SENSITIVITY ANALYSIS OF ERRORS IN RESERVE EVALUATIONS DUE TO CORE AND LOG MEASUREMENT INACCURACIES.

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ABSTRACT. Reserve evaluations, using the volumetric reserves equation, are very dependent on the accuracy of measurements used to calculate initial water saturation. Water saturation is calculated from petrophysical parameters including porosity, cementation and saturation exponents, formation water resistivity and true formation resistivity. The effect of inaccuracies in these parameters upon reserves is often intuitively, rather than quantitatively, understood by geologists, engineers and management.

Sensitivity analysis of the petrophysical parameters address this problem by using a set range of errors for each individual parameter. The benefit of sensitivity analysis is that it can rapidly establish the most significant core and log measurements in terms of the greatest quantitative effect on calculated reserves. They are simple to use and can be performed in a minimal amount of time at negligible cost.

Establishing the most significant reserve sensitivities leads to the objective identification of priorities regarding which petrophysical parameters require greatest precision. Thus, a systematic approach can be applied to planning of coring and logging programmes. The result is improved confidence in the planning and cost effectiveness of coring, core analysis (special and conventional), SEM and petrological studies and wireline logging programmes when evaluating reserves.

Examples representative of a Rotliegende Group gas reservoir and a Brent Group oil reservoir and of the Southern and Northern North Sea respectively illustrate why analyses should be conducted using values representative of the actual reservoir. The results also demonstrate that precision in some petrophysical parameters is a greater requirement than for others.

In these examples, reserve evaluation is far more sensitive to porosity, cementation and saturation exponent inaccuracies in the Rotliegende than in the Brent example. This is significant since porosity, cementation exponent and saturation exponent are measured by core analysis and not with such confidence from wireline logs. Reserves in both examples are relatively insensitive to formation water resistivity and log-derived true resistivity.

INTRODUCTION.

If an exploration well encounters hydrocarbons, answers are required to fundamental questions regarding the technical viability and economic risk of appraising and subsequently developing the field. A major source of risk is reserve estimate inaccuracy (Cockcroft,1990). This can arise from the lack of a representative geological and petrophysical dataset. As a result, premature assumptions can be made that may adversely effect decision making by geoscientists, engineers and managers.

The effects of uncertainties and inaccuracies upon reserves can be estimated by probabalistic methods such as Monte Carlo simulations (Aguilera,1979). This method can be inconvenient as different outputs can be obtained from repeat analysis using the same inputs. When an input is changed the relationship between the inputs and outputs may not be apparent (Martin, 1988). The advantages of sensitivity analysis are that no prior knowledge of distribution types or probabilities are assumed, results are directly attributable to a parameter change and they can be conducted on hand-held calculators.

SENSITIVITY ANALYSIS.

The objectives of a sensitivity analysis are to identify the core and log measurements of petrophysical parameters whose potential inaccuracies yield the largest reserve errors, and to assign reservoir evaluation project priorities.

The basis for sensitivity analysis is the volumetric reserves equation:

$$\text{STOOIP or GIIP} = \frac{C \,.\, A \,.\, h \,.\, \phi \,.\, (1-S_{wi})}{FVF} \qquad ....[\text{Eq } 1]$$

Where,

STOOIP	original oil in place, STB (S.T.m^3)
GIIP	gas initially in place, SCF (m^3)
C	conversion factor (ie 7758.4 for STB, 43560 for SCF)
A	area of reservoir, acres (km^2)
h	thickness of net pay, ft (m)
ϕ	average porosity, decimal fraction
S_{wi}	initial water saturation, decimal fraction
FVF	formation volume factor, (Res Bbl/STB (Res m^3/S.T.m^3)

Hydrocarbon saturation (S_h) is obtained as:

$$S_h = (1-S_{wi}) \qquad ....[\text{Eq } 2]$$

Water saturation is obtained from log calculations or capillary pressure data. The sensitivity analysis investigates the relationship between potential inaccuracies in the core and log measurements used to calculate S_{wi} (porosity, cementation and saturation exponents, formation water resistivity and true water resistivity) and the resultant reserves that are calculated. The fundamental equation used to calculate water saturation is the empirically derived Archie (1942) equation:

$$S_w^n = \frac{(R_w)}{(\phi^m . R_t)} \qquad ....[Eq\ 3]$$

Where,

S_w	water saturation, decimal fraction
R_t	true resistivity, ohm.m
R_w	formation water resistivity, ohm.m
ϕ	porosity, decimal fraction
m	cementation exponent
n	saturation exponent

It is essential to calculate S_{wi} from values considered most representative of the area to obtain meaningful sensitivity analysis results. These values are the preliminary "correct" values. It may be preferable to analyse layers individually in a multilayered reservoir.

