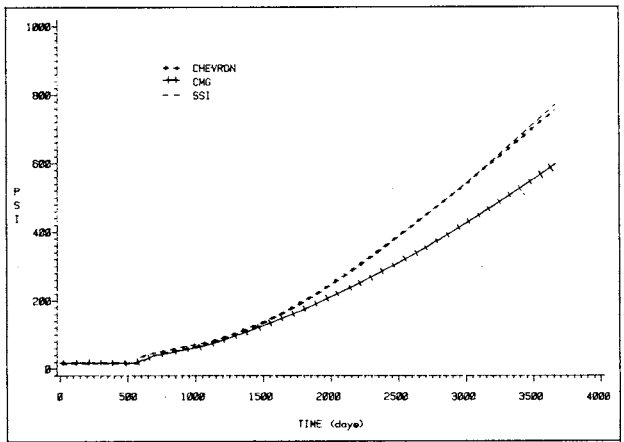

Fig. 18—Problem 3: BHP near producer.

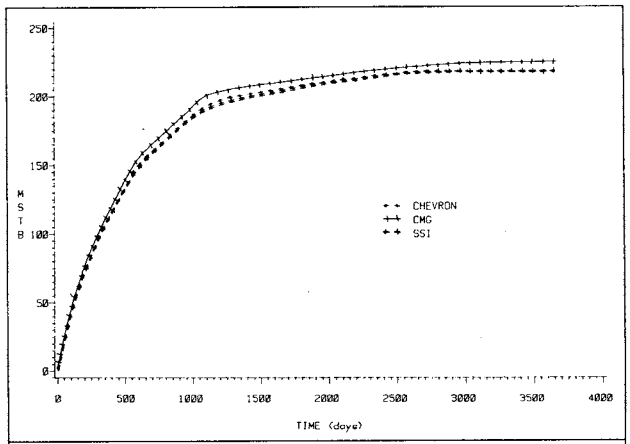

Fig. 19—Problem 3: cumulative oil production for full pattern.

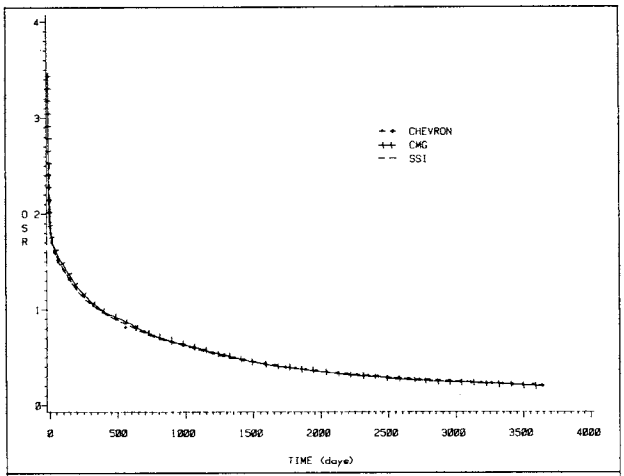

Fig. 20—Problem 3: cumulative OSR for full pattern.

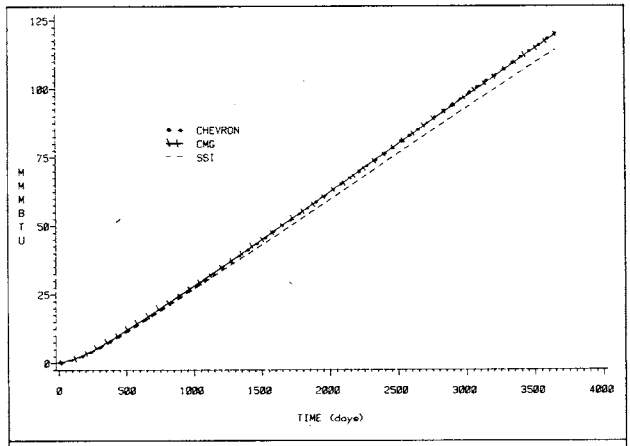

Fig. 21—Problem 3: cumulative heat loss for full pattern.

through 9 show oil and water production rates. Fig. 10 shows BHP for the near producer. Figs. 11 through 13 show cumulative oil production, oil/steam ratio (OSR), and heat loss for the pattern. All well data presented are on a full-well basis, and pattern results are for the full pattern consisting of four one-quarter (far) producers and four one-half (near) producers.

Problem 3. Only three participated in this problem. There is very little variation in the computed oil and water initially in place.

Table 2 shows the computed time for each of the producers to reach 10 STB/D [1.59 stock-tank m^3/d] of steam production. Figs. 14 through 17 show oil and water production rates. Fig. 18 shows the BHP for the near producer. Figs. 19 through 21 show cumulative oil production, OSR, and heat loss for the pattern.

