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THE PREDICTION OF SATURATION USING THE CARBON/OXYGEN
LOG SUPRI TR-40

By
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Work Performed Under Contract No. AC03-81SF11564

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ABSTRACT

This project investigates the nature of Dresser-Atlas Carbon/Oxygen Log gamma ray spectra. It presents an attempt to improve the signal-to-noise ratio of the C/O and Si/Ca parameters used by Dresser-Atlas to determine oil saturation.

Two techniques were developed to subtract the Compton background from the spectral data. Neither technique significantly improves the accuracy of the cased-hole prediction of oil saturation. However, it has been shown that it is possible to develop a satisfactory correlation for oil saturation on a well-by-well basis. This correlation can then be used to generate oil-in-place from the C/O and Si/Ca ratios.

1. INTRODUCTION

The Dresser-Atlas Carbon/Oxygen Log (C/O log) is a tool capable of measuring oil saturation behind casing. It is one of two spectral gamma ray devices offered by the two competing logging firms: Schlumberger and Dresser-Atlas. In zones of high water salinity, the common practice is to use a pulsed-neutron capture log (for example the Schlumberger Thermal Decay Time log), since the response is better understood. However, in fresh water reservoirs the tool cannot distinguish between oil and water. It was for such situations that the C/O log, and the Schlumberger Gamma-Ray Spectral tool (GST) were developed.

The GST is, at the time of writing, still an experimental tool. Measurements are made during five minute stationary readings, so that the logging speed is very slow. Consequently, it is an expensive tool to run. In contrast, the C/O log is routinely run in enhanced oil recovery projects where water salinity is low. Capable of operating in the continuous mode, the tool is fast and inexpensive. While the characteristics of the spectral gamma ray devices are fairly well understood, interpretation of C/O log data has proved to be much more complex with most analysis techniques being empirical.

This study consists of two parts. First, the raw gamma ray spectra were obtained from C/O logs run in several wells in the Kern Front Field, Bakersfield, California. The wells formed part of an enhanced oil recovery project. These data were collected with the intention that new means of processing the data would be developed, yielding more accurate information about reservoir properties such as porosity and oil saturation. Core data were available, in addition to a comprehensive suite of open-hole logs. The objective was to look for a correlation between the open-hole log measurements and the processed C/O log parameters.

The second part of the study involved the application of the results to a field project at the Kern River Field, Bakersfield, California. Core data, open-hole log measurements and GST-derived values of oil saturation were available for comparison.

2. THE GAMMA RAY SPECTRUM

The principle of the C/O log is similar to that of Neutron Activation Analysis.¹ This is a common laboratory analysis technique capable of detecting trace elements in the parts per billion range. A pulse of neutrons from a downhole generator, excites the formation, producing radioactive nuclei. These then decay through processes that are usually accompanied by a gamma ray emission. Each element has a set of gamma rays whose energies are uniquely determined. By counting the number of these gamma rays, and normalizing to a standard source, the abundances of the elements can be determined. In the logging environment, this simple laboratory technique has severe problems. Generally, a low resolution sodium iodide crystal detector is used.² Yet the gamma ray spectrum is very complex (due to the number of contributing elements). The result is a poorly resolved spectrum, in which the gamma ray peaks tend to overlap (Figure 1).

A process, called Compton scattering, whereby higher energy transitions deposit only part of that energy in the crystal, contributes to the background on top of which the discrete full energy photopeaks are superimposed (Figure 2).³ Electronics are available to discriminate against this background, but it has proved impossible to include this in the downhole tool so far.

FIG.2 SCINTILLATION DETECTOR RESPONSE

FIGURE 1 - SURFACE CALIBRATION

AFTER V.C. MCWHIRTER²

Two energy spectra are fact recorded. The inelastic spectrum is detected during the neutron burst, the other is recorded about 50 μ sec later,⁴ just before the next burst (see Figure 3). This is the thermal neutron capture

FIG.3 GST INELASTIC MODE TIMING PROGRAM

AFTER WESTAWAY, HERTZOG AND PLASEK¹⁰

spectrum, so called because the remaining neutrons in the formation have kinetic energy reduced to the thermal energy level, primarily by elastic scattering. Continuous logging is made possible by using a high frequency neutron generator. This results in poorer statistics than in a laboratory experiment, but peaks due to the transitions of the more common elements are clearly visible (Figures 4 and 5).

