INTELLIGENT SOLUTIONS, INC.

SURROGATE RESERVOIR MODELS

ANALTERNATIVE TO TRADITIONAL NUMERICAL RESERVOIR SIMULATION AND MODELING

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SURROGATE RESERVOIR MODELS

AN ALTERNATIVE TO TRADITIONAL RESEROVIR SIMULATION

Surrogate Reservoir Model (SRM) is an accurate replica of the traditional numerical reservoir simulation model. It may be questioned that when a numerical reservoir simulation model exists why an AI-Based Reservoir Model would be necessary. Necessity of SRM has to do with the fact that massive potentials of the existing numerical reservoir simulation models go unrealized because it takes a long time to make a single run. Numerical models that are built to simulate complex reservoirs require considerable run-time even on cluster of parallel CPUs. Exhaustive and comprehensive evaluation of the solution space for designing field development strategies as well as quantification of uncertainties associated with the static model are the type of analyses that require large number of simulation runs in order to provide meaningful and usable results. When a numerical simulation model takes hours for a single run, performing such analyses become impractical and the engineers have to compromise by designing and running a much smaller number of runs in order to make decisions.

SRM has the capability of reproducing highly accurate well-based and grid-based simulation responses as a function of changes to all the involved input parameters (reservoir characteristics and operational constraints) in fraction of a second. This can be accomplished for reservoir simulation models that take hours or days to make a single run. SRM has been successfully tested and validated with several commercial and in-house (belonging to NOCs) reservoir simulators such as ECLIPSE™[1], IMEX™ and GEM™[2] and POWERS™[3] and replicating models with up to 6.5 million grid blocks. Among the major advantages of SRM over proxy models or response surfaces is the required number of simulation runs for their developments. While hundreds of simulation runs are required to build proxy models or response surfaces, building SRM requires only a small number of simulation runs (usually between 10 to 15 runs). This is due to a unique an innovative sampling of data for the generation of the required spatio-temporal database. Furthermore, none of the existing technologies (proxy models, reduced models or response surfaces) even claim to be able to reproduce pressure and saturation distribution throughout the reservoir (at the same spatial resolution of the simulation model) at the grid-block level. This leaves SRM as the only technology with such a capability.

SURROGATE RESERVOIR MODELS (SRM)

In recently published papers (Mohaghegh 2006 - Mohaghegh 2009) that reported the findings of SRM development for a giant field in the Middle East, the predictions made by an SRM were examined against more than two and a half years of production from the field. It was demonstrated that all SRM predictions proved to be accurate. The SRM was developed based on a reservoir simulation model with about one million grid blocks that included 165 horizontal wells. Historically, oil production from this field had been capped at 1,500 barrel of liquid per day (BLPD) with a total field production that was capped at 250,000 barrels of oil per day (BOPD). Water is injected for both pressure maintenance and displacement of oil. The production at each well (and the entire field) was being controlled

[1] Schlumberger Information Service
[2] Computer Modeling Group
[3] Saudi Aramco, In-House Simulator

(capped) in order to avoid premature water breakthrough. Increase in water cut in some wells had started to be a concern.

The objective of the project was to increase oil production in this field by identifying the wells that would benefit from relaxing the production rate from 1,500 BLPD to higher rates (up to 4,500 BLPD). The risk associated with this reservoir management decision was that while some wells would benefit from such action (rate relaxation) other wells would run the risk of high water cut that could eventually result in killing the well. The key was to know which wells should and should not be subject to rate relaxation. This became a search and optimization problem with the reservoir simulation model at the center of the optimization routine as the objective function. The solution space (the universe of all possible parameter being modified within their given range) of this hyper dimensional problem was so vast that a reasonable search for the optimum solution (which wells should be subject to rate relaxation) would require hundreds of thousands of simulation runs. With a single simulation run taking 10 hours on a cluster of 12 CPUs, reaching a reasonable solution became impractical.

