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THE EVOLUTION OF THE

ARAMCO

Reservoir Behavior Simulator

(ARBS)

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The Evolution of the ARAMCO Reservoir Behavior Simulator (ARBS)

The seminal paper on oil reservoir simulation was published by Bill West, Walt Garvin and John Sheldon in 1954 .[1] West was head of CRC Lab's (California Research Corp → Chevron) reservoir research group (aka Project 5219) and Garvin was the Lab's brilliant mathematical physicist. Sheldon [2], a mathematical genius, was recruited away from his PhD thesis by IBM to serve as consultant to support new applications of that company's new 701 computer. The simulator used then evolving finite difference methods to solve the nonlinear partial differential equations describing two-phase flow in porous media. The study focused on gas saturation buildup around the wellbore in a solution gas drive.

ARAMCO RESEARCH

Aramco provided partial financial support for this work under a newly instituted research contract with CRC. Aramco set up parallel contracts with Esso Production Research Lab and Mobil Corp Labs. I believe that Aramco's far-sighted Chief Engineer, Dr. Richard Zinszer, was instrumental in arranging this support. The scope of the technical assistance covered all aspects of exploration and production. A portion of each lab's work concentrated on prediction of reservoir behavior.

EPRL, ably assisted by their consultant Dr John von Neumann, made significant advances in digital simulation. The alternating direction method of solving simulation equations came out of this research. For Aramco EPRL concentrated on detailed reservoir performance studies. One commendable publication gave results of a simulation of edgewater drive in a vertical cross section. Vertical saturation distributions at various stages of water advance were used to compute average relative permeabilities for use in two-dimensional areal simulations. Although not stated in the paper, anyone familiar with Aramco's main reservoirs readily recognized the cross section to be that of the Arab D limestone in Abqaiq Field.

Mobil Labs was given the job of building an analog simulator – an RC network analyzer - to simulate Saudi oil fields. An RC analyzer is an electrical network of resistors and capacitors. When a current passes through the network, the change with time of the voltage follows the same linear partial differential equation as pressure of a fluid with constant compressibility in a porous media. Drawdown of charge from the capacitors is the analog of expansion energy of the fluid. This tool is of limited use for simulating multi-phase flow of oil, gas and water because the equations become nonlinear. The coefficients in the equations – permeabilities of the phases – are not constant. As the saturations of oil, gas and water change, their relative permeabilities change. So the coefficients are a function of the solution, which is what makes the equations nonlinear. A great deal of effort was spent – with no return, but that's how new technology is threshed out – trying to make the analog simulator approximate multi-phase flow. Variable resistors and capacitors that could be manually adjusted were introduced into the network. But just imagine the frustration of the human operator trying to determine when and how much to change the settings of an entire array of resistances and capacities.

From today's vantage point – with powerful digital simulators used night and day - you may wonder why the interest in the analog simulator. In the 1950's digital simulation was a technology in evolution. Although those of us working to develop and prove the concept had no doubt of ultimate success, we were a small minority. Then, only a small fraction of technicians and managers in the oil patch had ever had any direct contact with a digital computer. Some evinced animosity against this machine that was touted to replace human brain power, others were merely doubtful of computer messiahs, while the open-minded and tolerant were skeptical and, if not enthusiastic and supportive, not antagonistic. The RC analyzer, on the other hand, was a concrete tool. Developed by Bruce in 1943, it was based on fully-understood, 100-year old technology – flow of electric current through wires, resistors and capacitors. So it was not until we had, in 1961, proven the validity of the digital approach with a successful simulation of the Safaniya Field that Aramco's management abandoned the analog simulator, once and for all.