FIG.4 TYPICAL INELASTIC SPECTRUM

FIG.5 TYPICAL CAPTURE SPECTRUM

During the neutron burst, two types of interactions between the neutrons and the nuclei in the formation are possible in addition to simple elastic scattering.⁵ The first is the activation reaction. For example:⁶

The new nucleus is radioactive and β -decays back to ^{23}Na , occasionally giving off a 1.62 Mev gamma ray when the transition is to an excited state of ^{23}Na . The second interaction is termed inelastic scattering. For example:

This reaction also occurs during the neutron burst, and the gamma ray is recorded in the inelastic spectrum:

Similarly oxygen activation is possible:

The same gamma ray appears in the inelastic spectrum through the reaction:

It is important to realize that while the activation or inelastic reaction is very fast, the β -decay is much slower. The resulting gamma ray is then delayed and appears in the capture spectrum. Prompt gamma rays appear only during the neutron burst.

For carbon there is only one important reaction:

Many commonly occurring earth elements have large neutron capture cross-sections,⁷ and produce many peaks in the capture spectrum. The most important capture process is that of thermal neutrons by hydrogen:

Table I provides a list of the more intense gamma rays produced by the earth elements.

The output of the detector electronics is not a spectrum of counts versus energy, but counts versus channel number. This is a computer generated division of the energy range. The calibration is performed by placing the hydrogen peak in channel 64,² and one of the iron peaks in channel 204. (see Figure 5). This is not always done properly, so there is some variation in the positions of the photopeaks in the spectrum.

Note that as the energy of the gamma ray reaches about 3 Mev, the main photopeak (see Figures 4) is accompanied by two others. The escape peaks are respectively 14 and 28 channels down on the photopeak. This gap translates into 0.51 or 1.02 Mev, or one or two electron rest masses. One way the incoming gamma ray can deposit its energy in the detector is by the photoelectric effect. This gives rise to the main photopeak. If the energy of the gamma ray is high enough it can generate an electron-positron pair. In each case, the generated electron(s) deposit the majority of the photon energy in the crystal through ionization processes. Eventually, however, a positron is annihilated by an electron when it comes to rest. The energy of annihilation appears as two photons, one or both of which may escape the detector, each one carrying off 0.51 Mev. A third process, known as Compton scattering, has been noted as causing the background on which the photopeaks are superimposed.⁸

Table I

The Most Intense Gamma Rays of a Natural Formation

Inelastic Spectrum

<u>Parent Nucleus</u>	<u>Energy (MeV)</u>	<u>Channel Number</u>
^{28}Si	1.78	51
^{12}C	4.43	128
^{16}O	6.13	177
^{23}Na	1.62	48

Capture Spectrum

<u>Parent Nucleus</u>	<u>Energy (MeV)</u>	<u>Channel Number</u>
^{25}Mg	1.62	48
^{23}Na	1.62	48 (from activation)
^{28}Si	1.78	51 (from activation)
^{40}Ca	1.96	57
H	2.2	64
^{28}Si	3.54	104
^{28}Si	4.93	143
^{35}Cl	6.00	172
^{16}O	6.13	177 (from activation)
^{40}Ca	6.42	184
^{56}Fe	7.64	218

Most of the gamma rays outlined in Table I appear in the logged spectra, especially several spectra are added together to improve the statistics (Figures 4 and 5). The exception is carbon--no evidence of a photopeak or either of the escape peaks is seen. There are cases where peaks overlies one another due to the poor resolution of the sodium iodide crystal. For example, it is not possible to distinguish between ^{28}Si at 1.78 Mev and ^{23}Na at 1.62 Mev. It is also difficult to resolve the peaks due to oxygen activation and chlorine capture.

Output from the field log is normally in the form of C/O and Si/Ca ratios. These are derived from measurements that reflect the number of gamma rays emitted by these elements. The gamma ray spectrum in fact contains much more information than this.

