From Mega-Cell to Giga-Cell Reservoir Simulation

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ABSTRACT

Saudi Aramco has giant oil and gas reservoirs. Availability of a vast amount of seismic, geological and dynamic reservoir data enables geoscientists to build geological models in high resolution. In practice, high resolution models are upscaled to flow simulation models by reducing the number of cells from millions to a few hundred thousand due to limitations in the conventional simulator technology. Simulators using upscaled (averaged) reservoir properties produce highly averaged results and fail to predict ultimate recovery accurately.

Realizing the limitations of the conventional simulators specifically for the giant oil and gas reservoirs of the Kingdom, Saudi Aramco has developed its own parallel reservoir simulator, POWERS, for handling millions (Mega) cells. POWERS is used by the company in managing oil and gas reservoirs, improving productivity, locating new wells and developing new oil and gas fields. Although smaller grid sizes are used for several reservoir studies, the average areal grid size is still about 250 m.

In order to construct higher resolution simulation models at seismic grid scale such as 50 m or less, billion (Giga) cell simulation capability is necessary for the giant reservoirs. This can be achieved by introducing new innovations into reservoir simulators by building new solvers and introducing new pre- and post-processing tools.

In an effort to build a giga-cell simulator, recently Saudi Aramco's scientists completed a reservoir simulation model run for the Ghawar Arab-D reservoir using 258 million active cells. The computational performance of this run and research results on solving billions of unknowns indicate that giga-cell simulation is achievable within a few years.

This article describes the development history of Saudi Aramco's mega cell simulator POWERS and its evolution to the next generation of reservoir simulators, POWERS II, a giga-cell simulator.

INTRODUCTION

In order to simulate the giant oil and gas reservoirs of the Kingdom with sufficient resolution, parallel reservoir simulator technology is an absolute necessity since the conventional simulators based on serial computations cannot handle these systems.

Interest in parallel reservoir simulation started over a decade ago in the oil industry. The earliest attempt was by John Wheeler[1]. This was followed by work of John Killough[2], Shiralkar and Stevenson[3]. These efforts mainly focused on shared memory parallelization. The majority of the tested models were under one million cells, with ovenight turnaround times.

Realizing the importance of the reservoir simulation technology for Saudi Aramco, in 1992, Saudi Aramco executive management decided to start a Petroleum Engineering R&D Division under the General Manager of Petroleum Engineering. This division, after forming a core expertise team, initiated a program for developing the company's first in-house, Parallel Oil Water and Gas Reservoir Simulator, POWERS[4]. In 1994, Saudi Aramco purchased a state of the parallel computer Connection Machine, CM-5 for this project. By 1996, the prototype version of POWERS was running a 1.3 million cell Berri Hadriya reservoir model with 30 years of production/injection history in four hours. Besides its attractive speed, results closely matched the crucial field observations. The differences between this model and an earlier model were in the number of layers and smaller areal grid size. The new model had 74 vertical layers; old model had only 14 vertical layers. The new model used 250 m areal grid size. The old model had twice the size areal grid size of 500 m. This model was built by another company with 53,000 active cells.

It needs to be mentioned that at that time, the largest model was a 64,000 cell Safaniya/Safaniya model and it was running on Cray 2 or IBM SP-2 in about nine hours.

The first million cell simulation with the POWERS simulator also revealed some important findings: simulator showed by-passed oil zones behind the water front while the 53,000 cell model missed it. Based on the results of this study and the validation of the by-passed oil zones by drilling new wells, teams were given green light to add new options for POWERS. New options included dual porosity-dual permeability, linked surface facilities, and compositional features.

