SURVEY OF METHODS TO DETERMINE TOTAL DISSOLVED SOLIDS CONCENTRATIONS

U.S. ENVIRONMENTAL PROTECTION AGENCY
UNDERGROUND INJECTION CONTROL PROGRAM
WASHINGTON, D.C.
EPA LOE CONTRACT NO. 68-03-3416
WORK ASSIGNMENT NO. 1-0-13

KEDA PROJECT NO. 30-956
SEPTEMBER 1988

PREPARED BY
KEN E. DAVIS ASSOCIATES
UNDER SUBCONTRACT TO
ENGINEERING ENTERPRISES, INC.

TABLE OF CONTENTS

SECTION		PAGE
1.0	INTRODUCTION	1- 1
	1.1 Purpose and Organization of Report	1- 1
	1.2 Background Information	1- 2
2.0	CONCLUSIONS	2- 1
	PRINCIPLES	
3.0	LOGGING METHODS AND PRINCIPALS	3- 1
	3.1 Determination of Rw	3- 1
	3.2 Resistivity - Porosity Method	3- 2
	3.2.1 Resistivity Tools	3- 3
	3.2.2 Porosity Tools	3- 5
	3.3 Spontaneous Potential Method	3- 6
	3.4 Rw VS TDS Concentration	3- 8
4.0	PROCEDURES FOR TDS DETERMINATION	4- 1
	4.1 TDS Using Resistivity - Porosity (RP) Logs.	4- 1
	4.2 TDS From Spontaneous Potential (SP) Logs...	4- 7
	4.3 Precision and Accuracy of RP and SP Methods	4-12
	4.3.1 The Resistivity-Porosity (RP) Method	4-12
	4.3.2 The Spontaneous Potential (SP) Method	4-14
	4.3.3 Precision and Accuracy Summary	4-17
	4.4 TDS From Water Analysis	4-18
	4.5 Comparison of Methods Used to Determine TDS Concentrations	4-19

Table of Contents
Page Two

SECTION		PAGE
5.0	COMPARISON OF RESISTIVITY - POROSITY VS SPONTANEOUS POTENTIAL METHOD.....	5- 1
6.0	OTHER METHODS.....	6- 1
7.0	REFERENCES.....	7- 1

TABLES

NO.		
1	COMPARISON OF RP METHOD AND SP METHOD FOR TDS DETERMINATION.....	2 - 3

FIGURES

NO.	
1	SALINITY - RESISTIVITY CHART
2	NaCl - RESISTIVITY VS TDS CONCENTRATIONS
3	FORMATION FACTOR VS POROSITY
4	SP CORRECTION FACTOR VS BED THICKNESS CHART
5	EMPIRICAL SP CORRECTION CHART
6	MUD WEIGHT CORRECTIONS
7	ESTIMATION OF FORMATION TEMPERATURE
8	Rw VS Rweq AND FORMATION TEMPERATURE
9	Rweq DETERMINATION FROM THE SSP
10	RESISTIVITY SYMBOLS USED IN LOG INTERPRETATION

APPENDICES

APPENDIX 1 EXAMPLE 1-CALCULATION OF TDS USING RP AND SP METHODS

APPENDIX 2 WATER ANALYSIS AND LOGS FOR SECTION 4.0

APPENDIX 3 SINCLAIR VARIABLE MULTIPLIERS

APPENDIX 4 HINGLE CROSS PLOT

ACKNOWLEDGEMENTS

This report was prepared at the request of the Environmental Protection Agency, UIC Branch, Washington, DC. by Ken E. Davis Associates under subcontract to Engineering Enterprises Inc. and was funded through UIC Contract No. 68-03-3416, Work Assignment No. 700-013-01. The following individuals were involved in the preparation and review of this report:

Ken E. Davis Associates

Principal Author: Mr. Richard Lyle

Office Manager: Mr. Kim Forster

Engineering Enterprises, Inc.

Work Assignment Manager: Mr. J. L. Gray

UIC Program Director: Mr. Talib Syed

U. S. Environmental Protection Agency

Work Assignment Manager: Mr. Mario Salazar

Project Officer: Mr. Robert Smith

Technical Reviewer: Mr. Dan Chadwick

Technical Resource: Mr. Gene Coker (EPA Region IV)

Input and technical criticism by Mr. John Dewan, Dewan and Timko, is appreciated; especially in the area of precision and accuracy of TDS determination methods presented in this report.

SYMBOLS USED

a	- Pore Geometry	Dimensionless
F	- Formation Factor	Dimensionless
K	- Constant Related to Temperature	Fahrenheit
m	- Matrix Cementation	Dimensionless
R	- resistivity	Ohm-meters
Rm	- Mud Resistivity	Ohm-meters
Rmc	- Mud Cake Resistivity	Ohm-meters
Rmf	- Mud Filtrate Resistivity	Ohm-meters
Rmfeq	- Equivalent Resistivity of Mud Filtrate	Ohm-meters
Ro	- Resistivity of Formation 100% Percent Saturated with Water of Resistivity Rw	Ohm-meters
Rs	- Resistivity of Surrounding Formation	Ohm-meters
Rt	- True Formation Resistivity	Ohm-meters
Rw	- Formation Water Resistivity	Ohm-meters
Rweq	- Equivalent Resistivity of the Formation Water	Ohm-meters
SP	- Spontaneous Potential Reading	Millivolts
SSP	- Static Spontaneous Potential Reading	Millivolts
TDS	- Total Dissolved Solids Concentrations	ppm
T	- Temperature	Fahrenheit
Tf	- Formation Temperature	Fahrenheit
ø	- Porosity	Decimal

1.0 INTRODUCTION

1.1 PURPOSE AND ORGANIZATION OF REPORT

The intent of the U.S. Environmental Protection Agency's Underground Injection Control (UIC) regulations is the protection of underground sources of drinking water (USDWs) from improper injection operations. In order to protect USDWs, a necessary prerequisite is to identify USDWs and determine the depth to the base of the lowermost USDW in the vicinity of injection wells.

The purpose of this document is to survey the techniques used to identify USDWs via TDS concentration determination. A comparison of the most commonly used methods of estimating TDS concentrations from electric logs is presented with discussion of laboratory methods. The approaches utilized are simple, practical methods for determining TDS concentrations from open hole geophysical logs. In most field applications all of the data necessary to apply these techniques is available. The methods described will yield good (± 15%) approximations of TDS values in most cases when compared to chemical analyses. More elaborate techniques for special applications are referenced but not addressed in detail.

Section 3.0 of this document presents an analysis of the theory and tools involved in water salinity determinations using electric logs. Detailed procedures and a step-by-step checklist for two methods of electric log TDS determination are given in Section 4.0. Reference figures needed for calculating TDS values are included in a separate section at the back of the report. In

Section 4.0, illustrative examples utilizing the electric log procedures are explained and compared to other procedures to develop conclusions regarding the precision and accuracy of electric log methods.

A comparison of the two methods presented, reference to other methods of TDS determination, conclusions, and references are presented in Sections 5.0, 6.0, and 7.0 respectively.

This report is not intended to introduce the reader to geophysical logging techniques. A prior understanding of well construction, logging, and log interpretation is therefore recommended.

1.2 BACKGROUND INFORMATION

The objective of the Environmental Protection Agency (EPA) Underground Injection Control (UIC) Program is to protect underground sources of drinking water (USDWs), those aquifers that contain less than 10,000 parts per million (ppm) Total Dissolved Solids (TDS). UIC regulations were created to protect potentially usable aquifers from contamination related to the underground injection of fluids. Although aquifers with greater than 500 ppm TDS are rarely utilized for drinking water supply, it is believed that imposing protection for waters with less than 10,000 ppm TDS will ensure adequate supply (through treatment) for future generations.

EPA UIC regulations addresses five different well types:

- Class I wells, those that inject hazardous or non- hazardous industrial and municipal waste below any USDW;

- Class II wells, those that inject fluids related to the production of oil and gas;

- Class III wells, which inject fluids for extraction of minerals;

- Class IV wells, which inject hazardous wastes directly into a USDW (currently banned); and

- Class V wells, those not included in Classes I, II, III, and IV.

Although this report uses examples from Class I and II injection wells, the methodologies of determination of TDS concentration are applicable to the regulation of all well classes.

Three general criteria for Class I and II injection wells are:

1. Injection must take place below the lowermost USDW (unless exempted).

2. USDWs penetrated by the well must be protected (preferably by cemented longstring casing).

3. There should be a sufficient confinement zone separating the injection strata from the lowermost USDW.

Obtaining useful information regarding ground water quality is essential for a determination of whether the above criteria are met. For newly drilled wells, this information can often be documented directly through a comprehensive sampling program. For older wells or new wells where sampling was not performed, indirect methods must be employed to determine ground water quality. Electric log methods described in this report provide a means by which ground water quality information can be obtained indirectly from existing geophysical log data.

Historically, operators of Class I and II wells have run the necessary geophysical logs for ground water quality determinations. The current regulations promulgated under 40 CFR 144, 146 and 148 require an increasingly comprehensive suite of geophysical logs. These logs should provide a good basis for determining TDS concentrations which will, in turn, improve identification of USDWs.

2.0 CONCLUSIONS

The goal of current UIC regulatory programs is the protection of potential drinking water aquifers from injection operations. This goal can be accomplished by defining appropriate well construction in relation to the base of USDWs to ensure proper confinement of the injected fluids. This report describes two methods, Spontaneous Potential (SP) and Resistivity-Porosity (RP), which may be used to identify USDWs using geophysical logs. Both methods provide reasonable TDS estimates (± 15%) in relation to chemical analyses if sufficient, accurate data is available. Sampling and chemical analyses is the benchmark method to determine TDS concentrations.

However, in many cases chemical analyses may not be available, simply because the formations were not sampled when the wells were originally drilled and completed. In such instances, geophysical logs serve a useful purpose in estimateing TDS concentrations.

The relationship between TDS and formation fluid resistivity should be established for USDWs in the vicinity of all injection sites where water quality is uncertain. TDS values can be contoured and recorded for future reference, providing a library of USDW locations.

The SP method is the preferred measurement technique when:

1) Fresh borehole fluids (Rmf > Rw) were used during logging,

2) Deep reading Electric logs are not available

3) Formation and borehole resistivities are significantly different resulting in large SP deflections, and

4) Thick sand/shale beds are present.

The RP method should be used when:

1) Low porosity, thin bed carbonate formations are of interest,

2) Accurate formation porosity is available, and

3) Salt based muds occupied the borehole during logging.

