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On the future of Monte Carlo simulation for nuclear logs

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A B S T R A C T

The oil and oil well logging companies have long been innovators in many technologies that are used in oil well logging. This includes the development and use of radiation detection equipment in the harsh environment of oil wells. It also certainly includes the use of Monte Carlo simulation in the study, optimum design, and calculation of corrections and correction factors for the inverse logging problem. This latter area is the subject of this paper. Past milestones in this area are discussed along with those of the present and future work. The perspective is from the viewpoint of the authors.

1. Introduction

Oil well logging has been an essential part of the drilling and subsequent use of oil wells since 1927 when electrical logs were invented (Ellis, 1987). The three major types of logging include electrical, nuclear, and acoustic. Nuclear logs are probably the most important of these techniques, though each has its own importance. While the nuclear logs respond to very important oil well parameters like density, hydrogen content, natural radioactivity, and elemental amounts, their primary disadvantage is their lack of penetration depth and measured sample volume. It is often difficult or even impossible to obtain the desired responses with nuclear logs—especially when the boreholes have been cased and one desires the properties behind the casing. The electrical and acoustic logs have the advantage that their responses are generally much deeper. Therefore, the optimum use of nuclear logs is often in conjunction with the electrical log (particularly the resistivity log).

Nuclear oil well logging scientists and engineers were quick to realize the importance of Monte Carlo simulation in the study of nuclear logs, calculation of corrections and correction factors for nuclear log interpretation, and nuclear log design optimization areas. Very early they began to use the general purpose code MCNP. However, like most general purpose codes of that era, they found it to be (as Ralph Wiley of Amoco used to say) "user-surly". In particular the weight windows approach for variance reduction as delineated by Booth and Hendricks (1983), while a giant step forward, was very difficult for the novice to implement because it required splitting the required importance map into cells with the same geometry as the problem itself, which usually involved asymmetrically placed right circular cylinders. Preparing an input file to use this feature required a day or so of tedious effort. In spite of this drawback nuclear log specialists continued to use the general purpose code MCNP and it became the standard to which all others were compared. The weight windows with importance map approach allowed the deep penetration and low yield problems of the neutron porosity log and the gamma-ray density log to be satisfactorily treated—albeit with the difficulty of preparing input files that included importance maps that were tailored to the complex geometries required in nuclear logging.

At about this time (1985) the first author became interested in using specific purpose Monte Carlo codes designed for each nuclear log as an alternative to the use of the general purpose codes like MCNP. An Associates Program for Nuclear Oil Well Logging supporting the Center for Engineering Applications of Radioisotopes (CEAR) was formed at that time largely based on recommendations from a meeting we had with the nuclear logging group at Mobil including Bill Mills, Scott Allen, and their consultant Bill Tittle. Subsequently CEAR began devising specific purpose Monte Carlo codes for specific nuclear logs based primarily on the variance reduction technique of "expected value splitting". This technique is a generalization of the "DXTRAN" approach used in MCNP and consists of splitting a particle at each interaction site into one that goes from that point directly to the detector without further interaction and is detected and one that retains the remaining weight and can have any resulting transport that does not have the same result as the "expected value" split particle. When this approach was used in conjunction with the "implicit capture" technique enough variance reduction could be achieved to treat the logging applications like the gamma-ray density log, the neutron porosity log, and the pulsed neutron absorption log.

The present paper discusses the important contributions in the past, recent past and present, and some speculation on what the future will bring.

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2. Characteristics of nuclear logs

Existing nuclear log types include the Natural gamma ray, Gamma-ray density, Neutron porosity, Neutron absorption cross section, Neutron C/O (carbon to oxygen ratio), and Neutron Elemental analyzer. The natural gamma-ray logs can be simple GM counters, but presently are usually logs with long NaI detectors so that spectra can be obtained and one can determine how much of the three natural radioisotopes K-40, uranium, and thorium are present. These logs are often used to determine where layers of shale exist, which separate the various layers of dry and oil-bearing rock.