In 2000, the simulator code was converted to mix parallel environment composed of Massage Passing Interface (MPI) and shared memory parallelization (Open MP). With this hybrid arrangement, the new code could run on a wide range of computers including a single CPU machine, PC clusters and shared memory super computers.
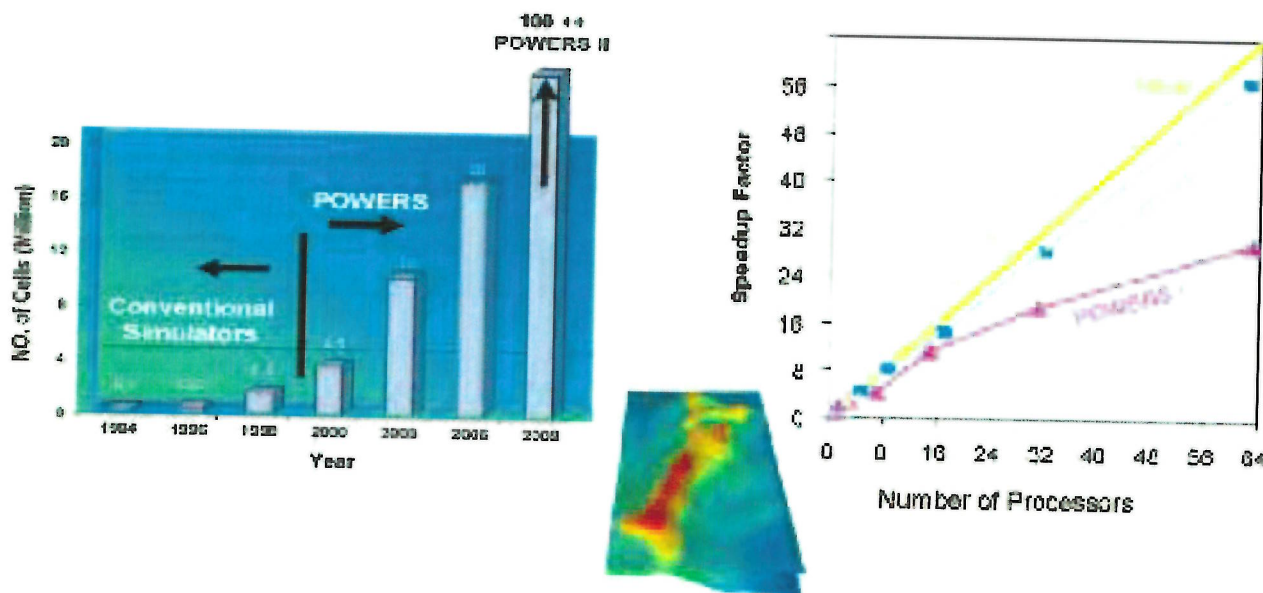
Fig. 1. Increase in model size growth over the years to giga-cell simulation.

In 2002, a full field Ghawar Arab-D model was run on the POWERS simulator for the first time. To date, the Ghawar Arab-D reservoir was simulated by many regional models. The new full field model had nearly 10 million active cells with 17 vertical flow layers, 250 m areal grid size, over 3,000 wells, and 60 years of production/injection history. The model was run on eight IBM Night Hawk shared memory computers (Appendix). Each computer box had 16 CPUs sharing a common memory. The Night Hawk machines were inter-connected to each other forming a Symmetric Multi-Processing (SMP) system. The first run took 53 hours. It was conducted over a weekend using all the machines. Results of the first run reasonably matched the field observations. This work showed that POWERS was capable of handling such a giant system with no numerical problems.

Beyond 2002, Saudi Aramco researchers continued developing new algorithms to handle larger models, 20 to 80 million active cells. Presently, in 2007, a preliminary version of the next generation reservoir simulator POWERS II successfully ran a 258 million Ghawar full field model with full history. Figure 1 shows the growth in model size over the years at Saudi Aramco. The same Figure also shows that the POWERS II linear solver demonstrates near ideal scalability providing the computational speed needed for the hundred millions to giga-cell simulation, i.e., the more processors the faster the simulator runs. Such algorithms and capabilities are essential for achieving a billion cell reservoir simulations.

Based on our preliminary results as demonstrated by the 258 million cell model run and current ongoing research, billion cell simulation capabilities at Saudi Aramco is approaching soon.

Industry wide, several efforts have been made to introduce new programming languages and algorithms for the parallel simulation starting in early 2001 by Beckner[8], DeBaun et al.[9]

and Shiralkar et al.[10] in 2005. Although, none has reported reservoir studies with more than a few million cells.

BENEFITS OF PARALLEL RESERVOIR SIMULATION

Parallel reservoir simulation offers several advantages over the traditional, single CPU simulators. Among several benefits of parallel simulation is the ability of handling very large simulation models with millions of cells. This feature provides reduced upscaling from the geological models to simulation models, resulting in better representation of the reservoir heterogeneity.

Figure 2 shows a typical industry simulation process. The geological models with millions of cells are upscaled to a hundred thousands cells simulation model. This produces highly averaged (diluted) results. Specifically, sharp saturation fronts and trapped oil saturations will not be captured by this approach. Simulators in this category use single CPU computers. Therefore, simulator codes use nonparallel sequential programming languages. We will refer to them as Sequential Simulators in this article.
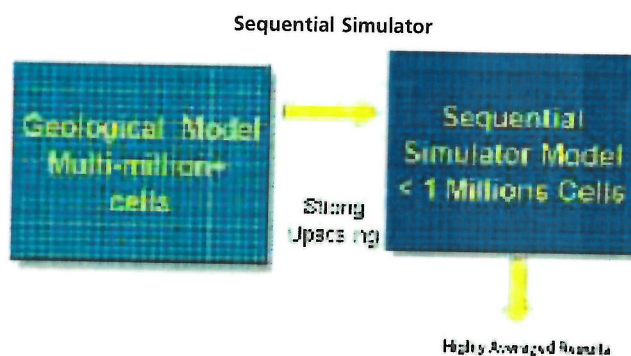
Sequential Simulator