The nature of the gamma ray spectrum is such that changes in the values of the C/O and Si/Ca ratios are not simply related to changes in the abundance of the elements themselves. In any given window of the spectrum, in which gamma rays of a certain element are counted, there are also Compton-scattered events whose contribution is difficult to predict.³ An effort was made to subtract out this background, and is detailed in the next section.

3. SPECTRAL PROCESSING

The GST spectrum is deconvolved using the responses of standard sources.⁹ Output is in the form of elemental yields, and yield ratios such as C/O and H/(Si+Ca). The yield ratios are directly related to elemental abundances; so interpretation is straightforward (see section 5).¹⁰

The Dresser-Atlas approach is simply to define windows about the known photopeak energies of the four important elements (C, O, Si, Ca - see Figures 6 and 7), and integrate the number of counts over that energy interval.² The Si/Ca and C/O count ratios are continuously recorded against depth to give a

Gamma Rays Assigned to Carbon and Oxygen by the Dresser Program

FIG.6 INELASTIC SPECTRUM

Gamma Rays Assigned to Silicon and Calcium by the Dresser Program

FIG.7 CAPTURE SPECTRUM

log trace. However, the element that has a transition in a given energy window makes only a small contribution to the total number of counts. The contribution of the Compton background is determined by the concentrations of elements having transitions of higher energy than the element under consideration.

3.1 The Spline Program

The first processing technique attempted to separate the background and photopeaks. The improvement in the signal-to-noise ratio should produce more successful correlating parameters. In conventional neutron activation analysis the peaks are clearly visible, and a set of gaussian peaks superimposed on a quadratic background is least-squares fit to the spectrum. The area of each gaussian peak is compared with that of a known quantity of the gamma ray producing element.¹ It was felt, however, that the quality of the data did not warrant such an elegant approach. Instead, it was decided that by simply drawing a smooth curve through the background it would be possible to achieve the same results. The interpolating function was chosen to be a cubic spline.

A spline is an interpolation device which has the unique property of fitting exactly all the fixed points (or knots) specified.¹¹

A running sum was performed over five depth stations (files) to improve statistics. The central file was depth correlated. A complication arose in that the Dresser-Atlas tape appeared to contain points where information pertaining to one depth was spread over two or more files. It was concluded that the electronics repeatedly misfired. (Figure 8 shows a misfire file). The first part of the processing program condensed the files back to one (Figure 9), and removed the extraneous file.

FIG.8 CAPTURE SPECTRUM OF A MISFIRED FILE

FIG.9 CAPTURE SPECTRUM OF A RECREATED MISFIRE FILE

A spline was drawn through the minima of the photopeaks, and subtracted from the log data (Figures 10 and 11). An integration was performed between successive pairs of knots set up around the important gamma ray peaks. Then normalizing to the total counts in the appropriate spectrum, an estimate of the concentrations of the elements involved is made.¹²

The spline program goes through two passes. The first pass uses knots specified by the user--being those channels most commonly associated with the spectral minima. At the end of the first pass, the program determines a new set of knots derived from the minima it finds in the first background-subtracted spectrum. This peak searching routine compensates for detector drift.

The program did successfully isolate the main peaks. This is especially true for hydrogen, which produced a strong gaussian photopeak. For the other elements the resulting peak is very jagged. This is due to the small size of the peak compared to the random error. This error ranges from 100 counts (for a five-fold summation) at the low energy end of the spectrum, to 40 at the higher energy end. Only carbon failed to produce a readily locatable peak. The carbon peak typically had a maximum value of fewer than 40 counts. The five most readily observable peaks (see Figures 12 and 13), plus the peak assigned to carbon by the program, were used for correlation with results from the open-hole log measurements (Schlumberger FDC and EPT). Analysis showed that the open-hole log measurements were in good agreement with the core data, but it was felt that the former provided a more complete record of the reservoir properties.

