REAL TIME SCAL QUALITY CONTROL: A SYSTEMATIC APPROACH

M.A. Velazco and I. Zubizarreta. Senergy (GB) Ltd. Aberdeen, United Kingdom

This paper was prepared for presentation at the International Symposium of the Society of Core Analysts held in Aberdeen, Scotland, UK, 27-30 August, 2012

ABSTRACT

Core analysis data acquired by commercial vendors generate crucial input for static and dynamic reservoir models. Safeguarding the value of these investments demands assurance of the quality of the data generated in the laboratory. Historically however, the lack of both reported experimental information and systematic approaches to laboratory data analyses have contributed to significant uncertainty in reservoir model parameters. This paper presents a methodology based on a simple 2^2 full factorial Design of Experiments (DoE) to systematically evaluate the different experimental factors, and interactions between these factors, that can affect the estimation of the electrical properties parameters from lab data. The methodology proposed is presented through an example of a Quality Control (QC) evaluation of formation factor, porosity compaction, and multiple salinity tests Co-Cw raw data used to estimate Archie and intrinsic cementation factor 'm' and 'm*' as part of a special core analysis lab (SCAL) programme for a gas reservoir. The selection of an adequate sleeve conformance pressure (SCP) value and brine resistivity (Rw) variability as a function of formation water salinity (FWS) were the two factors analysed to evaluate their potential effect on the estimation of 'm' and 'm*'. A statistical correlation model for 'm' found for this particular data set and based on the factors analysed, provides a design space for 'm' which gives the final user a better idea of the range in which 'm' can fluctuate based on the factors analysed as well as the associated experimental uncertainties. The statistical model obtained for intrinsic cementation factor 'm*' is limited by the experimental data available but could be improved by running a central composite experimental design to determine the effect of multiple factors instead of two. This QC approach assumes that the variability in the estimated values of m and m* are due to experimental factors, and not to inherent factors to the rock sample, which should be taken into account during the interpretation of the final QC data set containing m and m*.

INTRODUCTION

Core data provide essential input for estimates of hydrocarbons in place and recovery prediction. For this reason, it is very important that reliable and representative core analysis data are available for the evaluation and integration with log-reservoir simulation data [1]. Amabeoku *et al.*[2] emphasise the importance of reliable special core analysis laboratory (SCAL) data obtained from commercial labs as these can have a significant impact on the development field programme. McPhee [3, 4] conservatively estimated that almost 70% of SCAL are unfit for purpose, due to their unreliability, inapplicability or inappropriateness. Sprunt *et al.* [5] suggested that reviewing lab work in progress is the best way to detect problems that can be corrected or re-measured in "real" time, as once the lab contractor issues the report it can be too late to correct data or modify the test program.

EXAMPLE DATA INPUT: m and m*

Water saturation (Sw) for a reservoir with low matrix conductivity is determined by the Archie equation:

$$\frac{1}{Rt} = \frac{1}{Rw}\phi^{m} Sw^{n} \tag{1}$$

Where Rt is fluid-saturated rock resistivity, Rw is the water resistivity, ϕ is porosity, 'm' is porosity or cementation exponent, and 'n' is saturation exponent. To account for clay content, the Waxman-Smits equation is used[6]:

$$Sw^{n^*} + RwBQvSw^{n^*-1} = \frac{Rw}{Rt}\frac{1}{\phi^{m^*}} \tag{2}$$

where 'm*' and 'n*' are the intrinsic cementation factor and the intrinsic saturation exponents respectively, B is the specific counter-ion activity estimated by the Juhasz equation [7] (function of temperature and Rw), and Qv is the cation exchange capacity per unit pore volume (meq/ml). These parameters (m, n, m*,n* and Qv) are obtained by measuring electrical properties on core samples. Therefore, errors and uncertainties in the measurements have a direct effect on hydrocarbons in place. The main objective of this paper is to present a methodology that provides a systematic approach to assist the quality control of experimental data of electrical measurements (formation factor and Co-Cw in this case) by analysing simultaneously two factors: the effect of the selection of SCP value and the variation in the salinity of the formation water on the estimation of a composite m, PCF and m* at stress.