Fig. 2. Industry practice for building simulator models from the geological models.
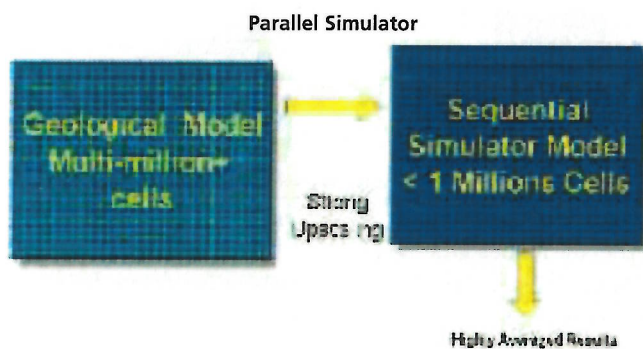
Parallel Simulator

Fig. 3. Parallel simulation process.

As mentioned above, parallel simulators do not require strong upscaling. Typically, with mild upscaling, these models can produce highly realistic simulation results. Figure 3 displays the concept for the parallel simulators.

As shown in Fig. 3, mild upscaling is applied to the geological models. This helps to retain the original reservoir heterogeneity. Hence, it is expected that this process will produce more accurate results for a good geological model. Another important side benefit is to enable engineers to directly update the geological model during the history matching. This feature is not available for the coarse grid models (Sequential Simulators).

To further demonstrate the benefits of the parallel simulation, we will present an actual field case shown in Fig. 4. Two modeling approaches will be compared. The first model is a 14 layer 53,000 active cells coarse grid (Dx = 500 m) on a conventional nonparallel industrial simulator, and the second model is a 128 layers 1.4 million active cell relatively fine grid (Dx = 250 m) parallel simulation model (POWERS). This Figure shows a vertical cross section between a down flank water injector and a crestal producing well. Reservoir has been water flooded over 30 years. Changes in the water saturation over 30 years are shown on this cross section. Red or brown color shows no change (unswept) where the green color indicates change in water saturation (swept).
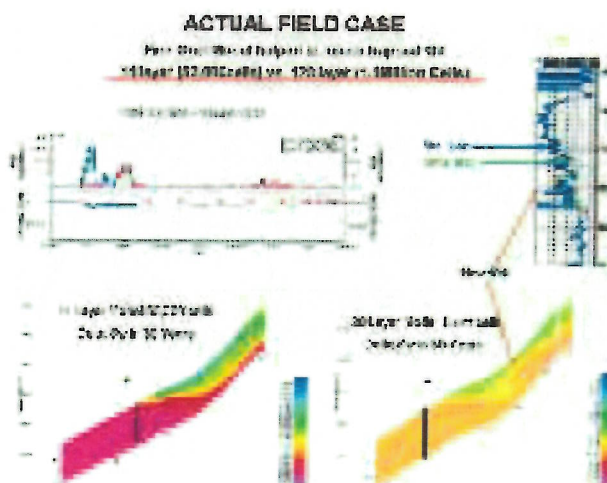

Fig. 4. Field case.

If one compares the computed performances of the crest well for water cut and pressure, one can see that both models match the observations very well. This indicates that the 14 layer model matches field data as well as the 128 layer model. Although, when the change in the water saturation (sweeping) was examined, it is observed that there are significant differences between the two model results: 14 layer model shows good sweep between the injector and crestal well while the 128 layer model shows unswept oil zone (brown color pocket). Based on these results, a new well location was chosen as shown in the Figure. A horizontal well was drilled and oil was found as indicated by the simulator[5].

Following the drilling, the same well was logged. Water saturation obtained by the log was plotted against the simulator calculated water saturations in Fig. 4. As seen, the simulator was able to closely predict the vertical water saturations prior to drilling the well.

Based on simulator results four new wells were drilled in 2003 and 2004 in similar locations to produce trapped oil. All the new wells drilled found oil. By the end of the first quarter of 2006 these wells had recovered about 17.4 million STB of additional oil. As of 2007, all of these wells are still in production.

MOTIVATION FOR GIGA-CELL SIMULATION

Presently, the company is using the multi-million cells POWERS simulator for reservoir management, recovery estimates, placing complex wells, making future plans and developing new fields. The remaining question is whether or not it would be beneficial to go to smaller grid sizes? Current grid sizes vary between 100 m to 250 m. Figure 5 provides a good insight for this question. Again we will use the largest reservoir, Ghawar Arab-D for this purpose. For illustration, we will assume 51 vertical layers with an average thickness of 5 ft.