An SRM that was able to accurately generate oil and water production rates as a function of time for all the 165 wells over the next 25 years was developed for this field. A single SRM run would take only a fraction of a second. The developed SRM was used to analyze the entire solutions space (all possible combinations of production scenarios) while quantifying the uncertainties associated with the static model that was used in the flow simulator. After hundreds of thousands of SRM runs the results were analyzed and recommendations on which wells should be subject of rate relaxation were made.

It is notable that in order to develop this SRM only 10 simulation runs were performed using the actual reservoir simulator. This is important since hundreds of simulation runs are required to develop the simplest response surfaces that would have limited applicability. Upon completion of the analysis with the SRM, wells in this field were divided into 5 clusters as shown in Figure 3. Wells in clusters 1 and 2 were identified as those that would benefit from rate relaxation and those in clusters 4 and 5 were identified as wells that should not be opened up to more production since SRM analyses had indicated high water production for these well if rates were relaxed.

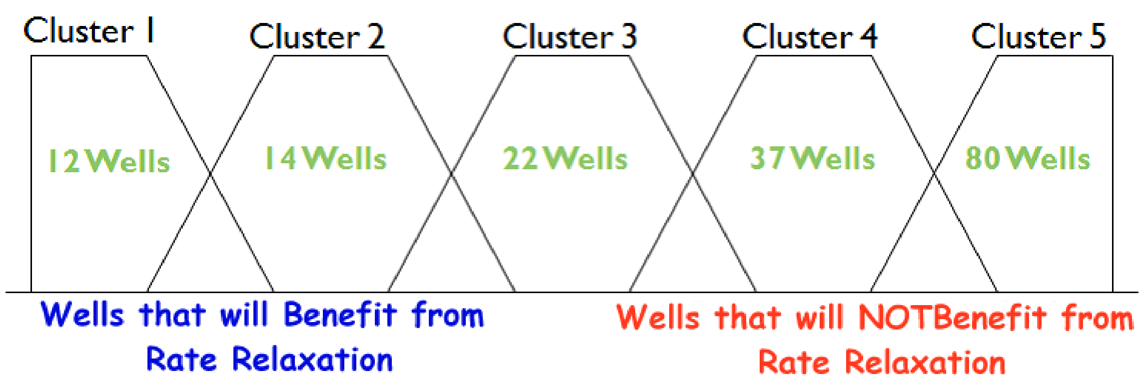

Figure 3. *SRM analysis divided the wells in the field into clusters based on their potential response to rate relaxation.*

Upon completion of this study rates were relaxed on 20 wells in this field. The 20 selected wells represented all the 5 clusters in SRM recommendations. After more than two and a half years of production, wells that were classified in clusters 1 and 2 showed high incremental oil production while water production increased insignificantly, or remained the same, resulting in lower water cut (as predicted by the SRM). On the other hand all wells from cluster 4 and 5 that became subject to rate relaxation produced large amounts of water increasing their water cut. Results of oil and water production in several wells and the corresponding clusters are shown in Figures 4 to 6.

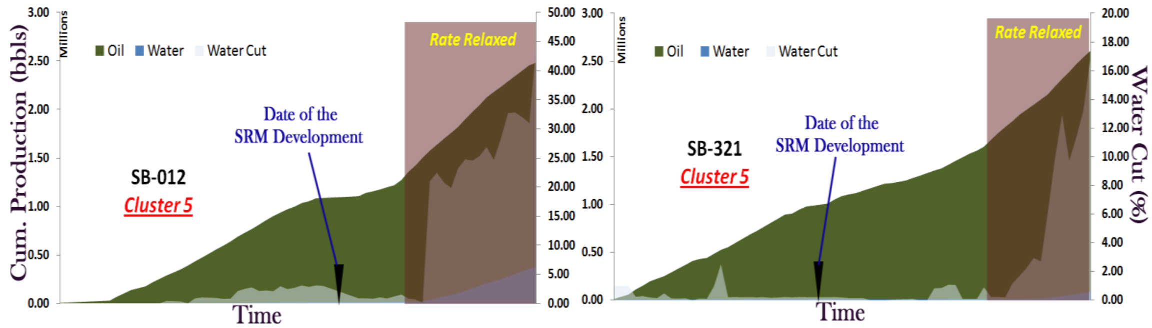

Figure 4. *Examples of wells classified in Clusters 4 and 5. These wells showed high water cut after rate relaxation.*

