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A Review on SPE's Comparative Solution Projects (CSPs)

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Abstract

The SPE's Comparative Solution Projects are very recognized suites of test datasets for specific problems and the hub of conducting independent comparison of reservoir simulation from different dimensions. The first one of this kind of projects was initiated in 1981 by Aziz S Odeh in order to compare solutions to a three-dimensional black-oil reservoir simulation problem obtained from different participants. Later, more nine independent CSPs were led by many investigators to examine other challenging problems of reservoir engineering. The aim of this article is to present an overview of these ten projects with brief description of the problems studied, the participants of each project, simulators or the solvers used, and any substantial differences of results obtained by the contributors found in any project.

Key words

Comparative Solution Project; SPE Reservoir Simulation; Case Studies; Black Oil; Compositional; Horizontal Well; Dual Porosity

List of Acronyms

AIM	Adaptive Implicit
BHP	Bottom Hole Pressure
CMG	Computer Modeling Group
EOS	Equation of State
FVF	Formation Volume Factor
GOR	Gas Oil Ratio
PVT	Pressure Volume Temperature
RSRC	Reservoir Simulation Research Corporation
SSI	Scientific Software Intercomp
SSC	Scientific Software Corp
SMC	Simulation and Modeling Consultancy, Ltd
TDC	Todd, Dieritch, and Chase, Inc
WAG	Water Alternating Gas
WOR	Water Oil Ratio

Introduction

The SPE Comparative Solution Projects (CSPs) is the attempt to provide independent comparison of methods and the renowned suite of test datasets for specific problems. This is designed to measure the state-of-the-art simulation capability for challenging and most up to date problems. Ten CSPs were completed in series. In each of projects, several commercial oil companies, software companies, research institutes, universities, and so on participated voluntarily. Aziz S. Odeh (1981) first started this project, which later incited considerable interest. Therefore, the SPE recommended to undertake the ongoing project. In this endeavor, in 1982 SPE Symposium on Reservoir Simulation, Khalid Aziz suggested to perform a comparison of results on another test problem. Upon his proposal, H. G. Weinstein and his co-workers organized second CSP (Weinstein and Chappelear, 1986). The enthusiastic response of industry and the academic community encouraged this kind of project to be continued from one after another. The problems in these projects 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 and simulators. The projects were focused on the simulators of black-oil, coning, gas cycling, steam injection, miscible flood, dual porosity, and horizontal wells. The study for the black oil simulation was reexamined. The techniques on gridding and upscalling were compared among different simulators.

In this paper, an overview of all the completed CSPs has been made. For each of the individual projects, brief description of the problem statements, number of participants, types of solvers/simulators used was presented. However, details of results were avoided for brevity. Any major discrepancies found in comparisons of any project were highlighted. Possible reasons behind the disagreements of the results were attempted to be addressed.

Ten CSP's: at a Glance

Table 1 shows the research areas on which previous ten CSPs were carried out. Number of participants is also reported in this table. Descriptions of each of these projects are illustrated in following subsections.

First SPE-CSP

The first project (Aziz Odeh, 1981) involved a three layer black-oil simulation with gas injection into the top layer. Along with stratification and reservoir properties, areal and cross section views were given. The reservoir initially was assumed to be undersaturated. All pertinent data and constraints, PVT properties, relative permeabilities, etc. for the simulation inputs were supplied. Upon solving the problem, the participants were asked to report oil rate vs. time, GOR vs. time, the pressures of the cell where the injector and producer are located, gas saturation, cell pressures, and saturation pressures for the variable saturation-pressure case. Both constants and variable bubble point pressure assumptions were accounted for solving the problems. Seven companies participated in this project. Computers and the models used are shown in Table 2. Other than some little variations, all model predictions from all parties were in fair agreement. The small variations were due to the use of different numerical schemes, number of grid cells, and upstream techniques etc. No simulator performance data like run times, timestep size, profiling history were reported.

TABLE 1 CONCENTRATION OF TEN CSP's

Project no.		Concentration	No. of participants
1.	CSP-1	Three-Dimensional Black-Oil Reservoir Simulation Problem	7
2.	CSP-2	A Three-Phase Coning Study	11
3.	CSP-3	Gas Cycling of Retrograde Condensate Reservoirs	9
4.	CSP-4	Steam Injection Simulation	6
5.	CSP-5	Miscible Flood Simulation	7
6.	CSP-6	Dual-Porosity Simulation	10
7.	CSP-7	Modeling of Horizontal Wells in Reservoir Simulation	14
8.	CSP-8	Gridding Techniques in Reservoir Simulation	5
9.	CSP-9	Black-Oil Simulation (reexamination of CSP-1)	9
10.	CSP-10	Upscaling Techniques	9