As shown in this Figure, using a 250 m areal grid size with 51 flow layers would yield 29 million cells. A seismic scale grid with 25 m areal grid size would yield nearly 3 billion cells. A 12.5 m areal grid would yield about 12 billion cells. This is just due to areal refinement. Similarly more cells will result in more vertical layers. For example, 25 m areal grid with 100 layers will result in 6 billion cells and 12.5 m areal grid would yield about 20 billion cells.

Ghawar Full-Field Model (with just 51 layers)

Grid Size	Number of Cells
• 250 meters grid resolution	29 million cells
• 113 meters grid resolution	258 million cells
• 25 meters grid resolution (seismic bin)	2.9 billion cells
• 12.5 meters grid resolution (full seismic)	11.5 billion cells

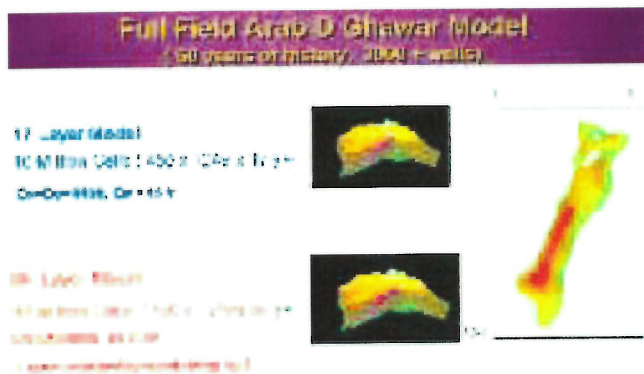Fig. 5. Total number of cells required for a seismic scale full field Ghawar model.

Fig. 6. Base model and vertically fined full field model definition.

Fig. 7. Benefits of more vertical layering in a thick reservoir.

This example was chosen for the largest company asset, the Ghawar reservoir, since a one percent recovery increase would yield an additional billion barrels.

ACCURACY INCREASE WITH MORE REFINEMENT

To demonstrate the benefits of a high resolution grid in full field simulation, we will consider the existing 17 layers, 250 m areal grid full field Ghawar model. This is our base model with 10 million cells. Next, we will increase the number of layers by a factor of five to 85 constructing a 48 million cell model. This is accomplished by dividing each vertical layer by five and assigning the property of each layer in the base model to the sub-layers. The objective is to see if the numerical refinement would make any difference in the accuracy of the model. Figure 6 shows the layering and total number of cells for both models.

It is expected that vertical refinement of layers for a thick reservoir with good vertical permeability should simulate the advancing water fronts better. This is due to inclusion gravitational effects which can influence the shape of the moving water fronts. As a result, water arrival times and cuts at the producers are expected to be more realistic. Finally, this would also reduce/eliminate the need of using pseudo functions and unrealistic multipliers in history matching. The reservoir in this example is a thick reservoir. The vertical fractures enhance the vertical permeability.

Figure 7 demonstrates the concept. It is shown that advancing water movement due to flank water injection is better represented by the fine grid model than the coarse grid (base) model. For example, water will move like a piston into a base model layer (15 ft) showing no vertical effects of the gravity. In the fine grid model (a 15 ft layer is divided into five layers (5 ft each)), it will pronounce the effects of the gravity. It is expected that more water will be in the bottom layer due to gravity (water is heavier than oil). Since the field in consideration has peripheral water injection, it is thick and has enough vertical permeability (some areas due to local fractures).

Results of the simulation runs are shown in Fig. 8. This Figure illustrates the calculated vertical water fronts in 1990. The left image is from the base model, the image on the right is from the refined grid model.
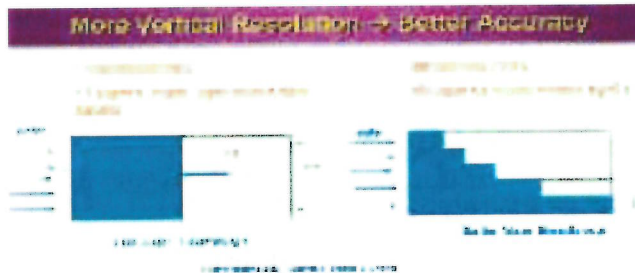
Figure 8 shows that calculated vertical water fronts due to west flank injection confirms the concept postulated in Fig. 7. The blue color represents oil, and green color represents the water saturation in this Figure.

The fine grid model shows water saturation has already broken at the producer but coarse grid shows no water breakthrough yet.

The next question is which of the results are correct? To answer this question we need to examine the observed water production and pressures at the producing well in this Figure.