FIG.10 CAPTURE SPECTRUM, RAW SPECTRUM(—) AND SPLINE(SHADED)

FIG.11 CAPTURE SPECTRUM SPLINE SUBTRACTED FROM RAW SPECTRUM

Gamma Rays Assigned by the Program Spline to Calcium, Hydrogen and Iron

FIG.12 CAPTURE SPECTRUM

Gamma Rays Assigned by the Program Spline to Silicon, Carbon and Oxygen

FIG.13 INELASTIC SPECTRUM

Table II illustrates the correlation between the open-hole log measurements and the cased-hole data. A correlation coefficient near one implies an excellent correlation between the two sets data being compared (e.g. Ca ratio and oil saturation). A negative correlation coefficient implies an anti-correlation while a coefficient near zero indicates no significant relation. Similar conclusions apply to the multiple correlation coefficient, which represents the overall quality of fit between the open-hole log measurements and the cased-hole parameters. A value greater than 0.7 is considered satisfactory.

Table II

Optimum Parameters and Correlation Coefficients From Program 'Spline'

Oil Zone 2465'-2628'

$$\text{Open-hole parameter} = A_0 + A_1 \text{ Ca} + A_2 \text{ Si} + A_3 \text{ Fe} + A_4 \text{ C} + A_5 \text{ O} + A_6 \text{ H}$$

Open-hole Parameter	A_0	A_1 (Ca)	A_2 (Si)	A_3 (Fe)	A_4 (C)	A_5 (O)	A_6 (H)	Multiple Corr. Coeff.
100S regression coefficient	1.824	0.334	-0.188	-0.182	-0.140	-0.107	0.063	
correlation coefficient (Open-hole logs)		0.385	-0.369	0.239	-0.091	-0.138	0.282	0.582
100S _w regression coefficient	1.164	0.674	-0.10	0.671	-0.615	-0.149	-0.070	
correlation coefficient (Cores)		0.314	-0.68	0.303	-0.289	-0.042	0.128	0.558
S _o regression coefficient	0.498	-0.225	0.034	-0.283	0.164	0.107	0.019	
correlation coefficient (Cores)		-0.318	0.251	-0.409	0.252	0.098	-0.113	0.640

3.2 The Window Selection Program (Windows)

An alternative approach was devised that was similar to the Dresser-Atlas analysis but utilized additional windows. These new windows included the higher energy gamma ray transitions which contributed to the Compton background of the more important peaks. By including these in the correlation procedure, the Compton scattering from the windows would be eliminated. A similar technique is used in processing natural gamma ray spectra in uranium logging.¹³

To investigate the relative importance of the individual windows, a large number (10) were defined about the most prominent peaks. To remove the effects of source strength variations, the integrated window counts were normalized by dividing by total counts in the appropriate spectrum. The windows were fixed, and operated on the raw spectra (without Compton background subtraction). Ten windows were initially specified, (Figures 14 and 15 give the locations of the windows in the capture and inelastic spectra) but the number was later reduced to eight (Figures 16 and 17).

Tables III and IV summarize the significance of the various windows in terms of the individual correlation coefficients. Also shown are the overall correlation coefficients for a selection of open-hole log parameters. The notation oil zone and water zone refers to two intervals in the same well. The water zone also contained a large number of shale beds.

Gamma Ray Windows Used by Program Windows (Ten Window Version)

CAPTURE SPECTRUM

SUMMATION OVER 231 FILES

FIGURE 14

Gamma Ray Windows Used by Program Windows (Ten Window Version)

INELASTIC SPECTRUM

SUMMATION OVER 231 FILES

FIGURE 15

Gamma Ray Windows Used by Program Windows (Eight Window Version)

CAPTURE SPECTRUM

SUMMATION OVER 231 FILES

FIGURE 16

INELASTIC SPECTRUM

SUMMATION OVER 231 FILES

FIGURE 17

TABLE III

Correlation Between Open-hole and Cased-hole Logs - Program Windows (Ten Window Version)

$$\text{Open-hole parameter} = A_0 + A_1 H + A_2 \text{Fe} + A_3 \text{OXIN} + A_4 C + A_5 \text{SiCl} + A_6 \text{SiC2} \\ + A_7 \text{SiC3} + A_8 \text{SiIn} + A_9 \text{Ca} + A_{10} \text{OXACT}$$

Oil Zone 2645-2600'