Figure 4 shows oil and water production as well as instantaneous water cut for two wells in cluster 5 before and after rate relaxation. Water cut in both wells is less than 5% (as low as 1%) in both wells before the rate relaxation. Water cut increases to 25% and 45%, respectively, in these wells a few months after the start of rate relaxation. Figure 5 shows oil and water production as well as instantaneous water cut for two wells in clusters 1 and 2, before and after rate relaxation. Water cut in the well from cluster 2 (left) is less than 2% before the rate relaxation and it does not go above 1% after rate relaxation. Water cut in the well from cluster 1 (right) is about 12% before the rate relaxation and it drops to an average of 3% after rate relaxation (decrease in water cut corresponds to large amount of oil production while water production stays constant or increases ever so slightly). All these results are exactly in-line with SRM predictions (see Figure 3). Figure 6 summarizes the results of all 20 wells that were subject of rate relaxation program in the past 2.5 years. These results are normalized on a per-well per-cluster basis for better comparison. These figures show that the production from the field in the past two and a half years correspond to the predictions made by SRM.

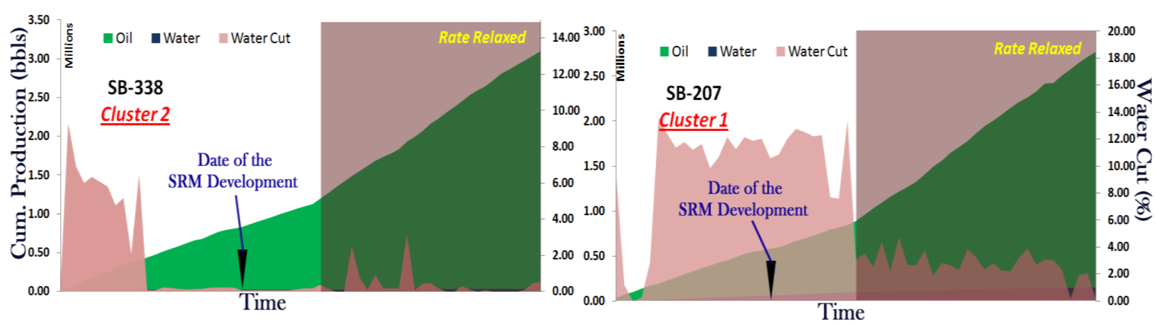

Figure 5. *Examples of wells classified in Clusters 1 and 2. These wells showed low water cut after rate relaxation.*