When simulator results are compared with the field observations, Figs. 9 and 10, one sees that close agreement is observed for the fine grid model for water arrival, water production rate and the well pressures. The coarse grid model (base model) miscalculates both water arrival (a few years), water production rate and pressures. Obviously in this case, the coarse grid model requires further adjustments in parameters for history matching in this area of the reservoir.

Motivation going to Giga-Cell Reservoir Simulation is not only limited to the reason explained above. As well-known, more and more new technologies are being deployed in the recent years in oil and gas fields. These new technologies provide a more detailed description of the reservoirs which wasn't available before. Some of the new technologies include deep well electromagnetic surveys; new borehole gravitmetric surveys, new seismic methods, geochemistry, use of geochemistry and implementation of many new sensor technologies. With the addition of these new technologies, it will be possible to describe reservoir heterogeneity more accurately and in details. This then will require more grid cells
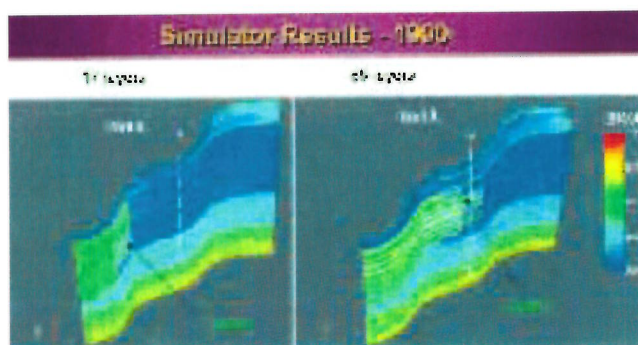

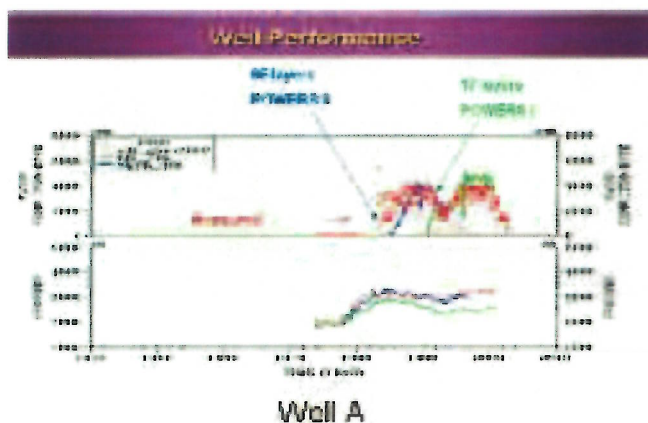Fig. 8. Vertical water profile in 1990.

Fig. 9. Well performance comparison of 17 and 85 layer models with field observed water production and well pressures.
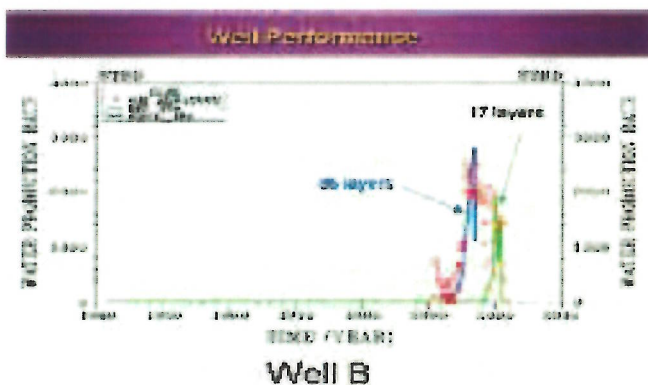

Fig. 10. Water rate predictions from both models.

to fully describe the fluid flow in the porous media. Even for regular size reservoirs, it will be possible to use giga-cell simulation for understanding the fluid flow better (pore scale physics), and develop better recovery methods.

PAST AND FUTURE TRENDS IN RESERVOIR SIMULATION

As mentioned before, in early 1990 the largest model size was the 64,000 active cells, Safaniya/Safaniya model. This model was running on the Cray 2 in about nine hours for a 40 year history. With the development of fast computers, the size of the models increased to an average of 100,000 cells in the industry. No color graphics and graphical pre- and post-processing software were available at that time. Input was handled by simple key words and outputs were in hard copy form.

By 1996 a prototype version of Saudi Aramco's POWERS simulator was able to run the 1.3 million cells Berri Hadriya model in four hours on a 32 node CM-5 computer.

This was a historic run covering 30 years of production and injection.

Six years later, in 2002, the number of grid blocks with POWERS reached 10 million cells. In the next five years various large models were tested. The largest actual field study model was a 17 million cell model. In 2007, a test model with real field data ran 258 million cells successfully.

