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Eighth SPE Comparative Solution Project: Gridding Techniques in Reservoir Simulation

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ABSTRACT

This paper reports the results of a Comparative Solution Project (CSP) which compares different flexible gridding techniques now available in some reservoir simulators. This CSP was performed by five participants and the problem posed is a 3D simulation of oil production associated with gas injection in a four layer reservoir. The participants were asked to provide two sets of results with the same simulator : the first set corresponding to a simulation run with a regular 10x10x4 Cartesian grid, and a second set corresponding to a simulation run with a flexible grid optimised to have as few grid nodes as possible.

Two different types of flexible grid have been used by the participants, Control Volume grids (CVG) [1,2], and Locally Refined Cartesian grids (LRCG) [3,4]. These grids are shown in the paper.

With flexible grids, all participants could reduce the number of grid nodes by a factor four or more, while keeping the simulation results close to those obtained with the regular 10x10x4 Cartesian grid.

INTRODUCTION

The interest in flexible gridding techniques applied to reservoir modelling has grown steadily during the past years. This Eighth Comparative Solution Project (CSP) compares different reservoir simulators which use flexible grid capabilities to reduce the number of grid blocks during numerical reservoir simulation.

The objectives of this paper are :

1) To compare predictions using flexible gridding techniques versus regular gridding techniques.

2) To compare predictions using different flexible gridding techniques available with different reservoir simulators.

3) To evaluate the grid block saving that can be obtained during a 3D full-field simulation by using flexible gridding techniques.

Problem Statement

The problem is a 3D simulation of oil production associated with gas injection in a four layer reservoir, as described in the associated Fig. 1 and 2 and Tables 1, 2 and 3. Fluid and rock property data are those of the first CSP [5] except that in the present case, there is no water.

The participants had to run the problem twice with the same simulator.

1) a first time with the 10x10x4 regular discretization grid described in Fig. 1.

2) a second time with a four layer grid but no imposed XY discretization pattern. The challenge, in this case, was to reduce the number of grid blocks as much as possible using a flexible gridding technique, while respecting the two following constraints on both producers :

    a) the gas breakthrough time predicted with the flexible grid model (fixed as the time corresponding to a GOR of 2,000 SCF/STB) had to match within 10% the breakthrough time of the 10x10x4 grid model,

    b) at the time that the 10x10x4 grid model has reached a GOR value of 10,000 SCF/STB, the flexible grid model had to predict a GOR within 10% of the 10,000 SCF/STB.

DESCRIPTION OF MODELS USED

Five organisations participated in this Eigth CSP (see Appendix). A short description of the models used by these organizations is given below.

Computer Modeling Group (CMG)

CMG used the STARS model which is an adaptive-implicit, multi-component, dual-porosity, advanced process simulator capable of handling both isothermal and thermal processes. For this study, the control-volume finite-element (CVFE) grid option [6] was used.

The model was run with two components in isothermal mode using the adaptive-implicit method. The base case Cartesian grid (10x10x4) was run using the nine-point option. A five-point simulation was also made and was found to give result significantly different from the nine-point simulation in terms of the two GOR acceptance criteria set out in the project.

This is likely caused by the well-known grid orientation effect of the five-point parallel grid. Therefore, the nine-point result was used as the base case for comparing with the CVFE flexible grid result.

The flexible grid entry was generated using the CVFE grid generator in CMG's interactive graphical pre/pro processor RESULTS.

Initially a coarse CVFE grid with grid density decreasing away from the well locations was generated. Near-well resolution was improved further by a subsequent local refinement step. The resulting CVFE grid has 27 blocks per layer.

INTERA Information Technologies (INT)

ECLIPSE 100 is a widely used commercial black-oil simulator due to its flexibility and the range of optional enhancements that can be used to describe more complex phenomena. It uses robust numerical techniques to ensure the reliable and accurate solution of a given problem. In addition to the usual block centered and corner point geometries the ECLIPSE 200 local grid refinement and local grid coarsening facilities allow the design of grids with regions of varying grid block density so that fine structures can be resolved where required, but the total number of simulation grid blocks can be kept to a minimum. A local grid refinement is used to increase the number of cells in a section of the grid, whereas a local grid coarsening will amalgamate cells and reduce the number of cells in it. The implementation of these local refinements is such that modifications can be applied to an initial grid without the necessity of resampling the original map data.

Another type of grid that can be input to ECLIPSE is a VORONOI grid, also known as a PEBI or perpendicular bisection grid. These grids are point centred, with the cell boundaries defined by the perpendicular bisectors of the lines joining neighbouring centres. The centres may be placed arbitrarily in the XY plane thus producing high and low cell densities as required. The cells extend into the Z direction as prisms and the gridding of depth and thickness are controlled by the independent specification of the depth of each corner. It is also possible to generate a hybrid grid by inserting regions of radial cells into a VORONOI grid.

Beicip-Franlab (B-F)

Beicip-Franlab used the FRAGOR model to performed this Comparative Solution Project. FRAGOR is a multipurpose reservoir simulator which includes black-oil and multicomponent, single and dual porosity capabilities [7]. For this CSP, the Locally Refined Cartesian grid option (LRCG) was used [3]. This option allows selected regions of a Cartesian grid to be replaced by finer detailed local grids. The local grid refinement definition is recursive (this means that local grid refinements may be defined inside another local grid refinement, and this with no limitation), different local grid refinements may have common boundaries, and the grid definition may differ from one layer to the other. A special flux correction method [8] to calculate fluid flows at local grid refinement boundaries is used to provide reliability. Optimisation and vectorization techniques specially adapted to unregularly distributed grid cell connections are used to enhance computing speed on scalar and vector machines [9]. For these reasons, most reservoir simulation studies performed with FRAGOR now use the LRCG option. In many cases, this option allows the number of grid nodes to be reduced by a factor as much as ten compared to a regular grid with the same grid spacing in areas of interest.

While FRAGOR has both the five-point and the nine-point discretization grid option, the base case Cartesian grid (10x10x4) of this CSP was run using the five-point option. The flexible grid is made of 24 grid cells per layer.

