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Use of PEBI Grids for Complex Advanced Process Simulators

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Abstract

PEBI ("perpendicular bisector") grids have been shown in the past to have the potential to reduce computational times for the simulation of relatively straight-forward processes. It is the purpose of this paper to investigate PEBI-based gridding for a much more complex thermal process in a full field setting using commercial simulation products. The goals are to study both computing efficiency and accuracy by comparing results obtained by modelling a field using the more conventional corner point-based gridding with local grid refinement to those obtained using a PEBI gridding approach.

The field in question has been produced for about 20 years, with an operational history that includes cyclic steam stimulation in portions of the field. Many vertical faults have been mapped in the reservoir, and over 140 wells, many of them deviated or horizontal, have been drilled. A simulation study had been done using approximately 170 000 active corner point cells. It was found that the inclusion of foamy oil behaviour was necessary to get a good match of the production history. It appeared though that this simulation was lacking in accuracy near horizontal wells. This was probably due to the inability of the model to align its locally refined grids properly with many of the wells, and the difficulty in getting reasonable refinement levels where cyclic steam stimulation was being carried out, without making the problem considerably larger.

A second simulation study was carried out using a PEBI-based grid. The more flexible aspects of this gridding system allowed construction of a better aligned grid, especially near the horizontal wells and near faults. Moreover, the characteristics of the PEBI-based grid also allowed efficient grading of grid cell sizes, so that particularly fine-scale gridding could be used near wells, while still maintaining an overall model size that was about half that of the corner point model. All processes modelled in the original simulation were replicated in the PEBI-gridded model, including the foamy oil and thermal aspects.

The PEBI gridded model ran in about a third of the time of the original corner point model, and showed accuracy improvements which were attributable to the better placement of grid cells. These results showed that the simulator's ILU-based sparse matrix solver technology was very capable of computing in an unstructured grid environment, even while using cells near wells that were smaller than those used in the corner point model.

Thus, PEBI-based gridding can be used to efficiently model complex processes in a full field setting. These grids can demonstrably improve accuracy and are much more adaptable for modelling near wells and in a complex geological setting. A three-fold run time improvement was noted for the field in question when comparing to a more conventional, corner point gridded model.

Introduction

PEBI ("perpendicular bisector") grids were introduced into reservoir simulation as early as 1989[1]. These early grids used stacked layers with a PEBI grid in each layer. The construction of these two-dimensional PEBI grids could be based on first laying down a collection of nodes (points) in the reservoir, and then constructing a cell around each node that consists of all points in the reservoir that are closer to that particular node than any other. The resulting (several-sided) cells form what is known as a Voronoi tessellation[2], and the cells become the "control volumes" for the discretization. The associated PEBI grid is the triangulation that consists of the nodes and connecting segments that join pairs of nodes wherever the nodes' associated cells meet at a common face. The procedure of building the triangulation as a dual grid to a Voronoi tessellation shows why the inter-nodal segments between connected nodes are perpendicular to their associated common faces, and why the faces intersect the mid-points of the segments; hence the term, "perpendicular bisector". Of course, the preceding discussion ignores numerous details concerning node layout, boundaries, and many other issues, and is only meant for illustration, but it does give a brief indication of how things might work.

Given a PEBI triangulation, it is easy to discretize the reservoir flow equations by writing a mass balance for each cell (control volume), where the inter-cell flows use simple differences in pressure between connected nodes divided by the inter-nodal distance and multiplied by the area of the common face. Many theoretical facts are known about this

type of control volume discretization[1]. For example, a recent paper[3] shows that this numerical scheme is convergent for a single phase pressure equation even in the presence of certain kinds of poorly shaped cells ("slivers").

The PEBI grid utilized in this study also uses stacked layers with control volume cells in each layer. The main philosophy of the gridding approach is to keep the grid as simple as possible, but as complex as is necessary. The actual grid generation technology is based on work of Heinemann et. al[4,5]. This approach uses Cartesian gridding wherever reasonable. "Window" grids, providing local refinement near wells, are also incorporated. Thus, starting from a basic grid made up of square, Cartesian cells, cell faces are adjusted locally by the automated grid generator to model discontinuities such as fault traces, transitions to locally finer grids, and horizontal well paths, while the underlying (square) Cartesian grid cells are retained in the rest of the model. An example is shown in Figure 1.

Figure 2 shows a portion of a more complex PEBI grid around an undulating well. This grid does not use stacked layers. This type of gridding was too detailed for the purposes of this study however and was not used.

When so-called "window" grids are used by the grid generator to effect local refinement, the transition from coarser to refined cells is done smoothly, retaining ratios such as 1:2 or 1:3 between adjacent cell volumes, so as to avoid drastic changes in the grid. In most cases this is beneficial to the behavior of the reservoir simulation engine during the simulation. Of course, these transitions from coarser to finer cells follow the basic PEBI philosophy and maintain perpendicular flow across cell faces. Again, this is very important for the elementary discretization of the flow equations, as flow calculations can be reduced to evaluating the potential gradient between grid cells that make up a connection, and avoid issues that arise with non-orthogonal grids, which have to account for the other components of the potential gradients at a cell face.

When modelling horizontal well-trajectories using the grid generator, the number of grid points along the trajectory and the number of cell rows perpendicular to the well trajectory can be specified so that the flow towards the wellbore remains orthogonal to the cell faces.

SAGD Modelling

It is the purpose of this paper to investigate the benefits of PEBI-based gridding for a complex thermal process in a full field setting using commercial simulation products. The goals are to study both computing efficiency and accuracy by comparing results obtained by modelling a field using the more conventional corner point-based gridding with local grid refinement to those obtained using a PEBI gridding approach.

The target process for this paper is "Steam Assisted Gravity Drainage (SAGD) [6]" modelling in heavier oils. This is an important process for thermal simulation as it is a process used in many fields in several different parts of the world. Its modelling requires special care in grid selection due to the problems associated with resolving the creation of a steam chamber around an (upper) injector when using horizontal injector/producer well pairs.