TABLE 2 FEATURES OF SPE-CSP 1

Participants	Computer used	Method used	Name of Simulator	Comment
1. Amoco Production Co.	IBM 3033, IBM 370/168, and Amdahl V/6	IMPES		Their method is proved to be quite satisfactory; additional computations for implicit handling of interblock flow were not needed.
2. Computer modeling group of Calgery (CMG).	Honeywell 600 DPS	Fully implicit		The model is fully implicit in its basic formulation. When the options for two point upstream or centralized upstream weightings are used or when multiblock completion wells are modeled, the method becomes highly implicit but not fully.
3. Exxon Production Research Co.	Amdahl 470/V5 and IBM 370/168	Sequential Implicit Solution (Spillete et al., 1973)	GPSIM	GPSIM can account for reservoir heterogeneity, rock compressibility, and solution of gas in both oil and water. It can model vaporization of oil into the gas phase and hysteresis in the capillary pressure and relative permeability. The minor restriction is that it has the number of grid blocks can be used; large problems can be run using only relatively modest amounts of central memory.
4. Intercomp Resource Development and Engineering Inc.	Cray-1 and Harris/7		BETA II Black-Oil	BETA II has a large variety of user oriented features. It can solve for both saturations explicitly (IMPES) and either or both saturations implicitly (sequential).
5. Mobil Research and development Corp.	CDC Cyber 175		ALPURS (Bansal et al., 1979)	ALPURS is a three- dimensional, three phase, multiwell, black-oil reservoir simulator which uses a strongly coupled, fully implicit method to solve simultaneously all unknowns.
6. Shell Development Co.	Univac 1110/2C Level 36	IMPES or implicit mode		There are several indirect and direct solution methods as a user option. Additionally, two-point upstream weighting is used to calculate phase mobilities.
7. Scientific Software Corp (SSC).	CDC Cyber 175	AIM (Adaptive Implicit Method)		This technique developed at SSC, seeks to achieve an optimum with respect to stability, truncation errors, and computer costs. This simulator also provides a wide variety of user oriented features (Thomas and Thurnau, 1982)

TABLE 3 FEATURES OF SPE-CSP 2

Participants	Method used	Name of Simulator	Comment
1. Arco Oil and Gas Co.	Arco's two coning simulators are implicit, three-phase, Black-oil simulators.		The numerical formulation in both versions is a linearized semi-implicit scheme with upstream weighting for phase mobilities. Within a timestep, only the nonlinear accumulation term is updated if necessary. The algebraic equations are solved directly. The D4 reordering scheme was used to improve efficiency (Price and Coats, 1974). Three-phase relative permeabilitis are calculated by Stone's method (Stone, 1970, 1973).
2. Chevron Oil Field Research Co.	General-purpose Black-oil reservoir simulator.	CRS-3D	The program performs a fully implicit, simultaneous calculation of pressure, saturation, and wellbore BHP. This method used finite-difference discretization.
3. D&S Research Development Ltd.		The D&S Simulator	This is a fully implicit, 3D, three phase program that solves simultaneously for all unknowns. The systems of equations are solved by ITD4MIN techniques (Tan and Lakeman, 1982).
4. Franlab Consultant, S. A		The Franlab Simulator (Sonier et al., 1973)	This is a 2D, three-phase program based on finite difference techniques.
5. Gulf Research and Development Co.	Black-Oil		The Gulf black-oil coning model employs standard point centered spatial differencing and fully implicit backward time differencing.
6. Harwell	General-purpose implicit, three-phase, 3D Black-oil Simulator	PORES (Cheshire et al., 1980)	This contains an extensive well model that is numerically stable, meets production targets precisely, and approaches flows accurately to individual layers of the reservoir model.
7. Intercomp.	Implicit flow model		This model simulates one-, two-, or three-dimensional isothermal flow of three phases in Cartesian or cylindrical coordinates.
8. McCord-Lewis Energy Services.	General Purpose 2D model.		This model employs an FVF PVT description with a variable saturation pressure feature. Relative permeability approximations are semi-implicit (extrapolated over the time step), and finite-difference equations are solved sequentially.
9. J. S. Nolen and Assocs.	VIP (vectorised implicit program), a general purpose, 3D, three-phase black-oil simulator (Nolen and Stanata, 1981; Stanata and Nolen, 1982).		VIP efficiently solves both single-well and field-scale production problems. This is fully implicit in saturations and bubblepoints and uses a modified Newton-Raphson iteration to solve simultaneously for three unknowns per gridblock.
10. SSC.	same as in Table 2.		
11. Shell Development Co.		The Shell isothermal reservoir simulation system (Chapplear and Rogers, 1974).	This operates either in an IMPES or semi-implicit mode.

TABLE 4 FEATURES OF SPE-CSP 3

	Participants	Computer used	Method used
1.	Arco Oil and Gas Co.	IBM 4341	IMPES
2.	Chevron oil Field Research Co.	VAX-11/780	same
3.	Core Laboratories Inc	CDC 6600	same
4.	CMG	Honeywell DPS 68	same
5.	Soc. Natl. Elf Aquitaine.	IBM 3081	same
6.	Intercomp (now Scientific Software-Intercomp)	Harris 800	same
7.	Marathon Oil Co.	Burroughs B7900	same
8.	Mccord-Lewis Energy Services.	VAX-11/780	same
9.	Petek, The Petroleum Technology Research Inst.	ND-560	same

Second SPE-CSP

After successfully completing the first project, Aziz Odeh suggested that extension of the cooperative effort started with the publication on first CSP to cover more complex models and problems would be very beneficial to the industry, as well as that the SPE continues such an attempt. Khalid Aziz then recommended organizing a comparison of results on another test problem during the organization of the 1982 SPE Symposium on Reservoir Simulation. Since first CSP had been a field-scale simulation, a coning study was thought to be of interest. To this end, a problem drawn from an actual field case was simplified somewhat to provide a challenging test problem (Weinstein et al., 1986). It was a single-well radial cross section that involved gas and water coning as well as gas repressuring, meanwhile a difficult problem which provided a good test of the stability and convergence behavior of the simulators. Name of participants and the simulators used are as follows in Table 3. Surprisingly the numerical results obtained agreed well though there was diversity of discretization and solution methods used. Some participants remarked that the problem was rather impractical because rate variations mentioned in problem statements would not be likely to occur. More so, the solution GOR was unusually high for oil with a high density. These cases made the problem more difficult to solve, representing a mere test of simulation techniques.