Simulation and Modelling Consultancy (SMC)

Simulations have been performed with S.M.C.'s model, GENESYS [10], a general purpose black-oil / compositional, single / double porosity / permeability simulator. Two types of gridding techniques are available :

- a finite-difference technique
- a control-volume/finite-element technique [6,11,12]

This last scheme is used for this project to promote a flexible type of gridding very well designed for local grid refinement simulations. It has been shown to be mathematically correct [13]. In GENESYS, the triangular mesh is automatically generated with respect to space step sizes on the boundaries of the reservoir. The generated triangles can be refined for better local representation. Control-volumes, in which discretized balances are solved for each component, are located at the nodes of the grid. Transmissivities are computed from the variational formulation using piece wise finite elements of the elliptic equation. Wells are located at the nodes of the mesh and productivity indices are calculated from a Peaceman's like formulation.

In the first part of this project, 2 finite-difference methods, five-point and nine-point schemes, have been used. Results are quite different (for instance, at the producer 1, the "gas breakthrough time" is 800 days for the five-point scheme and 940 days for the nine-point scheme) due to grid-orientation effects. Assuming the nine-point scheme as a reference, several CVFE triangular meshes have been generated and tested. Detailed discussion is available in the S.M.C.'s paper [12]. Results from a 23-Node mesh are provided: they are very close to the nine-point results (less than 3% all along the simulations) with a computer-time divided by more than five times.

Standford University (STA)

META is the simulator used for this problem. It was developed by Nacul [14,15] for his PhD work on local grid refinement and domain decomposition. It is a fully implicit three-dimensional black-oil simulator with adaptive implicit and IMPES options. The refinement in a specified region can be either Cartesian or cylindrical, but two refined regions are not allowed to be in contact with each other. The simulator has both block-centered and point-distributed grids, and several variations of these grids. It has been used and enhanced by several graduate students.

RESULTS

The simulation case proposed for this project corresponds to an oil displacement by a gas much more mobile than oil. The well boundary conditions were defined as oil rate at surface conditions for both producers and gas rate at surface conditions for the gas injection well. The producer bottomhole pressure limit was low enough so that no participant reached this value during the reported simulation period. For these reasons, the cumulative oil production and gas injection volumes are identical for all participants. For the comparison, the really important parameter is the producing Gas-Oil Ratio (GOR) at surface conditions for both producing wells.

Fig. 3 and 4 show the producing GOR versus time for Producer 1 and Producer 2 respectively, predicted by the different participants with the 10x10x4 basic Cartesian grid. Table 4 shows the gas breakthrough time, defined as the time for which the production GOR equals 2000 SCF/STB, and the time corresponding to a 10.000 SCF/STB production GOR, for both producers. The production GOR values of CMG and SMC differ with values from the other companies probably because both have used a nine-point scheme while the other companies have used a five-point scheme. Numerical dispersion, due to the highly unfavorable displacement, is another factor which can explain some differences between the results from the different participants. But it is difficult to say, at this stage, which predictions are most reliable.

The participants were then asked to provide a second set of results obtained with the same simulator but a flexible gridding technique in order to minimize the number of grid nodes, while keeping the simulation results close to their reference run.

The different flexible grids used by the participants are shown in Fig. 5 to 10. A Control Volume grid (CVG) was used by CMG and SMC, and a Locally Refined Cartesian grid (LRCG) was used by Beicip-Franlab and Standford University. INTERA proposed two sets of results, one set obtained with a LRCG (INTa) and another set obtained with a CVG (INTb). It can be noted that all participants used the same gridding for the four layers while the three bottom layers, less permeable than the top layer, probably play a less important role than the top layer where the wells are located. One reason for this may be that in all cases, the top layer gridding has been so optimised that it has been impossible to further optimise the bottom layers gridding.

The number of grid nodes and grid node connections of these grids are shown in Table 5. Because some calculations made during a simulation depend on the number of grid nodes and some other calculations directly depend on the number of grid node connections, the computer running time and memory storage necessary to a reservoir simulation is a function of these two parameter values.

Fig. 11 to 14 show, for both producers and for each participant, a comparison of the producing GOR values calculated with the flexible grid on the one hand, and with the 10x10x4 Cartesian grid on the other hand. Tables 6 and 7 show, for both producers and for each participant :

a) the gas breakthrough time (time for which the production GOR equals 2000 SCF/STB) calculated with the flexible grid and with the10x10x4 basic Cartesian grid,

b) TGR the time corresponding to a 10.000 SCF/STB production GOR calculated with the 10x10x4 basic Cartesian grid,

c) the production GOR at time TGR calculated with the flexible grid.

A comparison between the Producer 1 bottomhole pressures predicted by the different simulations is shown in Fig. 15 to 17 (the comparison between the Producer 2 bottomhole pressure predictions is very similar).

Whatever type of flexible grid they have used, a CVG, or a LRCG, all participants could reduce the number of grid nodes by a factor four or more with their flexible grid while keeping the results close to those obtained with the same simulator but a 10x10x4 basic Cartesian grid. As a matter of fact, the differences between the results obtained with the same simulator and a flexible grid on the one hand and a 10x10x4 basic Cartesian grid on the other hand are in general much less than the differences between the results obtained with different simulators and the same 10x10x4 basic Cartesian grid. This shows that the CVG or the LRCG methods used by the participants effectively reduce the number of grid nodes without significantly distorting the simulation results even in cases of severe numerical dispersion constraints.

Observations

While the present test is an academic exercise only aimed at comparing different flexible gridding techniques, the amount of grid node savings reported here still reflect those which can be obtained from these techniques during a 3D full-field reservoir simulation. The difference between the present case and a full-field simulation is that during the latter, there are in general several areas of interest which naturally break off one from the others at a scale larger than the inter well spacing, and which call for a particular small space gridding for their description. These may be different reservoirs or different groups of wells linked by a large aquifer, faulted reservoir zones, confined pilot areas, or reservoir areas with different permeability values. In such cases, a flexible gridding technique allows significant grid node savings by limiting the small grid spacing to these particular areas. Nacul [16] emphasised a reasonable rule for the definition of a flexible grid during a full-field study. This rule is that, to ensure good quality simulation results, the small grid spacing defined around a well should extend to the whole well drainage area (this was not the case for the flexible grids exhibited during this CSP).

A flexible gridding technique also allows a significant amount of grid node saving when the reservoir has irregular contours.

This CSP only checked the reliability of different flexible gridding techniques now available in some reservoir simulators. There are several interesting questions which arise with flexible gridding techniques and which have not been addressed during this CSP because they are beyond the scope of this project.