WORKFLOW

Figure 1 presents part of the workflow of a SCAL programme that has been designed for a gas reservoir well. From routine core analysis results, it is known that the clay content is significant in the reservoir. The SCAL programme consists of two separate suites of tests: Set 1 formation factor (F) and multiple salinity tests (Co-Cw) and Set 2 resistivity index (RI). Eight core plug samples were selected for Set 1 and six different core plug samples for Set 2 based on their air permeability (0.2 mD to 30 mD) and porosity (6% to 12%) to ensure a good coverage from poorer to better quality rock, avoiding bias. A lab contractor executed the tests. The main objective of the electrical measurements SCAL programme was to obtain the composite Archie and Waxman-Smits equations parameters: m, n, m* and n* at reservoir stress. Once unprocessed data from the lab contractor were available, they were checked for errors and omissions so no uncertain data are introduced in the analysis, and to ensure that the specified test procedures and conditions were followed. In this new real time SCAL QC approach, based on Design of

Experiments (DoE) [8], raw data is evaluated using a two level factorial experiment 2^2 (equal to four runs or sensitivity cases), in which each factor is evaluated at only two levels (high or low) by run, to analyse the effects of both selection of sleeve conformance pressure (SCP) value and Rw uncertainties on the final calculated parameters. For this evaluation only m and m* were considered. The methodology investigates their impact at two levels: higher value and lower values from the reported lab data. A single replicate of this experimental design requires four runs of sensitivities. Figure 2 shows a geometrical representation of the 2^2 design using a square with the four combinations lying at the four corners. The treatment of the design is customised for every test (e.g. formation factor and multiple salinity tests). A statistical method, Analysis of Variance (ANOVA), was used to analyse the output. If issues are found with the data using this approach, then the lab is contacted to provide more information to evaluate any unreported issues that can compromise the validity of the results. As the data are being reviewed in real time, it is possible to take action to correct, re-measure, or in the worst-case scenario, repeat the measurements using a back up sample before the programme is completed.

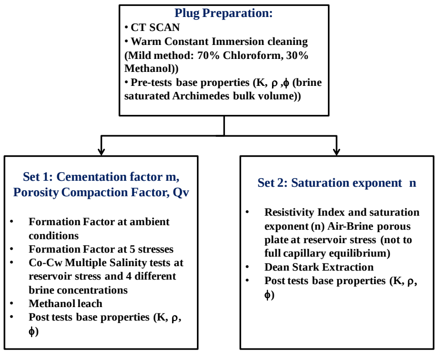

Figure 1 Generic SCAL programme for electrical properties

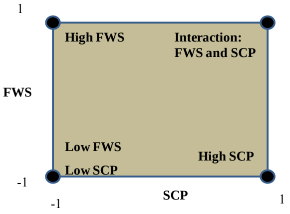

Figure 2 Schematic diagram of the 2^2 factorial experimental design (SCP: sleeve conformance pressure and FWS: Formation water salinity)

RESULTS AND DISCUSSION

The raw lab raw data were systematically evaluated. Tests were performed on a brine-saturated core plug in a Hassler cell at incremental stresses. It is essential to correct for the annular volume between the outside of the core plug and the inside of the rubber sleeve (SCP correction), which it is determined by monitoring volume of brine expelled and resistivity as function of stress over a low stress range (usually 40 psi to 300 psi). This value is used to correct expelled volume measurements at higher stresses and therefore, correct stressed pore volumes and ultimately, ‘m’ [4]. As the determination of SCP can be highly subjective, an upper and a lower estimate of SCP are normally made. Water resistivity (Rw) was also checked to account for potential variability on Rw due to experimental errors (e.g. errors in brine salinity concentration or conductimetric measurements). For this study, the predicted Rw values were obtained as a function of brine salinity using the Worthington *et al.* [9] method. Measurements of porosity and formation factor were made at five stress stations until the net reservoir stress was reached. Values of volume of brine expelled from the porous media are used to calculate porosity compaction factor (PCF) under isostatic conditions. Sensitivity analyses for SCP selected and brine resistivity (Rw) on the composite cementation factor 'm' and PCF were performed according to the 2^2 (equivalent to 4 sensitivity runs) factorial design shown in Table 1. The DoE analyses were carried out using a single repetition of the formation factor tests at 5 stresses on the selected 8 sample plugs tests planned for Set 1 (Figure 1) due to limitations in number of samples available (no twin or plugs available). The response 'm' and PCF correspond to the results obtained from the force fit linear regression of the log(F) at and log(ϕ) at reservoir stress and from the linear regression of ϕ at reservoir stress vs. ϕ ambient respectively after varying SCP and FSW as indicated in Table 1.