Third SPE-CSP

The problem in third CSP (Kenyon and Behie, 1987) selected was to study gas cycling in a rich-gas retrograde condensate reservoir. Numerical comparisons of the PVT data match were considered important. Computational speed of the simulators was not to be of concern. 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 introduced in Table 4. The participants were asked for matches of total volume in constant–composition expansion, liquid dropout and equilibrium gas yield in constant-volume depletion, and swelling volume and dewpoint pressure during swelling of reservoir gas with lean gas. In addition, they were requested to describe techniques used for equilibrium *K* values, phase densities and viscosities, and EOS parameters used for the PVT match. A 16 component PVT simulator was used to prepare *K* value data by convergence pressure techniques. Slight heavy – component *K*-value adjustment was used to match dewpoint pressures, liquid volumes, and depletion-gas compositions. The two major parts of a compositional model study were the PVT data and the reservoir grid, respectively. For the PVT data, participants were supplied with a companion set of fluid analysis reports. The specification of the reservoir model and the grid were given. In comparisons of results: depletion data and lean-gas swelling data for the retrograde gas condensate matched well by all participants. In early years of cycling with partial pressure maintenance, the surface oil rates disagreed by about 20%. Probably, differences in pressure caused by physical property errors (*Z* compressibility factors) and/or surface–separator molar split errors were responsible for the discrepancies. Large discrepancies (as shown in Figure 1) were observed in incremental oil obtained by gas-sales deferral; and the range was 3 to 8% of initial condensate in place. There was considerable disagreement about condensate saturation in the producing node. This was probably because *K* values were used as tables or as calculated in line with an EOS.

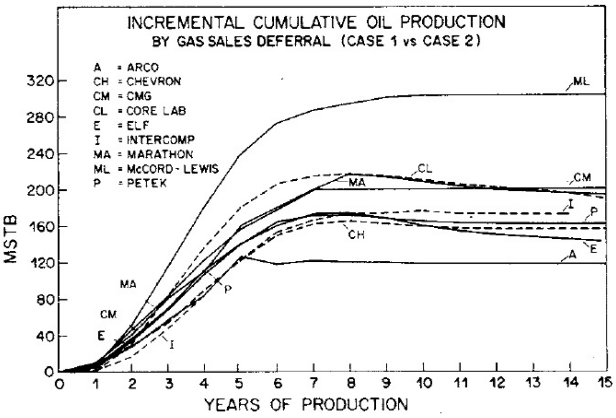

FIG. 1 INCREMENTAL RESERVOIR MODEL STOCK-TANK OIL PRODUCED BY GAS-SALES DEFERRAL (Kenyon and Behie, 1987)

Fourth SPE-CSP

The fourth CSP conducted by Aziz et al., (1985) was a two-dimensional radial steam injection (thermal) simulation, in which there are three related but independent problems for the comparison of steam injection models: (1) cyclic steam injection in a nondistillable oil reservoir with a 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, and (3) displacement of an oil consisting of two volatile components and one nonvolatile component in the same patterns as problem 2. The oil properties were the same in first two problems. The participants had the flexibility to submit results for one, two, or all three problems. These problems were selected to exercise features of the models that are considered to have practical applications though they do not represent real field simulations. Six companies (shown in Table 5) participated in this project with only three submitting results for the compositional case (problem 3). The authors (Aziz et al., 1985) discussed the models used comprehensively with some minor editorial change of originally submitted reports by the companies. The results submitted were mostly in good agreement except some significant differences. Possible reasons can be included as handling of interblock terms in the model, handling of wells, different convergence tolerance set, timestep selection, heat-loss computation process, different program control parameters, errors in data entry, nine point data entry used, possible bugs in the program, etc.

TABLE 5 FEATURES OF SPE-CSP 4

Participants	Method used	Comment
1. Arco Oil and Gas Co.	Scinetific Software-Intercomp's (SSI's) THERM model.	SSI's THERM is 3D generalized numerical simulation model applicable to design and analysis of projects involving steam flooding and cyclic stimulation and in-situ combustion. The model's optional nine-point difference scheme (Yanosik and McCraken, 1979; Coats and Modine, 1983) reduces grid-orientation effects associated with the conventional five-point scheme (Todd et al., 1972; Coats and Ramesh, 1986).
2. Mobil R&D Corp.	same	same
3. SSI.	same	same
4. Chevron Oil Field Research Co.	IMPES	Chevron's steamflood simulator is a fully implicit, fully compositional, finite-difference model.
5. CMG.	ISCOM model.	ISCOM (Rubbin and Buchanan, 1985) is a fully implicit four-phase (oil, water, gas, and solid) multicomponent finite difference thermal simulator.
6. Societe Nationale Elf Aquitaine.	IMPES	Elf's model (Corre et al., 1984) is based on the water component, and energy conservation equations.