STEPS ON THE ROAD TO ARBS

To repeat, I commend Dick Zinszer for spearheading the development of ARBS. Three events led to its inception. First, in 1956 Zinszer created the position of Chief Mathematician and filled it by hiring Dr Charles D Harris, competent in the new math of the decade – finite difference solution of partial differential equations – and reservoir engineering. Second, in the same year Sheldon left IBM and formed Computer Usage Company in NYC. CUC was the tiny foundation stone of today's massive industry – systems analysis, design and programming. Rapping with him a couple of years later, I asked what stimulated him to form CUC. "I foresee a great demand for consulting know-how to support computer applications" was his visionary reply. Reflecting, I apologize to myself for my insular view at being surprised at the concept. CUC maintained Sheldon's consulting relation with CRC, via which connection I later came to be the ARBS project leader. The third plank in ARBS' evolution was signing of a contract – negotiated by Harris (domiciled in Aramco's office in NYC) and Sheldon – between Aramco and CUC to develop a numerical reservoir simulator for a digital computer - called the ARAMCO Reservoir Behavior Simulator. The program was written in FORTRAN. CUC's programmer was a bright New Yorker named Don Bavly (3).

Time passed. Dr. T. D. Mueller, USC's first Petroleum Engineering PhD, replaced Bill West. I joined CRC in mid-1958. Mueller and Walt Garvin both transferred to Standard of Calif→Chevron's Computer Center, 225 Bush St, San Francisco. I succeeded Mueller – and had the good fortune to work closely with Sheldon for a year on a computer model of a miscible displacement. We withdrew a paper on this work in 1959 because of numerical dispersion. This phenomenon, which is inherent in compositional simulation, has been deemed to be the analogue of physical dispersion of components in the formation. Little did we know?

Programming of ARBS was finished Fall 1959 and testing begun. Early in 1960 Chuck Harris decided to leave Aramco resulting in the request for CRC to take over management of ARBS' development – and my succession to Project Leader. The project was moved to California. Chuck Harris came out for a few months in the Spring to coordinate the transition. Howard Schlieman, who Aramco had reassigned from Arabia to NYC as engineer on ARBS, moved to California. Bavly came out for a while to assist in debugging and testing. An unfortunate, but not serious, accident that sticks in my mind occurred maybe in April. Chuck bought a bright red MG convertible of which he was most proud. The labs at CRC were surrounded by a chain link fence that had strong iron gates across the entryways. The gates were closed for the night around 7 PM. Harris was not aware of this practice. Leaving work late one evening after dark he drove smack dab into a gate. Fortunately, he was only going about 15 mph so he was not injured and damage to his prize car was not severe. But his disappointment at blemishing his special toy was severe!

We ran ARBS tests on the most modern computer of the time, IBM 704. The computing power of this machine was at most 2 per cent of the mid-range PC that is now on every engineer's desk. Our perception, however, was that the computer was adequate – since it's speed was a lion's leap from the IBM 650 or 1401 available before. Access was a different story. Remote computing was only a possibility for the future. So we had to go to the computer – when it was available. And that was always at night since more important business applications loaded the day. We had two choices, both of which we used on the occasion. Fly to San Francisco and use SoCal's 225 Bush St machine or drive across Los Angeles and use a 704 at Aerospace Corporation. The first choice was more expensive and time consuming – and was not management's first choice. The second invariably led to 18 hour days starting at noon and ending at 6 AM.

The session that sticks firmly in my mind was the last one at Aerospace and the last with Don Bavly in attendance – at a time when the pressure was severe to 'get going or give up.' Then, debugging was by brute force, the FORTRAN compiler having no Debug mode that stops the program at a designated point and allows one to step through the code to see the numbers generated. We made run after run looking for the cause of two problems that literally caused the calculations to blow up. Fortunately, those doubters who said the program would never run correctly were not there to discourage us as we ground away through the night. We found the source of one problem about 2 AM. We determined that negative values of permeability appearing seemingly at random were causing the matrix solution to go out of control. Further tracing revealed the negatives to be coming from quadratic equations used to fit the end point of relative permeability curves. A quadratic is a parabola and parabolas have minimum values. With these parabolas the minimum was less than zero.

ARBS used the IMPES technique – implicit pressure, explicit saturation. With this method pressure is calculated at the end of a time step using saturations at the beginning of the step. Saturations are calculated at the end of the time step using flow rates computed with a weighted average of the beginning and ending pressures. The weight must be greater than 0.5, the value that minimizes truncation error. Desired time step is 1 year, but smaller values may be necessary when pressure is changing rapidly.