Open hole Parameters	A ₀	A ₁ (H)	A ₂ (Fe)	A ₃ (OXIN)	A ₄ (C)	A ₅ (SiCl)	A ₆ (SiC2)	A ₇ (SiC3)	A ₈ (SiIn)	A ₉ (Ca)	A ₁₀ (OXACT)	Multiple Corr. Coef
regression S _w coefficient	-1.075	-0.299	0.294	0.161	-0.715	0.558	-0.906	0.950	-0.085	-0.084	0.843	
correlation coefficient		-0.392	0.189	0.243	-0.434	-0.319	-0.464	0.133	-0.129	-0.125	0.450	0.819
regression Ø coefficient	-0.349	0.042	-0.049	-0.093	0.043	-0.031	0.042	-0.066	0.048	0.131	-0.020	
correlation coefficient		0.434	-0.228	0.094	0.375	0.254	0.327	-0.067	0.050	0.481	-0.324	0.626
regression 100S _w coefficient	-9.789	-0.207	0.153	2.237	-1.009	0.392	-1.406	1.693	0.385	0.749	1.598	
correlation coefficient		-0.275	0.015	0.241	-0.333	-0.270	-0.381	0.015	-0.007	-0.027	0.379	0.659

Water Zone 1300-1402'

regression S _w coefficient	1.769	-0.081	0.234	0.077	-0.265	-0.158	-0.092	0.331	-0.003	0.100	-0.070	
correlation coefficient		-0.481	0.360	-0.402	-0.422	-0.317	-0.342	0.086	-0.211	-0.288	0.307	0.674

TABLE IV

Correlation Between Open-hole and Cased-hole Logs - Program Windows (Eight Window Versions)

$$\text{Open-hole Parameter} = A_0 + A_1 H + A_2 \text{Fe} + A_3 \text{OXIN} + A_4 C + A_5 \text{SiCl} + \\ A_6 \text{EX} + A_7 \text{Ca} + A_8 \text{OXACT}$$

Oil Zone 2465'-2600'

Open-hole Parameters	A ₀	A ₁ (H)	A ₂ (Fe)	A ₃ (OXIN)	A ₄ (C)	A ₅ (SiCl)	A ₆ (EX)	A ₇ (Ca)	A ₈ (OXACT)	Multiple Corr. Coeff.
regression S _w coefficient	-1.628	-0.135	0.240	0.967	-0.719	-0.218	0.348	-0.128	0.787	
correlation coefficient		-0.392	0.189	0.243	-0.430	-0.468	0.164	-0.125	0.445	0.796
regression 100S _w coefficient	7.383	0.415	-0.643	-0.271	1.947	0.566	-0.895	0.339	-0.221	
correlation coefficient		0.390	-0.184	-0.246	0.428	0.458	-0.158	0.127	0.452	0.794

Water Zone 1300'-1402'

regression 100S _w coefficient	-2.904	0.158	-0.670	-0.273	0.426	0.220	0.406	-0.429	-0.248	
correlation coefficient		0.466	-0.347	0.388	0.415	0.386	0.242	0.283	-0.291	0.629

3.3 The Dresser Program

For control purposes a program was written which recreates a Dresser Log from the spectra. The Dresser windows were used (see Figures 6 and 7), and the output is therefore in the form of C/O, Si/Ca ratios and Silicon counts. Multiple correlation coefficients obtained from this program would provide the basis for comparison for the other processing programs developed.

The field data did not have the depth encoded in each logical record, so it was necessary to synthesize a paper log so that depth correlation could be performed. In this way it would be apparent that the misfire files (records) had been successfully combined.

A regression analysis was once again performed. Correlation coefficients are shown in Table V.

TABLE V

Correlation Between Open-hole and Cased-hole Logs - Program Dresser

Open-hole parameter = $A_0 + A_1 \text{ C/O} + A_2 \text{ Si/CA} + A_3 \text{ Si}$

Oil Zone 2465'-2600'