TABLE 6 FEATURES OF SPE-CSP 5

Participants	Method/Simulator used	Computer used	Comment
1. Arco	IMPES or fully implicit	CRAY X/MP	The Arco miscible flood reservoir simulator is based on a limited-compositional formulation (Bolling, 1987)). This simulator is a modified version of SSI's COMP II (Coats, 1979).
2. British Petroleum (BP).	same	same	same
3. CMG.	Adaptive-implicit compositional model	Honeywell Multics DPS8/7	For the four-component cases CMG's IMEX, four-component, adaptive-implicit, black-oil model was used with pseudo-miscible option. A semi-analytical approach was used to decouple the flow equations from the flash equations.
4. Chevron.	Fully implicit	CRAY X/MP	The Chevron miscible flood simulator ("four component simulator") is a fully implicit three-component based on the concepts outlined by Todd and Longstaff, 1972.
5. Energy Resource Consultants Limited (ERC)	PORES black-oil simulator	NORSK DATA ND 570/CX	same as in Table 2 for black-oil simulator
6. Reservoir Simulation Research Corp (RSRC)	IMPES	CRAY X/MP	RSR incorporated an IMPES-type equation-of-state compositional model for the simulations.
7. Todd, Dietrich, and Chase, Inc. (TDC)	Multiflood simulator (Chase and Todd, 1984)	CRAY 1S	This simulator has been designed to reproduce the effects of major mass transfer and phase transport phenomena known to be associated with the miscible flood process with particular emphasis on CO_2 enhanced oil recovery.

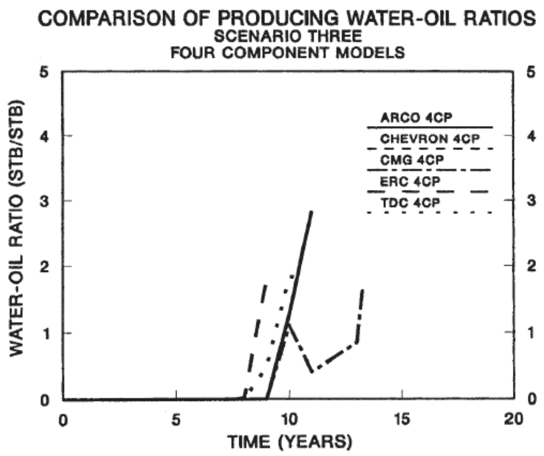

FIG. 2 SCENARIO THREE: COMPARISON OF PRODUCING WATER/OIL RATIOS FOR FOUR COMPONENT MODELS (Killough and Kossack, 1987)

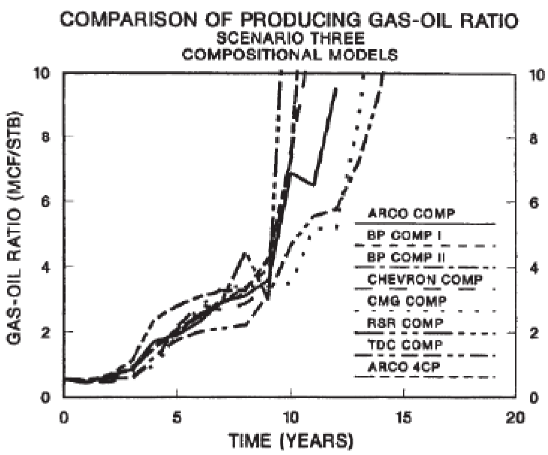

FIG. 3 SCENARIO THREE: COMPARISON OF PRODUCING GAS/ OIL RATIOS OF COMPOSITIONAL MODELS (Killough and Kossack, 1987)

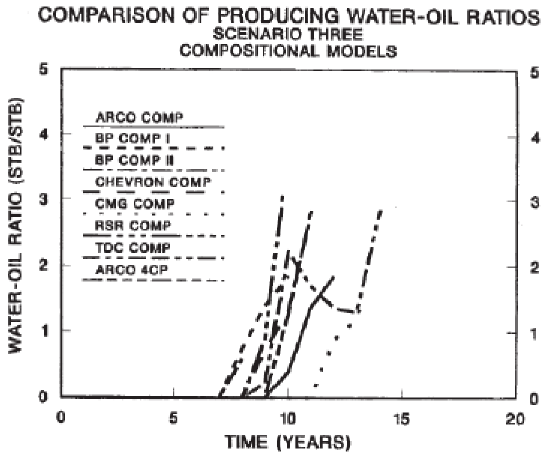

FIG. 4 SCENARIO THREE: COMPARISONS OF PRODUCING WATER/OIL RATIOS FOR COMPOSITIONAL MODELS (Killough and Kossack, 1987)

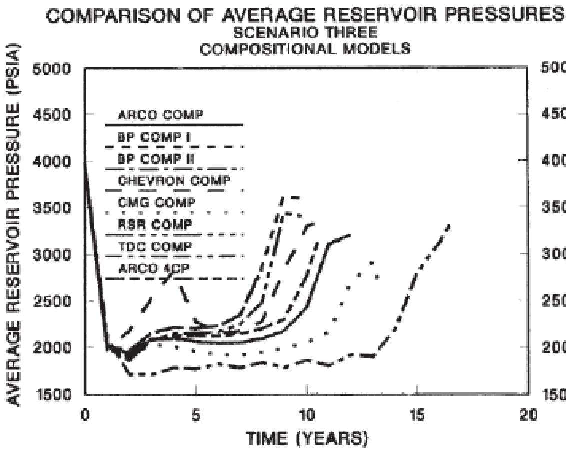

FIG. 5 SCENARIO THREE: COMPARISON OF AVERAGE PORE VOLUME WEIGHTED PRESSURE FOR COMPOSITIONAL MODELS (Killough and Kossack, 1987)