Table 1. 2^2 full factorial design applied to analyze 'm' as function of SCP and salinity variability on Set 1

Run	**Factors**		**Response**	
	SCP (psi)	**FWS (ppm)**	**m**	**PCF**
1	Low (-1)	Low(-1)	1.78	0.855
2	High(1)	Low(-1)	1.83	0.903
3	Low(-1)	High(1)	1.89	0.855
4	High(1)	High(1)	1.94	0.903

Salinity: high value: +25% of FWS – low value: -25% of FWS. FWS: 20000 ppm (Rw@77F=0.299 Ohm.m)
SCP: high value: 280 psi – low value: 160 psi

Correlations between salinity and SCP were obtained for 'm' and PCF where SCP and FWS are given according to the factor levels -1 or 1 from the full factorial analysis DoE:

$$m = 1.86 + 0.025SCP + 0.055FWS \quad \text{and} \quad PCF = 0.88 + 0.024SCP \qquad \text{(3) and (4)}$$

The ANOVA gives values of Prob>F (< 0.0001) indicating that m the model (equation 3) is significant for both factors on 'm' and model (equation 4) is only significant for factor SPC on PCF (for a significant result, Prob>F should be less than 0.05). The response obtained from the analyses gave a range of values for 'm' between 1.78 and 1.94, and PCF between 0.855 and 0.903. This means that the selection of SCP can be optimised within the range obtained from the DoE analysis performed that was found to have a significant effect on 'm' and 'PCF'. The design space for the variation of 'm' is illustrated in Figure 3. The composite 'm (1.82)' value obtained from the data as reported by the lab was included (experimental data: filled dots and linear regression: dotted green line) in this figure. In terms of data utilization, this gives the final user a better idea of the range in which 'm' can fluctuate depending on the selection SCP and the variability of the FWS. Even though this was designed for this particular SCAL program, the model could be updated with additional lab data and extended to analyse different sample sets with similar rock and fluid properties. If for instance composite 'm' values fall outside the design space, experimental data should be further scrutinise by including additional information. The outcome can be used to review, correct or re-measure data if required.

Raw lab data from multiple salinity tests performed straight after the formation factor tests on the same 8 sample plugs were analysed in a similar fashion to the formation factor tests. The Co-Cw tests were carried out by the lab contractor immediately after formation factor measurements at stress by flushing the samples successively with brines at 4 different concentrations using a high salinity contrast to optimise ionic equilibration periods. Measurements of Co and Cw pairs for each brine were used to determine the intrinsic formation factor, F* ($F^* = F\ (1 + BQvRw)$), BQv (via regression analysis of Co-Cw) and the intrinsic 'm*'. An initial QC step of this data set was to reconcile the Cw for each brine against estimated values using Worthington *et al.* correlations [9] as small errors in Cw affect the regressed value of BQv. All the calculations made by the lab contractor were also reviewed. The composite m* obtained from the raw data as reported by the lab is 1.85. Table 2 presents a sensitivity analysis on m* performed by setting a 2^2 full factorial DoE. The response m* values were obtained by linear regression of the stressed F* and stressed porosity by a combination of BQv estimated from values of Rw estimated from Worthington *et al.* [9] for each tested salinity and SCP as setup for every run in the experimental design presented in Table 2.

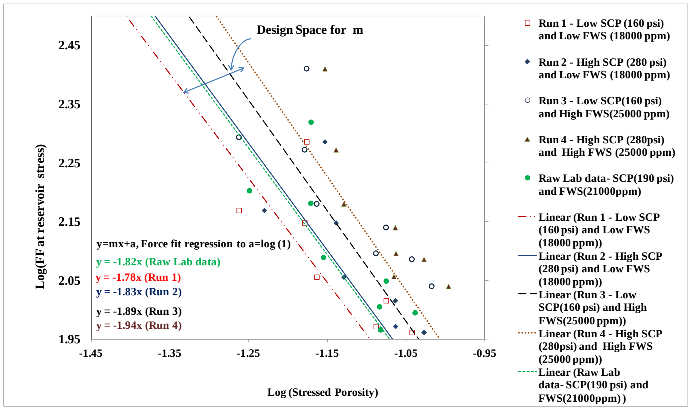

Figure 3 Designed space obtained for m based selection of the sleeve conformance pressure correction and experimental errors associated with the preparation of brine