The first step is to remove C, A, h and FVF from the error analysis as they are not core or log measurements. Note that a given percentage change in the net rock volume (A.h) results in an identical change in calculated reserves, both in terms of the percentage change and its sign (ie a 5% increase in A.h yields a 5% reserve increase). A FVF change by a given percentage produces an identical but opposite percentage reserves change (ie FVF increase by 5% reduces reserves by 5%).

Investigation of net thickness sensitivity to inaccuracies in core and log measurements requires a representative geological and petrophysical database. Once the database exists, analysis could investigate the relationship between potential parameter inaccuracies, cut-off criteria and the net thickness.

A volumetric constant, V, is substituted for A, h, FVF and C in the sensitivity analysis. The constant is calculated as:

$$\text{GIIP} = \frac{\text{Assumed GIIP}}{(1-S_{wi}) . \phi} \qquad ....[Eq\ 4]$$

$$\text{STOOIP} = \frac{\text{Assumed STOOIP}}{(1-S_{wi}) . \phi} \qquad ....[Eq\ 5]$$

Assumed GIIP and STOOIP can be any value, whether the current best estimate or an estimate that is convenient to use, ie 100MMbbls STOOIP or 1Tcf GIIP used in the examples. Once values have been selected, a set range of errors for the parameters is assigned. The examples use +/-10% which corresponds with the work of DeSorcy (1980). The reserves and sensitivities are calculated by varying the parameters individually.

The results from the sensitivity analysis of individual parameters have two attributes. Firstly, they quantify the change in reserves that would be calculated due to the inaccuracies. Secondly, the results show which error caused the reserve increase and which caused the decrease. The most significant reserve sensitivities are established by comparing the results.

EXAMPLES OF SENSITIVITY ANALYSIS.

To illustrate some applications of sensitivity analysis, two examples from contrasting hydrocarbon provinces of the North Sea are described. The parameter values are not from specific fields but typify data from the two areas. For simplicity, m=n=2.0 was adopted. The calculations were completed on a programmable calculator within minutes, indicating the minimal time required and the nominal cost. Consequently, several "what if" analysis should be conducted when there is great uncertainty.

Example 1: Rotliegende Group Gas Field, Southern North Sea.

The first example is from the Southern North Sea, commonly referred to as the Southern Gas Basin. The reservoirs are comprised of Early Permian Rotliegende Group sands which are predominantly a sequence of stacked aeolian dune deposits. The sands generally have little or no shale and provide good quality reservoir rock. They unconformably overlie Carboniferous Coal Measures which are the source rock for the region. The reservoirs are overlain by Zechstein salt which is responsible for the salt-saturated formation water.

A gas reserve of 1Tcf was assumed for the sensitivity analysis. The Archie equation was used without requiring shale corrections. Values representative of porosity, formation water resistivity, true formation resistivity, cementation and saturation exponent were selected as the "correct" values for the analysis.

The results (Table 1, Figure 1a) show that the gas reserves are most sensitive to porosity inaccuracies. Note that the plus and minus change in reserves are equal. This is not so for m and n where, in addition, an inverse relationship exists between the inaccuracy and reserve change. This is significant as porosity, m and n are parameters which are primarily obtained from core analysis measurements. Less sensitivity is indicated to R_t (obtained from logs) and R_w (obtained from chemical analysis and wireline log calculations). Furthermore, by using errors of upto +/-50%, it is seen that errors induced by m,n and R_t are not linear (Figure 1b).

TABLE 1 Sensitivity analysis results. Rotliegende Group gas field (Southern North Sea).

"CORRECT" VALUE		+/-10% ERROR	S_h $(1-S_{wi})$	GIIP (BCF)	CHANGE (%)
		0.0162	0.575	1041.52	+ 4.15
R_w	0.018			1000.00	
		0.0198	0.531	960.51	- 3.96
		0.135	0.503	819.10	-18.09
$\emptyset$	0.15			1000.00	
		0.165	0.593	1180.90	+18.09
		3.6	0.528	956.20	- 4.38
R_t	4.0			1000.00	
		4.4	0.573	1037.65	+ 3.77
		1.8	0.630	1139.80	+13.98
m	2.0			1000.00	
		2.2	0.459	831.00	-16.90
		1.8	0.591	1069.20	+ 6.92
n	2.0			1000.00	
		2.2	0.518	938.60	- 6.14