The field to be studied here has been produced for about 20 years, with an operational history that includes cyclic steam stimulation in portions of the field. Many vertical faults have been mapped in the reservoir, and over 140 wells, many of them deviated or horizontal, have been drilled. A simulation study had already been done using approximately 170 000 active corner point cells. It was found that the inclusion of foamy oil behaviour was necessary to get a good match of the production history. It appeared though that this simulation was lacking in accuracy near the horizontal wells. This was probably due to the inability of the corner point model to align its locally refined grids properly with many of the wells, and the difficulty in getting reasonable refinement levels where cyclic steam stimulation was being carried out without making the problem considerably larger.

PEBI grids have been shown in the past to have the potential to reduce computational times for the simulation of relatively straight-forward processes, as seen from several applications of PEBI gridding to isothermal problems[7,8]. In the thermal realm, single well PEBI-gridded cyclic steam problems[9] have been studied. In this work, a large PEBI grid will be evaluated, and its results compared to a study using a corner point grid.

"Control Volume Finite Element (CVFE)" techniques have also been used both for isothermal[10] and thermal problems[11,12]. CVFE techniques are related to the methods used here, and may give performance advantages as well. However, they use more complicated inter-cell connectivities which may be useful in anisotropic situations[11]. But, since the reservoir to be modelled exhibits relatively isotropic areal permeabilities, the PEBI techniques used here should work well.

All numerical simulation runs conducted in this study were done using the STARS[13,14,15] simulator from Computer Modelling Group Ltd. (CMG) and the grids were generated using SureGRID[4] from Veritas DGC Inc.

Simulator Interfacing Issues

Properties must be passed from the gridding package to the simulator to carry out simulations using PEBI grids. The gridding package has an export feature that generates lists of properties for each control volume cell. The properties exported include cell bulk and pore volumes, porosities, permeabilities, nodal locations, initial pressures and saturations. The gridding package can also provide a list of connected neighbours for each cell, along with an accompanying list of transmissibilities computed using the simple properties of the control volume discretization discussed above.

A new interface was created in the simulator's grid reading routine to load all of the above lists in place of the simulator's usual grid keywords. The simulator then populates its usual internal grid arrays as if the information had come from a large, single dimensional, generic grid. The simulator's sparse ILU factorization technology[14] is then able process these lists, particularly the connectivity list, as usual.

The gridding package also manages the placement of wells through the use of well trajectories, and it also computes appropriate well indices. This information is exported to a file

of well locations and indices, which had to be re-formatted into the simulator's well input format.

An additional array writing format had to be added to the simulator, but this proved to be no more difficult then initializing a certain data base through a few function calls, and then writing simulator arrays to a file using a new function call. This additional array writing format is based on the HDF5[16] data format, which is a format that can be read and processed by the grid processor, allowing simulator output to be visualized in a PEBI grid setting.

Because the grid processor was not designed with thermal processes in mind, certain thermally aware properties had to be inferred from other input. For instance, for over- and under-burden heat losses, the grid processor supplied layer number had to be used to determine if a cell was at the top or bottom of the reservoir. Then, that cell's vertical connection to its internal neighbour needed to be decomposed to obtain an appropriate face area for use in computing heat loss on the opposite vertical face of the cell. But since inter-nodal distances are known and since averaged permeabilities can be computed, an area can be extracted from the known transmissibility. Then, this area, the inter-nodal distance and a simulator provided thermal conductivity can be passed on to the heat loss routine for calculating the appropriate losses.

Further improvements to this interface are envisioned to allow greater functionality from the combined products.

Single Well Pair Models

It has generally been thought that SAGD simulation studies require grid cell sizes of 2 m (6.6 ft) or less in width in the direction perpendicular to horizontal wells in order to properly model the steam chamber creation, and subsequent oil drainage. Cell sizes in the direction parallel to the horizontal wells can be much larger because of the small saturation and pressure changes in this direction.

In order to determine whether grid cell sizes larger than 2 m (6.6 ft) could be used, while still modelling the SAGD process correctly and predicting correct fluid recoveries, a number of smaller single well pair models were studied.

All single well pair models use properties that were derived from the full field model at a particular location, around wells SAGD 41 and SAGD 42 (see Figure 10). Five single well pair models were set up and run for 27 years of SAGD operations (see Figure 3). Normal well controls for SAGD operations were used as set out in Table 1.

The well pair models are as follows.

Fine Grid Model

This model (Figure 3) was constructed for use as a base case. Since this model had constant 2 m (6.6 ft) grid cell sizes in the J direction, it was assumed that this was the most correct model and that all other models could be compared to this model to determine their correctness. This model used a 5 × 150 × 52 corner point grid system (39 000 cells).

Case 1: Coarse Grid with 7 Parallel Cells (Like PEBI grid)

This model (Figure 4) was designed to replicate the size of grid cell that could be constructed in a full field PEBI grid model using the horizontal well "Window" grids. This model used a 5 × 15 × 13 corner point grid system (975 cells).

Case 2: Coarse Grid with 7 Parallel Cells (Like PEBI grid) with 1 × 1 × 4 Refinements

This model (Figure 5) was the same as Case 1 above, except it had 4 vertical refinements in each fundamental cell (3 900 cells).

Case 3: Coarse Grid 152.4m (500 ft) cells with 5 × 5 × 1 refinements and 3 × 3 × 1 secondary refinements

This model (Figure 6) was designed to duplicate the grid system that could be constructed in a full field corner point model with multi-level refinements. The fundamental grid was 5 × 2 × 13 and the total number of cells was 5 850 cells.

Case 4: Coarse Grid 152.4m (500 ft) cells with 5 × 5 × 3 refinements and 3 × 3 × 1 secondary refinements

This model (Figure 7) was the same as Case 3 except that it had 3 vertical refinements in each refined cell. The fundamental grid was again 5 × 2 × 13, for a total number of 17 550 cells.

