WHAT YOU SHOULD KNOW ABOUT EVALUATING SIMULATION RESULTS-PART 2

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What You Should Know About Evaluating Simulation Results—Part 2

Mike Carlson graduated from the University of Toronto with a degree in geological engineering in 1979. He started his career in the Drayton Valley field office of Amoco Canada Petroleum Company Ltd. as a lease engineer and as a completions engineer. Following this he worked for Home Oil Company Limited as an operations engineer, Group Leader Northern Alberta Reservoir, and as Group Leader Reserves. During the latter assignment, Home was purchased by Gulf (through Hiram Walker Resources) and sold internally (to IPL). He was also responsible for securities reporting. Subsequent to this, Mike was employed by Scientific Software-Intercomp, where he did independent corporate evaluations, a number of simulation studies and taught courses on reservoir simulation.

Currently, Mike is president of Applied Reservoir Engineering & Evaluation Ltd. (ARE) where he manages economic evaluations, general reservoir engineering and reservoir simulation studies.

He has been active within the technical societies in Calgary. A past technical program chairman for The Petroleum Society's Annual Technical Meeting, he was responsible for newsletter advertising (SPE) for two years, and currently serves on the National Board of the Petroleum Society. He has written eight technical papers and has been invited to make a number of industry presentations. The substance of this article was presented at the Petroleum Society's Calgary Technical

Introduction

This is the second of a two part article on assessing simulation results. Evaluation engineers are often provided with a numerical simulation study as part of the technical support for an economic evaluation of an oil and gas property. Simulation involves many specialized techniques which many people may not be familiar with. A procedure is outlined, in this article, which will aid in assessing the applicability of simulation results to an economic evaluation.

Part 1, in the May issue of *JCPT*, contained the Introduction, discussed Consistency Checks and Identifying the Critical Issues. Model design was the last topic, where implementations for waterflooding, multiple (gas-oil, water-oil, or gas-water) contacts, mature production, retrograde condensation and miscible floods were discussed. In Part 2, the discussion continues with Evaluating the Simulation Technique, Report Review followed by Conclusions.

Evaluating the Simulation Technique

Check that Grid can Physically Model Reservoir Flow

Reducing the number of grid blocks can be taken too far. The following example occurred in a study proposal which was submitted to the author. The objective was to determine horizontal well potential in a tight sandstone reservoir. Production in vertical wells was uneconomic due to low rates and GOR penalties. The study was to determine if a horizontal well would increase productivity enough to enable economic production and if GORs would be low enough to avoid penalties.

Flow nets are a very useful tool to help mentally picture the flow in the reservoir. A flow pattern something like that shown in Figure 6 should exist. Since the reservoir is tight (less than 1 mD) localized gas saturations would exist. A fine grid made with small grid blocks and thin layers would be required around the well. An element of symmetry could be utilized through the centre of the well to reduce computation.

The proposal, for the situation described above, recommended three layers with the wellbore centred in blocks with 100 foot horizontal x and y dimensions. It is important to realize that the simulator would still have run. Although these large grid blocks could not correctly represent the physics in the reservoir, the model would still produce results. The proposal was not considered favourably by the author.

Many wells have been hydraulically fractured. Usually models are run and minor adjustments made via "pseudo well relative permeability curves." Wells that have been fracced will show slower GOR increases than unfracced wells. This will not always produce correct results if the combined propped half length of the fractures is greater than 25% of the interwell distance. Under these conditions, the deviation from a radial flow pattern is too severe to be represented radially in conjunction with pseudo well curves.

Studies by the author have shown that waterflood response in a reservoir that has large fracs is not as pronounced as predicted by radial flow models. The approach to such a simulation had to be changed—a type well study with the fracture modelled directly was more appropriate.

Grids are not always correctly implemented. Unfortunately physically incompatible results will not automatically cause the simulator to crash. In such cases the model will calculate, with great precision, meaningless results.