For establishing reserve evaluation priorities, the sensitivity analysis shows that porosity

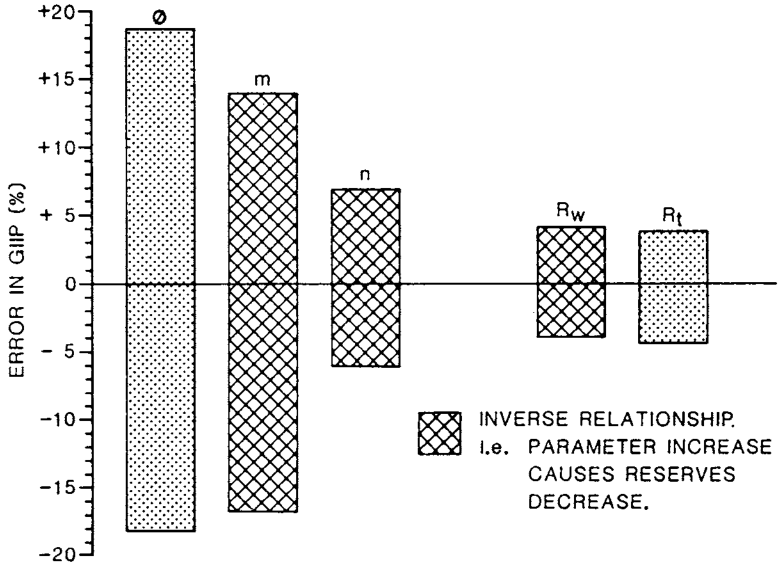

FIG. 1a SOUTHERN NORTH SEA EXAMPLE (ROTLIEGENDE GAS FIELD)

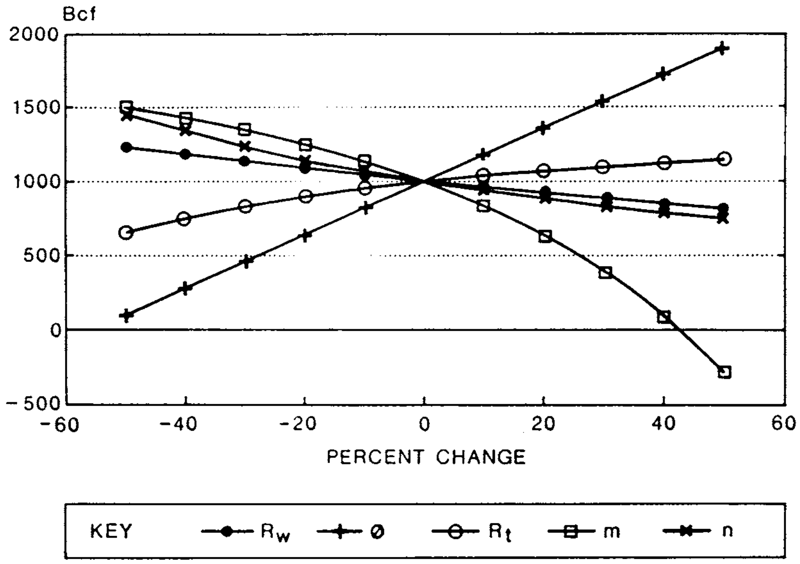

FIG. 1b ROTLIEGENDE GAS FIELD

requires greatest precision both from wireline logs and core analysis. This is because it occurs twice in the reserve calculation, firstly as porosity, and secondly it is used to calculate S_w. Porosity can appear a third time if used as a cut-off criterion for net thickness. Cores will be also required for the precise evaluation of m and n by special core analysis techniques. Thus, coring and wireline logging programmes can be planned accordingly.

Example 2: Brent Group Oil Field, Northern North Sea.

The second example is a Middle Jurassic Brent Group oil reservoir from the Northern North Sea. The Brent Group is considered to represent a prograding delta sequence comprised of five formations. They are interpreted as deposits of the prodelta at the base, overlain by delta slope, barrier bar complex, delta plain and marine transgressive depositional environments. The formation water is similar to sea water.

In contrast to the Rotliegende Group example, the Brent Group contains shale, mica and carbonaceous material in the layered reservoirs. These can complicate log analysis. The presence of shale may require the use of shaly sand equations for the calculation of S_w. Sensitivity analysis can be used to investigate the problem by two methods. Firstly, a shaly sand equation can be used, or secondly, low or zero shale volume (V_{sh}) net reservoir can be analysed with the Archie equation.