From the production and injection response shown in Figures 8 and 9, it is apparent that the best match of the fine grid model is obtained from the "like PEBI grid" models. This probably occurs because the grid is much finer at the horizontal well location, which allows a better match of pressure gradients and fluid movements between the producer and the injector. Production/injection response from the different models appear to be not very sensitive to larger grid cell sizes further away from the horizontal well center line.

Therefore, from the results of these single well pair models, it appears that a full field model could be constructed with a reasonably small number of appropriately chosen cells, while maintaining a good numerical representation of the SAGD process.

Full Field SAGD Models

As noted above, a large, heavy oil field that has been producing for about 20 years with many existing vertical and horizontal wells was selected for this study. This field has had an operational history that included cyclic steaming on most wells. In order to create a prediction of the effect of full field SAGD operations, all existing wells were replaced with horizontal well pairs arranged in 9 repeated patterns. Each pattern contained 4 well pairs drilled from a central platform (see Figures 10 through 12). Some of the reservoir and fluid properties for this pool are given in Table 2.

The fundamental grid system for the new corner point model, which was also the starting point for the PEBI grid generator, had 66 × 45 × 13, or 38 610, cells. Each of these fundamental cells was 152.4 m × 152.4 m (500 feet × 500 feet).

The corner point grid model had additional refinements of 5 × 5 × 1 in the cells located close to the horizontal well pairs (see Figures 11 and 12). Thus, the grid cell size for these first level refined cells was 30.5 m × 30.5 m (100 feet x 100 feet). In the refined cells where the horizontal wells were perforated, additional levels of 3 × 3 × 1 refinement were added, making these cells 10 m × 10 m (33.3 feet x 33.3 feet). After all the refinements were added for the 36 well pairs, the total number of cells was 241 410 for the corner point model.

The PEBI grid model used the concept of "window grids", each attached to a horizontal well and integrated into the

fundamental grid system. Each window grid had 7 cells perpendicular to the well, and between 7 and 14 cells in the direction along the horizontal well. The perpendicular cell sizes were 4, 4, 8, 8, 16, 16, and 32 m, beginning at the cell closest to the horizontal well. The cell sizes along the well were simply the horizontal well length, 670 m to 914 m (2200 to 3000 feet), divided by the number of cells (7 to 14). These window grids are illustrated in Figures 13 to 15. After all window grids for all 36 well pairs were integrated into the grid system, the total number of cells was 129 194 for the PEBI grid model.

Thus the PEBI model had roughly half of the total cells required for the corner point model.

Results

Both corner point and PEBI grid models were run for 27 years of SAGD operations beginning in January 1, 2003, and ending January 1, 2030. From the comparison of the run statistics for these two cases given in Table 3, it is obvious that the PEBI grid model had a grid system that was better suited to simulating the reservoir. Besides the important fact that the PEBI grid was able to be constructed with 54% of the cells required for the corner point grid, the simulator was able to solve the problem with 61% fewer iterations, and with only 20% of the time step cuts. All these factors put together resulted in a total CPU time of 32% of the corner point problem, or a three fold run time improvement. (The machine used a single Intel P4 processor running at 2.5 GHz). These results indicate that the simulator's ILU-based sparse matrix solver technology was very capable of computing in this unstructured grid environment.

From the comparison of temperature profiles given in Figures 16 through 23, it is apparent that the PEBI grid case is better able to model the steam chamber creation and development because of its use of smaller cell sizes close to the horizontal wells. The corner point case tends to smear some of the temperature effects over its larger grid cells located close to the wells.

A comparison of typical production/injection responses, given in Figures 24 and 25 for well SAGD 42, shows that the PEBI grid model is able to match the earlier fine grid model within reasonable accuracy limits. However, the corner point model steam injection rates are significantly higher than the fine grid model because of the larger grid size at the horizontal well. These higher steam injection rates cause higher water cuts at the production well and lower oil production rates. The well indices for the corner point model could be adjusted so that they match the fine grid model, however, this matching is outside the scope of this study.

Conclusions

The more flexible aspects of the PEBI gridding system allowed construction of a better aligned grid, especially near horizontal wells. Moreover, the characteristics of the PEBI-based grid also allowed efficient grading of grid cell sizes, so that particularly fine-scale gridding could be carried out at the wells, while still maintaining an overall model size that was about half that of the corner point model.

The results from the PEBI grid model showed that the simulator's ILU-based sparse matrix solver technology were very capable of computing in an unstructured grid environment, while using cells near wells that were smaller than those used in the corner point model.

Thus, PEBI-based gridding can be used to efficiently model complex processes in a full field setting. These grids can demonstrably improve accuracy and are much more adaptable to modelling near wells and to being used in a complex geological setting.

The PEBI gridded model achieved a 32% run time improvement over the more conventional corner point model for the field in question.

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SI Metric Conversion Factors

bbl	× 0.15898 E+00	=	m^3
deg C	× 9/5 + 32.0 E+00	=	deg F
ft	× 3.048 E-01	=	m
mD	× 0.9869 E-03	=	m^2
psia	× 6.894 757 E+00	=	kPa

Tables

Production Well Controls	
Maximum Liquid Rate	6000 bbls/day
Minimum BHP	50 psi
Minimum Steam Trap Threshold	30 deg F.
Injection Well Controls	
Maximum Steam Rate	15 000 bbls/day
Maximum BHP	500 psi

Table 1: Normal Well Operating Controls

Minimum Depth	2302 ft sub-sea
Maximum Depth	3445 ft sub-sea
Average Thickness	646 ft
Average Net Pay Thickness	365 ft
Average Horizontal Permeability	6454 mD
Average Vertical Permeability	774 mD
Average Porosity	27.2 %
Average Initial Water Saturation	12.6 %
Initial Reservoir Temperature	122 deg F
Initial Reservoir Pressure	1181 psi @ 2600 ft
Dead Oil Viscosity	5385 cp
Live Oil Viscosity	1958 cp
Gas Oil Ratio	100 scf/stb
Oil Formation Volume Factor	1.075 rb/stb