Simulators can provide answers which are physically incorrect. In some cases it may be possible to obtain a "reasonable" history match, based on limited data, despite basic errors. In conclusion, check to see that the model grid can represent the physical flow patterns in the reservoir.

Check Implementation Of Wells

The wellbore equation used in grid blocks is for steady state

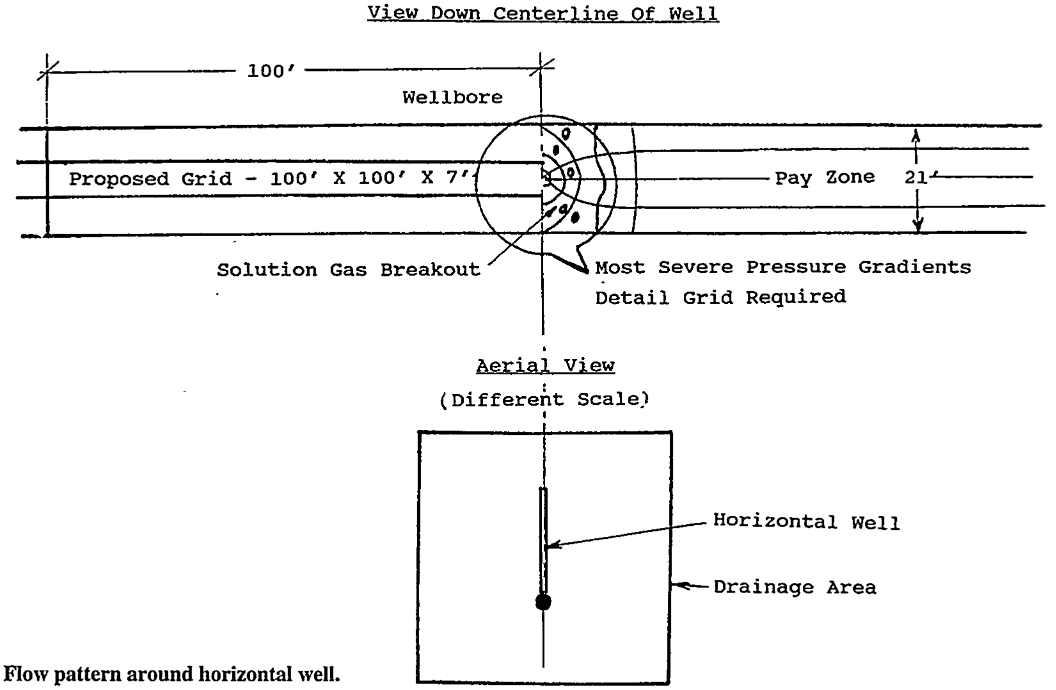

FIGURE 7: Flow pattern around horizontal well.

grids. When the differences are small enough, when compared to the accuracy of the input data, an adequate solution has been obtained. These sensitivities are rarely run. The amount of error in a simulation is normally not known.

The errors in modelling are amplified when dealing with multiple phases. Buckley-Leverett theory predicts a sharp shock front in waterflooding. Some simple one-dimensional tests with a simulator can show very interesting results. First, these tests can show the nature of the numerical error—which results in the smearing of the shock front. Second, the use of timesteps which are too large may introduce instabilities.

This simple one-dimensional situation has been modelled using two different commercial simulators. In Figure 7 the high values of water saturation represent a numerical stability problem. Look in the simulation output for values of Sw that are higher than (1-Sor). They will most likely be in the well blocks. This will identify only the worst errors. Look for a stability calculation in the report. The flood front should not advance more than one grid block per timestep[1].

Stability problems occur more frequently with gas. Due to its low density and low viscosity, this phase will most likely move faster than the simulator can handle. This will usually manifest itself as negative values of gas saturations in the output arrays. Once again, expect the problems to coincide with well blocks. These problems are far more likely to exist on one of the older "IMPES" type simulators. The more modern simulators use adaptive implicit techniques. The switch from IMPES to implicit can be based either on threshold values (fast) or stability calculations (slower); so this type of error can still occur. The author has found these instabilities in actual studies.