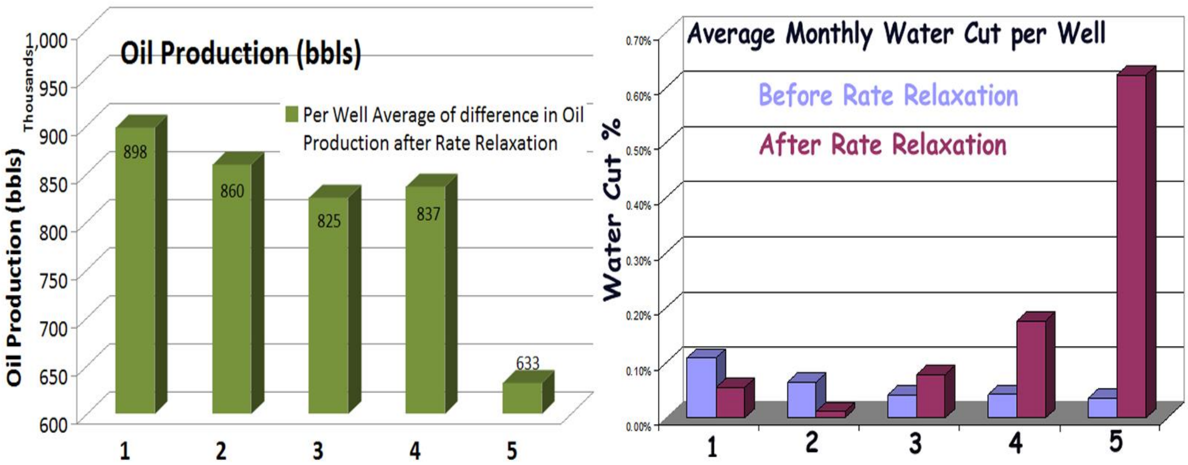

Figure 6. *Incremental oil production and average monthly water cut due to rate relaxation for all five clusters.*

It should be noted that results shown above demonstrate that the numerical reservoir simulator for this asset performed very well in modeling and consequently predicting the complex fluid flow behavior in this naturally fractured carbonate reservoir. On the other hand, without an SRM that allowed hundreds of thousands of simulation runs to be made in a short period of time, achieving such results from the numerical simulator would have been next to impossible. It can be concluded from this study (and other similar studies) that massive potentials associated with existing numerical reservoir simulation models goes unrealized because of their huge computational overhead.

Using SRM will tap into this unrealized potential and can result in much higher return on ADCO's reservoir simulation and modeling investment. SRM can be looked at as an enabling reservoir management tool that makes comprehensive analysis of reservoir simulation models, possible. Furthermore, the near real-time speed of SRM runs provides means for practical quantification of uncertainties associated with the static model. Real-Time Reservoir Management as an enabling technology for the smart fields is another application of this technology.

ANOTHER SRM CASE STUDY

In another project (Mohaghegh 2012a – Mohaghegh 2012b) SRM was applied to three green fields (two off-shore and one onshore fields) in Saudi Arabia. The objective was to develop a tool for fast track reservoir analysis and field development planning. Being classified as "Green Fields", the geological model used for these assets called for extensive uncertainty analysis. The reservoir engineering and reservoir management teams needed a tool with capability of performing hundreds or thousands of simulation runs in a very short period of time, in order to be able to examine a large number of operational scenarios. Given the fact that some of the numerical models for these fields were quite large (up to 6.5 million grid blocks) performing comprehensive reservoir engineering and reservoir management analyses would have become impractical in the absence of SRM.

Figure 7 shows an example of part of the porosity and permeability distributions for two of these assets. The distributions shown in this figure are porosity and permeability pairs for one of the many simulation layers. These distributions show the degree of heterogeneity that has been incorporated in the static models of these full field simulation models. As mentioned before, one of the strengths of

SRM is that only a small number of numerical simulation runs is needed for its development. In this project, only nine runs of the numerical simulation model were proven to be sufficient for the development of the SRM for each of the assets. A tenth run was also made and used as the blind simulation run for the validation of the SRM.