Open-hole parameters Log Data	A_0	A_1 C/O	A_2 Si/CA	A_3 Si	Multiple Regression Coeff.
S_w regression coefficient	6.752	-0.252	-2.421	2.03×10^{-5}	
S_w correlation coefficient		-0.519	-0.671	-0.306	0.759
$\emptyset$ regression coefficient	-0.174	0.093	0.260	0*	
$\emptyset$ correlation coefficient		0.205	0.461	0.130	0.475
100S _w regression coefficient	-15.687	6.172	6.508	-4.49×10^{-5}	
100S _w correlation coefficient		0.519	0.668	0.318	0.756
Water Zone 1300'-1402'					
100S _w regression coefficient	0.906	2.270	-0.996	0*	
100S _w correlation coefficient		0.259	-0.257	-0.091	0.331
S_w regression coefficient	1.849	-0.191	0.529	0*	
S_w correlation coefficient		0.111	-0.504	0.228	0.552
100S _o regression coefficient	-2.698	0.690	1.579	0*	
100S _o correlation coefficient		-0.092	0.485	-0.263	0.552

* Too small to measure

3.4 Correlation Procedure

The analysis made extensive use of a Chevron in-house log trace manipulation package.¹⁴ Depth correction, smoothing, plotting and multiple linear regression were performed by this package.

A comparison of the success of two of the Fortran programs (Dresser and Windows) is shown in Figures 18 and 19. Figure 18 illustrates the results for an oil zone and Figure 19 is for a water zone. The recreated least squares fit trace using the optimum (regression) coefficients is shown for both programs, and plotted alongside the original porosity times oil saturation trace. The fourth trace is the correlation suggested by Dresser-Atlas:¹⁵

$$S_{or} = C/O + 0.8 Si/Ca - 2.36 \quad (1)$$

DRESSER PREDICTED RESULT=PHISOR
WINDOWS PREDICTED RESULT=PHISCH
DRESSER-ATLAS RESULT=OARESCOR
OPEN-HOLE VALUE=PHISOR

Figure 18--Prediction of Porosity Times Oil Saturation
Performance of Programs Dresser and Windows and
Dresser-Atlas Suggested Correlation in an Oil Zone

DRESSER PREDICTED RESULT=PHISOR
 WINDOWS PREDICTED RESULT=PHISOW
 DRESSEH-ATLAS RESULT=DRESCOR
 OPEN-HOLE VALUE=PHISOR

Figure 19
 Prediction of Porosity Times Oil Saturation
 Performance of Programs Dresser and Windows
 and Dresser-Atlas Suggested Correlation in a Water Zone

4. DISCUSSION

4.1 The Spline Program

Multiple correlation coefficients are uniformly low whatever open-hole log parameter is chosen for correlation purposes. No multiple correlation coefficient better than 0.65 was found. This is an unsatisfactory result. The reason for this is thought to be that where the peaks are poorly resolved, the peak searching routine of the spline program is unable to lock onto the minima accurately. Much of the variation in each output integrated count rate is then simply due to variation in the window size and position. This is particularly important for the carbon window, where no consistent peak is

observable. Variations in the amount of carbon give rise to subtle changes in what appears to be the background. The same is true to a certain extent for oxygen. This proves to be a fatal flaw since the measurement of saturation depends on measuring one or other of these accurately.

4.2 The Windows Program

The second program, which simply extends the number of windows over which counting is performed proved much more successful. Multiple correlation coefficients in the range 0.8-0.82 were recorded. The conventional Dresser approach leads to multiple correlation coefficients over the same interval of about 0.75. The improvement is due to the Compton stripping effect of adding new windows.

It is important to consider the individual windows and their contribution to the overall quality of fit. In particular consider the results for the ten window version of the program (Table III). The carbon window parameter (C) proves to be significant although there is no visible peak, and it anti-correlates with water saturation as expected. The other important windows are a silicon capture window (SiC2) and the oxygen activation window (OXACT). The OXACT window correlates with water saturation, but for the SiC2 window the converse is true. It is strange that, although the silicon content of the formation must be constant, these two windows (which correspond approximately to the "calcium" and "silicon" windows of the Dresser log - see Figure 14) have the most significant correlation coefficients. It seems that oxygen activation must indeed be contributing to the counts in the window OXACT¹⁶, but it is not apparent why a window set around a silicon peak should correlate with oil saturation. An anticorrelation with porosity would be expected. The silicon inelastic window (SiIN) in fact shows no correlation with either porosity with either porosity or saturation.