Use of explicit saturations gives rise to the second problem, which was less severe than the first – the program continued to run for awhile but the impact was equally devastating. In computing cells in which oil and water saturations were changing rapidly, saturation would begin to change erratically, sometimes oscillating. If bounds were not imposed, the values would have become less than zero or greater than 1.0. This was serious!! Unless we could correct this behavior, we were dead in the water. Fortunately, the way to eliminate the problem was already in place. To determine flow between two adjacent cells the simulator computed a weighted average of the saturations in the two cells, calculated the relative permeability at that average saturation and used that in the flow equation. Changing the weight from 0.0 to 1.0 moved the average from the upstream cell to the downstream cell. Finite difference logic said use the midpoint so the weight was set to 0.5. In an effort to fix the problem, we varied the weight. Around 4 AM we made a run with weight = 0.0. Beauty in the morning! Instabilities in saturations just disappeared. With this setting ARBS performed precisely as intended. The cloud of uncertainty lifted from our horizon By 5 AM when we started home, we knew we had a working digital simulator. Since that hour, calculating the relative permeability of each phase using the upstream saturation has remained the standard procedure in multi-phase reservoir simulators.

ARBS Validation Test – Modeling Abqaiq, Ghawar and the Arab-D Limestone

A model of the Arab-D limestone was used to test ARBS. Although I do not know its limits, the aquifer extends a long ways. The Arab-D contains the Abqaiq and Ghawar anticlines. In these fields thickness is about 280 ft at a depth of 6000 – 7000 ft subsea. To have the test vehicle ready when programming of ARBS was finished, Harris and Schlieman began construction of the model in 1958. The limited power of digital computers made building the model a difficult and time-consuming design problem – in addition to the drudgery of digging the data out of printed reports and data sheets scattered throughout Aramco's field offices and headquarter units. What a difference from present day simulators that generate a computing grid in minutes and call upon a computerized database for the bulk of the data.

Limited speed and memory dictated a computing grid containing no more than 3000 mesh points. To get sufficient resolution in the oil field one square-mile cells were deemed necessary. Abqaiq's 35x7 mile area required 250 points to cover the oil zone – plus at least another 50 cells extending into the aquifer. This outer ring was essential to accurately model constrained water influx through the low-permeability tar barrier at the o/w contact. [In the final history-matched model ARBS computed a several hundred psi pressure drop across the barrier.]

Because of the relatively short distance between Abqaiq's 'nose' – the southwest end with the greatest drawdown – and the north end of Ghawar, [now called Ain Dar and Shedgum] the 'fine' grid had to extend through this region. This required around 200 more cells. But covering all of Ghawar's 2500+ square miles with 1 mi^2 cells was out of the question. So, we pass the limit for number of grids before we even consider how many cells are required to model the vast extent of the Arab-D aquifer – without whose influence performance cannot be predicted. The requirement is apparent – the model must contain cells of different size. But how does one maintain material balance when fluid from one cell may flow into two – or more – other cells? This problem was handled by doubling mesh sizes. In this way a 2 mi^2 cell fits neatly against two 1 mi^2 cells, a 4 mi^2 cell covers two 2 mi^2 cells, an 8 mi^2 abuts two 4 mi^2 cells, etc. What was the limit? That escapes me but the largest cell was probably 32 mi^2 at the outer edge of the aquifer. Think how much simpler this task would have been if Fetkovitch [(4)] had provided his aquifer model 15 years earlier. Since use of a Fetkovitch aquifer sweeps this complication away, such is nearly universal simulation practice today.

To support mesh-size changes required special mathematical procedures that split flow from a large cell into two smaller cells, with each flow responding to a separate pressure difference. Sheldon and Zondek worked out an elaborate set of finite difference equations that calculated the two flows and maintained material balance. These were programmed into ARBS giving rise to an additional feature that had to be thoroughly tested for validity and reliability. Back to what to do with Ghawar. To keep the number of mesh points within the required limit mesh sizes were doubled within the Ghawar Field. The maximum was probably 4 mi^2. This aggregation was not of great import relative to performance predictions – since in the late 1950s the south end of Ghawar was not well established. But this aggregation did require further mathematical work to handle two-phase flow between cells of different size.