Contrary to popular belief, these instablity errors will not show up on the material balance. They will overestimate waterflood recovery if the history match is based on primary production. It will make history matching difficult if a waterflood history is being matched.

Another numerical error, called dispersion, is shown in Figure 8. A smearing of the waterflood front occurs in simulation. A small "tongue" of water (saturation) will sneak out ahead of the flood front predicted by Buckley-Leverett theory. To counteract this, a simulation engineer will often make this problem go away by using a "pseudo well relative permeability curve." Some simulation engineers will try and match breakthroughs at the 20% water cut to ensure the proper breakthrough is being matched. Note that the dispersion is higher on the newer "fully implicit" simulators than on the old "IMPES" type simulators. The newer simulators don't necessarily give better results.

In summary, numerical errors are very real. A grid sensitivity, although rare in areal simulations, should be taken as a very positive sign if it's in the report. It should be done with all of the phases which will eventually be present in the field. Some relatively simple tests on a five-spot waterflood pattern will show that simulation results are less sensitive to recovery than to water breakthrough timing. A seven × seven grid, for a quarter element of symmetry for a five-spot waterflood pattern, would not be an unusual requirement to match water breakthrough times.

Coarser grids are commonly used and history matched via water breakthroughs. Suspect that the history matched "pseudo well/reservoir relative permeability curves" compensate for dispersion, in addition to well completion, coning, or layering effects.

Check Layering (Heterogeneity) for EOR

The effects of layering, as discussed earlier, is perhaps the most important design criterion for enhanced oil recovery. Coincidentally, single layer areal studies are common.

Choosing appropriate layers requires detailed work. The most comprehensive approaches will feature:

- A detailed description of the layers by a geologist. Different physical reservoir properties will usually correlate to different stratigraphic units.
- A detailed petrophysical study in which the porosity and permeability, and rock lithology have been correlated.
- A computerized log analysis of all the wells. Computerized log analysis allows more consistent calculations and more sophisticated correlations are also usually possible using a computer.
- Statistical layering techniques developed by Testerman which provide a quantitative basis for determining layers.
- If none of the above are available a range of typical heterogeneities can be evaluated by using a Hearn type "pseudo relative permeability" technique in conjunction with Dykstra-Parsons type coefficient.

At least one of the above must be used, particularly if only primary production has been history matched. Water saturations during primary production will remain close to the connate water saturation. Therefore, almost none of the real relative permeability curve will have been traversed. Under these circumstances, the effects of layering and heterogeneity will not be accounted for.

If no layering calculations have been made, the resulting water-

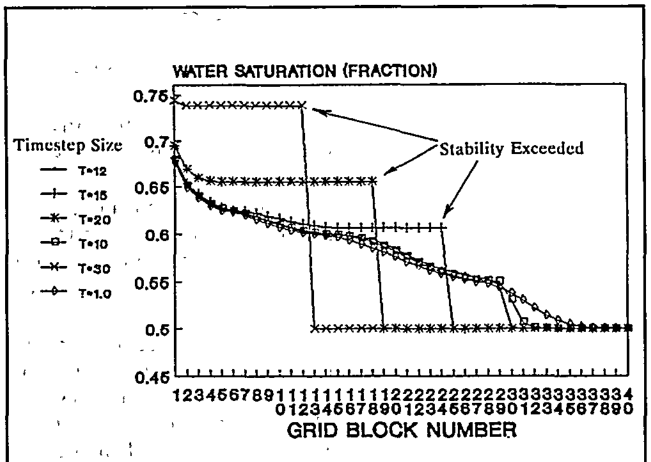

FIGURE 8: One dimensional IMPES model.