Table 2 2^2 full factorial design applied to analyze 'm*' as function of SCP and salinity variability on set 1

Run	**Factors**		**Response**
	SCP(psi)	**FWS (ppm)**	**m*(Qv)**
1	Low(-1)	Low(-1)	1.75
2	High(1)	Low(-1)	1.82
3	Low(-1)	High(1)	1.78
4	High(1)	High(1)	1.82

Salinity: high value: salinity was setup to be 10000ppm higher or 10000 ppm lower than the reported lab values for each 4 different brine concentrations tested. Rw values were estimated using Worthington *et al.* [9] correlations for each tested salinity. SCP: high value: 280 psi – low value: 160 psi

The model for 'm*' was:

$$m^* = 1.79 + 0.026SCP + 0.0075FWS \qquad (5)$$

where SCP and FWS are given by the high and low levels of variation (1 or -1). Even though, the analysis of variance (Prob>F =0.2355) estimates that ‘m*’ is not significantly affected by the two experimental factors considered, a variation in ‘m*’ was observed. This is mainly due to the limited number of factors considered and the limited experimental data. The model can be improved by running a central composite design [8] to determine the effect and interactions between multiple factors and non-linearities.

CONCLUSIONS

The Design of Experiments (DoE) approach for “real time” quality control allows the detection of anomalous behaviour of experimental SCAL electrical properties data by underlining hidden information that is generally difficult to observe using conventional analysis. The method allows several experimental factors to be taken into consideration simultaneously, instead of one factor at a time which makes the QC of the SCAL data tedious and time consuming. The method was illustrated by applying the simplest case of a full factorial 2^2 with two levels on a sensitivity evaluation of the selection of SCP and the variation of the brine concentration to obtain cementation factor ‘m’ and ‘m*’. Statistical correlations for ‘m’ and ‘m*’were found based on the variability of two factors: brine concentration and selection of the SCP. This approach assumes that the variability in the estimated values of m and m* are due to experimental factors, and not to intrinsic factors of the sample, Further work needs to be performed to optimise the methodology proposed to extend it to more complex SCAL data cases that also considers all possible factors, which will be subject of future work.

REFERENCES

1. Worthington, P. F. “The Petrophysics of Problematic Reservoirs” *JPT* (2011) **64**, 12, p.p 88-97

2. Amabeoku M. A., Nakagawa F., and BinNasser R. H. “Quality Control/Quality Assurance Assessments of Core Analysis Data from Multiple Commercial Laboratories” *SPWLA 52nd Annual Logging Symposium Procedings* Colorado Springs, Co, USA (2011) SPWLA-D-10-00092

3. McPhee C. A. and Arthur K. G. “Relative Permeability Measurements: An Inter-Laboratory Comparison” *SPE 28826*, London UK 25-27 October (1994)

4. McPhee C. A “The Core Analysis Elephant in the Petrophysics Room”, Society of Core Analysts Paper SCA2012-29, presented at International Symposium of the Society of Core Analysts, Aberdeen, 2012

5. Sprunt E. S. and Humphreys N. V. “Obtaining Reliable Laboratory Measurements” *JPT,* (1994) **46**, 4, pp 281

6. Waxman, M.H., and Smits, L.J.M. “Electrical Conductivities in Oil-Bearing Shaly Sands” *SPEJ* (1968) **8**, pp107-122.

7. Juhasz I. “Normalised Qv - The Key to Shaly Sand Evaluation using Waxman-Smits Equation in the Absence of Core Data”, *SPWLA 22nd Ann. Logging Symp.*(1981)

8. Montgomery D. C. “*Design and Analysis of Experiments*” John Wiley & Sons, Inc. USA (2004) 6th edition

9. Worthington A. E., Hedges, J. M and Pallat, N. “SCA Guidelines for Sample Preparation and Porosity Measurement of Electrical Resistivity Samples: Part 1 – Guidelines for Preparation of Brine and

Determination of Brine Resistivity for Use in Electrical Property Measurements”, *The Log Analyst* (1990), **31**, 1 p.p 20-28.