On to Saudi Arabia

After getting the calculations to behave properly we began in earnest to history match performance in Abqaiq and Ghawar. This effort had barely gotten underway when the date set for the official handoff from Harris to Dougherty – June 1960 – arrived. For that ceremony we were ordered to appear before Dr Zinszer in Dhahran. What a memorable June that was for me. On D-Day, June 6, we buried my Father, a fighter pilot in WWI, with full military tribute beside my Mother in a windswept graveyard outside Bunker Hill, Kansas. Ironically, 30 feet from his grave still stood the platform upon which he – a dignitary of Russell County - had stood to give the traditional Memorial Day oration on May 30.

On to NYC then to liaise and reconnoiter with Harris before we departed for Arabia. A dinner at a popular restaurant with a wandering violinist stands out. First, a cab driver walked into the middle of the floor, took off his cap and sang a magnificent aria – probably in Italian – and put his cap back on and strolled out. Then, entered the Australian Premier, Robert Menzies, and some group gave a fine rendition of "Waltzing Matilda."

Next day, Aramco Airline's DC-6 or 7 carried us to refuel in Gander, New Foundland. From there just after sunup the following day we crossed the Emerald Isle – green - green it is – before landing in Amsterdam. After a 24-hour layover, we were off to Rome, Beirut – with beautiful beaches filled with European tourists – and finally Dhahran. Pleasant it was not, temperature 109 ^{o}F, mild sandstorm, airport consisting of two rows of 6-inch diameter posts supporting a tin roof. Glad we were to reach Steineke Hall's comfortable air conditioning.

Then on June 14 began our wait for the call from the 'always in conference' Zinszer. With the expatriate engineers on Zinszer's staff we discussed field performance and how ARBS should handle it, worked out the mathematics for a new feature in ARBS and visited the little fishing village with the big well in the center of town – El Khobar, if you can believe it. One day starting at 5 AM we played golf with red balls on what seemed to be the world's largest and longest sand trap. But no appointment could be made with Zinszer.

Finally, Harris passed the word to him that we were leaving on July 2, less than a week away. So at last the little sparkplug put us on his schedule. Finally, two days before departure the baton was passed from Harris to Dougherty in front of Zinszer's desk. The meeting did bring to light one of those improbable coincidences that seem to defy the laws of chance and make one wonder. We confirmed that Zinszer was raised in Hays, Kansas. I studied at Ft Hays State my first two years in college. Spring Semester 1947 I rented a student room in a basement of a house owned by – who else – Zinszer's Mother – where he had grown up!

Harris and I came home together – with a stop in London on July 4 followed by a brief tour of England. We parted company in NYC and our paths have crossed only once or twice since. Harris stayed on at New Mexico Tech in Socorro for a time and then moved on to Tulsa Univ.

Now history matching, particularly of Abqaiq, began in earnest. A most notable confirmation of the simulator's validity slipped by with little fanfare. The most problematic part of the HM was pressure in the Abqaiq nose where drawdown was the greatest. ARBS predicted too low a pressure. Increasing aquifer permeability was of no help. The low permeability assigned to the tar barrier prevented greater water influx. With this low value computed pressure drop across the barrier closely matched carefully controlled field observations so the value could not be raised. Increasing permeability in the oil-bearing formation to encourage migration from North Abqaiq into the nose had little effect. Finally, in desperation to obtain additional expansion energy, we filled the cells north of Ghawar as then defined with oil. This change, which looking back effectively defined the Ain Dar / Shedgum regions, doubled the compressibility of the fluid in these cells. With this change the pressure in the nose predicted by ARBS agreed closely with observations!! This phenomenon was reported in the next monthly ARBS Progress Report dispatched to Dr Zinszer. Jim Klotz, a former CRCer then serving a tour in Dhahran later told me the following. Upon reading the report, the Engineering staff commissioned Aramco's Drilling Dept to drill a well in the middle of the area. The drill bit found the Arab-D to be saturated with oil. Further drilling defined the oil-filled region. Two billion barrels of oil in place were added to Ghawar!!