The first concerns their performances in terms of computer time and computer memory savings. There are so many different types of computer hardware now available for reservoir simulation (scalar, vector, parallel computers...), that it is difficult to answer precisely to this question. A particular difficulty for a simulator allowing the use of flexible grids is that at each time step, such a simulator has to set-up and solve one or more matrix systems with irregularly distributed matrix connections. Its efficiency then depends directly on the solution methods it uses to solve such linear equation systems.

The second question concerns the ergonomics of the flexible grid definition. Flexible grids are more difficult than regular grids to define and sophisticated graphic grid builders are necessary for this purpose. Locally Refined Cartesian grids may be designed with a simple recursive process in which some windows of a Cartesian grid are redefined as new Cartesian grids. In this case, the grid design can use classical methods already used for No Locally Refined Cartesian grid definition. The design of less structured grids such as the Control Volume grids is more complex, but this is a problem encountered with finite element methods for which more or less automatic gridding methodologies have already been proposed. Probably that a good approach in this case is to use an automatic grid generation procedure [17] to easily get a first draft of the grid and then further enhance it by hand.

CONCLUSION

More and more reservoir simulators have flexible grid capabilities already available or in development. This is evidence of the growing interest in these features. This Comparative Solution Project (CSP) compares different flexible gridding techniques and try to answer the two following questions :

1) are these techniques reliable

2) can they allow a significant computer time saving during a reservoir simulation

While the conditions of the present test are not those met during an actual full-field reservoir simulation, it seems that the answer to both questions is yes. In a case of oil displacement by a much more mobile gas, all participants in this CSP could reduce the total number of grid nodes by a factor of four or more with a flexible gridding technique, while keeping the simulation results close to those obtained with regular gridding techniques

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APPENDIX

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Table 1 : Data and Constraints

Initial reservoir pressure, psia at 8,400 ft	4,800
The Gas Injector is perforated in the upper layer only, at a distance of 250 ft in the X direction and 250 ft in the Y direction	
The Producer 1 is perforated in the upper layer only, at a distance of 4750 ft in the X direction and 250 ft in the Y direction	
The Producer 2 is perforated in the upper layer only, at a distance of 250 ft in the X direction and 4750 ft in the Y direction	
Gas injection rate, MM SCF/D	12.5
Maximum oil production rate, for each producer, STB/D	1,875
Minimum oil rate, for each producer, STB/D	1,00
Minimum flowing bottomhole pressure, for each producer, psi	1,000
Rock compressibility, 1/psi	3×10^{-6}
Porosity value of 0.3 was measured at base pressure of 14.7 psi	
Wellbore radius, ft	0.25
Skin	0
Capillary pressure	0
Reservoir temperature, °F	200
Gas specific gravity	0.792
Runs are terminated either at the end of 10 years or when both producers have reached a GOR value of 30,000 SCF/STB.	

Table 2 : PVT properties

SATURATION OIL PVT FUNCTIONS

Reservoir Pressure (psia)	FVF (RB/STB)	Viscosity (cp)	Density (lbm/cu ft)	Solution GOR (SCF/STB)
14.7	1.0620	1.0400	46.244	1.0
264.7	1.1500	0.9750	43.544	90.5
514.7	1.2070	0.9100	42.287	180.0
1014.7	1.2950	0.8300	41.004	371.0
2014.7	1.4350	0.6950	38.995	636.0
2514.7	1.5000	0.6410	38.304	775.0
3014.7	1.5650	0.5940	37.781	930.0
4014.7	1.6950	0.5100	37.046	1270.0
5014.7	1.8270	0.4490	36.424	1618.0
9014.7	2.3570	0.2030	34.482	2984.0

UNDERSATURATED OIL PVT FUNCTIONS

Reservoir Pressure (psia)	FVF (RB/STB)	Viscosity (cp)	Density (lbm/cu ft)	
4014.7	1.6950	0.5100	37.046	
9014.7	1.5790	0.7400	39.768	

GAS PVT FUNCTIONS

Reservoir Pressure (psia)	FVF (RB/STB)	Viscosity (cp)	Density (lbm/cu ft)	
14.7	0.935829	0.008000	0.0647	
264.7	0.067902	0.009600	0.8916	
514.7	0.035228	0.011200	1.7185	
1014.7	0.017951	0.014000	3.3727	
2014.7	0.009063	0.018900	6.6806	
2514.7	0.007266	0.020800	8.3326	
3014.7	0.006064	0.022800	9.9837	
4014.7	0.004554	0.026800	13.2952	
5014.7	0.003644	0.030900	16.6139	
9014.7	0.002167	0.047000	27.9483	

Table 3 : Relative permeability data

OIL - GAS

Sg	Krg	Kro
0.	0.0	1.0
0.001	0.0	1.0
0.02	0.0	0.997
0.05	0.005	0.980
0.12	0.025	0.700
0.2	0.075	0.350
0.25	0.125	0.200
0.3	0.190	0.090
0.4	0.410	0.021
0.45	0.60	0.010
0.5	0.72	0.001
0.6	0.87	0.0001
0.7	0.94	0.000
0.85	0.98	0.000
1.0	1.0	0.000

This is a two-phase, gas/oil problem. Set the relative permeability to water equal to 0. for all values of water saturations.

Table 4 : Producer Gas Breakthrough and High production GOR Times calculated with the 10x10x4 Cartesian grid

Company	Gas Breakthrough Time (days) (GOR equal 2.000 SCF/STB)		10 000 (SCF/STB) GOR Time (days)	
	Producer 1	Producer 2	Producer 1	Producer 2
CMG	863	813	2382	2313
INT	805	755	2258	2192
B-F	784	736	2232	2166
SMC	941	891	2188	2121
STA	807	765	2230	2175

Table 5 : Number of Grid Nodes and Grid Node Connections of the Different Flexible Grids

Company	Grid Nodes	Grid Node Connections
CMG	108	341
INTa	96	224
INTb	68	175
B-F	96	256
SMC	92	277
STA	88	218

Table 6 : Producer 1 Gas Breakthrough and High GOR ValueTimes

Company	Gas Breakthrough Time 10x10x4 grid (days)	Gas Breakthrough Time Flexible grid (days)	10 000 (SCF/STB) GOR Time TGR 10x10x4 grid (days)	GOR at time TGR Flexible grid (SCF/STB)
CMG	863	804	2382	10.160
INTa	805	773	2258	10.404
INTb	805	856	2258	9.481
B-F	784	779	2232	10.415
SMC	941	915	2188	10.573
STA	807	795	2230	10.674