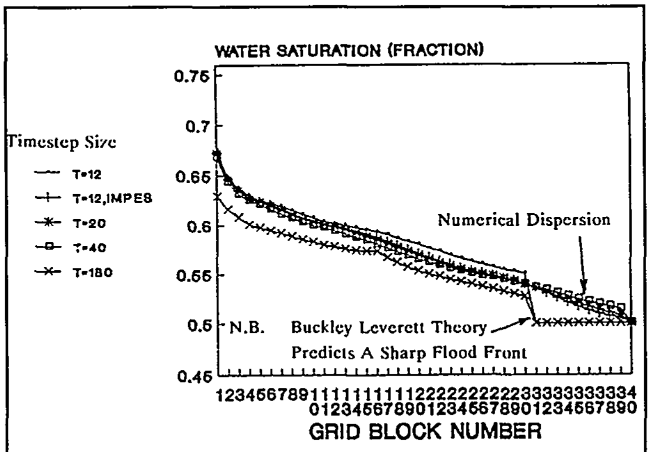

FIGURE 9:One domensional fully implicit model.

flood prediction may be seriously optimistic. Under these circumstances, the quality of the history match on primary production will not indicate the accuracy of the waterflood prediction.

If a significant period of waterflooding was history matched, it is likely that the history matched "pseudo relative permeability" accounts for the effects of layering and heterogeneity. For this reason, a waterflood feasibility simulation study will often recommend that the study be updated after water breakthrough has occurred. In this way, an improved optimization strategy can be developed.

The final element of the procedure is a detailed review of the simulation study report. Most reports will be written following the outline of the basic simulation procedure.

Report Review

A large study can take over a year to complete. If the report has not been kept up to date as the study progressed there is a good chance that important decisions were not recorded. Report writing also falls at the period where people will try and correct budget overruns, resulting in an incomplete explanation of the study. It is possible that a report may not be sufficiently documented to make a useful assessment of the results.

Check that the Geology is Thorough and Up to Date

The geological phase of data input is the most involved. Maps of net pay, porosity and permeability must be developed and input into the simulator. In most cases the geology should be updated immediately before the study. Using outdated geology, without all the wells and available information has proven, in the past, to be a waste of effort. Conversely, in the early stages of development a complete reservoir description is not possible. Hence, the results of the study will be incomplete. Correct geological interpretation also affects such parameters as layering, degree of fracturing as well as the probability of water influx. A comprehensive geological study is a "must" before simulation. As a general guideline, the geological segment should take about the same amount of time and cost as the reservoir simulation study.

The specifics of evaluating geological studies goes well beyond the scope of this article. However, most engineers should have seen enough geological studies to be aware of the depth of study.

In the author's opinion, most simulations that fail do so, directly or indirectly, because of inadequate geological descriptions.

Check Data Preparation

A model can only be as good as the input data. Input data should therefore be checked. The assumptions should be reasonable. The author feels simulation reports should include a copy of the final data input deck. This is easily imported into word processing packages. With appropriate comments, and a reduced text size available on almost all laser printers, there is no reason why there should not be a permanent record of the input file within a report.

An explanation should be included in this section of the report explaining the basic methodology or approach to the problem. For waterfloods check the relative permeability end point saturations.

Check for Proper Initialization

Check how the simulator has been initialized. The use of pseudo relative permeabilities creates the need for modifications to capillary pressure. Some programs implement these changes automatically, and others do not. Note that a model will likely run with incorrect data.

If the saturations have been manually specified, check to see that a run has been made with no well production. This ensures that the pool is in gravity equilibrium before starting the history match.

Check History Matching Technique and Changes Made

This section will likely be the largest section of the report. First of all, check for an organized approach. The history match process should be a variant upon the process shown in Figure 9. This is not fixed, since the requirements vary from study to study. For instance, a coning study with detailed layering and lab data should not require development of a pseudo relative permeability.

Second, a history match log outlining the various changes for each individual run is a very positive sign. This indicates a high degree of organization on behalf of the simulation engineer. Check that the process and the changes are consistent. A table containing all of the runs made, execution times, etc., is an efficient way of summarizing this data

Third, check that all of the production has been obtained on a cumulative basis. The base production should be almost 100% accurate. If not, then a well has probably been "turned of" by the simulator's bottom hole pressure routine. The history match base production will then not be correct. Also, the cumulative amounts of production on secondary products should be evaluated. Although history match trends may look very good, with rapidly rising watercuts, the cumulative volumes can be off by quite a bit. Realistically expect the values to fall within plus or minus 10% for the majority of values and 15 to 20% on the exceptions.