Table 1 presents a summary of the applicability and limitations of each method.

For quality control purposes, when data is available, both methods should be used to calculate TDS concentration. If inconsistencies are noted, a careful review of input data is necessary. Additional quality control measures can be incorporated by calculating TDS values at multiple well sites within a given area. If multiple well sites are used with similar hydrogeologic properties, the errors associated with the measure of TDS concentrations should become obvious and consistent TDS concentrations from log evaluation can be established.

TABLE 1: COMPARISON OF RP METHOD AND SP METHOD FOR TDS DETERMINATION

METHOD	DATA NEEDS AND PARAMETERS MEASURED	ADVANTAGES AND WHEN TO USE	DISADVANTAGES AND WHEN NOT TO USE	SENSITIVITIES	ACCURACY
RP	Data Needs: - Accurate formation porosity - Formation temperature - Formation factor (F) Parameters Measured: - Resistivity of formation (Ro) measured with deep reading electric log - Formation water resistivity (Rw) calculated from Ro - TDS calculated from Rw	Advantages: -Can be used in most cases if needed data is available When To Use: - When deep reading electric log is available - When porosity data is available - When highly saline borehole fluids were present during logging - When Rw > 1 ohm-m - Low porosity, thick bed, carbonate formations. - When formation and borehole resistivities are similar - When thin beds are present	Disadvantages: - Requires measurement of porosity (additional data) When Not to Use: - When logging tool electrode spacing is greater than bed thickness - When oil base muds were present during logging (resistivity logs should not exist)	- Major ion distribution - Formation porosity - Formation type and degree of sedimentation (affects F) - Formation temperature	- Absolute ±15% - Measurement of differences in same formation ±7% - Errors of up to 30% can exist at low TDS values (≤10,000 ppm) if major ion equivalents are not calculated. NaCl tends to become less dominant when TDS ≤10,000 ppm (shallower depths)
SP	Data Needs: - Approximate distribution of ions present - Formation temperature - Borehole fluid resistivity during logging (Rm) - Correction charts Parameters Measured: - Spontaneous Potential (SP) between formation and borehole - Equivalent formation water resistivity (Rweq) calculated from Rweq, Rmf, SP relationship - Rweq used to calculate Rw - TDS calculated from Rw	Advantages: - Quick and easy (requires only one log) - Many old electric logs can be used When to Use: - When porosity data is unavailable - When fresher (low-salinity) borehole fluids were present during logging - When Rw < 1 ohm-m - When Rmf >> Rw	Disadvantages: - Must assume major ion concentration is NaCl - Requires accurate Rm measurement - Correction factors must be applied for shale presence, hole diameter, mud invasion, and bed thickness When Not to Use: - When formation and borehole resistivites are similar - When thin beds are are present - When thick, low porosity carbonates are of interest - When highly saline borehole fluids were present during logging - When formation and borehole fluid resistivites are similar - When oil base muds were present during logging (SP log should not exist)	- Major ion distribution - Borehole fluid resistivity - Formation temperature - Shaliness of formation - Hole diameter - Mud invasion from borehole - Bed thickness	- Absolute ±14% - Measurement of differences in same formation ±7% - Errors of up to 30% can exist at low TDS values (≤10,000 ppm) if major ion equivalents are not calculated. NaCl tends to become less dominant when TDS ≤10,000 ppm (shallower depths)

If both logging methods are used to calculate TDS concentrations for a single well with no water analysis available, and both estimates are close, a conservative approach would be to choose the lower TDS concentration. If the difference becomes large, differing by a factor greater than 2, and a review of the input data reveals no obvious errors, accurate TDS concentrations can not be determined from geophysical logs.

Certain errors are inherent with geophysical logging techniques and can not be avoided. Existing data is usually developed from multiple sources and determining the origin of errors is difficult.

Errors associated with the accuracy and precision of TDS concentrations measured with chemical analysis include:

1) The original input data
2) Laboratory error
3) Non representative samples

TDS concentration developed from chemical analyses is the preferred method of determining formation water quality. Electric log methods can be used when chemical analyses are not available.

3.0 LOGGING METHODS AND PRINCIPLES

3.1 DETERMINATION OF Rw

Geophysical logging of the earth's subsurface provides a fundamental means of determining the properties of rock matrix, formation fluids, and the soundness of well construction. Through the interpretation of these logs, a variety of characteristics can be determined, including well-bore conditions, lithology, porosity, reservoir/aquifer conditions, and formation/fluid resistivity. Geophysical logs can provide base line records which, when compared to logs run in later years, indicate changes throughout the history and operation of the well. Through a comparison of logs and drilling data compiled at a single well point with logs from neighboring wells, the nature of subsurface strata can be determined for a given area. Geophysical logs and related geological data can be acquired from geologic surveys, petroleum information companies, log libraries, and other sources.

In this report we discuss the determination of TDS content utilizing log derived values for connate water resistivity (Rw). TDS concentrations can be estimated from Rw values, since resistivity is proportional to TDS content. The electrical resistivity of the rock (Rt) is dependent upon the rock matrix and the fluid contained within the pore spaces. Typically, the water contained within the rock is more conductive than the rock itself. In other words, it is less resistive. The resistivity of the formation that is completely saturated with 100% water of

resistivity Rw, is referred to as Ro. Resistivity terminology is shown graphically in Figure 10.

Formation water resistivity is a function of salinity and temperature as seen in Figure 2 (Alger 1966). The higher the temperature, the lower the resistivity for a specific salinity. At room temperature, the resistivity of potable water is about 10 ohm-meters, sea water about 0.2 ohm-meters, and a saturated saltwater solution 0.04 ohm-meters (Hilchie 1978).

A variety of work related to determination of water resistivity via indirect techniques has been published by the petroleum industry because of Rw's application to the location of oil and gas reserves. Two methods have been developed from oil and gas technology to indirectly determine Rw. One method, the resistivity-porosity (RP) method, relies on a response from a deep reading electrical log combined with the corresponding formation porosity. The second method, the spontaneous potential (SP) method, uses differences in the naturally occurring direct current potential and known borehole fluid characteristics. The two geophysical methods usually will not give specific ion concentrations, but do characterize ground water, and can be used to estimate Total Dissolved Solids (MacCary 1980).

3.2 RESISTIVITY - POSOSITY METHOD

The resistivity-porosity method requires knowledge of the formation resistivity and formation porosity. Formation resistivity may be determined from a deep reading electric log. The purpose of any deep reading electric log is to measure true

formation resistivity (Rt) independent of borehole fluid and invasion. Invasion refers to the contamination in the near wellbore area of the formation fluids by drilling fluids. Electric logs have different depths of investigation depending upon electrode spacing and type of focusing. In high porosity zones where beds are thick, the RP method can be used if the electrode spacing is less than the bed thickness.

Rw values from the RP method are derived from a combination of logs, using porosity and saturated formation resistivity (Ro) values. The RP methodology is presented in Section 4.0.

3.2.1 Resistivity Tools

Three types of resistivity tools have been commonly used for deep resistivity measurements. These include laterologs (focused current logs), induction logs, and the basic electrical survey.

Laterologs are focused or guarded electrode systems (Dresser Atlas 1982). Guard electrodes are placed above and below a current electrode and kept at the same potential to focus the formation current into a thin disc flowing perpendicularly to the borehole. The radius of investigation is approximately equal to the length of the guard electrode. The focused current log defines bed boundaries very well and is not affected much by adjacent bed resistivities. The short guard logs are used for measuring the resistivity of the flushed or invaded zone near the borehole. The longer guards are used for measuring the true resistivity of the uncontaminated zone when the mud filtrate

resistivity is not more than four times the formation water resistivity. The laterolog can resolve beds as thin as 2 feet.

The laterolog works well in salt based muds. Salt based muds are typically used when drilling in areas where salt sections, such as halite, are common. These muds are used to prevent washouts (borehole enlargement due to dissolving or sloughing). The laterolog also works well in formations with high resistivity. These tools are much superior to ES (Electrical Survey) devices for large Rt/Rm ratios (salt muds and/or highly resistive formations) and for large resistivity contrasts with adjacent beds (Rt/Rs or Rs/Rt) (Schlumberger 1987).

Induction logs apply an alternating current which induces an eddy current in the formation. The resulting secondary magnetic field induces a voltage in a receiver coil. This voltage is directly proportional to formation conductivity which is presented as a resistivity value on most logs. Focused induction logs have proven to be the best method for obtaining formation resistivity in wells drilled with fresh mud, air, or oil based mud; and with beds at least six (6) feet thick (Dresser Atlas 1982). Induction logs work best when the formation resistivity is lower than the borehole fluid resistivity. This is typical of fresh mud systems.

Under favorable logging conditions, induction log values may be used for true resistivity; however, charts are provided by

logging service companies to make corrections for thin beds, large diameter boreholes, etc.

Many older wells have only one log available for interpretation. These logs were difficult and, sometimes impossible, to interpret (Dewan, 1983). These logs, called Electric logs (today electric logs are a general term for all geophysical logs) or Electrical Survey tools, were the basic and most frequently used log until the middle 1950's. Electric logs are still useful in determining resistivity of the virgin formations provided the formations are relatively thick and the deep curve is used. Extensive charts are required to correct for borehole diameter, bed thickness, and adjacent-bed resistivity effects (Hilchie 1979). For further information about old Electric logs, Rollyn Frank (1986) has published an education guide which is very useful.

3.2.2 Porosity Tools

As mentioned earlier the RP method requires both true formation resistivity and formation porosity. Porosity may be determined from geophysical logs if core data is not available. Three types of logs available for porosity determination are the neutron log, density log, and acoustic log. All porosity logs are affected by rock matrix and borehole fluids. By isolating these effects, accurate porosity determinations can be made. If either the compensated neutron or the density log is used alone to calculate porosity, then the lithology of the zone must be

known in order that proper porosity calibration lines may be constructed (MacCary 1980).

3.3 SPONTANEOUS POTENTIAL METHOD

When fresh drilling mud filtrates are in contact with more saline formation water, a small electrical current is generated. This current creates a voltage change, or potential difference in the mud filled borehole opposite sand-shale interfaces. Measurement of this voltage change by a geophysical logging tool generates a Spontaneous Potential (SP) curve. The SP curve's deflection is indicated on the log in millivolts. SP values of a known shale section are usually constant and are depicted as the shale baseline. These values are typically the furthest deflections to the right of the SP curve. The SP curve shift is a response to the formation fluid and drilling mud resistivity differences. The SP method utilizes this response to determine formation water resistivity. A formation containing salt water must be at least slightly permeable, however, for SP character to develop (Dresser Atlas 1982).