The gamma-ray density logs are very important as they are capable of determining the lithology (rock type) and porosity (pore volume). They usually consist of a gamma-ray source (normally Cs-137 with a 0.662-MeV gamma ray) and two collimated NaI (or now BGO) detectors and different spacings from the source. A typical log of this type is shown in Fig. 1.

The gamma rays from the Cs-137 source are emitted into the rock surrounding the borehole and some are scattered several times until they are detected by one or the other NaI detector. The responses from this log can be used to measure density and, under certain restrictive assumptions, the porosity of the surrounding rock. More information is available from logs that yield spectral responses.

The neutron porosity logs consist of a high energy source of neutrons like the Am–Be source and usually two primarily thermal neutron detectors like proportional counters filled with He-3 at different spacings from the neutron source. Usually the ratio of the two neutron detectors is used to obtain porosity, since it has been found that this ratio is relatively independent of rock composition. Recently other neutron sources like Cf-252 and the D–T accelerator source are being considered.

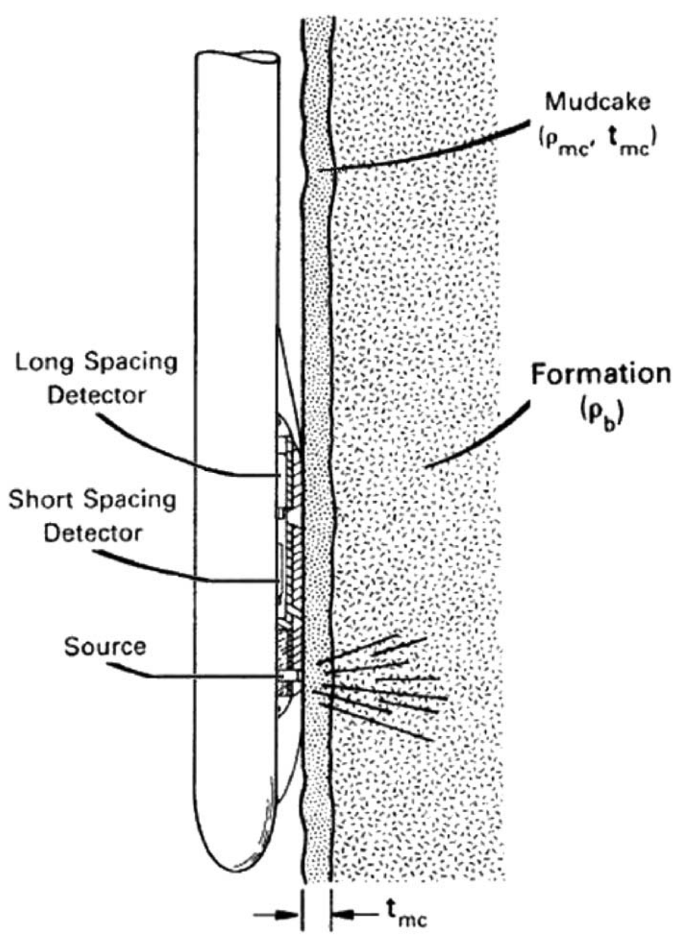

Fig. 1. A schematic drawing of a gamma-ray density log.

The neutron absorption cross section log became necessary because the response of the neutron porosity log was found to depend on the presence of large thermal neutron absorption elements like chlorine and gadolinium in the rock or water. It consists of a D–T source of neutrons (monoenergetic 14 MeV neutrons) that can be pulsed so that the "die-away" curves of neutron response can be obtained and used to measure the rock thermal neutron absorption cross section. Detectors can be either thermal neutron detectors like the He-3 filled proportional counter or NaI detectors for the prompt gamma rays that are emitted from the radiative captures within the rock and borehole fluids.

The neutron C/O log uses a D–T source of neutrons to obtain the high neutron energy that is required to give the inelastic scatter interactions in carbon and oxygen. Normally NaI or BGO detectors are used to detect the high energy inelastic scatter gamma rays from C and O. When the amounts of C and O are obtained by this log one can subsequently determine (with other information) the amount of oil or water that is present in the formation.