Finally, for an areal study, look for a summary diagram which has the total pore volume and permeability changes displayed. Simulators tend to be more sensitive to pore volume changes than permeability changes. A pore volume change of 15% should not cause concern, nor a doubling of permeability. Larger changes will occur, but should be the exception, not the rule. If there are extreme changes, or ridiculous faults that are necessary to obtain a history match, then it is likely that there was a problem in conceptual implementation.

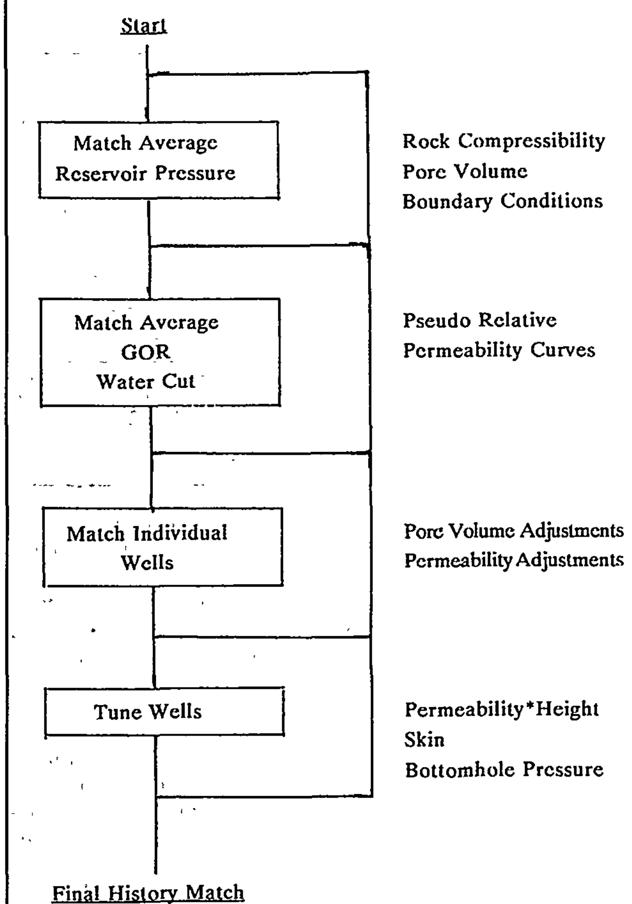

FIGURE 10: History match procedure.

A complete set of history match plots should be included either in the report or as an appendix. One item the author finds very helpful on history match plots is a small key map. With this it is possible to mentally correlate history match results and where the well is in the unit or pool.

Check History Match Effects on Prediction

In one of the studies referred to earlier, an aquifer was represented by close to a 40% increase in OOIP. For the prediction runs, injection was only implemented in the known oil leg. This apparently gave very low waterflood recoveries as a percentage of OOIP. An economic waterflood was rejected since it appeared the model was not working. When adjustment was made for the fact that nearly half of the OOIP had not been swept (rather did not exist), the waterflood recovery appeared very reasonable. Ironically, the study had a major flaw, but probably gave a reasonable estimate of recovery within the waterflood pattern area.

Check for Other Possible Schemes

Consider other likely schemes. For instance, one study reviewed by the author assumed a five-spot injection pattern. The author's analysis indicated that given pool geometry and offset performance, fewer injectors were actually required. Since no predictive run was made with this scenario, it was not evaluated. The economics of the waterflood were not that favourable due to lost production. A nine-spot implementation would most likely have allowed for an economic project. The author has observed the converse on a number of occasions.

The power of a numerical model is hypnotic because it can evaluate a production scenario very rigorously. However, it is quite incapable of identifying which scenario must be input in the first place.