BACK TO ARABIA FOR THE TECHNICAL REPRESENTATIVES MEETING

Back then, each Fall Aramco held a 'Technical Representatives Meeting in Dhahran. Each Aramco owner company, Chevron, Esso, Mobil and Texaco, sent one or more official representatives. These were ordinarily senior engineering advisers or middle level engineering managers. Each of the company labs would present results of accomplishments under their Aramco research contract. Aramco technicians and managers would review operations and present operating and investment plans for the coming year. Some of these were approved on the spot while others were referred back to the companies for review and follow up. For the October 1960 Meeting Chevron accorded me a dual role – report on ARBS and serve as a technical representative. The first part gave me the pleasure of reporting that ARBS was completely successful, that a history match of the Arab-D model had been achieved and that the simulator was ready for any reservoir study that Aramco might like to undertake.

The technical issues that year are interesting to review. Two investments, uneconomic relative to oil pouring smoothly out of Abqaiq, Ghawar and other fields onstream, but decreed by the Saudi Oil Ministry, were reviewed with acquiescent resignation. Firstly, in 1960 Arabia, like others Middle Eastern producing countries, was lighted at night by flares of associated gas. "Stop wasting our national resource!" was the edict so Aramco was budgeting for compressors – with no payout in sight.

Secondly, pursuant to the Ministry's requirement that any oil field discovered be put on production, money was required to lay a pipeline west from Ghawar to bring in oil from Khurais. [This light but relatively high sulfur field was later mothballed for nearly 40 years.] Observing the apathy re Khurais, the emphatic order given to the Exploration manager after his review of exploration activities in the Rub'al-Khali was no surprise, "**Do Not Drill On Structure!!**"

Research results from EPRL impressed me so deeply that it later changed the direction of my professional career. The presentation covered a linear programming study to optimize development of Safaniya Field. Resident Aramco engineers presented a parallel development planning study that covered a limited set of possible cases. The comparison was striking – a full scope deep-drilling search of all possibilities with a selection of the optimal vs essentially a pick and shovel dig in a few areas. Aramco's vp of production certainly saw the difference. His praise and endorsement of the Esso's results, while commending his own staff for their effort, was a careful exercise of tact.

The foregoing notwithstanding, the most exciting agenda item for the ARBS team was a discussion of actions in the Neutral Zone in the Gulf. After obtaining concessions from Saudi Arabia and Kuwait in 1957-8 Arabian Oil Co completed a discovery well in Khafji Field in Jan 1960. As we met, AOC was drilling a line of wells along the southern boundary of the Neutral Zone. Aramco's recent drilling had confirmed that Safaniya and Khafji were a single reservoir. Here were questions that excited any macho oilman producing from a non-unitized reservoir: How much oil will be pulled across the border from Aramco's Safaniya formation? How many offset wells are required to prevent loss of oil? And so, the ARBS team was challenged to prove that the digital simulator worked!