Significant corrections may be required for accurate SP measurement in many cases. If the formation is interbedded with shale, a shaliness correction may be applied. If the bed is thin, it should be corrected for thickness using charts or standard correction factors. Effects due to hole enlargements are generally small, and usually do not require corrections. Correction factors are published by major open-hole logging companies. One of the better sources is provided by

Schlumberger. It should be noted that, regardless of the magnitude of the bed resistivity, if the bed is thick enough, the SP will reach static conditions (Hilchie 1978). The static spontaneous potential (SSP) curve refers to a maximum deflection between two fluids of different salinity and a shale section.

Although the SP method works well in sand-shale sequences, it works poorly (if at all) in thick carbonate rocks of low porosity (MacCary 1980). The method works satisfactorily at less than 10,000 ppm TDS provided both mud filtrate and formation water are of similar composition, and Rmf is much greater than Rw (Vonhoff, 1966).

The SP log has its best application where fresh water based mud is used to drill a well. The SP curve cannot be recorded in holes with nonconductive drilling fluids, such as air or oil base muds. The SP method should not be used when resistivities of the borehole fluids and formation waters are similar unless additional logs are available to pick clean formations since the deflection of the SP curve will be extremely small. In typical salt water base muds, the SP is often useless because the SP magnitudes at depths of interest are small (Rmf = Rw) and because boundary definition with low resistivity mud and high resistivity formations is extremely poor (Dewan 1983). The log is still useful in salt water base mud provided the salinity of the mud is not too great.

The SP tool is an excellent choice for delineating permeable beds from shale beds, provided the resistivities of the borehole

fluid and formation water are not the same. The amplitude of the SP curve is not a function of porosity or permeability. However, the formation must be permeable in order for the SP deflection to occur.

3.4 Rw VS TDS CONCENTRATION

The preceding discussion has identified two methods by which formation water resistivity, Rw, may be determined. In the next section procedures are given to apply each of these methods to the estimation of TDS concentration in a zone of interest. It is important to realize, however, that water resistivity is not a direct indicator of the composition of dissolved solids. A strong correlation usually exists between water resistivity and the mass of ions present regardless of the dominant salt present (i.e. calcium chloride, sodium chloride etc.) (Kwader 1985). Typical water analyses for the majority of wells indicate that the dominant anion is the chloride ion (Cl^-) and the dominant cation is Sodium (Na^+) when TDS values are high (>10,000 ppm).

In this report, it is assumed that the formation waters in question are 100% saturated with NaCl solution. Sodium and chloride ions typically become less dominant in shallower formation waters with TDS concentrations of less than 10,000 ppm. If the suspected formation waters contain ions other than Na^+ and Cl^-, and if the chemical nature of the fluid is known, equivalent sodium chloride concentrations can be determined. If the concentration of each ion is known, the equivalent sodium chloride concentrations are determined by multiplying each ion

concentration by a "multiplier factor". A summation of the multiplied ions yields an equivalent sodium chloride concentration. The multiplying factors are more accurate at concentrations less than 100,000 ppm. If equivalent sodium chloride concentrations are not determined, TDS values derived by the methods presented in this report can be in error by as much as 30% (in fresh water sands with TDS $\leq$ 10,000 ppm).

A detailed method of determining sodium chloride equivalent solutions is included in Appendix 3. The method described is the Sinclair variable multiplier technique (Desai and Moore, 1969) which considers total ionic concentration of the water and converts all ionic constituents of the water into an equivalent NaCl concentration (MacCary, 1980). Other multiplying factors have been developed (Lynch 1962) which are also appropriate.

4.0 PROCEDURES FOR TDS DETERMINATION

4.1 TDS USING RESISTIVITY - POROSITY (RP) LOGS

The TDS concentration of an aquifer can be determined from appropriate combinations of porosity and resistivity logs. If adequate geophysical data is available, determining TDS concentration is possible with the following information: 1) true resistivity of the formation, 2) corresponding porosity, and 3) the application of appropriate equations.

Archie (1942) expressed an empirical relationship between formation resistivity [usually denoted as the formation resistivity factor (F)], porosity, matrix cementation (m), and pore geometry (a) using the following equations:

$$F = \frac{Ro}{Rw} \qquad (1)$$

Equation (1) may be rearranged as follows:

$$Rw = Ro/F \qquad (2)$$

and

$$F = a/\phi^m \quad \text{(Archie equation)} \qquad (3)$$

where

F = Formation resistivity factor (dimensionless)

a = Pore geometry coefficient (dimensionless)

ϕ = Porosity (decimal)

m = Cementation factor (dimensionless)

Ro = Resistivity of 100% water-saturated formation (ohm-meters)

Rw = Resistivity of formation water (ohm-meters)

The Ro and ø values can be determined using standard methods. If several values of Ro vs ø can be plotted on a log-log graph, then "m" can be empirically determined (by the slope of the resulting straight line) for any aquifer. The value of "m" varies with the type of rock encountered, however. Alternately, the table below can be used for typical ranges of magnitude.

Values of Cementation Factor "m" (after Guyod, 1944)

Rock Type	"m"
Highly cemented:	
limestone, dolomite, quartzite	2.0 - 2.2
Moderately cemented:	
consolidated sands	1.8 - 2.0
Poorly cemented:	
friable, crumbly sands	1.4 - 1.7
Unconsolidated sands	1.3

The constant "a" is related to pore geometry and has been developed through laboratory analysis. In the general case, a = 1. As illustrated in the subsequent discussion, the Humble equation assumes a = 0.62 and m = 2.15, while the Tixier equation uses a = 0.81 and m = 2.0.

Combining equations 2 and 3, and assuming a = 1 we have:

$$Rw = \phi^m Ro \qquad (4)$$

Equation (2) is an empirical relationship which holds well for waters having resistivities less than one ohm-meter. It tends to break down when Rw > 1 ohm-m, where surface conductance of sand grains becomes significant (Alger, 1966). Equation (4) shows that the product of the formation resistivity and the formation porosity raised to the power m is equal to a number that has a direct relationship with the formation water resistivity, Rw.

Estimated TDS determinations can be made using Figures 1 and 2 if porosity (ø) and 100% saturated formation resistivity (Ro) values can be obtained from a geophysical log, as discussed in Section 3.2.

For generalized use of the Archie equation, we can use one of the following empirical relationships. A more widely used relationship for sands and sandstone formations is the Humble equation:

$$F = .062/ø^{2.15} \qquad (5)$$

Another similar interpretation is reflected in the Tixier formula:

$$F = 0.81/ø^{2} \qquad (6)$$

which also applies to granular systems, but is easier to calculate (Hilchie, 1980).

Once porosity is determined, equations 5 and 6 can be applied, or, the general Archie equation with an appropriate m value may be used to determine formation factors. Equations 3, 5, and 6 are illustrated in Figure 3 along with recommended F-ø relationships for various formations. Next, Ro (Ro = Rt in clean water saturated zones) is picked from the electrical log. It is important to note that laterologs are designed to measure high resistivity while induction logs can be significantly in error when measuring high resistivity (Alger, 1988). Values of Ro and F are then substituted into equation 2, and a value of Rw is determined. Assuming only NaCl ions are present, TDS concentration of the formation can be determined using Figures 1 or 2 once Rw is known. However, when Rweq is greater than about one ohm-meter, other ions such as calcium (Ca), magnesium (Mg), bicarbonate (HCO_3), and sulfate (SO_4) will tend to be present and affect water resistivity in a manner different than sodium chloride (NaCl) (Alger, 1966). In such cases only an equivalent NaCl concentration is obtained from Figures 1 or 2.

The following procedural steps outline and summarize the Resistivity-Porosity method for determining TDS. These steps are followed in the examples included in Appendix 1.

1. Correlate porosity and electric logs if possible.

2. Determine clean permeable beds using SP, Gamma Ray (GR), and Ri/Rt separation.

3. Determine porosity (from charts) of permeable beds using:

   a. Known lithology and 1 porosity log,

   b. Cross plotting 2 or 3 porosity logs,

   c. Assumed lithology with 1 porosity log, or

   d. Core analysis.

4. Determine formation temperatures:

   a. From direct measured data, or

   b. Using Figure 7.

5. Determine formation factor (F) by:

   a. Calculation using the Humble (equation 5), Tixier (equation 6), or Archie equation (3), or

   b. Using Figure 3.

6. Determine Ro

   a. The deep reading resistivity curve for clean water bearing zones Rt = Ro (water saturated formation)

   b. Deep induction or laterolog picking a value for Ro directly from the log.

7. Determine Rw using equation (2)

8. Check calculated Rw against additional source if possible (SP method, water analysis).

9. Determine TDS concentration using Figures 1 or 2.

Rw, and therefore TDS, can also be determined using the more complex Hingle resistivity porosity cross-plot (RPCP) method.

The RPCP method involves plotting Ro (from deep resistivity logs) versus formation bulk porosity (neutron, density or acoustic velocity logs) (Kwader 1985). The RPCP method is outlined in Appendix 4. Examples of the RP method are presented in Appendix 1 and below.

CASE HISTORY - CLASS I DISPOSAL WELL
CALCASIEU PARISH, LOUISIANA

Well Log Heading

BHT 90°F Surface Temperature 80°F
TD 2250 ft
Rm 5.63 ohm - m @ 76°F
Rmf 5.5 ohm - m @ 75°F
Mud Weight 9.7 ppg

Using the RP method calculate TDS concentration at the suspected USDW, interval between 1110 - 1160 ft.

1) Determine porosity using bulk density and known lithology

$$\phi = 40\%$$

2) Determine formation temperature using Figure 7

$$Tf = 85^{\circ}F$$

3) Determine formation factor using Humble equation or Figure 2

$$F = 0.62/\phi^{2.15}$$

$$= 0.62/(0.40)^{2.15}$$

4) Pick Ro from Dual Induction Log

$$Ro = 3.1 \text{ ohm - m}$$

5) Determine Rw using equation (2)

$$Rw = \frac{Ro}{F}$$

$$Rw = \frac{3.1 \text{ ohm} - \text{m}}{4.45} = 0.7 \text{ ohm} - \text{m}$$

6) Determine TDS concentration using Figure 1 or 9

$$TDS = \underline{7000} \text{ ppm}$$

4.2 TDS From Spontaneous Potential (SP) Logs

A second method used to determine TDS utilizes the Spontaneous Potential (SP) curve. Static SP (SSP) refers to the maximum SP that can be obtained given a shale-aquifer boundary and two waters of different salinity. It is essentially the SP that would develop if no current flowed. In clean formations (non-shaley), the static SP is related to the resistivities of the connate water (Rw) and mud filtrate (Rmf) according to the following equation:

$$SSP = -K \log \frac{Rmfeq}{Rweq} \qquad (7)$$

where

SSP = the deflection of the SP curve from a shale baseline (millivolts) in a thick clean zone.