Table 2: Reservoir and Fluid Properties

Description	Corner Point Model with Refinements	PEBI Grid Model	Ratio: PEBI/CP
Number of Cells	241 410	129 194	0.535
CPU time	391.8 hours (16.3 days)	124.8 hours (5.2 days)	0.319
Actual RAM	1371 MB	845 MB	0.616
Virtual RAM	1717 MB	1013 MB	0.590
Number of Iterations	19 902	12 093	0.608
Ave Time Step Size	3.21 days	8.64 days	2.69
Ave Iters/Time Step	6.45	10.44	1.62
Time Step Cuts	278	56	0.20
Material Balance Err	2.033 %	0.111 %	0.06

Table 3: Comparison of Corner Point and PEBI Grid Models

Figures

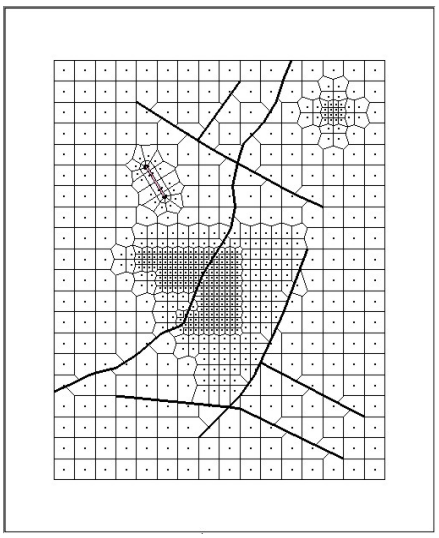

Figure 1: Example of a PEBI grid system.

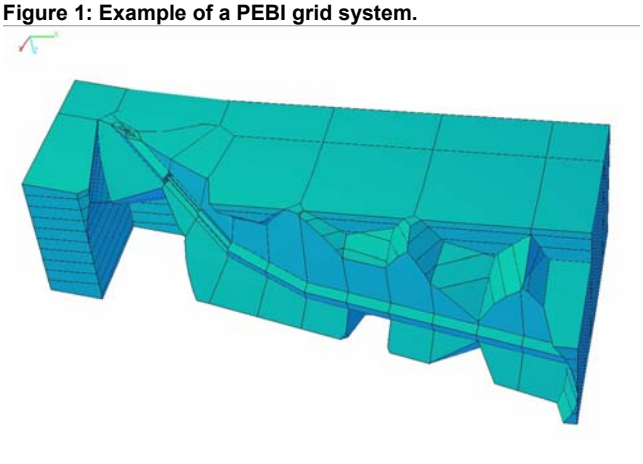

Figure 2: Example of a PEBI grid system around an undulating well.

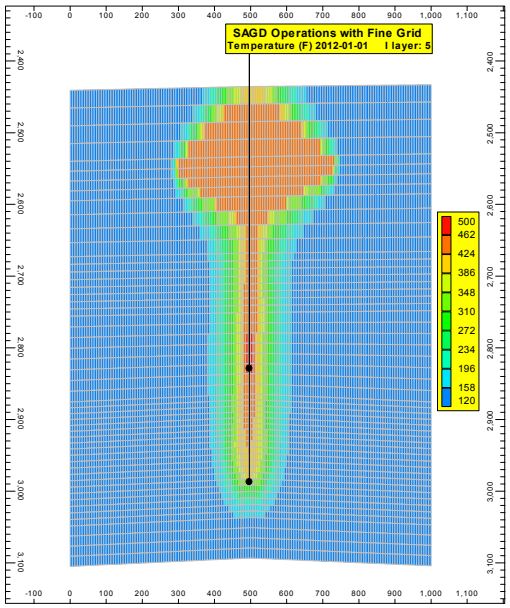

Figure 3: Fine Grid SAGD single well pair model, JK cross section.

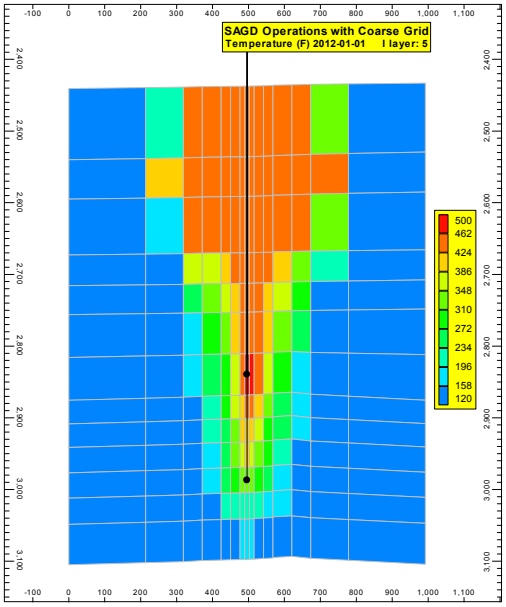

Figure 4: Case 1: Coarse Grid, 7 Parallel Cells (Like PEBI grid) SAGD single well pair model, JK cross section.

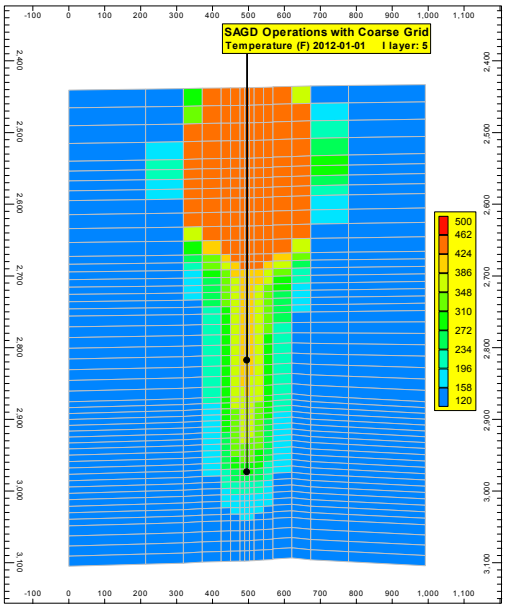

Figure 5: Case 2: Coarse Grid, 7 Parallel Cells (Like PEBI grid) plus 4 vertical refinements, SAGD single well pair model, JK cross section.