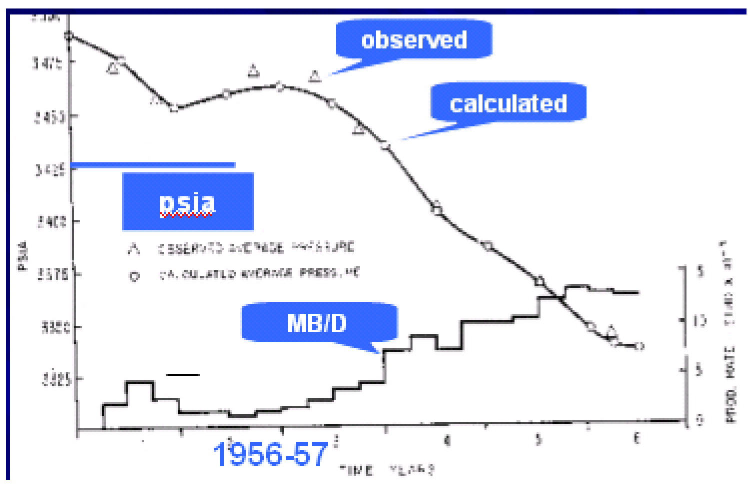
THE SAFANIYA STUDY

Aramco authorized the Safaniya simulation in time for work to begin in January 1961. The many pages of required data were boxed up in Dhahran and shipped to CRC in La Habra California. By this date Chevron had installed an IBM 7090 at 225 Bush St. In addition a telephonic link connecting magnetic tape readers in La Habra and San Francisco was then operational. Transmission of a tape in either direction required 1 – 3 hours. With this link the model – computing grid and input data – was built remotely on the 7090. With the model completed and checked out, turn-around time for a run made from La Habra was about one day. For projection runs with the history-matched model, this was acceptable. About a day was required to generate big contour maps of pressure and saturation on a line printer and then to assess results. But, as any experienced simulator knows, HM requires an intensive set of runs to achieve the required result.

Elapsed time for a run on the 7090 was 2 – 3 hours. So our HM of the Safaniya model involved many midnight hours looking through a glass window watching the 7090 roll through the calculations. What was there to watch? In addition to blinking lights, there was continual movement back and forth of a magnetic tape. Core storage of the 7090 was nowhere near large enough to hold values for all of the model's 1200 mesh points. The successive over relaxation method used to solve the equations on a time step can be broken down into calculations involving three adjacent rows of mesh points. After reading the first three rows, one of which is on the border, from tape, calculations for the border row and the middle row are done. The border row's values are then written to tape and the values for the next row inward are read. Calculations are made for the new middle row - and the process marches across the grid. This is but one iteration, and several iterations are required to converge on a time step.

Calculations at the end of a time step required a different sequence of tape movements. So with a little practice it was possible to watch calculations move from time step to time step. This somewhat vacuous pastime was a diversion for when you had not nodded off and hadn't the energy for more constructive work.

Details of the model of this 'hypothetical oil field', Safaniya / Khafji, are give in the paper [5] presented at Stanford Univ's Computer Conference in 1964. The paper contains two graphs that the illustrate the results of keen interest to Aramco's managers – cumulative oil migration and associated pressure sink in the north end of Safaniya – south side of Khafji.



From the standpoint of ARBS' validity the graph from the paper shown here is crucial. For the sands of Safaniya held a secret. Without uncovering that secret we could not have deciphered the mechanism controlling pressure and production in this reservoir. The plot shows average pressure vs time in wells in the middle of south Safaniya. Triangles are observations; circles are values computed by the history-matched ARBS model. At bit of history explains the hump in the curve, which is the key to the puzzle. Although the Saudi Aramco World now says that production began from

http://www.saudiaramcoworld.com/issue/196207/safaniya.field.htm

Safaniya in 1957, the data we were given shows pressure beginning to decline in 1955. In 1956 an armed conflict in the Sinai resulted in closure of the Suez Canal. There being no super tankers to sail around the Cape of Good Hope, oil exports from the Gulf stopped and production from Safaniya was cut back. [Hard to believe today, but in that bygone era there was enough extra capacity in West Texas to supply Europe's relatively small shortfall during the cutoff.]

The producing formation is sandstone. Although at the time, we were surprised by the permeability supplied – over 1 Darcy - in hindsight, this large value seems plausible. Oil gravity of 27 °API and 2 centipoise viscosity, as I recall. The composite oil and formation compressibility provided, I well remember – 12e-6 psi^{-1}. [I suspect this value was read from a book since I doubt that a core of the sand can be taken.] HM of the initial drawdown was easily gotten with little or no change in the permeability and oil-in-place data. But getting the calculated pressure to match the hump was a different story. Even with formation and aquifer permeabilities raised to ridiculously high values, ARBS predicted no buildup – just an unresponsive plateau.