Figure 11 highlights the growth of model size at Saudi Aramco from 1996 to the present for both active field studies and test models using real field data.

Similarly computers used in developing POWERS simulator followed the growth in capacity and processing power as shown in Fig. 12.

As shown in Fig. 13, at 1994 development computer, CM-5 had a total of four gigabytes (GB) of memory with the peak performance of 160 megaflops (Floating Point Operations per second). This number grew to half a terabyte of memory in 2004 with 384 gigaflops peak calculations with Origin 3800. By 2007 the development computer reached 2 teraflops peak performance for arithmetic computations with 2 terabytes of distributed memory. In 2007 the Computational Modeling Technology Team was able to construct a 258 million active cell full field Ghawar model with refined areal grid and more vertical layers than the base 10 million cell model. This model was run on a Linux AMD commodity cluster using 300 nodes in four days simulating 60 years of history with over 3,000 wells.

The Appendix provides more technical data for the computers used in development of the POWERS simulator.
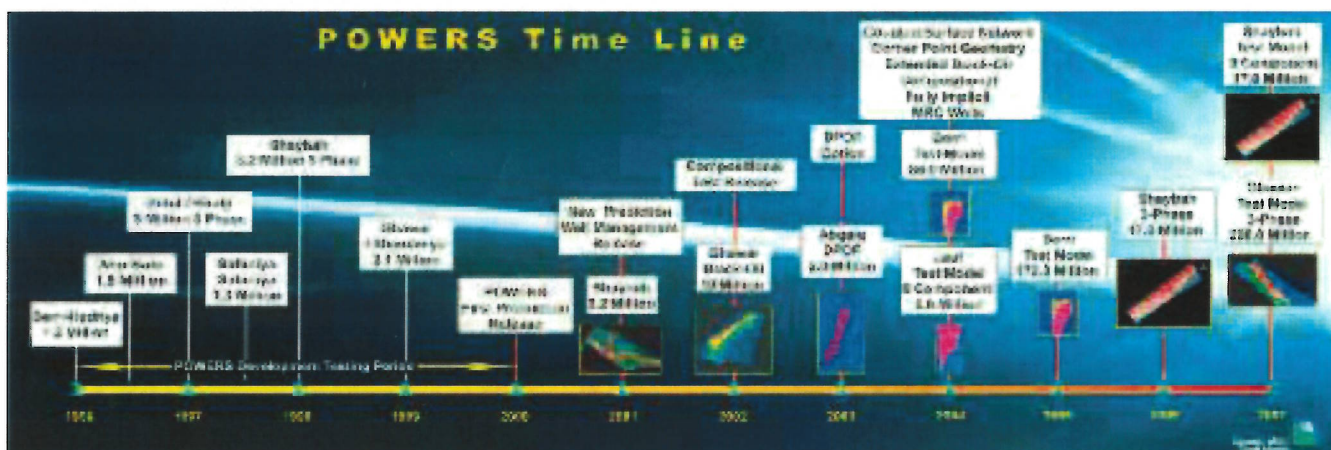

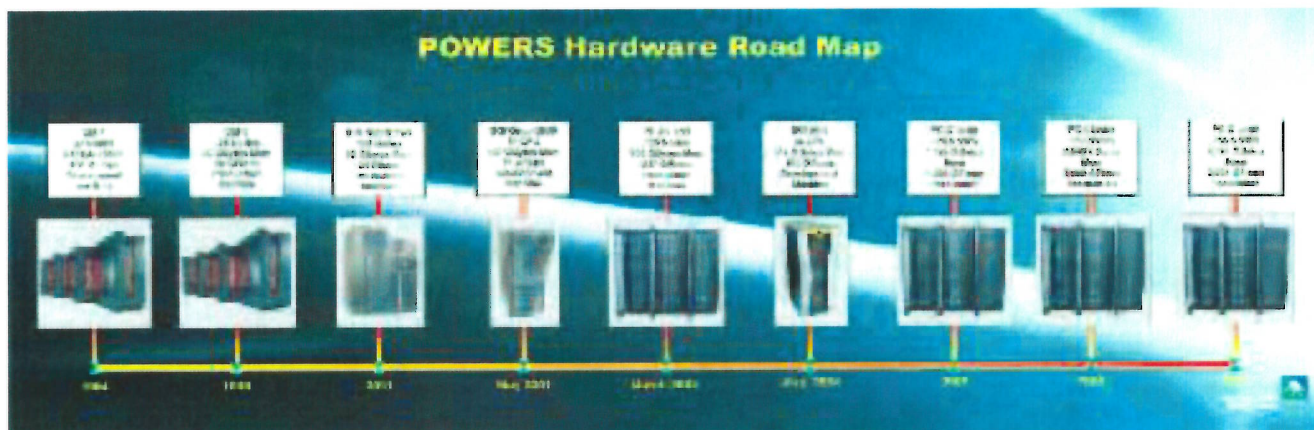Fig. 11. Growth of model size with the progress of POWERS simulator.