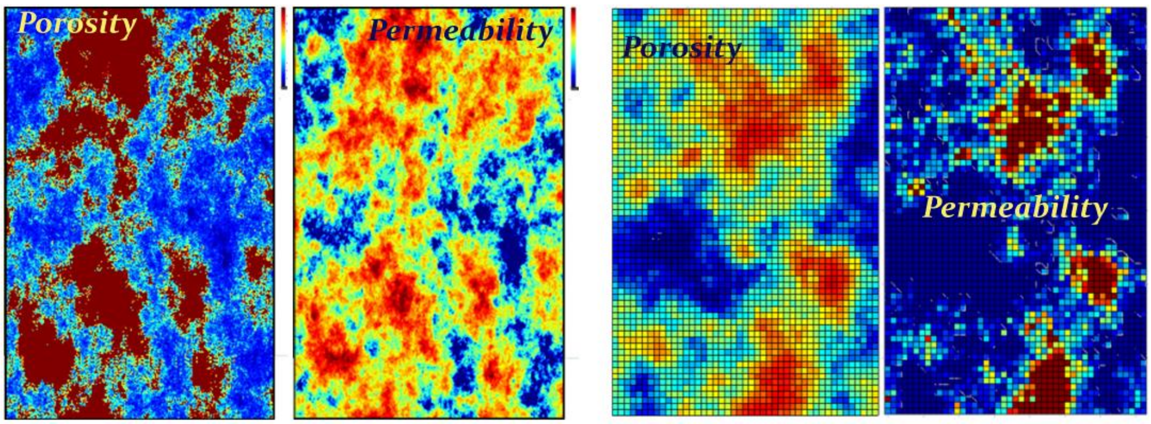

Figure 7. *Porosity and permeability distributions in for two of the reservoirs (green fields). These distributions represent one of the many simulation layers in the numerical model.*

The operational constraints of the tenth (blind) run were different from all the nine runs that were used during the training and history matching of the SRM. An accurate replication of the numerical simulation's result by SRM for the tenth (blind) run would prove that SRM is capable of providing accurate results (production rate versus time at each well) for any given scenario, i.e. operational constrains. Operational constraints, as used in the reservoir simulation models refer to specification of pressure at the well in order to generate rate versus time profiles (usually along with a maximum allowable rate) or specification of flow rate at the well in order to generate pressure versus time profiles. Of course, these specifications can be modified as a function of time (Figure 8).

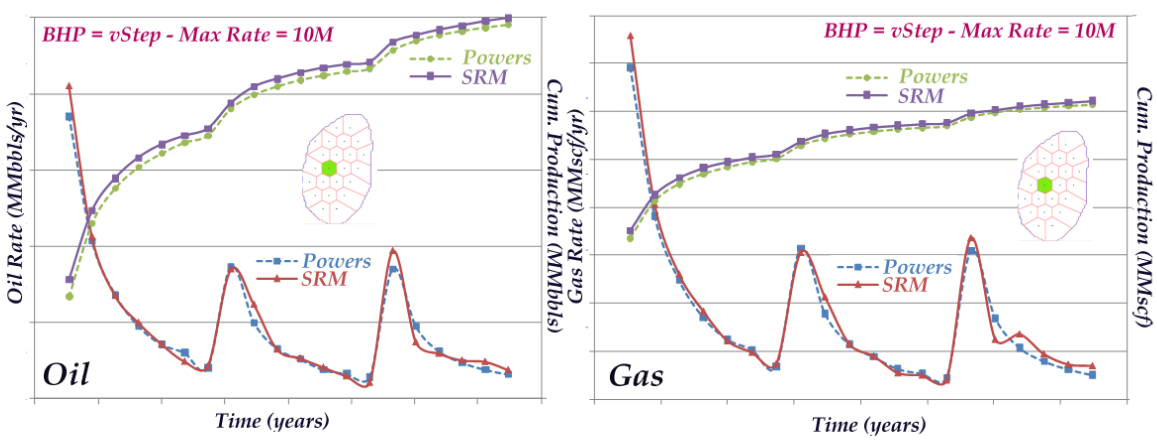

Figure 8. *Comparison of oil and gas production as a function of time (annual rate and cumulative production) generated by SRM with similar results from the NOC's in-house numerical simulation model for a given well in an onshore asset.*