The well and pattern results are presented on the same basis as for Problem 2.

Computer Work. The final CPU times, number of steps, and total number of iterations reported by the participants are shown in

TABLE 3—COMPUTER WORK

Company	Computer	Problem 1			Problem 2			Problem 3		
		CPU	Steps	Iterations	CPU	Steps	Iterations	CPU	Steps	Iterations
Arco	CRAY 1/S	59.3	414	1,073	161.3	330	803	*	*	*
Chevron	CRAY X-MP	20.0	132	568	45.0	60	357	103.3	54	316
CMG	Honeywell DPS8-MR10.2	1,330	124	650	4,298.0	89	409	13,214.0	98	510
Mobil	CRAY 1/S	49.7	382	1,126	*	207	655	*	*	*
Elf	CRAY 1M2000	12.17	297	1,081	68.4	289	864	*	*	*
SSI	CRAY 1/S	22.18	93	364	47.18	44	234	114.58	46	274

*Results not provided.

Table 3. Some of the participants indicated that considerable reduction in computer time, timesteps, and iterations is possible through fine-tuning. However, not all the participants considered this worthwhile.

Discussion of Results

Differences between the results submitted for the same problem by different companies may result from a variety of reasons: (1) handling of interblock terms in the model, (2) handling of wells, (3) tolerance on the convergence of iterations, (4) timestep selection procedure, (5) heat-loss calculation procedure, (6) nine-point scheme used, (7) selection of program control parameters, (8) possible bugs in the program, and (9) errors in data entry. Because the basic flow equations used by all the companies are the same and the fluid properties were fixed in the problem statement, they should not cause any significant differences in results. The biggest differences in the results shown are probably caused by the treatment of wells and numerical instabilities resulting in lack of convergence of iterations. Differences in Arco and SSI results are probably caused by differences in the specification of control parameters by the two users of the same model.

Concluding Remark

While the results that are of importance from a practical standpoint are in good agreement, there are some significant differences. We believe that the problem and results presented here will be of value in enhancing the state of thermal reservoir simulation technology.

Nomenclature

h = thickness, ft [m]
J = productivity index, RB-cp/D-psi [$m^3 \cdot mPa \cdot s/d \cdot kPa$]
k = permeability, md
k_{rgro} = gas relative permeability at residual oil saturation in gas/oil system
k_{rl} = relative permeability of Phase l
k_{rog} = oil relative permeability in gas/oil system
k_{roiw} = oil relative permeability at interstitial water saturation
k_{row} = oil relative permeability in oil/water system
k_{rwro} = water relative permeability at residual oil saturation in water/oil system
K = equilibrium ratio or K values
$p_{l,k}$ = pressure of Phase l in wellblock of Layer k, psia [kPa]
$p_{w,k}$ = pressure of well in Layer k, psia [kPa]
r_e = effective external radius in well flow term, ft [m]
r_w = well radius, ft [m]
S_{gc} = critical gas saturation
S_l = saturation of Phase l
S_{org} = residual oil saturation in oil/gas system
S_{orw} = residual oil saturation in oil/water system
S_{wir} = irreducible water saturation
T = temperature, °R [K]
$\Delta x, \Delta y$ = block size, ft [m]
α = constant in Eq. 2
θ = fraction of well in the element of reservoir being simulated
μ_l = viscosity of Phase l, cp [mPa·s]

Subscripts

1,2 = Components 1 and 2
k = layer index
l = Phase l

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Appendix A—Problem Statement

General Comments. This project deals with the simulation of the following three independent problems:

1. Cyclic steam injection in a heavy-oil (14°API [0.97-g/cm^3] gravity, no volatile component) reservoir.
2. Steam displacement in an inverted repeated nine-spot pattern with oil and reservoir properties the same as in the first problem.
3. Same as Problem 2 (above) but with a steam-distillable oil of 22°API [0.92-g/cm^3] gravity.

The problems have as many common features as possible. For each problem, you are requested to provide important results for some well-defined base cases. In addition, you are given the option to provide additional results by changing some of the modeling parameters to "improve" the simulation within the constraints of this study. While we would like to receive results of all three problems, those of the first two are considered the most important. Standard conditions for these problems are 14.7 psia and 60°F [101 kPa and 15.6°C].

Description of Problems.

Problem 1A: Cyclic Steam. The objective is to simulate cyclic steam injection in two dimensions (closed system).