Finally the neutron elemental analyzer log is becoming more important in recent times. It consists of a neutron source (either Am–Be, Cf-252, or the D–T source) with a NaI detector. The prompt (and inelastic scatter) gamma rays that are produced are detected and yield both qualitative and quantitative measures of the elements (and subsequently the minerals) in the rock formation. This log is relatively expensive to operate and was not used much when it was first introduced. But now it is recognized to give additional valuable information and it is receiving more and more attention because it gives very unique and complete information. It may eventually be able to replace several of the other nuclear logs.

3. Past work and milestones

The work referred to here is biased to that of CEAR or Ex-CEAR personnel, but also refers to others that the authors feel are important.

Booth and Hendricks (1983) published their paper on the use of importance estimation with the weight windows variance reduction approach. This approach gave very large variance reduction factors (as much as 100) for the nuclear oil well logging applications and, therefore, allowed many of them to be treated with the individual computers of that time. Most of the logs described in the previous section are very low yield problems and, therefore, require a very large number of histories for adequate accuracy. So this was a very big contribution in that it enabled Monte Carlo simulation to be used for nuclear oil well applications that were previously not possible.

Soon after that Gardner and Co-workers designed a number of specific purpose Monte Carlo codes for the nuclear oil well logging tools. The elemental analyzer logging tool was actually treated before the Associates Program for Nuclear Techniques for Oil Well Logging (APNTOWL) was formed by Clark et al. (1982). After APNTOWL was formed the first logging tool treated was the neutron lifetime or pulsed neutron absorption log by Choi et al. (1986), Choi et al. (1987). The neutron porosity log was next treated by Mickael et al. (1988). The gamma-ray density log was then treated later by Ghanem et al. (1993). Several papers were published on the general topic of specific purpose Monte Carlo codes including those by Gardner et al. (1988), Mickael et al.

(1989), Gardner et al. (1991). A specific purpose Monte Carlo code on a very specialized logging tool—the epithermal neutron lifetime tool invented by the Mobil research group was devised by Prettyman et al. (1993). This code was the first to use weight windows by the CEAR group. Finally a Monte Carlo code for the natural gamma-ray logs was developed by Guo et al. (1994). The CEAR group began to use MCNP at about this time since it became much more user-friendly with the addition of the geometry-independent importance mesh.

Some modifications to MCNP began to be made in the early 1990s that led to improvements in the efficiency of the MCNP code for nuclear well logging applications. Mickael (1992) used simple diffusion models to obtain adjoint solutions for providing importance maps for Monte Carlo weight windows. This avoided the use of the forward generation of an importance mesh that had been so troublesome in prior use of the MCNP code. Following this Liu and Gardner (1997) developed a "patch" for MCNP that provided a geometry-independent importance mesh for MCNP. MCNP personnel (1998) incorporated the work of Liu and Gardner into MCNP5. Then Gardner and Liu (1999) combined the approaches of Mickael (1992) and Liu and Gardner (1997) so that one could use either the simple diffusion model approach as an initial estimate of the importance map or one could use the geometry-independent importance mesh approach directly if a good initial estimate of the importance map existed.

Things other than technical advances also affected the status of Monte Carlo in nuclear oil well logging. Gardner et al. (1990) held a workshop to investigate Monte Carlo accuracy for nuclear well logs. In this workshop specific purpose, MCNP, and McBEND Monte Carlo codes were studied with calculational benchmarks that were proposed by CEAR. Pat Soran (1991) originally with the MCNP group at Los Alamos National Laboratory was hired by Schlumberger to head up a Monte Carlo modeling group. After that he started a CRADA on this topic with members including Baker Atlas, Halliburton, Chevron, and CEAR (NCSU). Mickael (1992) designed a logging tool entirely by Monte Carlo simulation—experiments were not used until the design was finally tested. Mickael (1994) also developed the technique of using company computers in off-work hours for parallel computing.

Gardner et al. (1989, 1990) published three papers on correlated sampling that were used in specific purpose (CEAR) Monte Carlo codes. This possibly led to MCNP adding differential operators in MCNP5. The papers were by Mickael et al. (1989), Gardner et al. (1989, 1990). John Butler and Co-Workers in about 1990 developed the Monte Carlo code McBEND, which was later leased to oil and oil well logging companies.