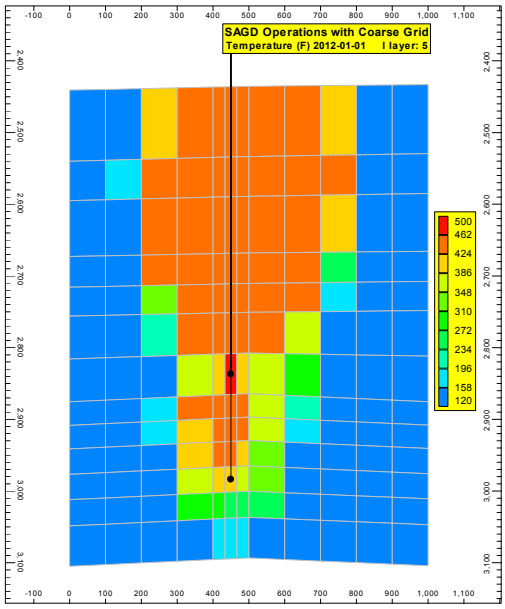

Figure 6: Case 3: Coarse Grid 152.4m (500 ft) cells with 5 × 5 × 1 refinements and 3 × 3 × 1 secondary refinements, SAGD single well pair model, JK cross section.

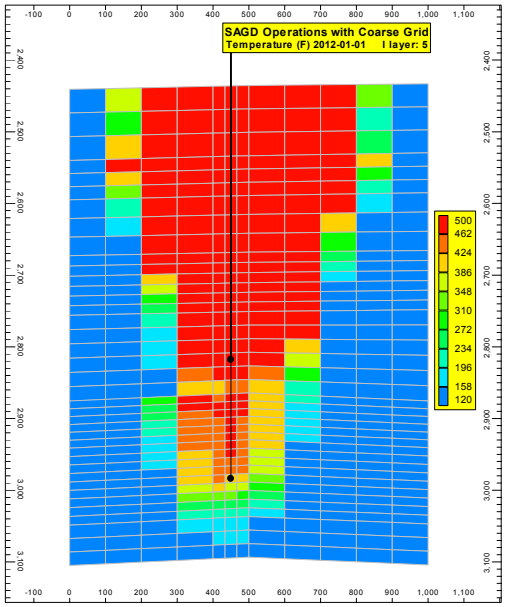

Figure 7: Case 4: Coarse Grid 152.4m (500 ft) cells with 5 × 5 × 3 refinements and 3 × 3 × 1 secondary refinements, SAGD single well pair model, JK cross section.

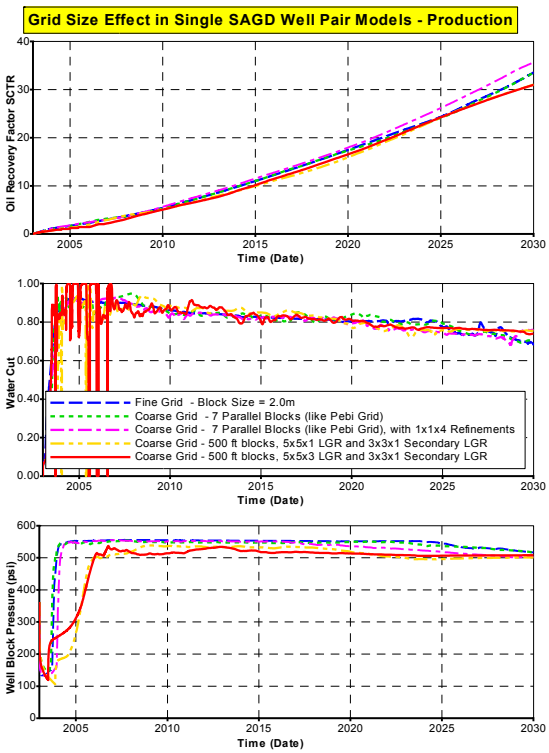

Figure 8: Comparison of production response

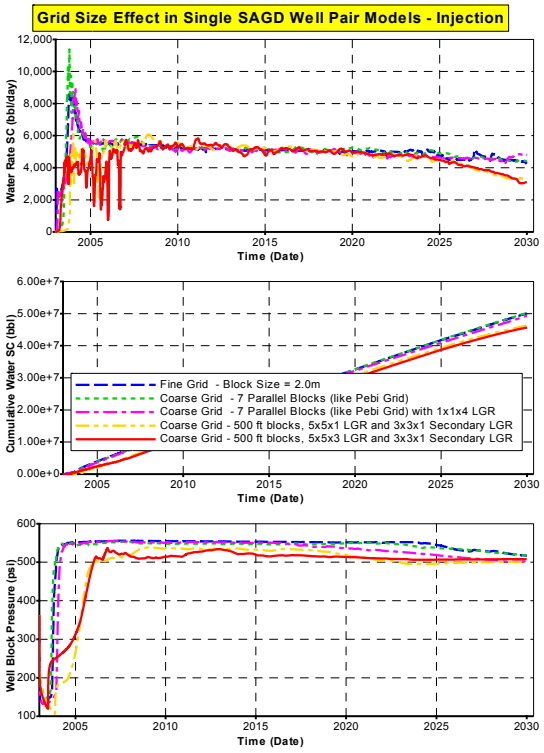

Figure 9: Comparison of injection response.

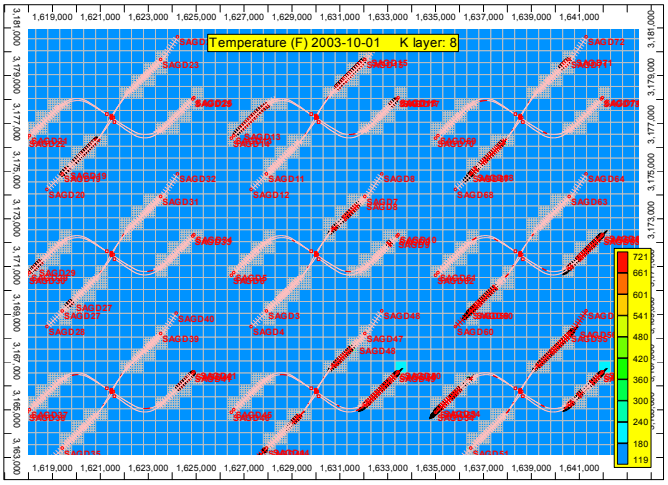

Figure 10: Full Field SAGD Corner Point Model.