The hydrogen capture window (H) is a good indicator of porosity, as expected. The calcium capture window (Ca) also shows a high correlation coefficient, but this possibly represents Compton scattering of hydrogen gamma rays. (Note that the calcium and hydrogen windows are adjacent--Figure 14). The iron window (Fe) has two functions. It acts as a shaliness indicator and is important for stripping purposes. A surprising result is the poor performance of the oxygen inelastic window (OXIN in Figure 15). Oxygen peaks in the capture spectrum (OXACT) make a significant contribution to the overall correlation coefficient, but this is not the case for the inelastic peaks. The reason for this is not clear.

4.3 The Dresser Program

There is one very important point to note from the results illustrated in Table V. The multiple regression program arrives at regression coefficients (Equation 2) very different from those given by Dresser-Atlas in their standard correlation (Equation 1).

$$S_{or} = C/O + 0.8 Si/Ca - 2.36 \quad (1)$$

$$S_{or} = 0.252 C/O + 2.421 Si/Ca - 5.752 \quad (2)$$

Figures 18 and 19 show that using Equation 1 can lead to serious errors.

4.4 Comparison of the Programs Dresser and Windows

The program Dresser simulates the analysis made in the field by Dresser-Atlas. The program Windows should provide considerable advantages over Dresser before one would contemplate routinely reprocessing the spectral data. It has been noted that the improvement in total correlation coefficient is not great.

At the outset it was hoped that additional parameters could be developed to provide shaliness, porosity and lithology indicators. To some extent this has been achieved. The hydrogen and calcium capture windows prove useful for

predicting porosity. Information about porosity and lithology is generally available from core and open-hole log measurements, however. The difficulties of gathering and processing the spectral data are perhaps not justified by the results. A large amount of data is stored on a spectral tape, so that any processing is not generally cost-effective. In certain situations, with complex lithology, it is possible that knowledge of the individual elemental count rates could be of great value. For example, the occurrence of unusual minerals could be followed in-situ.(e.g. siderite by an iron window count).

4.5 The Water Zone

In the zone that contained mainly shales and water sands, the overall correlation coefficients were below 0.7--significantly lower than in the oil saturated zone. The data for this zone occurs at the end of the tape. So, perhaps the file recovery subroutine failed to piece together correctly the misfire records. This would put the open-hole log measurements and cased-hole data out of synchronization.

If the data are considered to be properly correlated, then the problem must lie with the complexity of the lithology. The Dresser program is least successful in this interval. It is likely that the interpretation model used in this program is too simple. A Dresser-Atlas field interpretation would not be reliable in this zone. Therefore, detailed spectral processing is necessary. More windows should be introduced to deal with the additional gamma rays being produced. In this particular example, the gamma ray spectrum is modified by the presence, in shales, of elements with large capture cross-sections.

5. APPLICATIONS

A comprehensive suite of logs was run in two wells in the Kern River Field. Open hole logs used were Dual Induction (DIL) , Electromagnetic

Propagation Time (EPT) , Density (FDC) , Neutron (CNL) , Gamma ray (GR) , and Spontaneous Potential (SP) . The GST was run in one of the wells, and the Thermal Decay Time log (TDT) in both.

This formed part of an enhanced oil recovery field test in which in-situ foaming was being used to prevent gravity override during steam injection.¹⁷ The C/O log would be used to monitor oil saturation. The first C/O log was run immediately after cementing of the casing. Thus there were three independent measurements of saturation (DIL, EPT and GST) to use to calibrate the C/O log. A somewhat incomplete core record was also available, but it did not prove to be very useful except as a check on the log-derived values.

Once the calibration had been performed, the C/O log could be used to follow the saturation changes during the injection of the surfactant slug. However, at the time of writing, only the data from this calibration run was available.

Agreement between the resistivity and EPT derived measurements of oil saturation was excellent for one of the wells (214M). GST data is also available for this well. However, a calculation of oil saturation from the station readings of the GST tool yielded results which were far too low to be realistic. The explanation lies in the fact that the oil sands in this particular field are very shaly. The analysis suggested by Schlumberger has not been extended to shaly sands.

In well 208M it is difficult to interpret the resistivity data in terms of the shaly-sand model. To be consistent, the calibration of the C/O log must therefore rely on the EPT value for oil-in-place in both wells.