Gardner and others developed the detector response function (DRF) approach for Monte Carlo simulation of radiation detector spectral responses, a Monte Carlo code called CEARPPU for correcting pulse pile-up distorted spectra, and the Monte Carlo-library least-squares (MCLLS) approach for treating the inverse problem for non-linear radiation analyzers. The detector response function early work was by Gardner et al. (1986), Jin et al. (1986), Yacout et al. (1986). Later work was by Gardner and Sood (2004) and Sood and Gardner (2004). The recent work on pulse pile-up was done by Guo et al. (2005). The recent work on the MCLLS approach for PGNAA analyzers and XRF analyzers was by Han et al. (2007) and Li et al. (2007), respectively.

4. Recent work and milestones

Oil and oil well logging companies have begun to routinely use computer clusters for Monte Carlo calculations to generate logging correction factors and new log designs.

MCNP has become very user-friendly—perhaps too user-friendly!

Computers are still getting cheaper and faster—problems that were once difficult to handle are becoming easier and easier!

5. Discussion, future work, and conclusions

Automatic methods for optimizing weight windows and other similar variance reduction techniques are being introduced for applications of interest. These things are becoming automatic in some codes like MCNP.

One very promising idea (CEAR) is to pre-calculate many cases of interest with Monte Carlo codes that contain differential operators. This allows one to use the excellent accuracy of Monte Carlo simulation with the linear or quadratic interpolation afforded by the differential operators to yield very fast or essentially real time solutions for log interpretation purposes.

Another very promising relatively new approach (several groups have already worked in this area) that will surely receive much additional work is the idea of appropriately combining the responses of a number of tools (both nuclear and non-nuclear) to obtain considerable additional information about the oil well. CEAR is pursuing this idea by applying the pre-calculation idea discussed in the previous paragraph so that near real time calculations can be made. The CEAR approach will also include the use of semi-empirical models—especially for the logs that use gamma rays.

One final additional idea that appears to be of considerable interest (Solomon et al., 2009) is the use of the weight windows technique for two or more detectors simultaneously. This is of particular interest to those tools that use two or more detectors such as the neutron porosity and gamma-ray density tools. This work is being pioneered by one of the authors (Sood) and will also be pursued by CEAR.

References

Booth,, T.E., Hendricks,, J.S., 1983. Importance estimation in forward Monte Carlo calculations. Nuclear Technology/Fusion 5, 90–100.

Clark, T.C., Gardner, R.P., Verghese, K., 1982. A Monte Carlo model for in situ prompt gamma-ray analysis probes. Nuclear Instruments and Methods 193, 365–370.

Choi, H.K., Gardner, R.P., Verghese, K., 1986. Monte Carlo simulation of the neutron lifetime logging tool. Transactions of the American Nuclear Society 52, 354–356.

Choi, H.K., Verghese, K., Gardner, R.P., 1987. Monte Carlo simulation of the temporal and spectral responses of the pulsed neutron logging principle. Nuclear Geophysics 1 (1), 71–81.

Ellis, Darwin V., 1987. Well Logging For Earth Scientists. Elsevier, New York.

Gardner, R.P., Yacout, A.M., Zhang, J., Verghese, K., 1986. An Investigation of the possible interaction mechanisms for Si(Li) and Ge detector response functions by Monte Carlo simulation. Nuclear Instruments and Methods in Physics Research A 242, 399–405.

Gardner, R.P., Verghese, K., Choi, H.K., Mickael, M., 1988. Specific purpose Monte Carlo modelling of nuclear well logging tool responses. IEEE Transactions on Nuclear Science 35 (1), 882–885.

Gardner, R.P., Mickael, M.W., Verghese, K., 1989. Complete composition and density correlated sampling in the specific purpose Monte Carlo codes McPNL and McDNL for simulating pulsed neutron and neutron porosity logging tools. Nuclear Geophysics 3 (3), 157–165.

Gardner, R.P., Mickael, M.W., Towsley, C.W., Shyu, C.M., Verghese, K., 1990. Correlated sampling in the McDNL and McPNL codes for neutron porosity and neutron lifetime log corrections. IEEE Transactions on Nuclear Science 37 (3), 1360–1366.