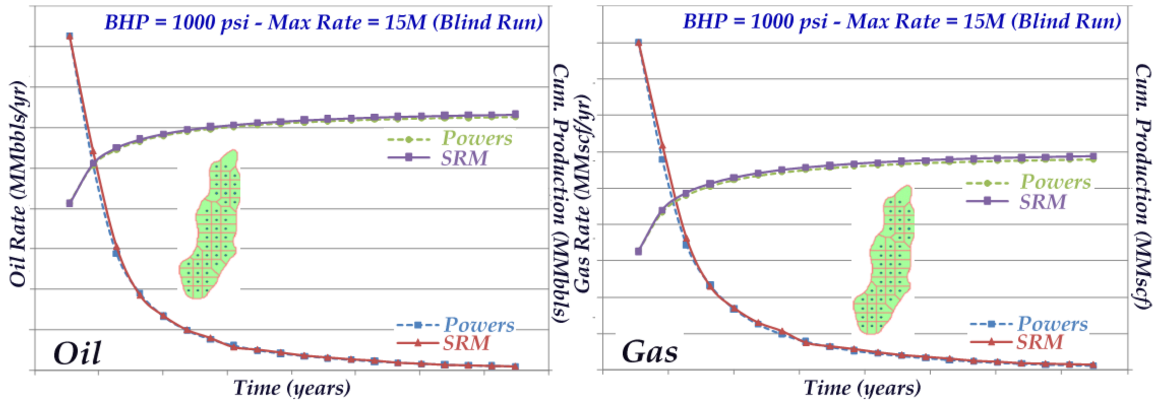

Figure 9. *Comparison of oil and gas production as a function of time (annual rate and cumulative production) generated by SRM with similar results from the NOC's in-house numerical simulation model for a given well in an onshore asset.*

Figure 8 and 9 show the results of the validation of SRM in two of the assets. In Figure 8 oil and gas production generated by the numerical reservoir simulator and the corresponding SRM are shown for one of the wells of an onshore asset. In this figure production rates are plotted as a function of time (both annual and cumulative). This figure shows that SRM can match both oil and gas production for an arbitrarily selected well in the given asset with high accuracy. Please note that the operational constraints of the well have been modified at least twice during the life of the well and the SRM reacts properly and accurately to such modifications.

Figure 9 is the result of SRM validation (a blind numerical simulation run) for one of the offshore assets. In this figure both oil and gas production generated by the numerical reservoir simulator and the corresponding SRM for the entire field is shown. Again the operational constraint in this particular scenario is completely new and is not one of the constraints that were included in the nine simulation runs used during the training and history matching of the SRM. The accuracy of SRM results that can be generated in seconds rather than hours are demonstrated for new scenarios that emphasizes the value of SRM for planning field development strategies.

Another important contribution of SRM to model analysis is its ability to generate type curves for any given well, any group of wells or the entire field, in only a few seconds. An example of this capability is demonstrated in Figure 10 for one of the offshore assets. In this figure the set of curves in both plots show the changes in the first year oil production as a function of flowing bottom-hole pressure for a given well in the asset. The set of curves on the left shows these changes as the permeability very close to the wellbore and at the layer 1 (geological layer – formation) is modified while the set of curves on the right shows these changes as the permeability at some distance away from the wellbore and at the layer 2 (a producing formation) is modified.

The set of curves on the left indicate that the sensitivity of the first year oil production to the permeability very close to the wellbore and at the layer 1 diminishes as the flowing bottom-hole pressure increases to values above 1700 psi while showing significant sensitivity at lower values of flowing bottom-hole pressure (between 500 to 1500 psi). On the other hand, the set of curves on the right indicate that the first year oil production has no sensitivity to the permeability at some distance away from this wellbore and at the layer 2 at any value of the flowing bottom-hole pressure. This is important since it challenges the notion of permeability multipliers as a tool for achieving history matches. In other words, permeability values throughout the reservoir should not be treated equally. A fact that is well understood and justified from a reservoir engineering point of view but often times neglected during modeling (history matching) practices.