Grid. Use cylindrical (r-z) grid with 13 gridpoints in the radial (r) direction. The well radius is 0.3 ft [0.09 m] and exterior radius is 263 ft [80.2 m]. Block boundaries in the radial direction are at 0.30, 3.0, 13.0, 23.0, 33.0, 43.0, 53.0, 63.0, 73.0, 83.0, 93.0, 103.0, 143.0, and 263.0 ft [0.09, 0.9, 4, 7, 10.1, 13.1, 16.2, 19.2, 22.3, 25.3, 28.3, 31.4, 43.6, and 80.2 m]. Block boundaries in the vertical direction are at 0.0 (top of pay), 10, 30, 55, and 80 ft [0, 3, 9.1, 16.8, and 24.4 m]. Depth to top of pay is 1,500 ft [457 m] subsea.

Rock Properties. Horizontal permeabilities starting with the top layer are 2,000, 500, 1,000, and 2,000 md. Vertical permeabilities are 50% of horizontal values. Porosity of all layers is 0.3 (fraction). Thermal conductivity of reservoir, overburden, and underburden is 24 Btu/(ft-D-°F) [3.5 W/(m·K)]. Heat capacity of reservoir, overburden, and underburden is 35 Btu/(ft^3 of rock-°F). [2347 kJ/(m^3·K)]. Effective rock compressibility is 5×10^{-4} psi^{-1} [7.3×10^{-5} kPa^{-1}].

Water Properties. Assume pure water and use standard properties.

Oil Properties. Density at standard conditions is 60.68 lbm/ft^3 [972 kg/m^3]. Compressibility is 5×10^{-6} psi^{-1} [7.3×10^{-7} kPa^{-1}]. The coefficient of thermal expansion is 3.8×10^{-4} °R^{-1}, the specific heat (constant) is 0.5 Btu/lbm-°R [2.1 kJ/(kg·K)], and the molecular weight is 600. Temperature and viscosity data are shown in Table A-1.

Initial Conditions. The oil saturation is 55% and the water saturation is 45%. Reservoir temperature is 125°F [51.7°C], and the pressure at the center of the top layer is 75 psia [517 kPa]. The pressure distribution is according to gravity head (capillary pressure=0).

TABLE A-1—TEMPERATURE AND VISCOSITY DATA FOR PROBLEM 1A

Temperature (°F)	Viscosity (cp)
75	5,780
100	1,380
150	187
200	47
250	17.4
300	8.5
350	5.2
500	2.5

Relative Permeability Data. The capillary pressures equal 0. Assume no effect of temperature or hysteresis on relative permeability. The interstitial water saturation, S_{iw}, equals the irreducible water saturation, $S_{wir}=0.45$. The residual oil saturation (water/oil system), $S_{orw}=0.15$, the residual oil saturation (gas/oil system), $S_{org}=0.10$, and the critical gas saturation, $S_{gc}=0.06$. Oil relative permeability at interstitial water saturation, $k_{roiw}=0.4$, water relative permeability at residual oil saturation (water/oil system), $k_{rwro}=0.1$, and gas relative permeability at residual oil saturation (gas/oil system), $k_{rgro}=0.2$.

The relative permeability expressions for the water/oil system are

$$k_{rw}=k_{rwro}\left(\frac{S_w-S_{wir}}{1-S_{orw}-S_{wir}}\right)^{2.5} \quad \text{.....(A-1)}$$

$$k_{row}=k_{roiw}\left(\frac{1-S_{orw}-S_w}{1-S_{orw}-S_{iw}}\right)^{2} \quad \text{.....(A-2)}$$

For the gas/oil system,

$$k_{rog}=k_{roiw}\left(\frac{1-S_{iw}-S_{org}-S_g}{1-S_{iw}-S_{org}}\right)^{2} \quad \text{.....(A-3)}$$

and

$$k_{rg}=k_{rgro}\left(\frac{S_g-S_{gc}}{1-S_{iw}-S_{gc}}\right)^{1.5} \quad \text{.....(A-4)}$$

(See the Comment at the end of Appendix A.)

Operating Conditions. All layers are open to flow during injection and production (zero skin factor). The energy content of the injected steam is based on 0.7 quality and 450°F [232°C]. The quality of the steam at bottomhole conditions will vary with pressure, but for simplicity you may assume that it remains constant at 0.7. Simulate three cycles. Each cycle is 365 days with injection for 10 days followed by a 7-day soak period. The cycle is completed with 348 days of production. Inject steam at capacity subject to the following constraints: (1) maximum BHP of 1,000 psia [6.9 MPa] at the center of top layer and (2) maximum injection rate of 1,000 STB/D [159 stock-tank m^3/d] cold water equivalent (CWE). Produce well at capacity subject to the following constraints: (1) minimum BHP of 17 psia [117 kPa] at the center of top layer and (2) maximum production rate of 1,000 STB/D [159 stock-tank m^3/d] of liquids.

Problem 1B: Cyclic Steam (Optional). All data are same as in Problem 1A except now you may, if you wish, alter the radial grid to what you consider to be more appropriate for this problem. You must, however, keep the total number of gridpoints in the radial direction the same as in Problem 1A.