Checks for Prediction Consistency

The prediction scenarios must be analysed for consistency. A few suggested techniques are as follows:

- Using a photocopy of the pool map, shade in projected waterflood sweeps. If the zone is thick, try this methodology on a cross-section.
- Look at the pressure history. Frequently, rapid injection is required to fill voidage, after which water injection rates can be reduced. Rapid pressurization will improve the speed of response and hence economics. The injection rates must remain realistic.
- Check that the date for implementation of injection is realistic. The speed of waterflood response is usually strongly affected by the amount of solution gas that has broken out. It takes time to drill wells, build water injection plants and get government approvals. If a study was predicated on injection starting five years prior to when the facilities were actually installed, suspect that the actual response will not be as quick. In smaller pools, considerably less than five years of production could be significant.

Since most simulation results may be used in economic runs, the predictive cases in the report should not only be plotted, but should be provided in tables on a yearly basis.

Look Through Computer Output

Ask for a copy of the final computer outputs and timestep logs. This may be the only method of finding numerical instabilities.

Limitations

It is not possible to describe everything that should be checked in a simulation without writing a book on simulation. The above discusses the most common problems the author has encountered or is aware of.

The technical explanations in this article are oversimplified. If one encounters a specific problem or needs more information a more detailed explanation will be required. There are a number of excellent books available on simulation. A selection of recommended books have been included in the references. For some of the newer areas, such as reservoir characterization and geostatistics, the literature must be consulted directly. The discussion of the more involved topics such as compositional modelling and EOR modelling have not been addressed in this article.

Reserves Assignment

Suppose that a simulation study had been reviewed, as described in this article, and the projected recovery and forecast appear to be reasonable estimates of recovery. This would normally be sufficient justification for management to approve a waterflood. From a securities reporting perspective, booking waterflood reserves based on a numerical model is more difficult. Differences in risk threshold are difficult to explain to investors.

If, however, a waterflood had been implemented by an offset operator in a nearby part of the field and waterflood response was obtained, assigning a percentage of simulated reserves would normally be easier to obtain.

The evaluation engineer will likely assign some percentage of the "reasonable" forecast as "reasonably certain of recovery." This represents a Proven Reserve assignment. Since the forecasts from the simulation report is a "reasonable estimate," some further upside will potentially exist. This further upside will form the basis for Proven Plus Probable Reserves. Economics can then be run. The final reserves will be determined at the appropriate economic limit.

Reservoir simulation can augment the reserves process, but will not replace the need for engineering judgement in both assessing simulation results or assigning reserves.

Conclusions

- A systematic procedure to evaluate a simulation is presented. This has been found to be an effective method. The four steps are:
  1. Consistency Checks
  2. Identifying Critical Issues
  3. Evaluating Simulation Technique
  4. Report Review
- The use of some relatively straightforward common sense checks will usually screen out major flaws in a simulation study.
- Simulation is not a substitute for common sense reservoir engineering. The results of a simulation study may compliment the evaluation process; however, it cannot replace all of the elements which should be considered.
- To effectively model a reservoir, the simulation engineer must have understood the critical depletion mechanisms in the first place. To use the results of a simulation study, one's opinion of the critical components must agree with the way in which the study was performed.
- An explanation of some of the basic simulation techniques have been made in this article. The details of the techniques are important and consume a considerable volume of the petroleum engineering literature. For this reason, a specialist is often required to do both the studies and evaluate their effectiveness. This is particularly true for the more involved miscible and compositional simulations. Don't hesitate to get this help.
- Be particularly wary when dynamic pseudo relative permeability functions have been used and when waterflood performance has been predicted based on a primary production history match.
- In the majority of cases the evaluation engineer will have to make some adjustment to the "reserves" predicted in a simulation report. In particular, risk and economic limits must be assessed in a financial reserves evaluation.
- If the report does not pass the aforementioned tests, the evaluations engineer must rely on his own judgement and use other methods, such as analogy, for assigning reserves.

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