How to get out of this dilemma? A fortunate convergence provided a solution. A year earlier a bright mathematician on my research staff, Dr. Donald Squier, had obtained an analytical solution to the classical material balance problem – a compressible oil pool surrounded by an aquifer – an extension of the analysis of Hurst and Van Everdingen. Taking the graphs from his report, we constructed an aggregate model of Safaniya to answer the question, "What compressibility in the oil pool would yield the observed pressure buildup?" The number found was 72e-6, six times the value we were using. When we put that value into ARBS, the result was a gratifying relief for a very concerned simulation team. The match obtained is what you see in the graph above.

In retrospect the effect is well understood – subsidence in an unconsolidated sand. The south portion of Long Beach California sank 15 feet before the State of California required injection of 1.1 barrels of liquid for every barrel withdrawn. Boberg in his book on thermal recovery concludes that nearly 50 per cent of the displacement energy in an unconsolidated reservoir in Venezuela comes from pressure of the overburden squeezing the sand grains together. But in 1961 the prospect of subsidence was almost as questionable as global warming is today.

This questionable uncertainty in the Safaniya study led to an interesting sequel, which gives me pleasure even today. After completing the study and writing the final report, I was promoted to Group I – the Ensign level in Chevron's officer grades. And, I transferred to the Electronic Computer Center in San Francisco – trying to fill the big shoes of Walt Garvin as Staff Mathematician, Walt having died of a sudden heart attack a few months before. Before CRC released a research report, it had to be signed by an officer grade – who took responsibility for the technical content. No one at CRC would sign my report. So, like John Hancock, I was given the satisfaction of endorsing the work of the ARBS team. This skepticism continued. My replacement at CRC was a refinery guy who knew little about computers - and nothing about reservoirs!! So he commissioned John Martin, CRC's highly respected, very competent senior engineering adviser and author of many SPE papers, to evaluate ARBS. I never sought out his report but I assume ARBS passed muster since Chevron later purchased a copy of the commercial version of ARBS programmed and sold by McCord & Associates!!!

A Final Note on ARBS

Not long after the Stanford paper became public D. R. McCord extracted the know how from it – and programmed the McCord Simulator [(6)]. This first commercially available digital simulator was widely used – until it was swept away by a wave of more advanced tools. However, the ARBS technology that Aramco supported and nurtured was given new life by the US DOE when in 1981 it contracted with Keplinger and BDM Corp to develop the BOAST [(7)] simulator – whose equations are again remarkably similar to those of ARBS. And so, the ghost of ARBS lives on, now in BOAST-3, a PC version. Since BOAST has always been freeware, a large percentage of petroleum engineering graduates have cut their simulation teeth on the foundation that ARBS laid. Truly, ARBS is a milestone that marks one of the main trails leading to the highroads of digital simulation.

Bibliography

1. West, W.J., Garvin, W.W. & Sheldon, J.W., "**Solution of the Equations of Unsteady State Two-Phase Flow in Oil Reservoirs**," Trans AIME, Vol. 201, 1954.

2. Sheldon, J.W., Zondek, B. & Cardwell, W.T., "**One-Dimensional, Incompressible, Noncapillary, Two-Phase Fluid Flow in a Porous Medium,**" Trans AIME, Vol 216, 1959.

3. Sheldon, J.W., Harris, C.D. & Bavly, D., "**Method for General Reservoir Behavior Simulation on Digital Computers,**" SPE Fall Meeting, 1960.

4. Fetkovitch, M.J., "**A Simplified Approach to Water Influx Calculations - Finite Aquifer Systems,**" JPetTech, July 1971.

5. Dougherty, E.L. & Mitchell, H.C., "**Simulation of Oil Reservoirs on a Digital Computer,**" Proc 3rd Annual Conference on Computers In The Mineral Industries, Stanford Univ. Press, 1964.

6. Schwabe, K., Brand, J. (D.R. McCord Associates), "**Prediction of Reservoir Behavior Using Numerical Simulators,**" SPE Fall Meeting, 1967.

7. Fanchi, J.R., Harpole, K.J. & Buinowski, S.W., "**Boast:A Three-Dimensional, Three-Phase Black Oil Applied Simulation Tool, Vol. 1: Technical Description and FORTRAN Code,**" U. S. DOE, BETC 1982.

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