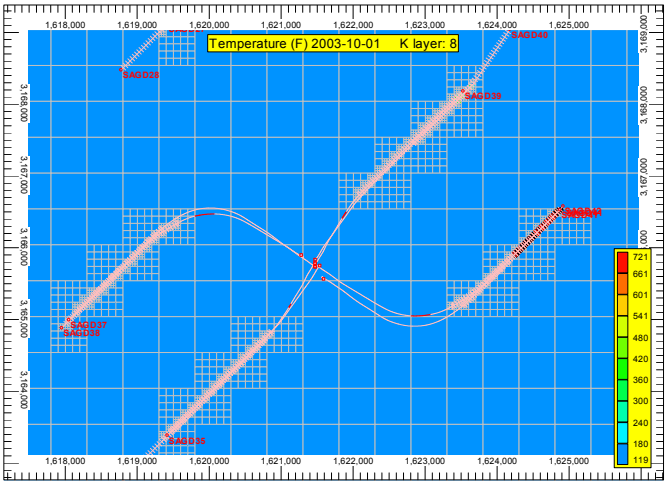

Figure 11: Full Field SAGD Corner Point Model – Single Pattern (8 wells).

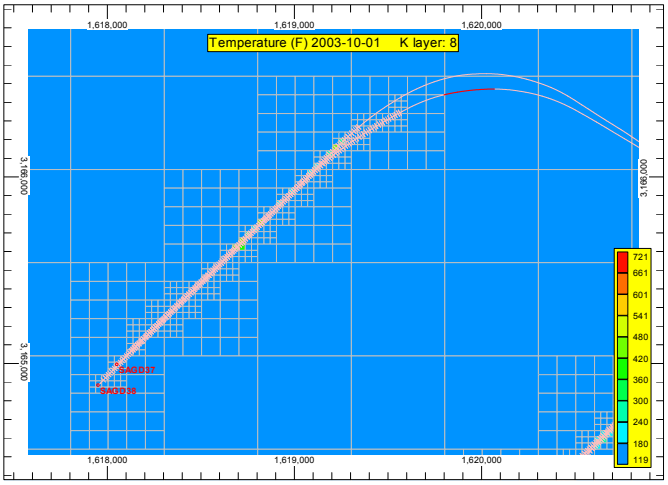

Figure 12: Full Field SAGD Corner Point Model – Single Well Pair.

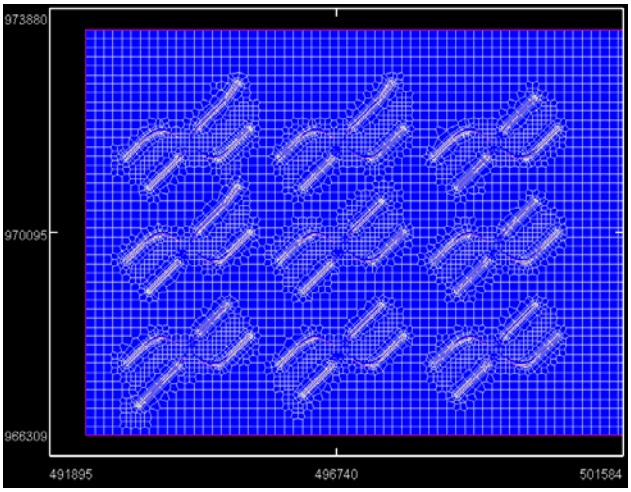

Figure 13: Full Field PEBI Model.

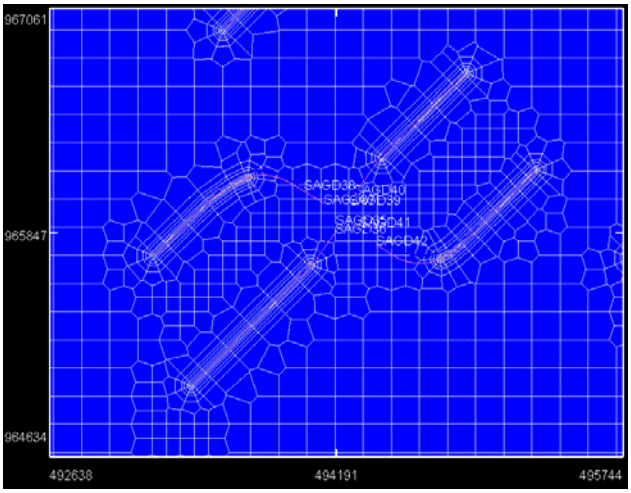

Figure 14: Full Field PEBI Model – Single Pattern (8 wells).