Using a shaly sand equation poses the question, "Which equation is most appropriate?" Equation selection affects the calculated S_w value, which will result in different reserve estimates being calculated. To investigate the consequences of selecting a particular shaly sand equation, sensitivity analysis can incorporate alternative equations and hence indicate the reserve sensitivities.

A field with a STOOIP of 100MMbbl and data from offset Brent Group fields were assumed as "correct" for the sensitivity analysis. The model was used with average values representative of the net reservoir. The Archie equation was used for this preliminary analysis.

The only measurement that cannot be corrected for shale effects (or selectively sampled) is R_t. Wireline logs are the only source of R_t. The results of this analysis show that reserves sensitivity to R_t in the net reservoir is low. Therefore, in this example, the analysis appears to be sufficiently robust to establish the most significant core and log measurements without the use of a shaly sand equation.

TABLE 2: Sensitivity analysis results. Brent Group oil field (Northern North Sea).

"CORRECT" VALUE		+/-10% ERROR	S_h $(1-S_{wi})$	STOOIP (MMbbl)	CHANGE (%)
		0.099	0.770	101.64	+ 1.64
R_w	0.11			100.00	
		0.121	0.746	98.44	- 1.56
		0.225	0.730	86.80	-13.20
Ø	0.25			100.00	
		0.275	0.779	113.20	+13.20
		27.0	0.744	98.27	- 1.73
R_t	30			100.00	
		33.0	0.769	101.49	+ 1.49
		1.8	0.789	104.14	+ 4.14
m	2.0			100.00	
		2.2	0.721	95.25	- 4.75
		1.8	0.793	104.66	+ 4.66
n	2.0			100.00	
		2.2	0.724	95.60	- 4.40

The Brent Group reserve sensitivities are generally less than in the Rotliegende example. The analysis indicates that the main priority for core and log precision is porosity (Table 2, Figure 2a). The reserves are also sensitive to m and n which are primarily obtained from special core analysis. The reserves are least sensitive to inaccuracies in R_w. The problem of establishing net thickness remains a high priority. The non-

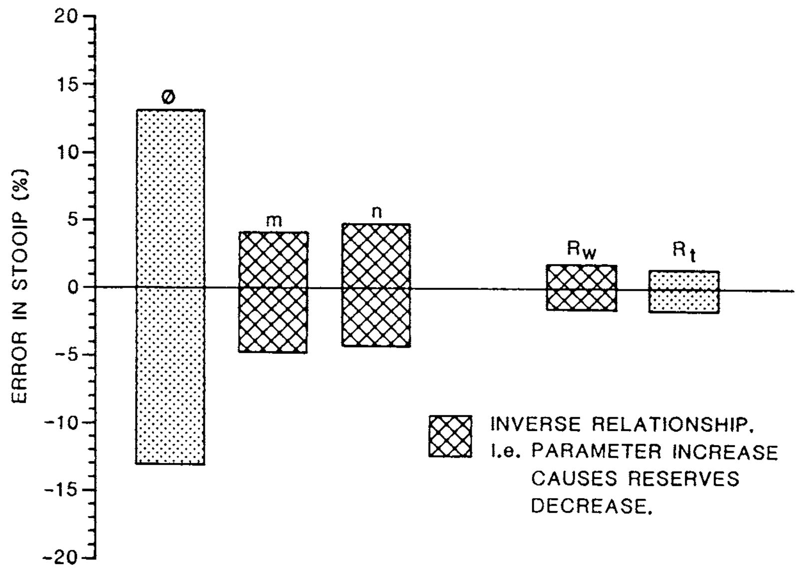

FIG. 2a NORTHERN NORTH SEA EXAMPLE (BRENT OIL FIELD)