K = a constant, (61 + 0.133)Tf for NaCl water, dependent on temperature.

Rmfeq = equivalent resistivity of mud filtrate (ohm-meters).

Rweq = equivalent resistivity of connate water (ohm-meters).

Tf = formation temperature (F).

Input parameters for the static SP method are usually readily available from standard logs. The value of SSP is read directly from the log as discussed in Section 3.3 and illustrated in Appendix 2. If the SSP needs to be corrected for thickness, use Figures 4 or 5. Formation temperature can be calculated using Figure 7 if bottom hole temperature and geothermal gradient are not known. Rm or Rmf values are usually listed on the log heading. A knowledge of mud resistivity is essential for electric log interpretation. This property is almost always measured by the logging crew, either on a surface sample or in the borehole, and appears on the log heading. Temperature corrections may be made using conversions presented in Figure 1. If the mud resistivity value Rm is used, it needs to be converted to Rmf. This is easily completed by using Figure 6. Rmfeq is then determined using the guidelines at the top of Figure 9.

In most formation waters, there is enough NaCl that the K value for NaCl (71 at 77°F) can be used. However, when other salts are predominant in very fresh waters SSP responses may be drastically altered. First the K value may be affected. For example, if both filtrate and formation water were pure sodium bicarbonate solution ($NaHCO_3$), K would be 56 at 77°F. For potassium chloride solutions (KCl), K is approximately 60 at 77°F, and for potassium bicarbonate solutions ($KHCO_3$), K is

approximately 45 at 77°F. More importantly the Rmfeq/Rweq ratio in Equation 7 must be replaced by the ratio of ion activities in the formation water and mud filtrate. If extensive logging work is anticipated in an area where unusual salts predominate in the formation water, empirical relations should be developed for that area (Alger, 1966). Unusual salts are those other than sodium chloride.

Rweq can now be determined by substituting Rmfeq, SSP, and Tf values into equation 7. The final step is a temperature correction made by converting the equivalent Rweq, just calculated, into actual Rw using Figure 8.

As stated earlier, the procedures presented above are applicable to Rw determination of formation waters that are predominantly NaCl waters. In fresh formation waters, salts other than NaCl may become more important. In such cases, the dashed lines in Figure 8 which approximate "average" fresh formation waters should be utilized to convert Rweq to Rw.

The following steps outline and summarize the SP method for determining TDS:

1. Establish the shale baseline on the SP.

2. Pick out thick, clean permeable zones.

3. Do all the thick zones have about the same SP?

   if yes -- read SSP in any thick zone.

   if no -- read SSP in a thick zone near the zone of interest.

4. Determine formation temperature, using Figure 7 if necessary.

5. Convert Rm from log heading to Rm at formation temperature using Figure 2.

6. Determine Rmf from Rm at formation temperature using Figure 6. Alternatively, if Rmf is given on the log heading, correct it directly to formation temperature using Figure 2. Convert Rmf to Rmfeq using guidelines of Figure 9.

7. Read SSP amplitude from shale baseline to maximum constant deflection.

8. If the SSP does not show a flat top, determine bed thickness from SP inflection points and make a bed thickness correction using Figures 4 or 5.

9. Determine Rweq using SSP from step 8 (corrected if necessary) and Rmfeq, using Figure 9.

10. Convert Rweq to Rw with Figure 8.

11. Check Rw from SP against another source if available.

12. Determine TDS concentrations using Figures 1 or 2.

Examples of the SP method are presented in Appendix 1 and below.

<u>CASE HISTORY</u> - CLASS I DISPOSAL WELL
CALCASIEU PARISH, LOUISIANA

Well Log Heading

BHT 90°F Surface Temperature 80°F
TD 2250 ft
Rm 5.63 ohm - m @ 76°F
Rmf 5.5 ohm - m @ 75°F
Mud Weight 9.7 ppg

Using the SP method calculate TDS concentration at the suspected USDW, interval between 1110 - 1160 ft.

1) Determine formation temperature using Figure 6

$$Tf = 85^{o}F$$

2) Determine Rmf at formation temperature using Figure 1 and Rmf value listed on log heading.

Note: It is best to use the measured Rmf value on the log heading, if shown, rather than calculate the Rmf value from Rm.

$$Rm = 4.9 \text{ ohm - m @ } 85^{o}F$$

3) Pick the value for SP at depth in question.

$$SP = -60 \text{ mv}$$

4) Determine Rmfeq using equations in Figure 9

$$Rmfeq = 0.85 \text{ Rmf}$$

$$= 0.85 \text{ (4.9 ohm - m)}$$

$$= 4.16 \text{ ohm - m}$$

5) Determine Rweq using Figure 9

$$\frac{Rmfeq}{Rweq} = 6.2$$

$$Rweq = 0.67 \text{ ohm - m}$$

6) Determine Rw from Rweq using Figure 8

$$Rw = 0.67 \text{ ohm - m}$$

7) Determine TDS concentration using Figure 1 or 2

$$TDS = \underline{7,500} \text{ ppm}$$

4.3 PRECISION AND ACCURACY OF SP AND RP METHODS*

4.3.1 The Resistivity-Porosity (RP) Method

This method is generally applicable, even when waters contain appreciable Ca or Mg ions, but does require a porosity measurement. The applicable equation is (for clean sands):

$$Rw = \frac{\phi^m}{0.81} Ro \qquad (4)$$

where ϕ is porosity (fractional), m is the cementation exponent, and Ro is the deep resistivity reading (ohm-m) corrected for invasion.

In the salinity range of interest, 500-10,000 ppm, the relation between salinity S (ppm NaCl) and water resistivity, Rw is (to an accuracy of 5%):

$$S = 5,500/Rw \qquad (12)$$

---

* By Mr. John Dewan

Differentiating and using Eq. (12) leads to the following uncertainty equations:

$$\frac{\delta S}{S} = - \frac{\delta Ro}{Ro} \quad \text{for } \phi \text{ and m constant} \tag{9}$$

$$\frac{\delta S}{S} = - m \frac{\delta \phi}{\phi} \quad \text{for m and Ro constant} \tag{10}$$

$$\frac{\delta S}{S} = - (\log_e \phi) \; m \tag{11}$$

These equations allow estimation of the uncertainty of salinity determination under different assumptions:

A) Absolute salinity determination with a single well:

If the USDW is thick enough ($\geq$7') and the deep resistivity reading (usually deep induction) corrected for invasion, then Ro should be accurate to a probable error of 5%. Eq. (9) gives the corresponding probable error in salinity also as 5%.

Assuming good porosity logs are available (specifically the density-neutron combination) the probable error in porosity is estimated to be 5%. Eq. (10), with m = 1.6, gives the corresponding probable error in salinity as 8%.

Values of m for USDWs can vary considerably. They are typically in the range 1.4 to 1.8. Without an independent measurement, one must assume an average value of 1.6 with probable error of 0.1, Eq. (11), with ϕ = .32, leads to a probable error in salinity of 11%.

Combining these results, assuming independence of error sources, leads to an overall probable error of $(5^2 + 8^2 + 11^2)^{1/2}$ or 15%, in absolute salinity determinations from a single well log. Note that, with an "old" porosity log, such as sonic or microlog, the probable error in porosity could be considerably larger than that indicated.

B) Salinity differences across a given USDW:

Assuming, as before, the USDW is consistent in characteristics across a number of penetrating wells, then the probable error in relative salinities could be significantly less. In particular, if the grain size distribution in the USDW is relatively constant, then m should be constant and the corresponding uncertainty in salinity due to m considerably less. Overall, an estimate of the uncertainty in relative measurements is 7%.

4.3.2 The Spontaneous Potential (SP) Method

This method is applicable if there is a good contrast between mud filtrate and formation water salinities and if sodium ions dominate in the chlorides. The SP equation (7) can be written

$$Rw = Rmf \cdot \exp\ (SSP/K) \qquad (7)$$

where Rw (ohm-m) is the resistivity of the formation water, Rmf is that of the mud filtrate, SSP is the SP deflection (mv) from

the shale line, in a thick, shale-free, water-bearing zone, and K is a temperature-dependent constant given by

$$K = (61 + .133T_f) \tag{13}$$

where T is the temperature in ^{o}F.

Combining eqs. (7) and (12) and differentiating we obtain the following uncertainty relations:

$$\frac{\delta S}{S} = -\frac{\delta Rmf}{Rmf} \quad \text{for SSP and T constant} \tag{14}$$

$$\frac{\delta S}{S} = -\frac{\delta SSP}{K} \quad \text{for Rmf and T constant} \tag{15}$$

$$\frac{\delta S}{S} = \frac{.056 \quad T \quad SSP}{K^2} \quad \text{for SSP and Rmf constant} \tag{16}$$

These equations allow estimation of the uncertainty of salinity determination under different assumptions:

A) Absolute salinity estimation with a single well:

Rmf is measured at the surface by the logging crew and is converted to the temperature of interest. Due to continual alteration of mud properties during drilling, Rmf downhole may deviate 10% (probable error estimate) from the surface value. Eq. (14) indicates that corresponding probable error in salinity determination will be 10%.

The SSP measurement from the log is subject to an estimated 3 Mv probable error from such sources as baseline drift, surface-generated noise, slight shaliness, etc. Assuming an average USDW temperature

of $100^{o}F$, Eq. (15) indicates the corresponding probable error in salinity to be 9.4%. Note, however, that appreciable amounts of Ca and Mg ions in the water can cause much greater errors in salinity determination.

Uncertainty in knowledge of the USDW temperature, obtained by linear interpolation between surface and bottomhole temperatures, is estimated to be 5° (probable error). Equation (16) gives the corresponding probable error in salinity (for an average SSP of 30 Mv and temperature of $100^{o}F$) as 0.8%. Thus temperature uncertainty is relatively unimportant.

Combining the results, assuming the sources of error are independent, leads to an overall probable error estimate of $(10^2 + 9.4^2 + 0.8^2)^{1/2}$ or 14%, for absolute salinity measurement from a single well.