Fig. 12. Computer hardware evolution for the development of POWERS simulator at Saudi Aramco.

PROJECTION FOR THE FUTURE

Growth of model size and improvement in computing power results presented above can be summarized on a new plot as shown in Fig. 13.

This Figure shows the growth of model size with years at Saudi Aramco.

The vertical axis is logarithmic, the horizontal axis is linear. This semi-log plot shows that model size is exponentially growing with time (nearly a straight line).

Extrapolation of the data beyond 2007 is evident that giga-cell simulation is attainable within the next few years. Giga-cell simulation process will bring its challenges with it. These challenges will be discussed in later sections.

It is interesting to note that behavior seen in Fig. 13 is similar to the computer power increase forecasted by Moore's law, Fig. 14. Although model size growth and computing power shows similar trends, one should not think that a given code, for example, in 1985 would be able run a giga-cell model by using more powerful computers. As indicated in Fig. 13, growth in model size using more powerful computers is achieved by introducing new programming languages (rewriting the code) and using innovative numerical solutions

taking advantage of the new computer architectures to improve simulator scalability[4]. Otherwise, an old code will not scale properly with the increased number of CPUs. After a certain number of CPUs, no more speed improvement will be possible. Ideally, scientist designs the algorithms such that the scalability plot is a straight line or close to it. This can be accomplished by new methods of domain portioning for load balancing, new programming techniques and new numerical algorithms compatible with the hardware architecture.

It should be noted that imbedded in Fig. 13 is the requirement of the speed of the simulator. As a rule of thumb a good speed means a giant model run should take hours to overnight for a typical reservoir study. Longer run times such as a week will not be attractive for a giant model run.

GIGA-CELL SIMULATION ENVIRONMENT

Building giga-cell reservoir models and analyzing the results generated by the simulator in practical times require totally new technologies in pre- and post-processing. Specifically, processing gigantic data set as input and output in practical times, is a major challenge for the conventional data modeling and visualization technologies. Limitations in the pre- and post-processing would limit the use of giga-cell simulation.
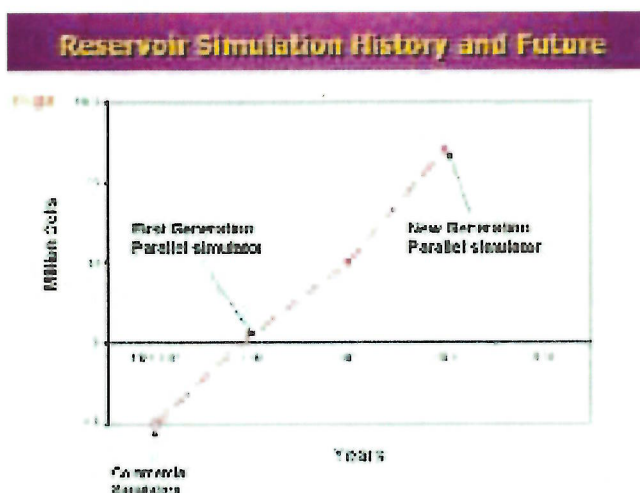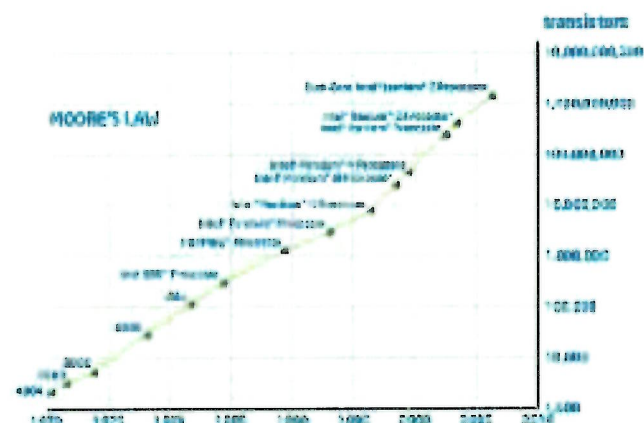

Fig. 13. Growth of model size.