Problem 2A: Steam Displacement—Heavy Oil. The objective is to simulate one-eighth element of symmetry of an inverted nine-spot pattern (if you prefer, you may simulate a one-fourth element of symmetry). Total area of the pattern is 2.5 acres [10 118 m^2].

TABLE A-2—PROPERTIES OF OIL COMPONENTS IN PROBLEM 3

	Component		
	1	2	3
Molecular weight	250	450	600
Specific heat, Btu/lbm-°R	0.53	0.55	0.6
Density at standard conditions, lbm/ft^3	52.3	57.64	61.2
Critical pressure, psia	225	140	—
Critical temperature, °F	800	950	—

TABLE A-3—INITIAL OIL COMPOSITION IN PROBLEM 3

Component	Mole Fraction
1	0.5030
2	0.1614
3	0.3356

Grid. The grid is 9×5×4. There are four layers as in Problem 1. The horizontal grid is shown in Fig. 1. Gridpoints are distributed uniformly in the horizontal plane as shown. Locate block boundaries as appropriate. The well radii for all wells are 0.3 ft [0.09 m]. All other data are the same as for Problem 1.

Rock Properties. Same as in Problem 1.

Fluid Properties. Same as in Problem 1.

Initial Conditions. Same as in Problem 1.

Relative Permeability Data. Same as in Problem 1.

Operating Conditions. Inject in the bottom layer only and produce from all four layers. Steam conditions are the same as in Problem 1. Inject steam at capacity subject to the following constraints: (1) maximum BHP of 1,000 psia [6.9 MPa] at the center of bottom layer and (2) maximum injection rate of 300 STB/D [47.7 stock-tank m^3/d] (CWE) on a full-well basis. Produce well at capacity subject to the following constraints: (1) minimum BHP of 17 psia [117 kPa] at the center of top layer, (2) maximum production rate of 1,000 STB/D [159 stock-tank m^3/d] of liquids, and (3) maximum steam rate of 10 STB/D [1.59 stock-tank m^3/d] (CWE). Simulate 10 years of injection and production (made intentionally long).

Problem 2B: Steam Displacement—Heavy Oil (Optional). All data are the same as in Problem 2A except now you may, if you wish, alter the grid in the horizontal plane to any other grid (curvilinear, nonuniform, etc.) that you consider more appropriate for this problem. You must, however, keep the total number of gridpoints in the horizontal plane the same as in Problem 2A.

Problem 3: Steam Displacement—Distillable Oil. The only difference between this problem and Problem 2A is in the oil properties. For this problem, the oil consists of three pseudocomponents (two distillable and one nonvolatile). You may combine the three pseudocomponents into two or even one component, if you wish. The combination will, of course, affect the results.

Oil Properties. Properties of three oil components are given in Table A-2. Assume no heat of vaporization for the oil phase.

Viscosity Data. Component 3 is the same as the oil in Problem 2. For Components 1 and 2 $\mu_1 = 4.4\times10^9 (T)^{-3.4}$ and $\mu_2 = 20\times10^9 (T)^{-3.4}$. The gas-phase viscosities of Components 1 and 2 are $\mu_1 = 0.5\times10^{-4} (T)^{0.9}$ and $\mu_2 = 1.0\times10^{-4} (T)^{0.9}$, where T is in °R. Phase equilibrium data (K-values) are described by the following equations:

$$K_1 = \left(1.23\times10^6 + \frac{833.4\times10^6}{p}\right)\exp-\left(\frac{16{,}000}{T}\right)$$

and

$$K_2 = \left(212 + \frac{155.4\times10^3}{p}\right)\exp-\left(\frac{4{,}000}{T-480}\right),$$

where p is in psia and T in °R.

Initial Conditions. Initial composition of the oil is shown in Table A-3. All other conditions are the same as for Problem 2.

Comment. The expression for k_{rg} (Eq. A-4) should contain S_{org} in the denominator. This does not alter the value of k_{rg} calculated by a significant amount and is left out in our problem statement. Some of the participants may have used expressions for k_{rg} with S_{org} in the denominator.

Appendix B—Participants in the Fourth SPE Comparative Solution Project

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SI Metric Conversion Factors

bbl	×	1.589 873	E−01	= m^3
Btu	×	1.055 056	E+00	= kJ
Btu/(lbm-°R)	×	4.186 8*	E+00	= kJ/(kg·K)
cp	×	1.0*	E−03	= Pa·s
ft	×	3.048*	E−01	= m
°F		(°F−32)/1.8		= °C
lbm/ft^3	×	1.601 846	E+01	= kg/m^3
psi	×	6.894 757	E+00	= kPa

*Conversion factor is exact.

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