B) Salinity differences across a given USDW from adjacent well logs:

It is not possible to monitor salt water injection into a USDW by running SPs successively over months or years in the same well because the well is always cased shortly after drilling. The next alternative is to try to spot salinity variation across a USDW from adjacent well logs.

Assuming the USDW is consistent in depth and in freedom from shaliness, and that much the same drilling mud practice has been used across the field, then the probable error in relative salinity measurements is estimated to be about half the absolute value given above, i.e. about 7%.

4.3.3 Precision and Accuracy Summary

Both methods of analysis lead to a probable error estimate of about 15% for single well measurements and about 7% for well-to-well relative measurements. Many factors can degrade these estimates, however, such as thin beds, washouts, no porosity logs, only old ES logs, shaliness, etc. The particular formations considered and the logs available need to be analyzed in any specific case.

The best method of observing salinity changes using geophysical logs is to have a plastic-cased observation well that can be repeatedly monitored. In this case ϕ and m are invariant so the only uncertainty is in resistivity measurement. With carefully calibrated tools, salinity changes as low as 3% should be observable.

4.3 TDS FROM WATER ANALYSIS

Determining TDS concentrations from laboratory analysis of water samples is the most precise method available. Analysis of 41 samples of water and wastewater were made with a standard deviation of differences of 6.0 mg/l, (Standard Methods for the Examination of Water and Wastewater, 1983).

The standard method for determining TDS in water samples is an evaporation technique where a sample is dried at constant temperature and the weight of the remaining solids represents the total solids. A detailed description of the technique is listed in "Standard Methods for the Examination of Water and Wastewater", 1983. This procedure is also described in EPA's Method #160.2, "Non Filterable Residue Method".

Formation fluid samples were obtained and analyzed for the Louisiana Class I disposal well case history. The average conductivity for the samples in the interval 1110 - 1160 ft were 13,500 micromhos/cm.

Using the empirical formula developed by Turcan (1966) for major aquifers in Louisiana:

$$(K)^{0.93} = \text{TDS in ppm}$$

$$K = \text{conductivity in micromhos/cm}$$

$$\text{TDS} = (13{,}500)^{0.93}$$

$$= 6938 \text{ ppm}$$

The fluid samples were also analyzed directly for TDS concentration in accordance with the 15th edition of <u>Standard Methods of the Examination of Water and Wastewater and Methods for Chemical Analysis of Water and Waste,</u> EPA 60014-79-020.

The laboratory analysis (see Appendix 2) indicated:

TDS = 7020 ppm

4.5 COMPARISON OF METHODS USED TO DETERMINE TDS CONCENTRATIONS

Results obtained using the described methods are summarized below. All of the methods used (SP, RP, Turcan, and Laboratory Analysis) are within an acceptable range.

A) The calculated difference between the RP and SP method is:

$$\frac{7500 - 7000}{7500} = 0.066 \text{ or } 6.6\%$$

B) The calculated difference between the RP method and laboratory water analysis is:

$$\frac{7000 - 7020}{7000} = 0.0028 \text{ or } 0.3\%$$

C) The calculated difference between the SP method and laboratory water analysis is:

$$\frac{7500 - 7020}{7500} = 0.064 \text{ or } 6.4\%$$

D) The difference between the SP and RP method is within an acceptable range. A review of the data did not reveal any obvious sources of error.

E) Since the RP method value is nearly identical to both the laboratory analysis and Turcan method, we can conclude that the TDS is approximately 7000 TDS.

Method	TDS Concentration (ppm)
RP	7000
SP	7500
Turcan	6938
*Water Analysis	7020

*Water Analysis contained in Appendix 2.

5.0 COMPARISON OF RESISTIVITY-POROSITY VS SPONTANEOUS POTENTIAL METHODS

Two methods of determining Total Dissolved Solids (TDS) concentrations using geophysical logs have been presented in this report. Both methods appear to have applications in determining TDS concentrations when care is taken in selecting the input data. There exists a workable relationship between water quality and the use of geophysical logs. If it can be safely assumed that major ion concentrations are composed of NaCl, the quickest and easiest method for TDS determination is the SP method. Therefore, for most situations, it is the preferred method. Results are equivalent to those obtained by the RP technique. Unlike the RP method, the SP method does not rely on correct porosity measurements. If accurate Rmf data is available, final results should be valid using the SP curve. The SP method is subject to error if precautions are not taken. Factors affecting the SP include: the presence of shale, borehole diameter, mud invasion, bed thickness, and resistivity. Many older Electric logs can be used for the SP method.

The RP method is equally accurate but requires additional data. Open hole logs such as induction and laterologs are required, as well as accurate porosity measurements. To obtain the best results, two types of porosity logs; such as the neutron, acoustic, or density logs; are required unless accurate lithologic descriptions are available. Factors affecting the RP include: the presence of shale, uncertainty in porosity if no

porosity log is available, and the affect of surface conductance in fine-grained high porosity formations.

Both the SP and RP methods have different but equally acceptable applications in determining TDS concentrations. The relative values of borehole fluid resistivity and formation water resistivity, and the quality of additional available data, will dictate which method should be used. If the USDW is in a low porosity, thick bed carbonate sequence the RP method must be used as the SP will not resolve the beds. The RP method will also need to be used if the borehole fluid is saline.

If Rw is determined to be less than 1 ohm-m (with the dissolved salt being NaCl) both the SP and RP method are valid, provided that good data is available. However, when Rw is greater than 1 ohm-m, salts other than NaCl are probably present causing the Rw value from the SP method to be low. Consequently, when Rw > 1 the RP method is likely to be more reliable.

6.0 OTHER METHODS

Several alternative methods are available for determining the base of a USDW. These methods are usually researched before geophysical logging techniques are selected.

Hydrogeological atlases are available from various Geologic Water Surveys and several have been published by universities in cooperation with state and federal governments. These publications contain TDS concentrations in select formations. Piezometric maps, oil and gas maps, water well location maps and many other useful maps and charts are available for many areas.

Often times Rw can be obtained from water catalogs which usually list chemical analyses collected from different locations within an aquifer. These catalogs are compiled by oil and gas companies, and professional organizations. Typically, Rw values in USDWs are not included in the listing since aquifers associated with oil and gas formations are normally not of low enough TDS to qualify as USDWs.

The U.S. Bureau of Mines publishes information on oil-field brines. Specifically, the U.S. Bureau of Mines publication No. 6167 has chemical analyses listed for brines in select Mississippi and Alabama formations.

Several methods of determining TDS concentrations through chemical analyses of water samples are available. Unfortunately samples of formation waters have rarely been taken near the base of USDWs. Where samples have been taken, direct measurements of Rw (i.e. conductivity) are often listed even if a complete analysis for all constituents is not performed.

Currently, new methods for ground water quality determination are being developed. Several papers related to the determination of ground-water quality and occurrence were presented at the "Surface and Borehole Geophysical Methods and Ground Water Instrumentation Conference and Exposition", NWWA, October 1986. Techniques presented were applicable only to new and exploratory wells. Thus, these techniques do not relate directly to the determination of USDWs characterized through use of existing geophysical logs from older wells.

7.0 REFERENCES

Alger, R.P. 1966, Interpretation of Electric Logs in Fresh Water Wells in Unconsolidated Formations, American Petroleum Institute API RP 4S

Alger, R.P. 1988, Improved Fresh Water Assessment in Sand Aquifers Utilizing Geophysical Well Logs, Presented at Conference on Southwestern Ground Water Issues, Albuquerque, N.M., March 1988.

Archie, G. E. 1942, The Electrical Resistivity Log as an Aid in Determining some Reservoir Characteristics: American Inst. Mining Metal. Engineers Trans. V. 146

Frank, Rollyn, 1986 Prospecting with old E-Logs, Schlumberger Educational Services, Houston, Texas

Desai, K.P. and Moore, E.J. 1969, Equivalent NaCl Determination From Ionic Concentrations, Log Analyst v. 10, no. 3

Dewan, J.T. 1983, Essentials of Modern Open-Hole Log Interpretation, Tulsa Oklahoma, Dennwell Publishing Co.

Dresser Atlas 1982, Well Logging and Interpretation Techniques, Dresser Industries Inc.

Gatlin, C., Petroleum Engineering-Drilling and Well Completions, Prentice - Hall, Inc., Englewood Cliffs, N.J., 1960

Guyod, H., Fundamental Data for the Interpretation of Electric Logs, Oil Weekly, October 30, 1944

Hilchie, D.W. 1979, Old Electrical Log Interpretation, Douglas W. Hilchie Inc., Golden Colorado

Hilchie, D.W. 1980, Applied Openhole Log Interpretation Douglas W. Hilchie Inc., Golden Colorado

Hingle, A.T., 1959 The Use of Logs in Exploration Problems, Transactions, Society of Exploration Geophysicists, Los Angeles, California

Kwader, Thomas, 1985, The Use of Geophysical Logs for Determining Formation Water, Formation Magazine v24, No. 1, Jan.-Feb. 86

Lynch, E.T. 1962, Formation Evaluation: New York Harper and Row Publishers

MacCary, L.M. 1980, Use of Geophysical Logs to Estimate Water-Quality Trends in Carbonate Aquifers, U.S. Geological Survey-Water Resources Division, WRI-80/007

Schlumberger Limited, 1979, Log Interpretation Chart, Houston Texas

Schlumberger Limited, 1986, Log Interpretation Charts, Houston Texas

Schlumberger Limited 1987, Log Interpretation Principles Applications, Houston, Texas

Turcan A. N. 1966 Calculation of Water Quality from Electric Logs -Theory and Practice, Louisiana Geol. Survey, Water Resources Pamph. 19

Vonhoff, J.A., 1966 Water Quality Determination from Spontaneous Potential Electric Log Curves, Amsterdam, Netherlands, North-Holland Publishing Co., Jour. Hydrology v. 4

Welex, A Division of Haliburton Services 1968, Charts for Interpretation of Well Logs, Houston, Texas