Using multiple linear regression to fit a curve of the type suggested above, we obtain:

$$\phi \cdot S_o = 0.674 \cdot C/O + 0.472 \cdot Si/Ca - 1.507 \quad (3)$$

For well 214M, and:

$$\phi \cdot S_o = 0.484 \cdot C/O + 0.223 \cdot Si/Ca - 0.941 \quad (4)$$

For well 208M. In the above equations, the C/O and Si/Ca ratios are derived from the Dresser-Atlas conventional log rather than the processed spectra.

6. CONCLUSIONS

- I. The Dresser-Atlas approach is generally valid. For most simple lithologies (e.g. sands), it is possible to predict oil saturation from the C/O and Si/Ca ratios. No spectral processing is required.
- II. It has been noted that the standard correlation supplied by Dresser-Atlas is not very accurate in this well. It is important that individual correlations be developed on a well by well basis. The earliest C/O log run, and the open-hole log measurements should be used for this purpose.
- III. The range of validity of the Dresser-Atlas approach has not yet been established. Certain complex lithologies will require spectral processing using a Windows type program. Furthermore, it is not yet known how much borehole environment and cement condition will affect the response of the tool.

7. REFERENCES

1. Multielement Neutron Activation Analysis of an Iron Ore, M.A. Raoof et al.; Proceedings of the Sixth Conference on the Application of Accelerators in Research and Industry, November 1980, Reprinted in IEEE Transactions on Nuclear Science, April 1981, Vol NS-28, No. 2, 1700-1702.

2. Introduction to Carbon Logging, V.C. McWhirter; SPE 5906, Rocky Mountain Regional Meeting of the SPE of AIME, Casper, Wyoming, May 1976.
3. A Theoretical and Laboratory Evaluation of Carbon Logging--Laboratory Evaluation, B.L. Lawson and J.D. Owen; SPE 2970, SPE Fall Meeting, Houston, Texas, October 1971.
4. California Applications of the Continuous Carbon/Oxygen Log, J.D. Heflin et al.; API Joint Chapter Meeting, Bakersfield, California, October 1977.
5. Neutron Activation for Elemental Determination in Borehole, P.A. Wichman, SPWLA 12th Annual Logging Symposium, May 1971.
6. Tables of Isotopes, C.M. Lederer and V.S. Shirley, Wiley 1978.
7. Gamma Ray Energy Spectra from Thermal Neutron Capture, F.E. Deloume, General Electric Co, Report No. APEX-407, USAEC Contract No. AT(11-1)-171.
8. Neutron Capture Gamma Ray Spectra of Earth Formations, P.E. Baker, Pet. Trans. AIME, 210, pp 97 (1957).
9. Laboratory and Field Evaluation of an Inelastic Neutron Scattering and Capture Gamma Ray Spectroscopy Tool, R.C. Hertzog; JPT, October, 1980.
10. Gamma Ray Spectrometer Tool, P. Westaway, R Hertzog and R. Plasek; SPE 9461, SPE Fall Meeting, Dallas, Texas, September 1980.
11. A Practical Guide to Splines, C. de Boors, Springer-Verlag, New York, 1978.
12. Importance of Neutron Energy Distribution in Borehole Activation Analysis in Relatively Dry, Low Porosity Rocks, F.E. Senftle et al.; Geoexploration, 15, 121-135 (1975).
13. Airborne Gamma-Ray Spectroscopy, A.G. Darnley, Canadian Inst. of Mining Trans. 73, 20-29.
14. M.S.P. Well Log Programs, Chevron Geosciences; Vols I and II.
15. Continuous Carbon/Oxygen Log Interpretation Techniques, T.D. Lawrence; SPE 8366, SPE Fall Meeting, Las Vegas, Nevada, September 1979.
16. Cased Hole Measurement of Residual Oil, C.H. Neuman and A.L. Oden; SPE 9918, California Regional Meeting of the SPE, Bakersfield, California, March 1981
17. In-Situ Foaming Field Experiment, Stanford University Petroleum Research Institute; USDOE Contract DE-AC03-80SF11445, First Annual Report, 1981