Table 7 : Producer 2 Gas Breakthrough and High GOR ValueTimes

Company	Gas Breakthrough Time 10x10x4 grid (days)	Gas Breakthrough Time Flexible grid (days)	10 000 (SCF/STB) GOR Time TGR 10x10x4 grid (days)	GOR at time TGR Flexible grid (SCF/STB)
CMG	813	762	2313	9.927
INTa	755	721	2192	10.053
INTb	755	819	2192	9.489
B-F	736	707	2166	10.139
SMC	891	865	2121	10.165
STA	765	794	2175	10.016

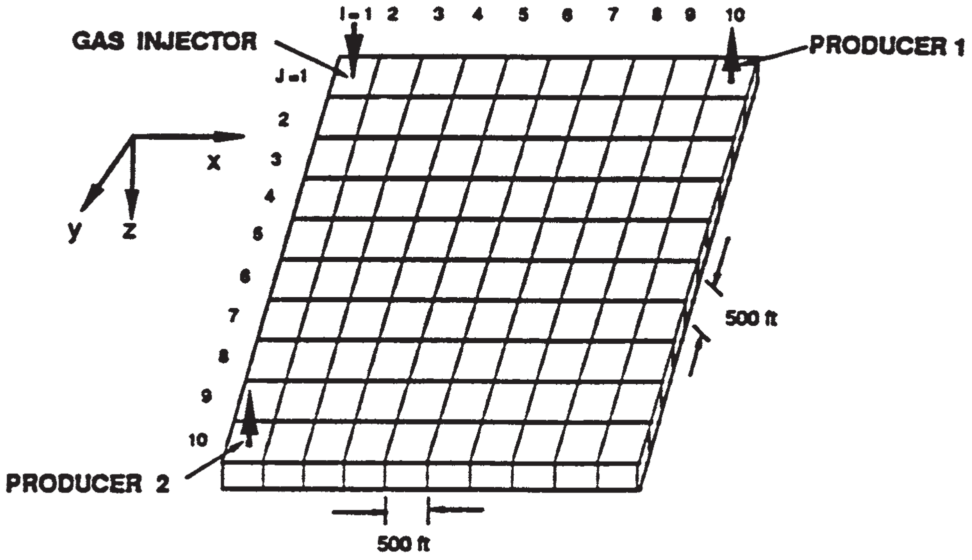

Fig. 1 - Reservoir and grid system

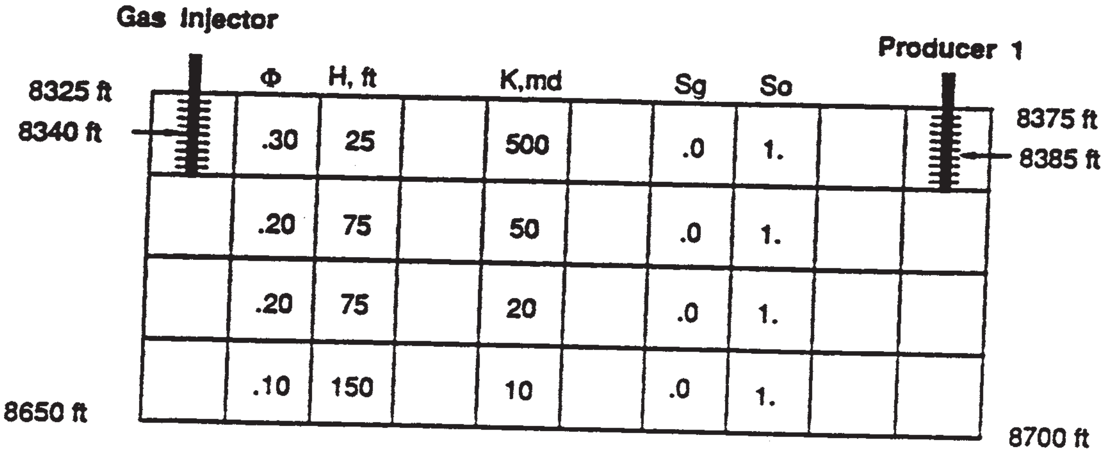

Fig. 2 - J=1 vertical cross section

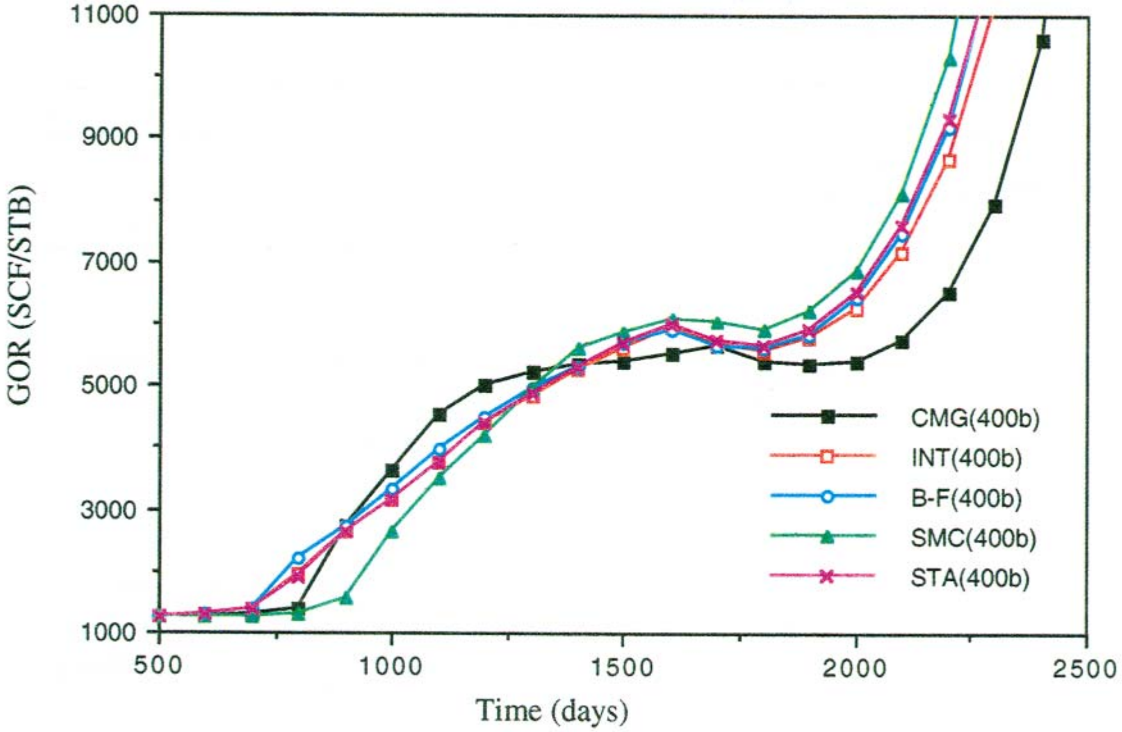

Fig. 3 - Producer 1 Gas/Oil Ratio

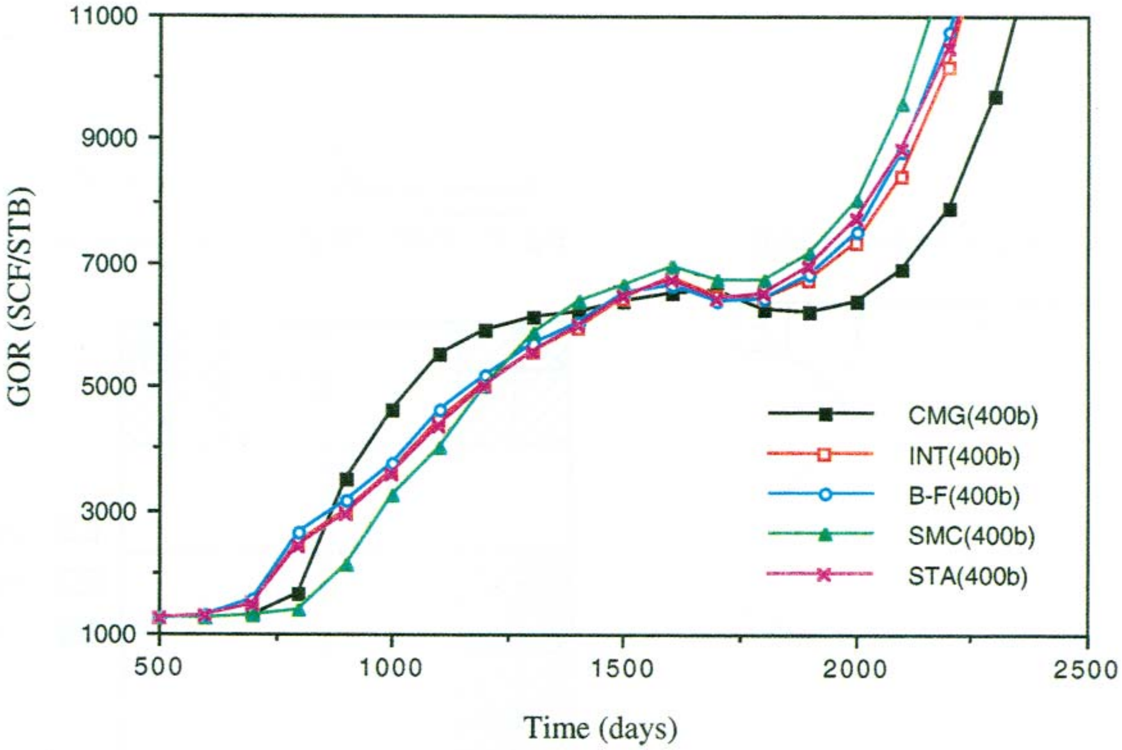

Fig. 4 - Producer 2 Gas/Oil Ratio