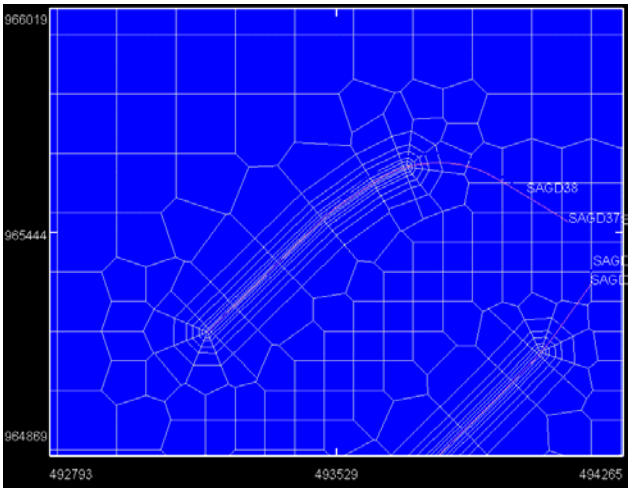

Figure 15: Full Field PEBI Model – Single Well Pair

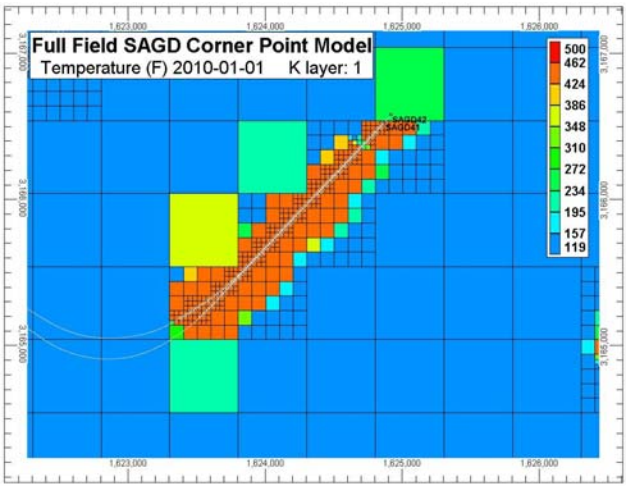

Figure 16: Corner Point Model Temperature at 2010 – Areal View.

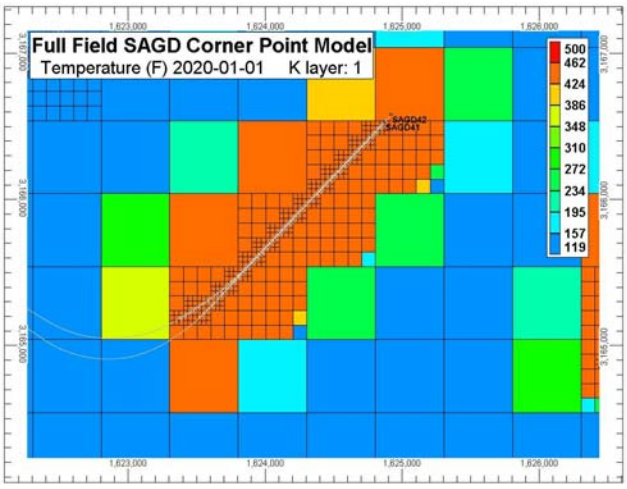

Figure 17: Corner Point Model Temperature at 2020 – Areal View.

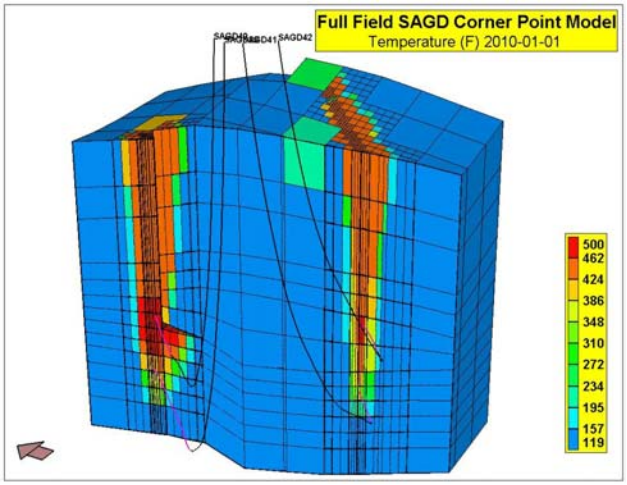

Figure 18: Corner Point Model Temperature at 2010 – 3D Cross Sectional View.

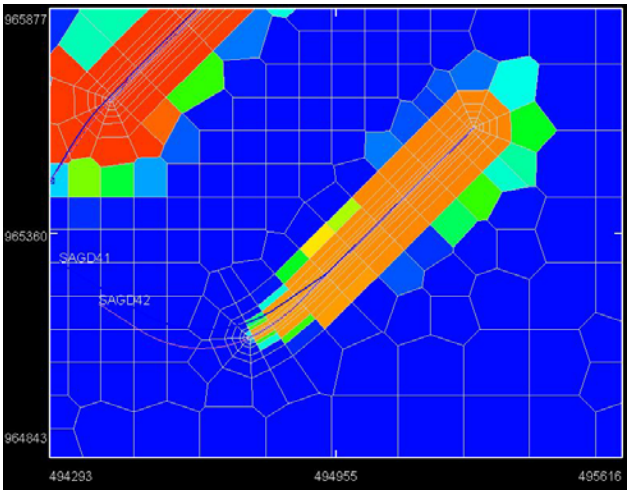

Figure 19: PEBI Grid Model Temperature at 2010 – Areal View.

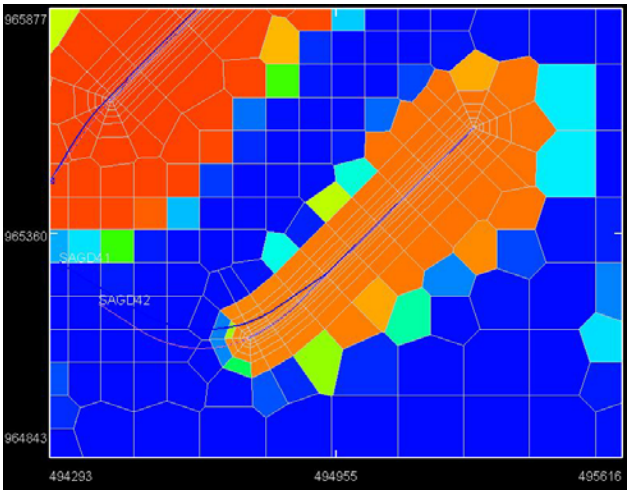

Figure 20: PEBI Grid Model Temperature at 2020 – Areal View.