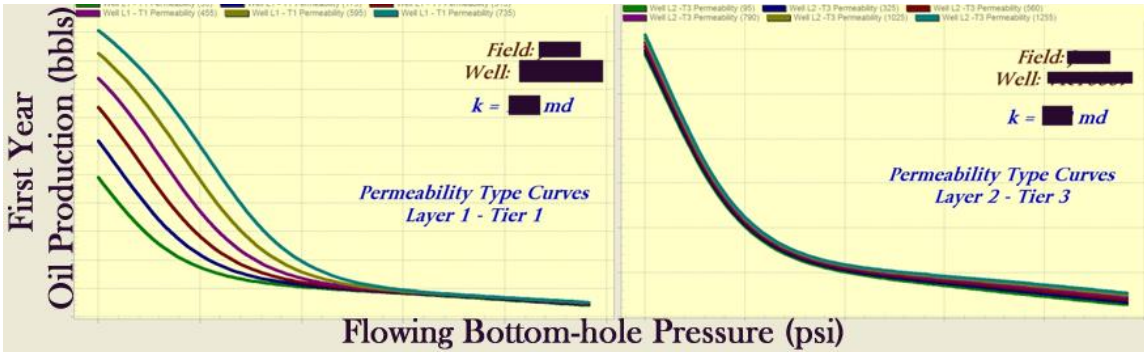

Figure 10. *Type curves generated for each individual well in the asset. Impact of permeability, in specific locations in the field on oil production of the given well as a function of flowing bottom-hole pressure.*

This figure demonstrates one of the important applications of SRM, namely fast track, AI-assisted history matching. During the history matching process the reservoir modeler's objective is to match the results produced by the simulation model to the observed production from the field on well by well bases. Furthermore, a good history match is one that is achieved by incorporating minimal modification to the static model that has been provided by the geosciences team in order to honor (as much as possible) the work that has been done by the geologist, petro-physicists and geo-physicists. Using the type curve generation capabilities of SRM, as shown in Figure 10, the modeler would know which parameter should be changed, at what locations in the reservoir and by how much in order to achieve the desired change in the production rate (or pressure) for a history match. Moreover, since multiple parameters can provide similar impact on the model, the modeler can deiced on modifying the parameter that requires the minimum adjustment in order to result in maximum change in rate (or pressure) to achieve an acceptable history match.

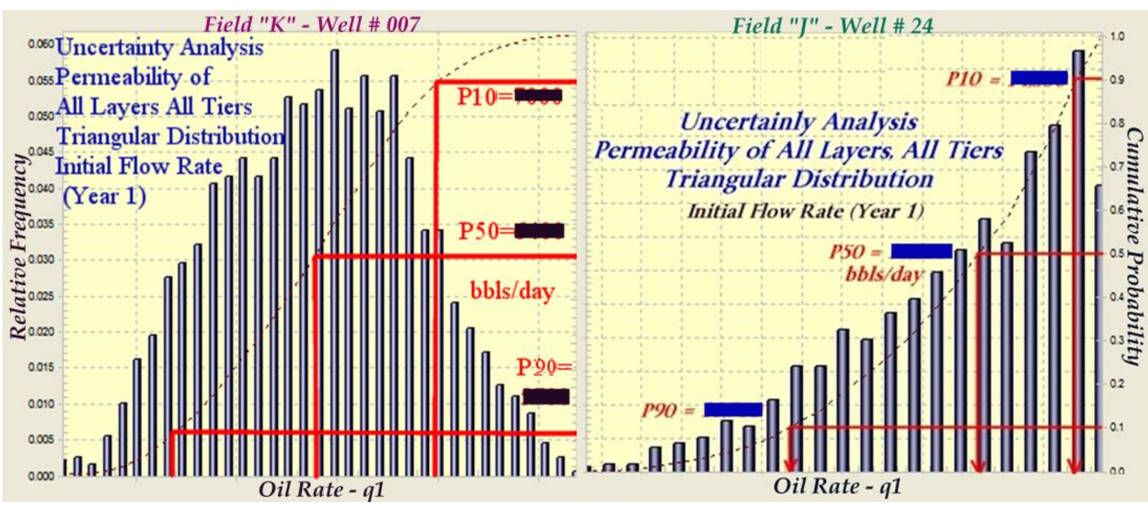

Figure 11. *Quantification of uncertainties associated with permeability, in an extended area around a given well using Monte Carlo Simulation method.*

Quantification of uncertainties associated with the static model is yet another value of the SRM. Extremely short run time of SRM makes it possible to perform meaningful uncertainty analysis (where thousands of simulation runs are required) in a short period of time (seconds). As shown in Figure 11, Monte Carlo Simulation can be performed on the results of production from any given well (or groups of wells or the entire field) by providing uncertainty bands (probability distribution function) for multiple parameters of the model, simultaneously, and calculating the resultant uncertainties in the production. For example in Figure 11 it is demonstrated how uncertainties associated with the permeability values around a wellbore can impact the first year production for two different wells in one of the offshore assets in this project. Upon completing such analyses, P10, P50 and P90 can be calculated quickly in order to assist reservoir management decision making.