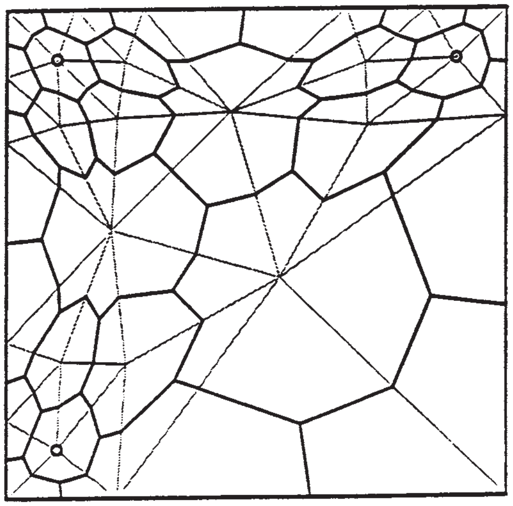

Fig. 5 - CMG : 27 grid nodes per layer

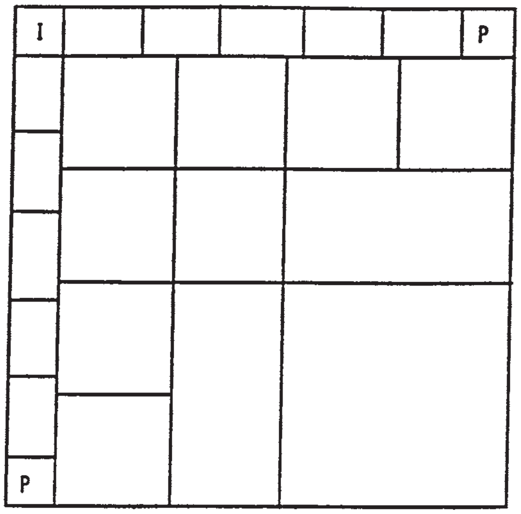

Fig. 8 - B-F : 24 grid nodes per layer

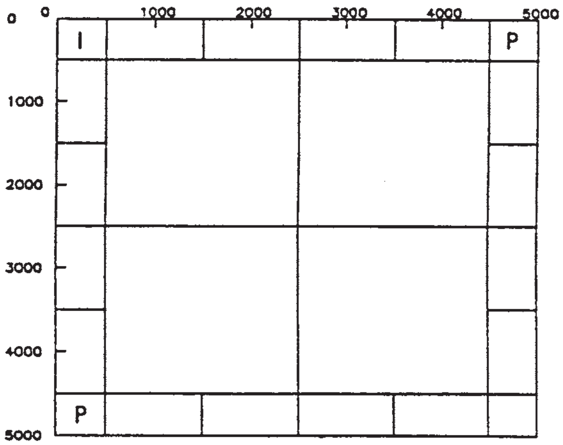

Fig. 6 - INTa : 24 grid nodes per layer

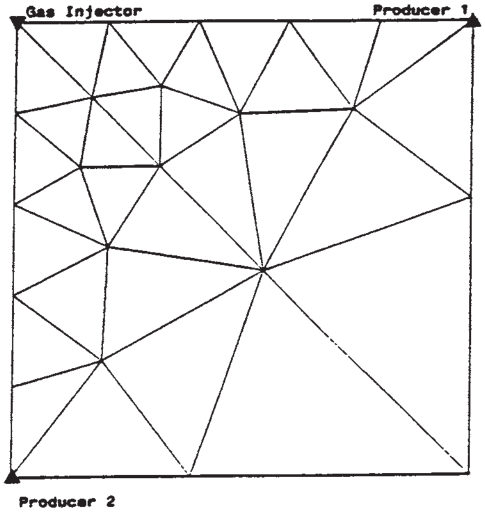

Fig. 9 - SMC : 23 grid nodes per layer

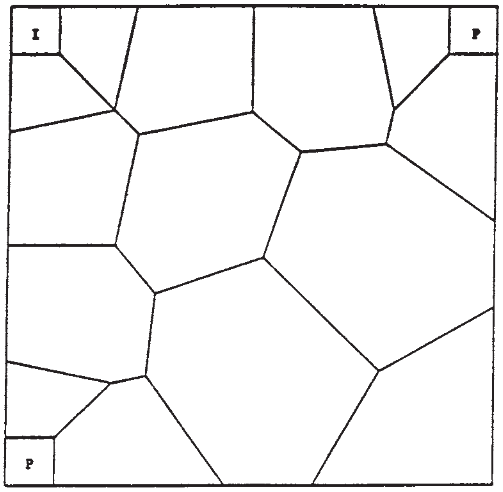