Gardner, R.P., Mickael, M.W., Verghese, K., 1991. Specific purpose Monte Carlo code development for nuclear well logging applications. Progress in Nuclear Energy 25 (2-3), 245–264.

Gardner, R.P., Sood, A., 2004. A Monte Carlo simulation approach for generating NaI detector response functions (DRF's) that accounts for nonlinearity and variable flat continua. Nuclear Instruments and Methods B 213, 87–99.

Ghanem, S.A., Gardner, R.P., Verghese, K., 1993. Monte Carlo simulation of the gamma-ray backscatter lithodensity logging tool response. Nuclear Geophysics 7 (2), 197–208.

Guo, P., Gardner, R.P., Verghese, K., 1994. Demonstrated log interpretation and design uses of the specific purpose Monte Carlo code McNGR for natural gamma-ray logs. In: Proceedings of the SPWLA 35th Annual Logging Symposium, Paper K, June 19–22.

Guo, W., Gardner, R.P., Li, F., 2005. A Monte Carlo code for simulation of pulse pile-up spectral distortion in pulse-height measurement. Advances in X-ray Analysis 48, 246–252.

Han, X., Gardner, R.P., Metwally, W.A., 2007. CEARCPG: a Monte Carlo simulation code for normal and coincidence prompt gamma-ray neutron activation analysis (PGNAA). Nuclear Science and Engineering 155 (1), 143–153.

Jin, Y., Gardner, R.P., Verghese, K., 1986. A Semi-empirical model for the gamma-ray response function of germanium detectors based on fundamental interaction mechanisms. Nuclear Instruments and Methods in Physics Research A 242, 416–426.

Li, F., Guo, W., Gardner, R.P., 2007. Implementation of the Monte Carlo-library least-squares approach to energy dispersive X-ray fluorescence analysis. Advances in X-ray Analysis 51, 9.

Liu, L., Gardner, R.P., 1997. A geometry-independent fine-mesh-based Monte Carlo importance generator. Nuclear Science and Engineering 125, 188–196.

Mickael, M., Gardner, R.P., Verghese, K., 1988. McDNL: A new specific purpose Monte Carlo code for simulation of dual-spaced neutron porosity logs. In: SPWLA 29th Annual Logging Symposium, Paper MM, p. 17.

Mickael, M., Choi, H.K., Gardner, R.P., Verghese, K., 1989. Specific Monte Carlo code development for nuclear well-logging tool responses. Nuclear Geophysics 3 (4), 339–350.

Mickael, M., Verghese, K., Gardner, R.P., 1989. Correlated sampling added to the specific purpose Monte Carlo code McPNL for neutron lifetime log responses. IEEE Transactions on Nuclear Science 36 (1), 1220–1222.

Mickael, M.W., 1992. Importance estimation in Monte Carlo modelling of neutron and photon transport. Nuclear Geophysics 6 (3), 341–350.

Mickael, 1994. Personal communication.

Soran, P., 1991. Personal communication.

Prettyman, T.H., Gardner, R.P., Verghese, K., 1993. The Specific purpose Monte Carlo code McENL for simulating the response of epithermal neutron lifetime well logging tools. IEEE Transactions on Nuclear Science 40 (4), 933–938.

Gardner, R.P., Liu, L., 1999. Monte Carlo simulation of neutron porosity oil well logging tools: Combining the geometry-independent fine-mesh importance map and one-dimensional diffusion model approaches. Nuclear Science and Engineering 133, 80–91.

Solomon, C.J., Sood, A., Booth, T.E., 2009. A weighted adjoint source for weight—window generation by means of a linear tally combination. In: International Conference on Mathematics, Computational Methods & Reactor Physics (M&C 2009) Saratoga Springs, New York, May 3–7, 2009.

Sood, A., Gardner, R.P., 2004. A new Monte Carlo assisted approach to detector response functions. Nuclear Instruments and Methods B 213, 100–104.

Yacout, A.M., Gardner, R.P., Verghese, K., 1986. A semi-empirical model for the X-ray Si(Li) detector response function. Nuclear Instruments and Methods in Physics Research A 243, 121–130.