FIGURES

FIGURE 1 SALINITY - RESISTIVITY CHART

Resistivity of NaCl Solutions

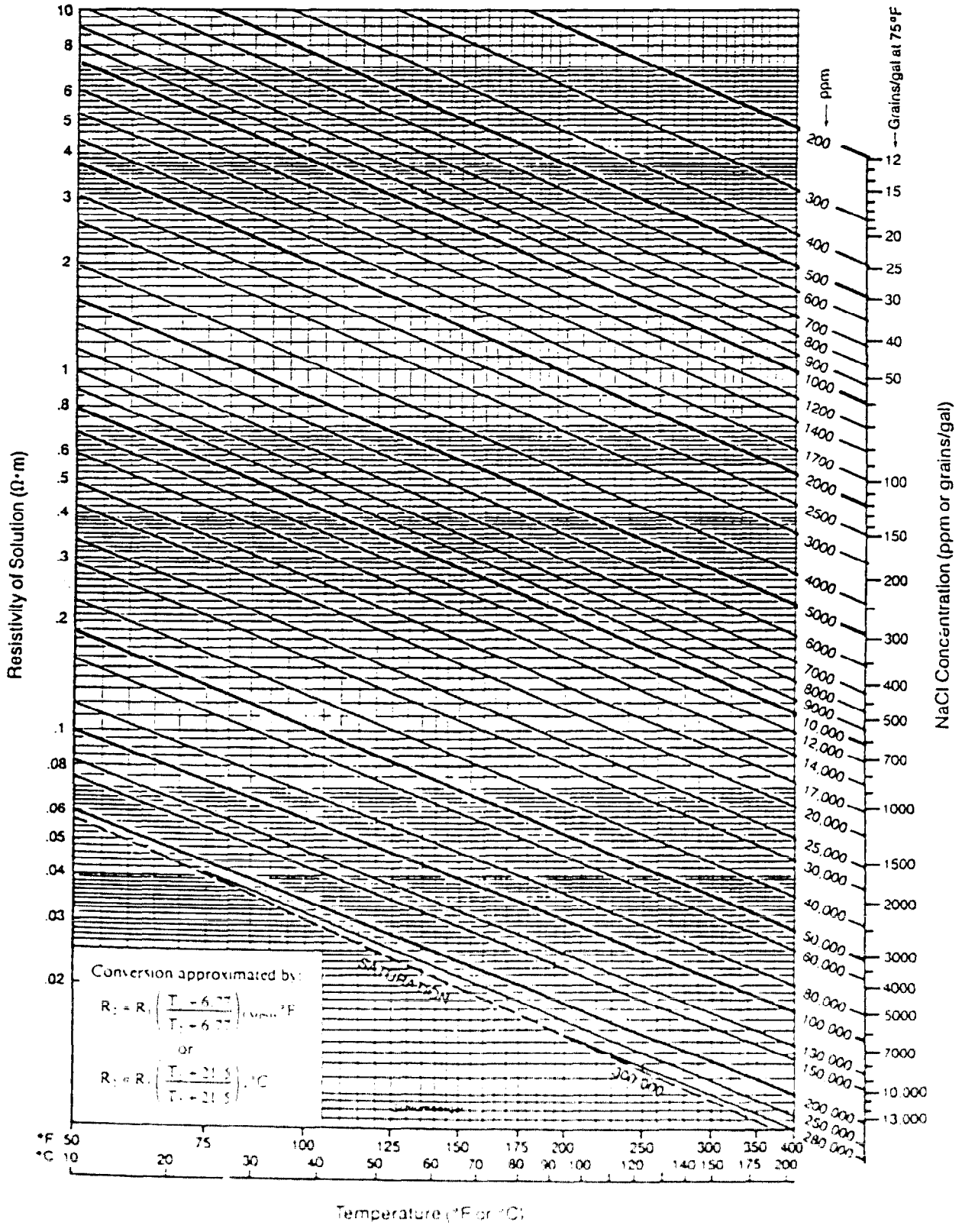
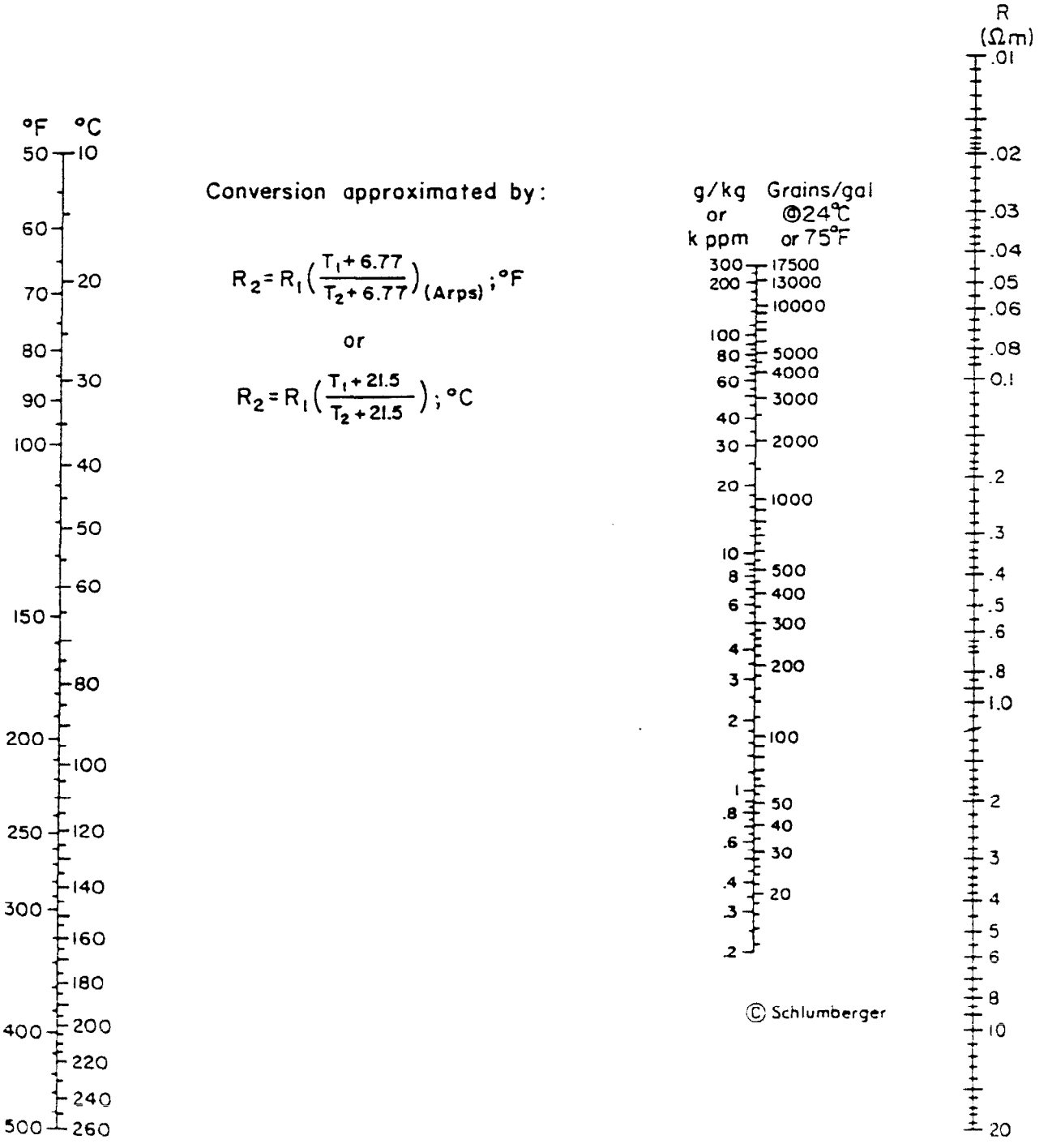


FIGURE 2 NaCl - RESISTIVITY VS TDS CONCENTRATIONS

Schlumberger

RESISTIVITY NOMOGRAPH FOR NaCl SOLUTIONS



Conversion approximated by:

$$R_2 = R_1\left(\frac{T_1 + 6.77}{T_2 + 6.77}\right)_{(Arps)};\ °F$$

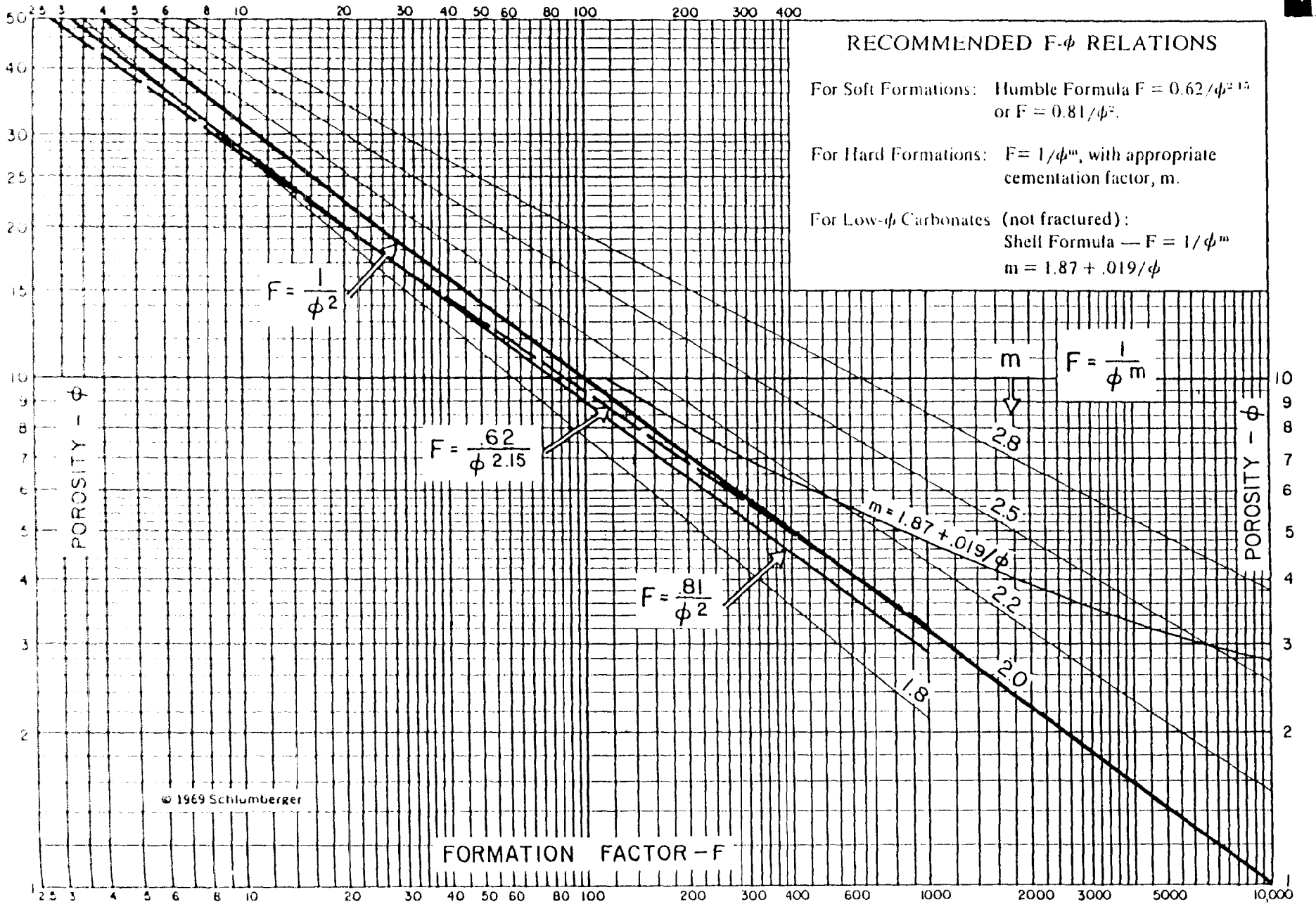
or

$$R_2 = R_1\left(\frac{T_1 + 21.5}{T_2 + 21.5}\right);\ °C$$

© Schlumberger

FIGURE 3 FORMATION FACTOR VS POROSITY

FORMATION FACTOR VERSUS POROSITY

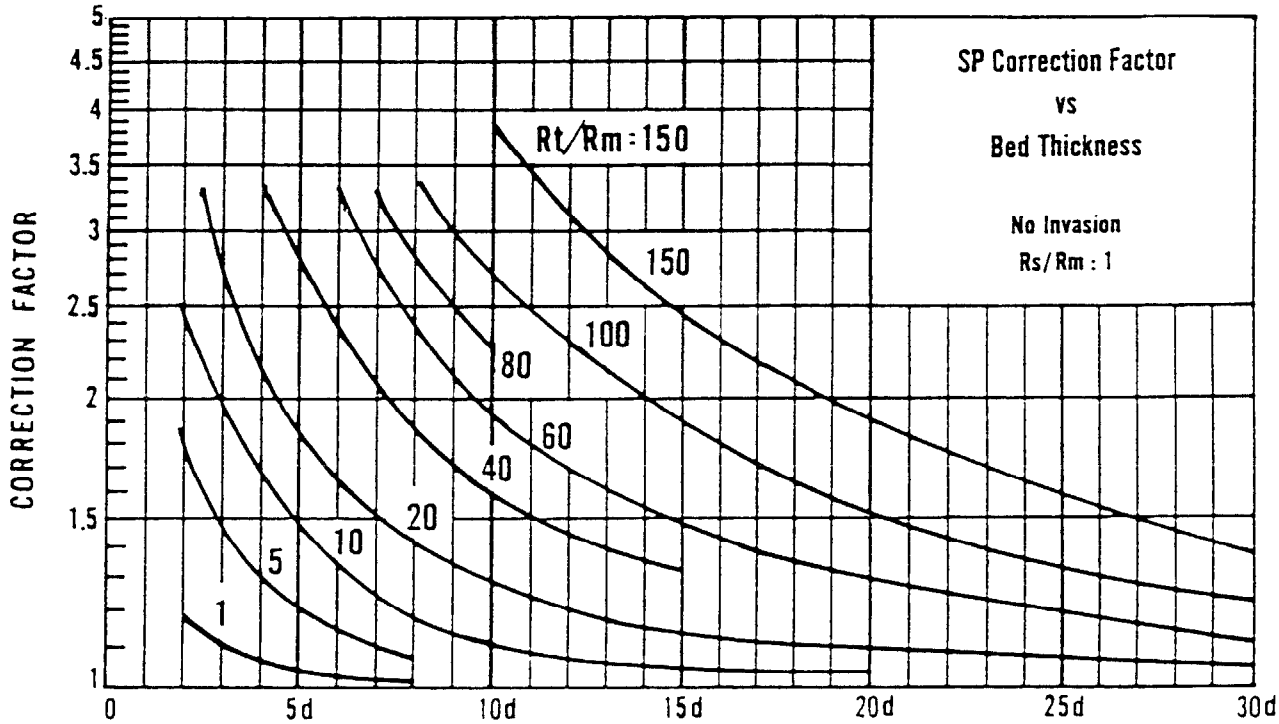


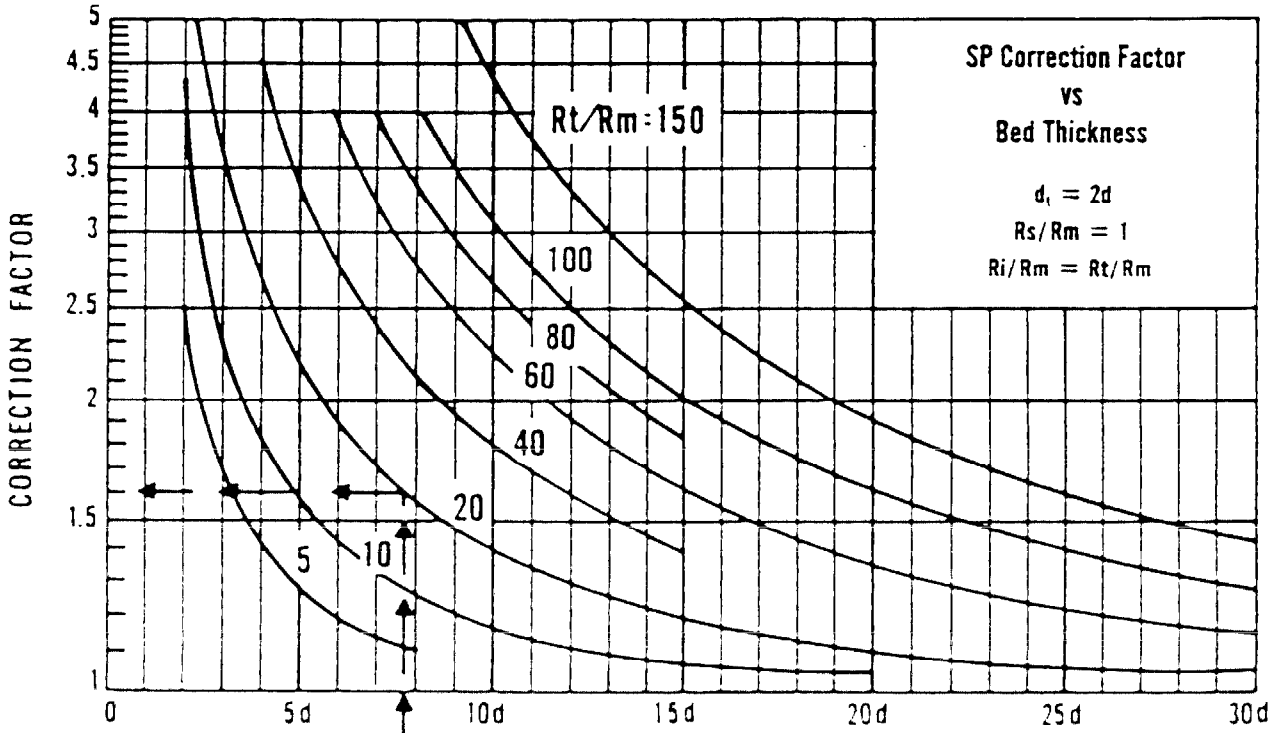
Schlumberger

FIGURE 4 SP CORRECTION FACTOR VS BED THICKNESS CHART

Welex

SP CORRECTION FACTOR vs. BED THICKNESS CHART





BED THICKNESS

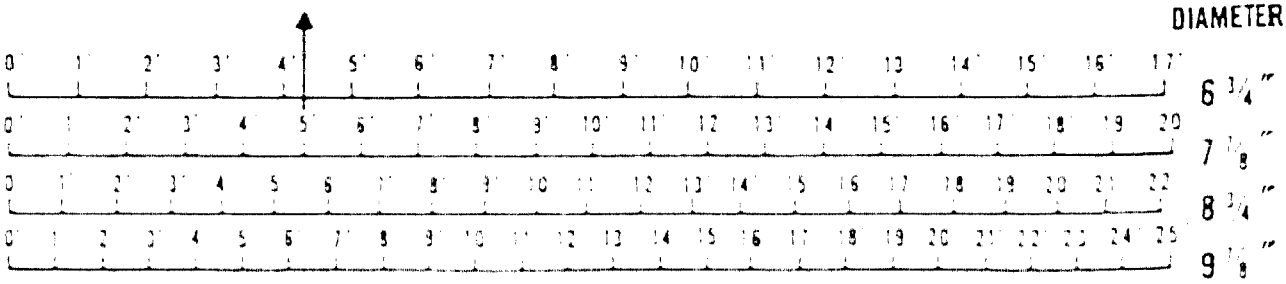


FIGURE 5 EMPIRICAL SP CORRECTION CHART

Empirical SP Correction Chart

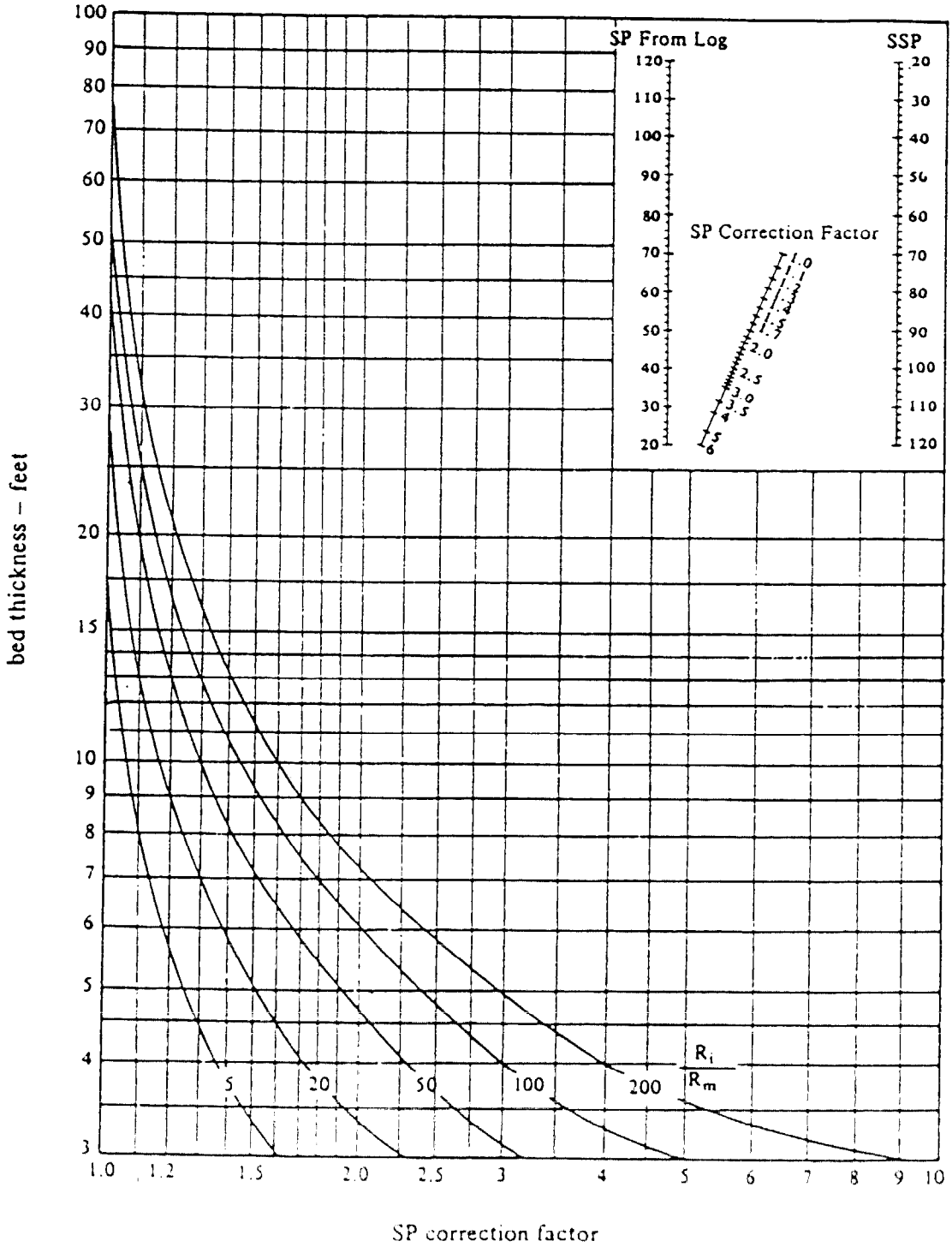
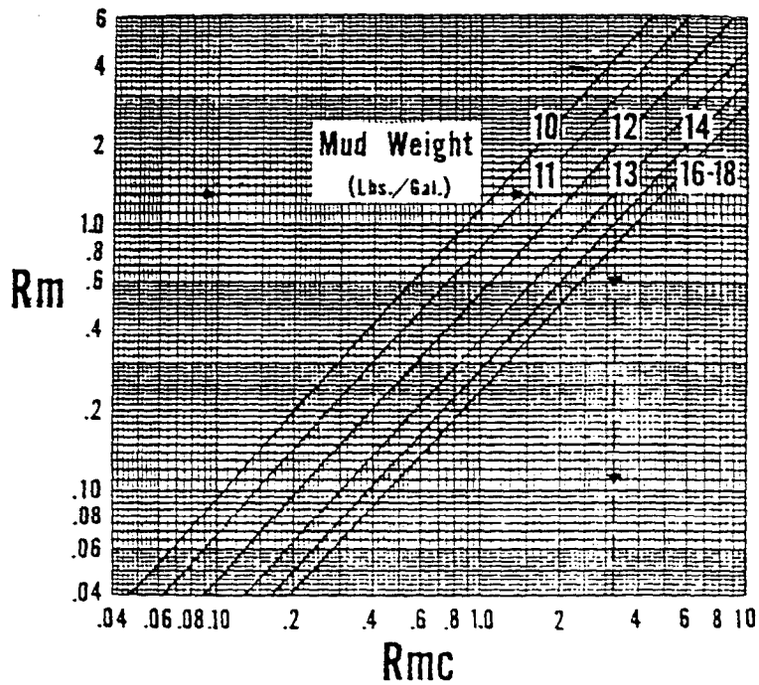


FIGURE 6 MUD WEIGHT CORRECTIONS

Mud Cake, Mud Filtrate, and Mud Resistivities for Various Mud Weights



PURPOSE