Fig. 7 - INTb : 17 grid nodes per layer

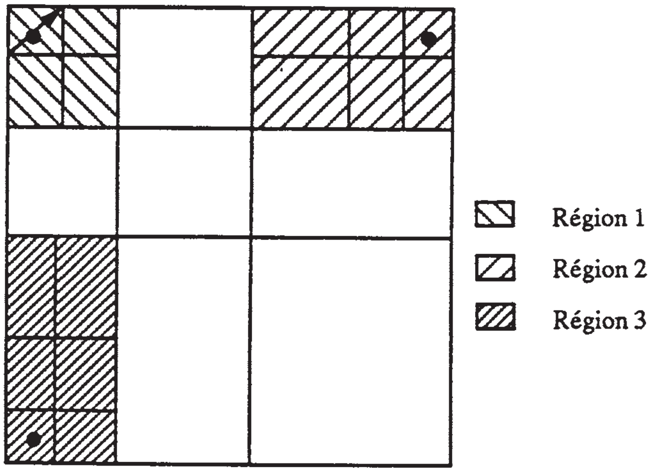

Fig. 10 - STA : 22 grid nodes per layer

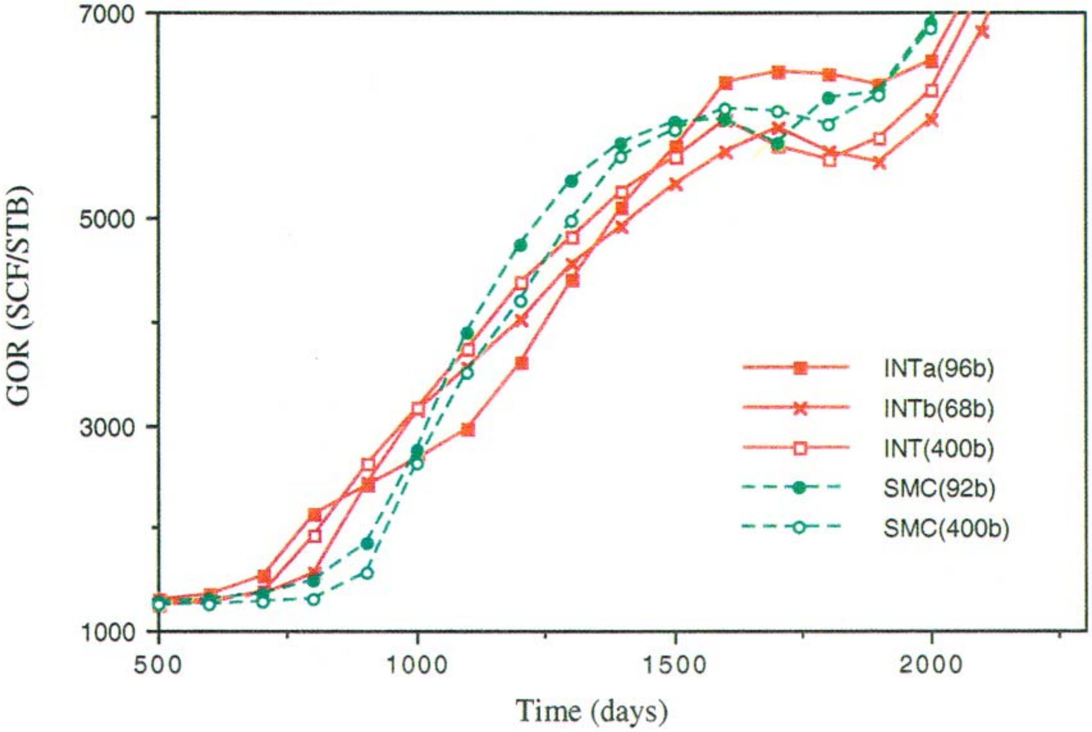

Fig.11 - Producer 1 Gas/Oil Ratio

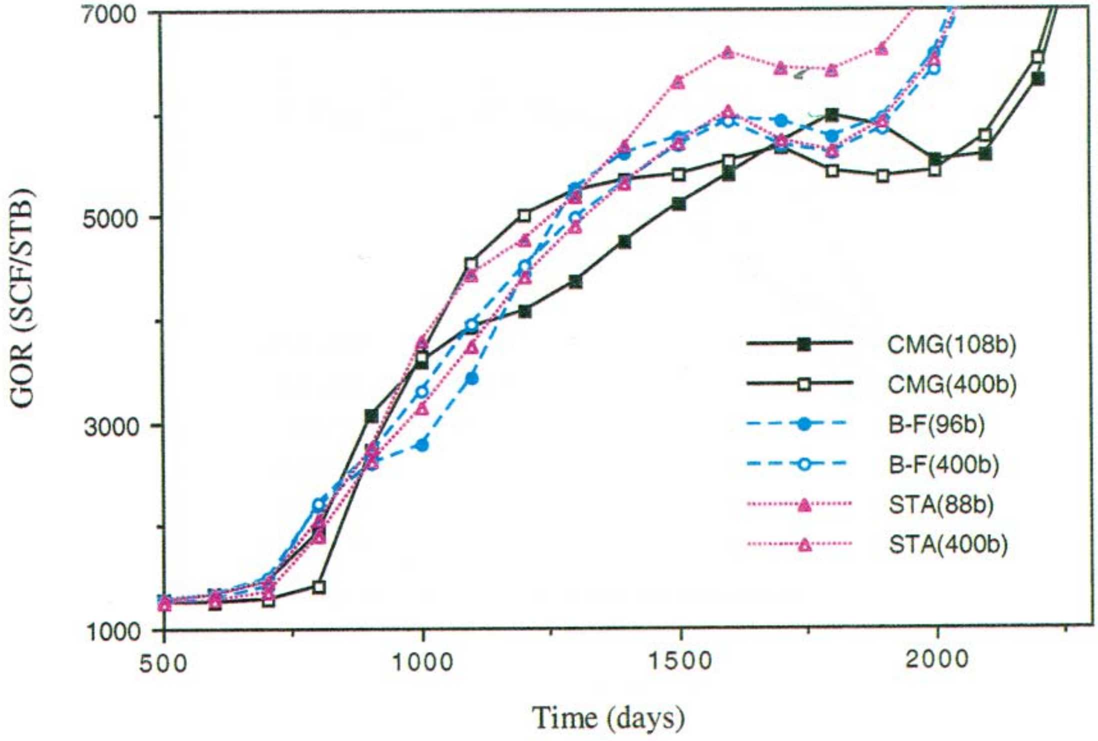

Fig.12 - Producer 1 Gas/Oil Ratio

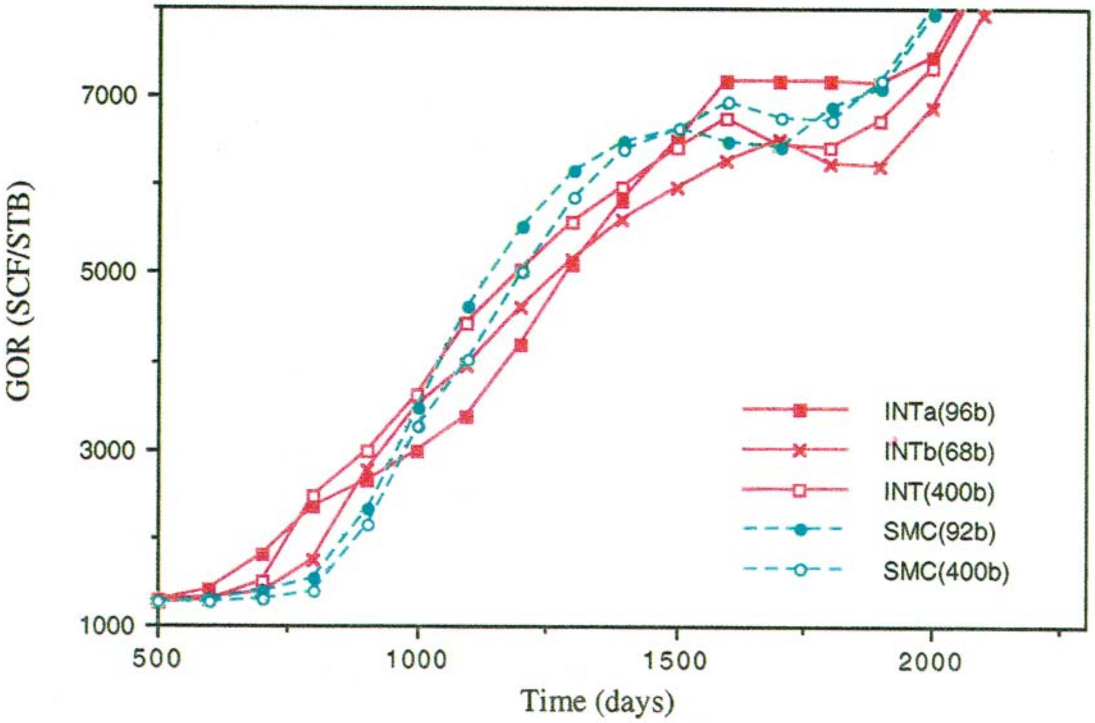