Fifth SPE-CSP

The fifth CSP presented the results of comparisons between both four-component miscible flood simulators and fully compositional reservoir simulation models from seven different participants (shown in Table 6) for a series of three test cases (Killough and Kossack, 1987). These cases varied from scenarios dominated by immiscible conditions to scenarios in which minimum miscibility pressures were maintained or exceeded throughout the simulations. Three injection and production scenarios were designed to test the abilities of the four–component and compositional models to simulate the WAG injection process into a volatile oil reservoir. The problem was not much practical, however, both the coarse grid and the extremely light reservoir oil were chosen to allow the problem to be simulated in a reasonable amount of computational time with a fully compositional simulator. Agreement between the models was good for the first two scenarios. However, relative permeability, pressure and compositional results for scenario three showed a substantial deviation among the participants. For instance, Figure 2 indicates that the main reason for the differences may be a minor difference in relative permeability treatment at the producer for the CMG case. Both GOR's and WOR's began increasing at the same time for all models except Chevron model. The WOR climbed somewhat more slowly for the CMG model in turn causing the GOR maximum to be reached well after the other models. As seen in Figure 3, GOR for all models began to rise above 2 MCF/STB at approximately the same time; however, GOR for the CMG and TDC models appeared to increase at a slower rate than the other models. This may be the result of the use of different injectivity treatments by the participants. Figure 4 shows that WOR behavior for all models was similar with breakthrough occurring at about the same time. Average reservoir pressure results for the compositional models were again erratic as it can be seen from Figure 5. For the test case in which reservoir pressure was maintained above the minimum miscibility pressure, agreement between four–component simulators, with the assumption of complete mixing of solvent and oil, and compositional simulators was excellent based on cumulative oil production as a function of cumulative water injection. For cases in which immiscible conditions dominated, the four-component models tended to be downbeat compared to fully compositional models because condensable liquids were not considered to be carried in the gasesous phase in the four – component simulations. Relative permeability treatment, especially near the injection well, pondered to dominating the timing of recovery and injection breakthrough.

Sixth SPE-CSP

As the simulation of naturally fractured petroleum reservoirs was in great demand, sixth CSP (Firoozabadi and Thomas, 1990) was designed to illustrate some aspects of the physics of multiphase flow in fractured reservoirs and modeling techniques to account for capillary and gravity forces. The approach to the solution of the problems has been limited to dual-porosity models. Two problems were selected to compare fractured reservoir models: a single-block example and a more complicated cross-sectional example developed to simulate depletion, gas-injection, and water-injection as well. The influence of fracture capillary pressure on reservoir performance has been addressed by cases with zero and nonzero gas/oil capillary pressure in the fractures. Ten organizations (shown in Table 7) participated in this project. The comparison of solutions from various participants indicated a noticeable difference in the results for some examples. There were large differences of results for the case of nonzero fracture capillary pressure. Different formulations for matrix/fracture exchange were considered to be the main reason for this disagreement. This project conveyed an important message that the difference between the cases with zero and nonzero fracture capillary pressure indicated the future need of development of the physics and numerical modeling of naturally fracture petroleum reservoir.

TABLE 7 FEATURES OF SPE-CSP 6

Participants		Method/Simulator used	Comment
1.	Chevron Oil Field Research Co.	Naturally fractured reservoir simulator (NFRS).	This simulator is based on the methodology outlined in Chen et. al., 1987.
2.	CMG	IMEX	This is both a single-porosity and a dual-porosity/dual permeability, four component, adaptive-implicit reservoir simulator. For the dual porosity option, IMEX allows the discretization of the matrix blocks into subblocks either in the nested format (Pruess and Narasimhan, 1985), for the representation of transient effects, or in the layer format, for the representation of gravity effect (Gillman, 1986).
3.	Dancomp A/S	DANCOMP/RISO Simulator.	This is a three phase, 3D, isothermal model that can be run in either black-oil or compositional models with a dual-porosity/ dual permeability option.
4.	Exploration Consultants Ltd. (ECL)	ECLIPSE	This is a fully implicit program and reinjects a fraction of the phase production or reservoir voidage from the current time step to model pressure-maintenance schemes. This approach has been used in the gas-injection runs rather than reinjecting gas from the previous timestep.
5.	FRANLAB	FRAGOR	This is a three phase, 3D, black-oil, pseudo- and fully compositional simulator with a dual-porosity/dual permeability model (Quandale and Sabithier,1988).
6.	Japan Oil Engineering Co. (JOE)	Fully implicit	JOE and Japan Natl. Oil Corp. jointly developed this simulator. This uses a finite difference spatial discretization in which flow terms are weighted upstream and applies a fully implicit backward Euler method for the time discretization.
7.	Marathon Oil Co.	Fractured Simulator	This is a fully implicit, three phase, 3D model. Matrix/Fracture fluid-transfer functions for each phase are based on the transmisissibilities reported by Gillman and Kazemi, 1983**.**
8.	Philips Petroleum Co.	Fully implicit	This is a fully implicit, 3D, three-phase, single or dual-porosity model.
9.	Simulation and Modeling Consultancy Ltd. (SMC)	GENESYS	SMC's three-phase, 3D GENESYS simulator is designed to model both fractured and unfractured petroleum reservoirs (Sonier and Eymard, 1987).
10.	SSI	SIMBEST II	This simulator was designed to expand traditional black-oil simulation to include dual-porosity and pseudocompositional behavior. This allows automatic accounting of phase pressure differences between the matrix and fracture when the matrix is subjected to capillary equilibrium and the fracture is in vertical equilibrium.