ADVANTAGES & DISADVANTAGES OF SURROGATE RESERVOIR MODELS

Advantages of Surrogate Reservoir Models include relatively short development time, since the complete development cycle of a Surrogate Reservoir Model is measured in weeks and not years. Needless to say, the complexity of the field being model may increase the development time to several months. Consequently, the resources that are required for the development of a Surrogate Reservoir Model will be much less than those required for a numerical reservoir simulation model.

Another advantage of Surrogate Reservoir Models is their minimal computational overhead and a small computational footprint. A Surrogate Reservoir Model will run on a PC workstation, a laptop, an iPad, or even on a smart phone providing results in seconds and minutes rather than hours and days. This high speed calculation allows for fast track analyses and decision making.

Surrogate Reservoir Models are organic in nature since they are data dependent. As more data becomes available, the model can be re-trained in order to learn from the new data and to enhance its performance. The field development design tool (a unique module of SRM that was not discussed in this summary article) provides a quick view of overall field performance (depletion, remaining reserves …) as a function of time and puts the overall performance of the reservoir in perspective for effective decision making.

The major disadvantage of Surrogate Reservoir Model is they are purpose-specific models. In other words, the overall objective of the SRM development must be identified at the start of the project. For example the SRM that is developed for the purposes of replicating a numerical reservoir simulation model for CO_2 enhanced recovery cannot be used to perform SAGD modeling. Of course, it is indeed possible to develop an SRM for the SAGD modeling but once developed the SAGD SRM cannot be used for CO_2 injection modeling.

CONCLUSIONS

Surrogate Reservoir Models use pattern recognition capabilities of Artificial Intelligence & Data Mining (AI&DM) in order to build relationships between fluid production, reservoir characteristics and operational constraints. This is indeed a new way of looking at a reservoir and its fluid flow behavior. This technology has the potential to contribute to the art and science of reservoir simulation and modeling and add to the existing set of tools that are currently used in our industry for reservoir management.

SRM has small computational footprint and runs in fractions of a second. As such it is an optimal tool to be ported on tablet computers such as iPad to be used by reservoir management team for performing fast track analysis.

REFERENCES

- Mohaghegh, S.D., Modavi, A., Hafez, H. and Haajizadeh, M.; 2009 "Development of Surrogate Reservoir Model (SRM) for Fast Track Analysis of a Complex Reservoir". *International Journal of Oil, Gas and Coal Technology*. February 2009, Volume 2, Number 1. pp 2-23.
- Mohaghegh, S.D., Hafez, H., Gaskari, R., Haajizadeh, M., and Kenawy, M., 2006; "Uncertainty Analysis of a Giant Oil Field in the Middle East Using Surrogate Reservoir Model". SPE 101474, Proceedings, 2006 Abu Dhabi International Petroleum Exhibition and Conference. Abu Dhabi, U.A.E., 5-8 November 2006.
- Mohaghegh, S.D., Liu, J., Gaskari, R., Maysami, M., and Olukoko, G., 2012a "Application of Surrogate Reservoir Model (SRM) to an Onshore Green Field in Saudi Arabia; Case Study", SPE 151994, North Africa Technical Conference and Exhibition held in Cairo, Egypt, 20–22 February 2012.
- Mohaghegh, S.D., Liu, J., Gaskari, R., Maysami, M., and Olukoko, G., 2012b "Application of Well-Based Surrogate Reservoir Models (SRMs) to Two Offshore Fields in Saudi Arabia, Case Study", SPE 153845, SPE Western North American Regional Meeting held in Bakersfield, California, USA, 19–23 March 2012.