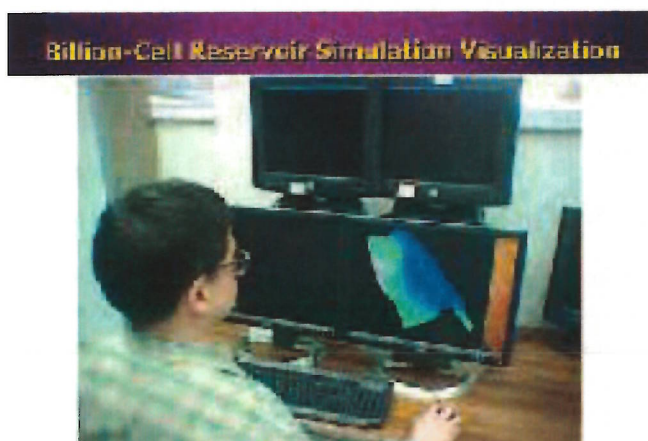Fig. 14. Growth of computer power (Intel Corp, Wikipedia).

Fig. 15. Billion cell reservoir Simulation Model Visualization[12].

Fig. 16. Virtual Reality (Fraunhofer Inst.).

Fig. 17. Immersive Work Bench (Fraunhofer Inst.).

Fig. 18. Auto-Stereoscopic display with gesture control (Fraunhofer Inst.).

Fig. 19. Touch, hear and visualize, talking giga-cell simulator analysis by Saudi Aramco[7].

Considering the importance of the subject, as for the first step, Saudi Aramco scientists have developed a billion cell reservoir simulation visualization technology, Fig. 15, by adopting Fraunhofer Institute's[6] OcTreemizer product. Up to a few billion cell models can easily be visualized in three dimensions using the new technology. Users can rotate the image, generate two dimensional cross sections at desired locations of the three dimensional image of a reservoir property (i.e., pressure, or permeability, etc.) by a mouse click. Generating images takes a few seconds only. This product allows engineers geologist to analyze the input and output of a giga-cell simulation in practical times. New software runs on an Appro Xtreme workstation which has a large memory of 128 GB of shared memory with eight CPUs and two GPUs (Graphical Processing Units). A technical paper is being prepared by Pita, et al.[12]

In order to fully utilize the results of a giga-cell simulation study, more needs to be done. For this purpose we have a vision. Our vision includes an R&D Visualization and Virtual Reality Room for giga-cell simulation. The new R&D Virtual Reality Room to include using virtual reality technologies, immersive work bench, touch, see and hearing data concepts, use sound in data analysis, and man machine interaction by speech (talking simulator). Figures 16 through 19 demonstrate the elements of giga-cell Virtual Reality R&D giga-cell simulation environment.

Virtual reality technology for giga-cell environments will be highly useful for understanding reservoir performance in great details by walking through the reservoir in a 3D space. This technology has been widely used in other areas of science but not much in the oil industry. Utilization of sound for input and output (man machine interaction by speech) would eliminate laborious work for handling gigantic data sets.

Immersive work bench technology[6] provides a work environment around a work bench for a team. Here simulator results can be displayed in three dimensions, by using a remote controller. Many different images needed for the project work, i.e., well logs or seismic cubes can be brought and projected with the simulator maps for analysis.

The Fraunhoffer Institute provides[6] new technologies such as Auto Stereoscopic display with gesture control. As shown in Fig. 18, users can use hand motions to rotate an image without using any controlling devices. This technology doesn't require special eye glasses to see 3D images in stereo. Users can manipulate the data with finger movements.

Regarding the use of touching sense as an additional element to help analyzing large data sets in Reservoir simulation, Pita, Zamel and Dogru[7] have developed a new technology for using the touching sense and hearing sense. By the aid of a Haptic device (3D mouse) users can navigate through the reservoir using the touching sense. For example, the 3D mouse will not move if one navigating through a hard rock vs. a soft rock (low permeability vs. high permeability). Similarly, sense of touching and use of sound can be used for identifying viscous oils or condensate drop out zones. A simulator can talk to the engineer while he is doing the history match. A user will not have to stay in the office all the time; he can use his cell phone and call the computer for an update in the history match. The computer will talk to the user reporting the status of the history match, i.e., which wells are matching and which are off, whether or not he should terminate the run.

SUMMARY AND CONCLUSIONS

Experience has shown that with the aid of rapidly evolving parallel computer technology and using innovative numerical solution techniques, a giga-cell reservoir simulator is within reach. Such a simulator will reveal great details of the giant reservoirs and will enable engineers and geoscientists to build, run and analyze highly detailed models for the oil and gas reservoirs with great accuracy. This will help companies to recover additional oil and gas. Further developments and innovative approaches are needed for the full utilization and manipulation of the giant data sets. Introduction of the virtual reality and sound will enhance the understanding of the results, locating trapped oil zones, placing new wells and designing new field operations. Overall, giga-cell simulation is expected to be beneficial for the mankind in its struggle to produce more hydrocarbons to sustain the world's economic growth.

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