TABLE 8 FEATURES OF SPE-CSP 7

Participants		Method/Simulator used	Comment
1.	ARTEP (Research association of Institut Francais du Petrole, Elf Aquitaine, Total-CFP and Gas de France)	Sigma-Core	This is three-phase, 3D black-oil and compositional model.
2.	Chevron oil Field Research Company	Fully implicit black-oil simulator	This simulator is with Cartesian local grid capability (Wasserman, 1987).
3.	CMG	IMEX	This is an adaptive implicit, three-phase, black-oil simulator with pseudo-miscible options (Fung et al., 1989).
4.	ECL Petroleum technologies (ECL)	Eclipse 100 and Eclipse 200	These are fully implicit, general purpose black-oil simulator with gas condensate.

5.	Robertson ERC Ltd (ERC)	TIGRESS (The Integrated Geophysics Reservoir Engineering Software System)	This is an integrated software system which includes application modules for geophysics, geology, petrophysics, mapping, reservoir engineering, reservoir simulation and economics.
6.	HOT Engineering (HOT)	SURE	This is a general non-isothermal compositional model which is formulated for any number of phases and components while the input data and results remain in well-known black-oil format.
7.	Integrated technologies (INTECH)	VIP-ENCORE	This is a three-phase, 3D, vectorized, fully implicit (or IMPES) simulator in which internally the hydrocarbon fluids are handled compositionally.
8.	Japan National Oil corporation (JNOC)	Fully implicit black-oil model	This coupled a fully implicit black-oil model to a model for multi-phase flow in pipes to include wellbore hydraulics in the calculations.
9.	Marathon Oil Company	Fully implicit	This is based on Gillman and Kazemi, 1983.
10.	Philips Petroleum Company		This is a general purpose three dimensional, three-phase reservoir model that can be used to simulate vertical, inclined and horizontal wells.
11.	RSRC		A detailed description of the simulator used in this study is presented by Young, 1988.
12.	Shell development Co.	Black-Oil	The simulator used was the implicit black-oil version of Shell's multipurpose isothermal reservoir simulator.
13.	Stanford University		The simulator used is a three-dimensional, three-phase research simulator with local grid refinement, hybrid grid and domain decomposition options.
14.	TDC	BLOS	This is a standard 3D, three-phase, three-component, IMPES, finite difference based simulator.

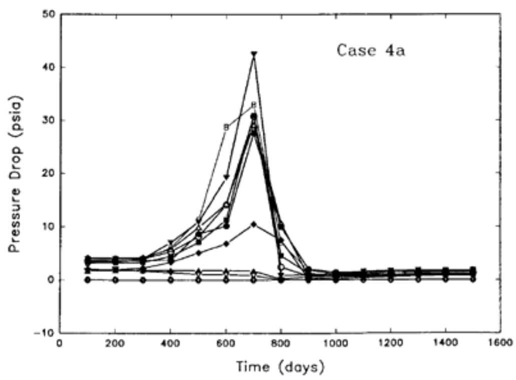

FIG. 6 TOTAL PRESSURE DROP ALONG WELLBORE FOR CASE 4a (Nghiem et al., 1991)

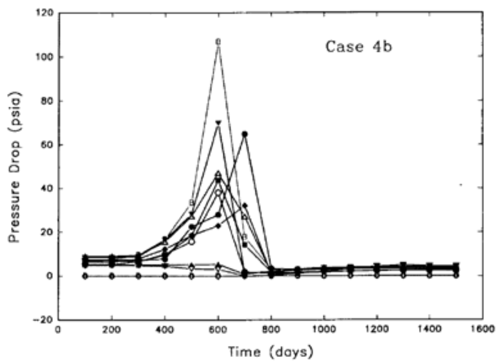

FIG. 7 TOTAL PRESSURE DROP ALONG WELLBORE FOR CASE 4b (Nghiem et al., 1991)

Seventh SPE-CSP

Because of improved drilling technology, and the increased efficiency and economy of oil recovery operations, interest in horizontal wells rapidly accelerated. Seventh CSP (Ngheim et al., 1991) presented a problem which dealt with the effect of horizontal well lengths and rates on the recovery, in which fourteen organizations participated. These are illustrated in Table 8. The problem designed with oil recovery by bottom water drive in a thin reservoir where coning was concerned. Black-oil fluid properties and relative permeabilities from the second CSP were used. However, reservoir and capillary pressure values were different. A variety of methods was used by the participants to model the inflow into the horizontal wells ranging from the use of productivity indices to grid refinement. A multitude of techniques was also used to calculate wellbore hydraulics while a few contributors were selected to represent the wellbore by a constant-pressure line sink. All participants consistently predicted a decrease in the coning behavior with an increase in well length. In comparisons, there were substantial variations in peak pressure drop among the participants. These are shown in Figures 6 and 7 as an example. The figures show the predicted pressure drop along the well bore. The pressure drop increased with increasing free gas flow rates. There were sizeable variations in the peak pressure drop predicted. The truncation errors, convergence criteria, time steps taken and implicit/ explicit formulation were possible grounds behind the differences. The effect of wellbore hydraulics could not be understood from the simulation results.