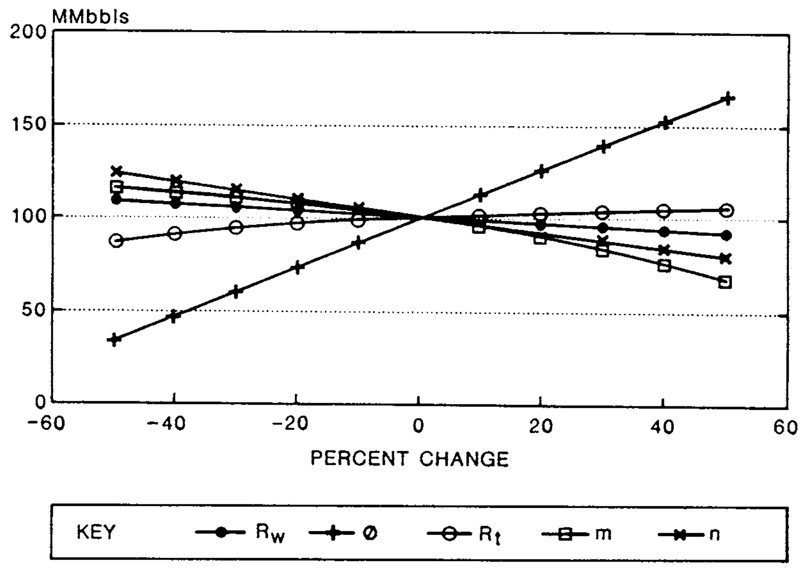

FIG. 2b BRENT OIL FIELD

linear sensitivity of reserves to large errors in m and R_t is again demonstrated (Figure 2b).

The precise calculation of log porosity in Brent Group reservoirs can be severely handicapped by the variable mica, shale and carbonaceous content. Complex lithology interpretation methods can be used to calculate log porosity. Measurements from core analysis are needed to ensure precision and confidence in the results. However, the selection of core plugs requires care with regard to the varying mineralogical content of the reservoirs. Poor sampling could lead to results that do not accurately represent the individual layers. The use of SEM and petrological studies could assist in this respect.

PERCENTAGE CHANGES VERSUS VOLUME CHANGES.

To define project priorities attention is focused on which core and log measurement inaccuracies yield the largest reserve sensitivities. This is assessed using the percentage change in the reserves.

However, it can be misleading if only percentages are considered. Volumetric changes in the reserves are also significant. For example, a 10% increase in reserves in the Brent Group reservoir is an increase by 10MMbbls. However, a 10% increase in a billion barrel field is a 100MMbbls increase. There is a significant difference between the two volumes although the percentage is the same. It is therefore necessary to consider both the percentage change and the volumetric change in reserves.

PLANNING OF RESERVE EVALUATION PROJECTS.

Results of a sensitivity analysis can be rapidly calculated once the petrophysical values of a specific field are selected. The examples illustrate different reserve sensitivities to core and log measurements in different reservoirs. The benefits are that results are repeatable, potential reserve evaluation errors attributable to specific sources are quantifiable, and the direction of reserve estimate change is indicated.

Based on the principle that the greater the reserve sensitivity, the greater the need for precision, sensitivity analysis are effective in objectively identifying the core and log measurements which require the greatest accuracy and precision for reserves evaluation.

Thus, a systematic approach can be applied to assigning project priorities. The result is improved confidence in the planning and cost effectiveness of coring, core analysis (conventional and special), SEM and petrological studies and wireline logging programmes when evaluating reserves. This can result in better reserves evaluation and reduced financial risk. The potential reserve errors obtained from the analysis can be used to emphasise that reserve estimates are subject to subsequent revisions. Consequently, geoscientists, engineers and management will be aware of potential fluctuations in reserve estimates.

LIMITATIONS OF SENSITIVITY ANALYSIS.

1). The "correct" values are assumed.

In the Brent and Rotliegende reservoirs sufficient information usually exists to enable reasonable "correct" values for reservoir parameters to be assumed. Where exploration has been sparse, this may not be the case. The potential success of a sensitivity analysis will be affected.

2). The results are based on a model in which all parameters are assumed to be independent.

This is not the case. However, in most cases with inaccuracies of less than 10-15% the method is sufficiently robust to fulfil its objectives.

3). The method assumes a clean formation or that reservoir parameters and water saturation have been corrected for shale volume.

For low V_{sh} (<10-15%) calculated water saturation is fairly insensitive to the use of a clean Archie equation. As shale content increases so will potential problems and a shaly sand equation should be used. These equations can be easily incorporated into a sensitivity analysis (a sensitivity analysis of the different shaly sand equations could be applied).

4). A consistent definition of porosity is necessary.

Discussion of the relative merits of total and effective porosity systems is beyond the scope of this paper. It is sufficient to state that consistent measurements should be used.

CONCLUSIONS.

1. Sensitivity analysis is easy to use and can be performed quickly and cheaply.

2. For valid results, a sensitivity analysis should be conducted using values considered most representative of the actual reservoir.

3. The effects of potential core and log measurement inaccuracies upon reserves can be quantified.

4. Establishing the most significant reserve sensitivities leads to the objective identification of priorities regarding which core and log measurements require greatest precision.

5. A systematic approach to core studies and wireline logging programmes can be determined which improves confidence in the cost-effectiveness of project planning.

6. Potential reserve errors resulting from core and log measurement inaccuracies can be given to project personnel to emphasise that reserve estimates are subject to subsequent revision.

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