Fig.13 - Producer 2 Gas/Oil Ratio

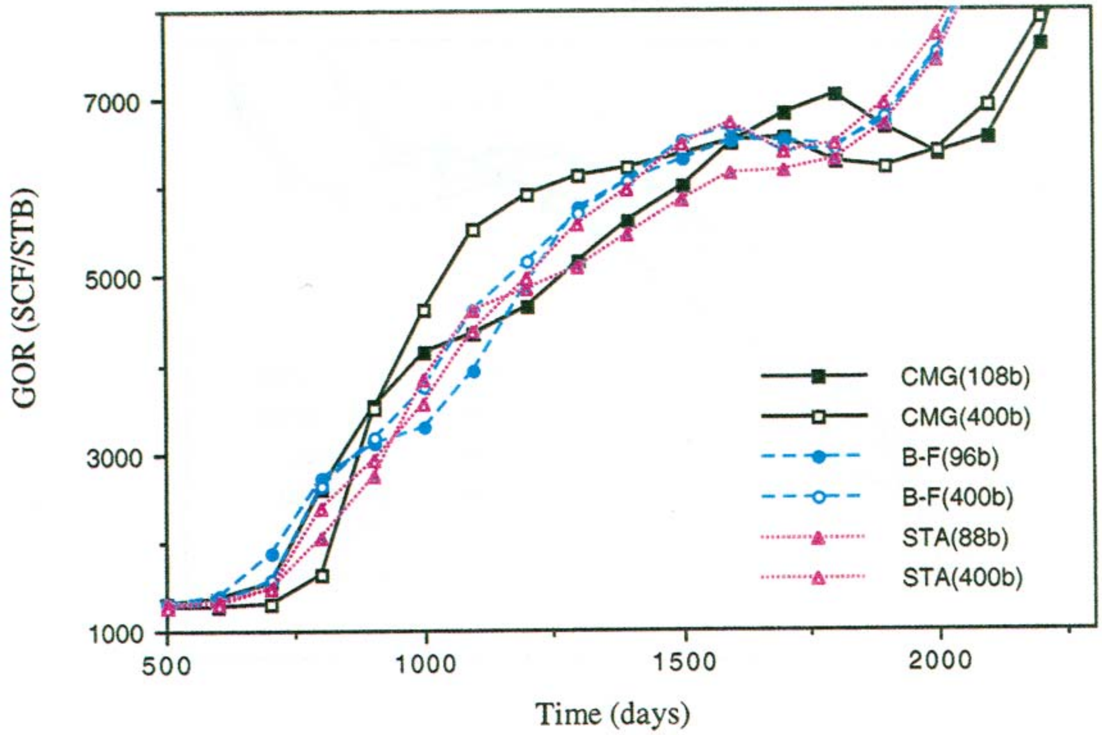

Fig.14 - Producer 2 Gas/Oil Ratio

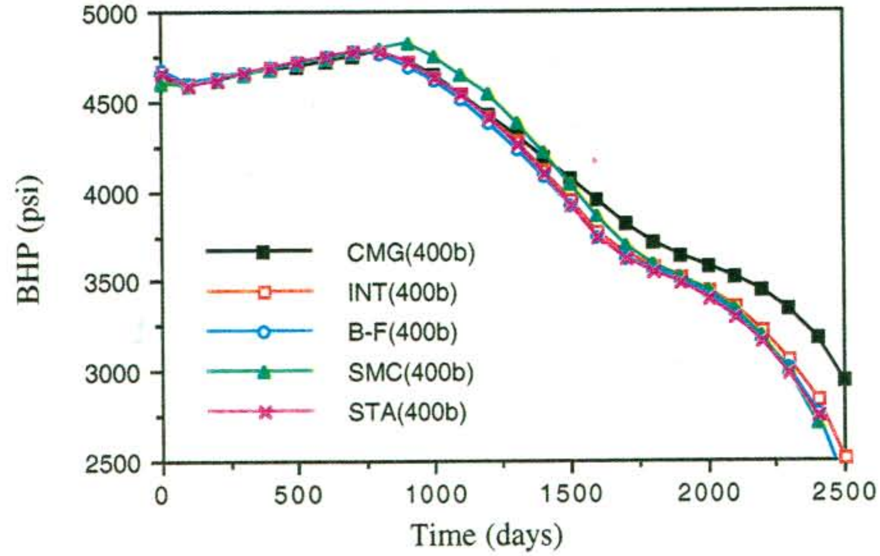

Fig.15 - Producer 1 Bottom Hole Pressure

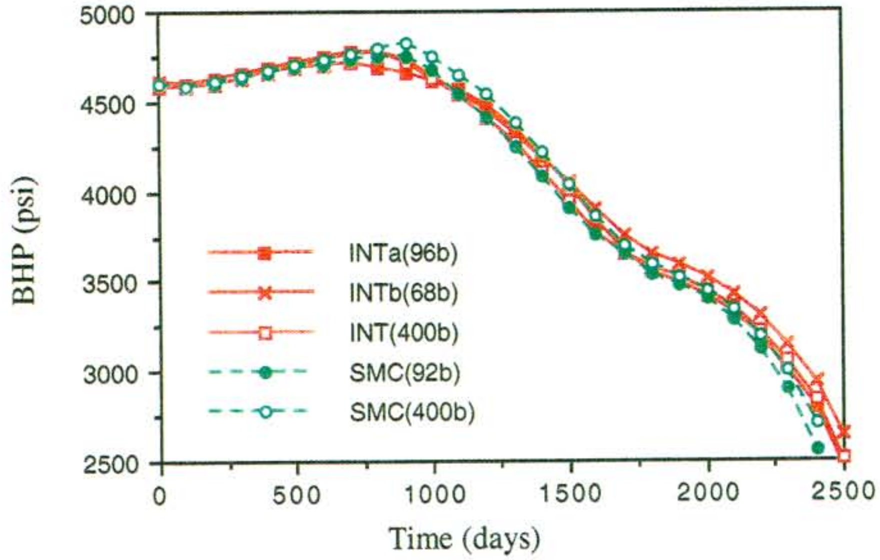

Fig.16 - Producer 1 Bottom Hole Pressure

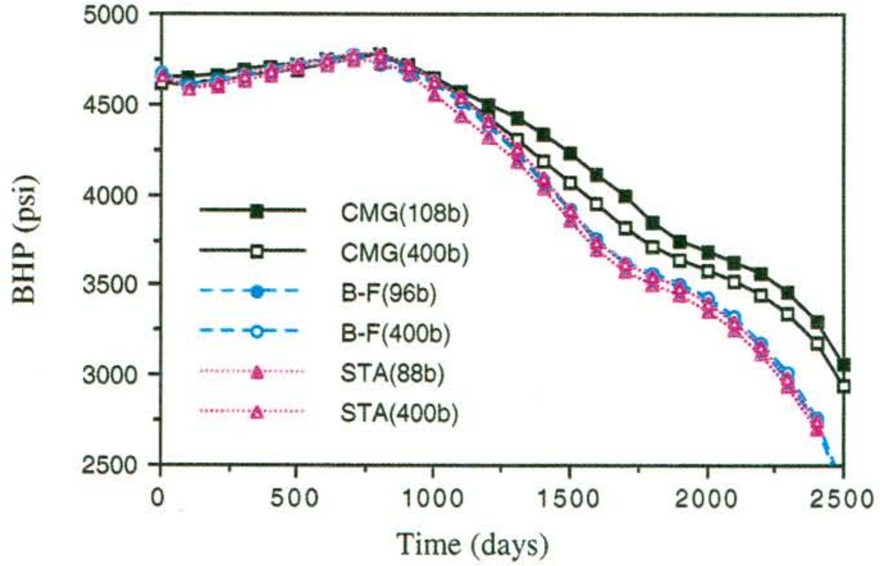

Fig.17 - Producer 1 Bottom Hole Pressure