Eighth SPE-CSP

The eighth CSP (Quandalle, 1993) was designed with the aim to compare flexible gridding techniques. This was performed by five participants and the problem posed was a 3D simulation of oil production associated with gas injection in a four layer reservoir. Organizations participated are shown in Table 9, who were asked to provide two sets of results with the same simulator, the first corresponding to a simulation run with a regular Cartesian grid 10x10x4, and a second set corresponding to a simulation run with a flexible grid optimized to have as few grid cells as possible. This CSP was also an academic exercise of flexible gridding techniques. The major conclusion of this study was that the flexible gridding schemes are reliable and they can allow a significant computer time saving for the reservoir simulation. In a case oil displacement by a much more mobile gas, all participants could reduce the total number of grid nodes by a factor of four or more with flexible gridding while simulation results could keep close to those obtained with regular gridding technique.

Ninth SPE-CSP

The ninth CSP (Killough, 1995) was designed to reexamine of black-oil simulation based on a model of moderate size (9000 cells) and with a high degree of heterogeneity provided by a geostatistically-based permeability field. Nine organizations participated in this project reported in Table 10 were asked to report results for the simulation several ways. The primary data collected were the field total producing rates for oil, gas, and water. The variation of field oil rates was within 9% of the mean value for all parties, slightly larger for the field gas rates than that in the case of the oil rates with the maximum deviation of 11% of the mean value. The water rate for all participants varied considerably. Maximum deviation after about 100 days was on the order of 20%. The main reason for this probably laid in the treatment of relative permeabilities and capillary pressures. As shown in Figure 8, near the end of the simulation, the variation in water saturation was about 25% among the participants. Variations may also has been due to the amount of water injection allowed due to bottom hole pressure constraint. Injection rates varied considerably due to conditions in the aquifer (i.e., use of 100% water saturation) as it can be seen in Figure 9. In this CSP, the participants also supplied data concerning the number of time steps, non-linear iterations and CPU time associated with the model simulations.

TABLE 9 FEATURES OF SPE-CSP 8

	Participants	Method/Simulator used	Comment
1.	CMG	STARS	This is an adaptive-implicit, multicomponent, dual-porosity, advanced process simulator capable of handling isothermal and thermal processes.
2.	INTERA Information Technologies(INT)	ECLIPSE 100/200	same as in Table 7 for ECLIPSE
3.	Beicip-franlab (B-F)	FRAGOR	This is a multipurpose reservoir simulator which includes black-oil and multicomponent, single and dual porosity capabilities (Quandalle and Sabathier, 1987).
4.	SMC	GENESYS	same as in Table 7 for SMC
5.	Stanford University	META	This is the simulator used was developed by Nacul (1991) and Nacul and Aziz (1991). This is a fully implicit three-dimensional black-oil simulator with adaptive implicit and IMPES options.

TABLE 10 FEATURES OF SPE-CSP 9

Method/simulator used	Comment
1. TechSIM simulator used by AEA Technology	This simulator uses a generalized compositional model and includes option for black oil, miscible flood and equation of state compositional simulation.
2. ARCO	This is a black-oil simulator employs IMPES and fully implicit techniques for time step discretizations.
3. CMG	same as in Table 8
4. INTERA Information Technologies	same as in Table 9
5. SENSOR	This is a three dimensional, three phase reservoir simulation model for black-oil and compositional applications (Coats, 1995).
6. SSI	same as in Table 7
7. Fina	same as SSI
8. TIGRESS	same as in Table 7
9. Desktop-VIP used by Western Atlas Software	This is a multicomponent, 3D, three phase reservoir simulator which contains a number of modules sharing a common compositional formulation.

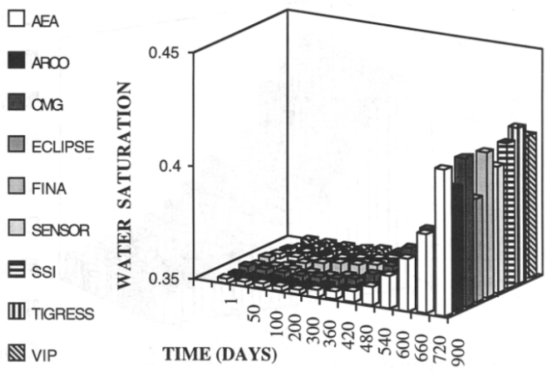

FIG. 8 COMPARISON OF WATER SATURATIONS (Killough, 1995)

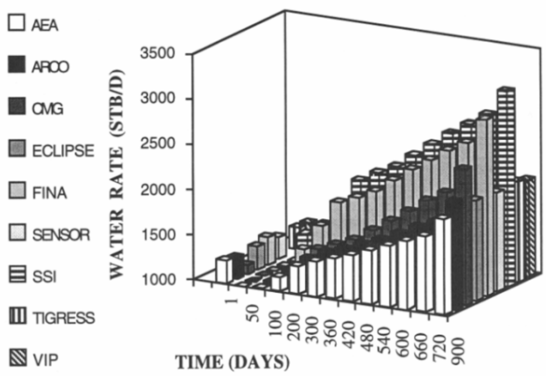

FIG. 9 COMPARISON OF WATER INJECTION RATES (Killough, 1995)