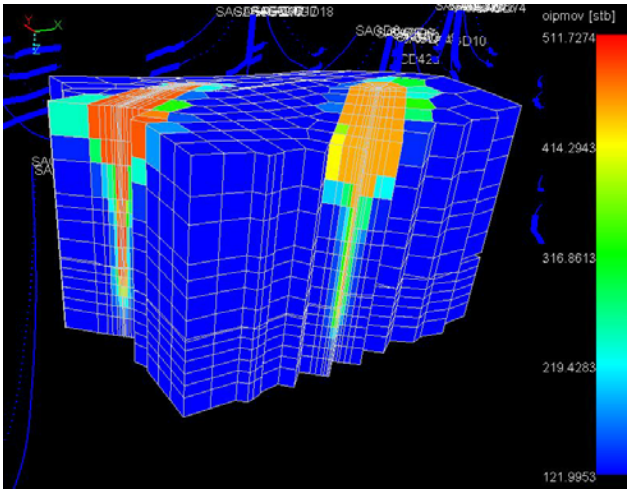

Figure 21: PEBI Grid Model Temperature at 2010 – 3D Cross Sectional View.

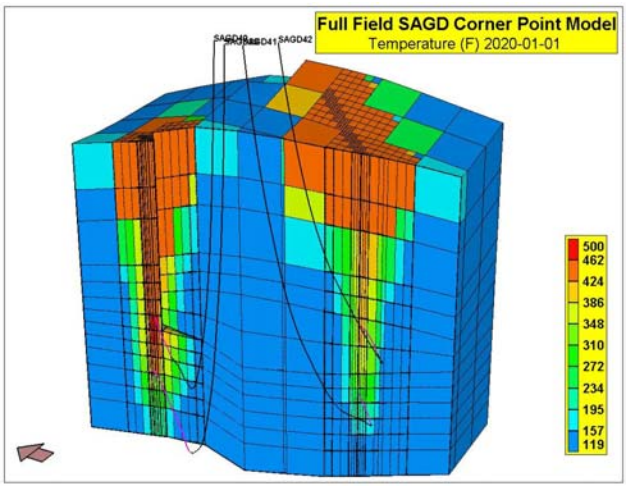

Figure 22: Corner Point Model Temperature at 2020 – 3D Cross Sectional View

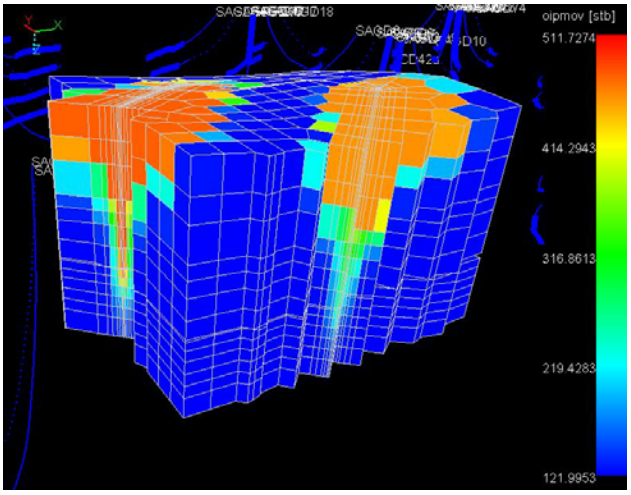

Figure 24: PEBI Grid Model Temperature at 2020 – 3D Cross Sectional View.

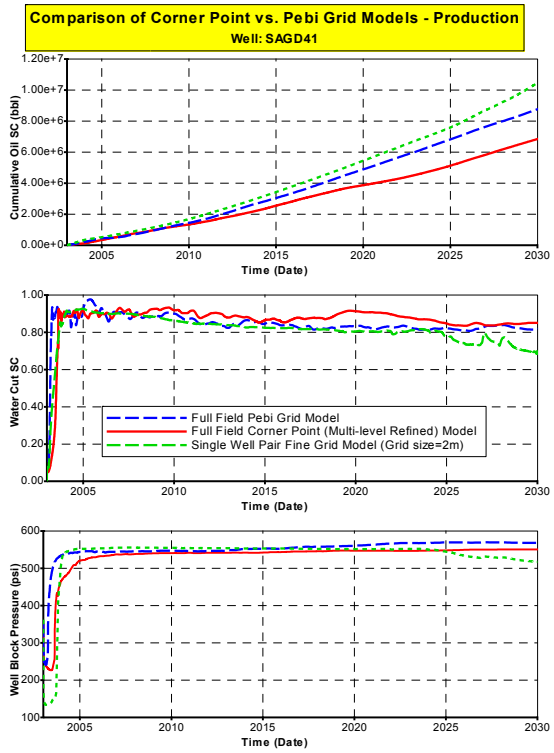

Figure 23: Comparison of Production From 1 Well

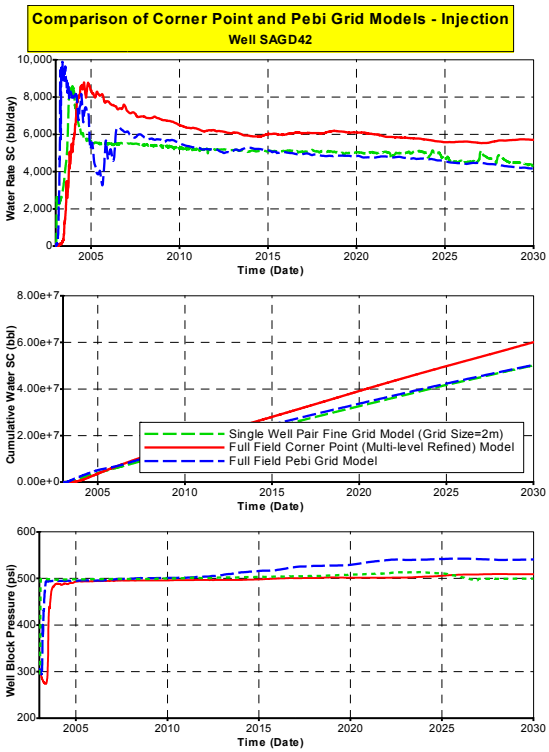

Figure 25: Comparison of Injection From Well SAGD 42.