TABLE 11 FEATURES OF SPE-CSP 10

	Participants	Method/Simulator used	Comment
1.	Chevron	CHEARS	Chevron used the parallel version and the serial version for the fine grid model, and the serial version for the scaled-up model.
2.	Coats Engineering Inc.	SENSOR	same as in Table 9
3.	GeoQuest	ECLIPSE 100 and FRONTSIM	FRONTSIM is a streamline simulator to check the accuracy of the upscaling (Christie and Blunt, 2001).
4.	Landmark	VIP	same as in Table 9 for Desktop-VIP
5.	Philips Petroleum	SENSOR	same as in Table 8
6.	Roxar	Nextwell and	The simulation results presented were generated using Roxar's Black-Oil, Implicit Simulator, Nextwell. The upscaled grid properties were generated using Roxar's Geological Modeling sofawre, RMS, in particular the RMSsimgrid option.
7.	Streamsim	RMSsimgrin	Simulations were run using 3DSL, a streamline based simulator designed by Batcky et. al., 1997.
8.	TotalFinaElf	ECLIPSE	Same as in Table 7 for ECLIPSE
9. Wales	University of New South		The University of New South Wales submitted results for model 1 only using CMG's IMEX simulator.

TABLE 12 SUMMARY OF AVAILABLE BENCHMARK TIMES FOR SPE 10 SOLUTIONS

Reference	Time	Notes
(Hammersley and Ponting, 2008)	328 Minutes	128 steps, uses algebraic multigrid
(Gong, 2011)	4.5 hours	General-purpose Research Simulator (GPRS), 1 CPU
(Gong, 2011)	5 hours	Eclipse on 8 CPUs, though no explanation of cores versus CPU
(Esler et al., 2012)	27 Minutes	In-house simulator; Uses operator split, pressures solved with 20-day steps, saturation propagated with 1000's of independent explicit steps; uses Tesla GPU, and single precision for saturations
(Esler et al., 2012)	24+ Hours	In-house simulator; Uses operator split, pressures solved with 20-day steps, saturation propagated with 1000's of independent explicit steps; uses sequential solver, single CPU
(Kwok, 2007)	16558 Seconds	53 steps
(Gratien et al., 2007)	7169 (1 CPU) /620 (64 CPU) seconds	2 processes on each CPU
(Natvigand et al., 2009)	170 seconds	Parallel streamline simulator, "highly optimized commercial simulator," 13 time steps

Tenth SPE-CSP

Upscaling techniques used in the tenth CSP in series performed by nine participants were investigated by (Christie and Blunt, 2001). Two problems were chosen, the first of which was a small 2D gas-injection problem where the fine grid could be computed easily and both upscaling and pseudoization method could be used while the other was a waterflood of a large geostatistical model where (though not impossible) the true fine-grid solution is difficult to compute. Name of participants are shown in Table 11. For the first problem, the permeability distribution was a correlated geostatistically field. The fluids were assumed to be incompressible and immiscible. Capillary pressure was assumed to be negligible. Gas was injected from an injector located at the left of the model and dead oil was produced from a well on the right of the model. This was a relatively easy problem, and all participants were succeeded to obtain coarse grid solutions that agreed well with their own fine grid results. Mostly, these results were obtained by a history matching process to compute cross grid relative permeabilities. Roxar showed that it was also possible to obtain good results using only single phase upscaling and local grid refinement, and Coats showed that it was possible to obtain a good match with a homogeneous permeability and the original rock curves on a coarse grid. For the second problem, the model had a sufficiently fine grid to make use of any method that relied on having the full fine grid solution almost impossible. The model had a simple geometry, with no top structure or faults. This was to provide maximum flexibility in selection of upscaled grids. For this model, the fine grid streamlines simulations submitted by Geoquest and Streamsim were in good agreement with the fine grid finite difference solutions submitted by Landmark and chevron. In addition, the intermediate grid solutions submitted by Philips and Coats were close to the full fine grid solutions, except for the field average pressure. In this project, it was found that going to a coarse grid (of the size that could be used if the model represented a pattern element of a full field model) induced large errors. Interestingly, there was little difference between the 20x44x17 and the 30x55x17 predictions, but both were some way away from the fine grid solution. At the grid size submitted, there was as much variation in results due to the choice of upscaling approaches. The results submitted by the participants also showed significant differences irrespective of pseudo-based and the upscaling techniques. From this study, it was concluded that the best single phase method is flow-based upscaling using no-flow boundary conditions.

It has been twelve years since the last (tenth) CSP was conducted. By this time, there has been tremendous improvement in computational power; numerous state-of-the-art models, simulators are developed. Table 12 provides a summary of reported timings for solution of the full SPE 10 problem from Refs (Elser et al., 2012; Gong, 2011; Gratien et al., 2007; Hammersley and Ponting, 2008; Kwok, 2007; Natvigand et al., 2009). After 2001, the single-core (sequential, non-parallel) floating point speed is improving each year by 21-52% as reported by Standard Performance Evaluation Corporation (www.spec.org). On the other hand, moving sequential simulators to parallel computations more speed-up can be achieved. Table 12 shows that through parallel computations the SPE-10 problem can be solved even within couple of seconds!

Concluding Remarks

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 necessarily does not ensure any valid result, and 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. The results presented in CSPs are very important from practical point of view although there were some significant differences in many cases. However, the problems and results presented in CSPs are of value in enhancing the state of reservoir simulation technology.

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