One of the factors affecting a mud's other properties is its weight. Resistivity charts usually do not consider such variables, although they may be significant. The relationship of mud weight and resistivity to the resistivities of mud cakes and filtrates is shown here.

The data is taken from "A Correlation of the Electrical Properties of Drilling Fluids with Solids Content," by Overton and Lipson; Petroleum Transactions, AIME, TP 8045, 1958.

APPLICATION

1. Determine R_{mc} at reservoir temperature
   When: R_m = 1.3 ohm-meters
   Mud Weight = 13 lbs./gal.
   THEN: R_{mc} = 3.2 ohm-meters
2. Determine R_{mf} at reservoir temperature
   When: R_m = 1.3 ohm-meters
   Mud Weight = 13 lbs./gal.
   THEN: R_{mf} = 0.65 ohm-meter

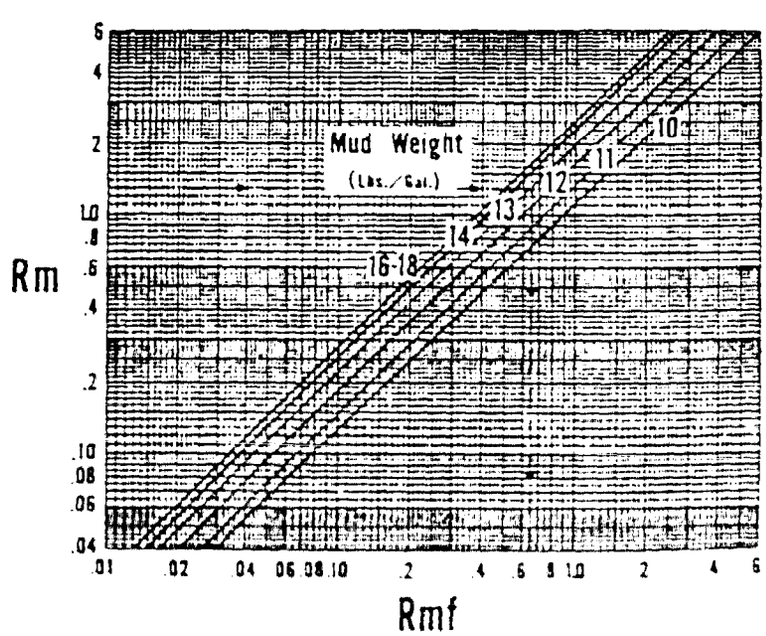
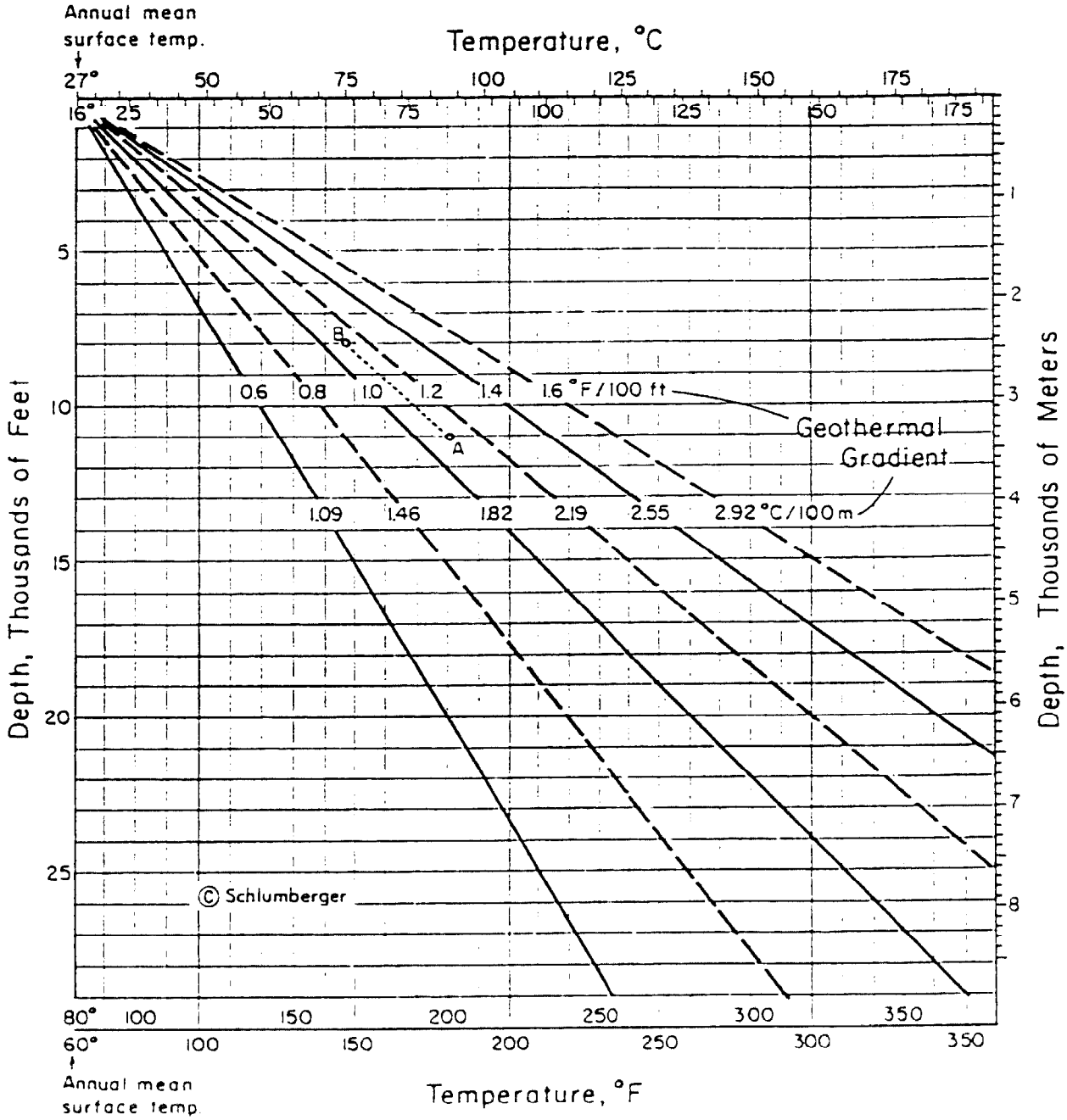


FIGURE 7 ESTIMATION OF FORMATION TEMPERATURE

Schlumberger

ESTIMATION OF FORMATION TEMPERATURE

(Linear Gradient Assumed)

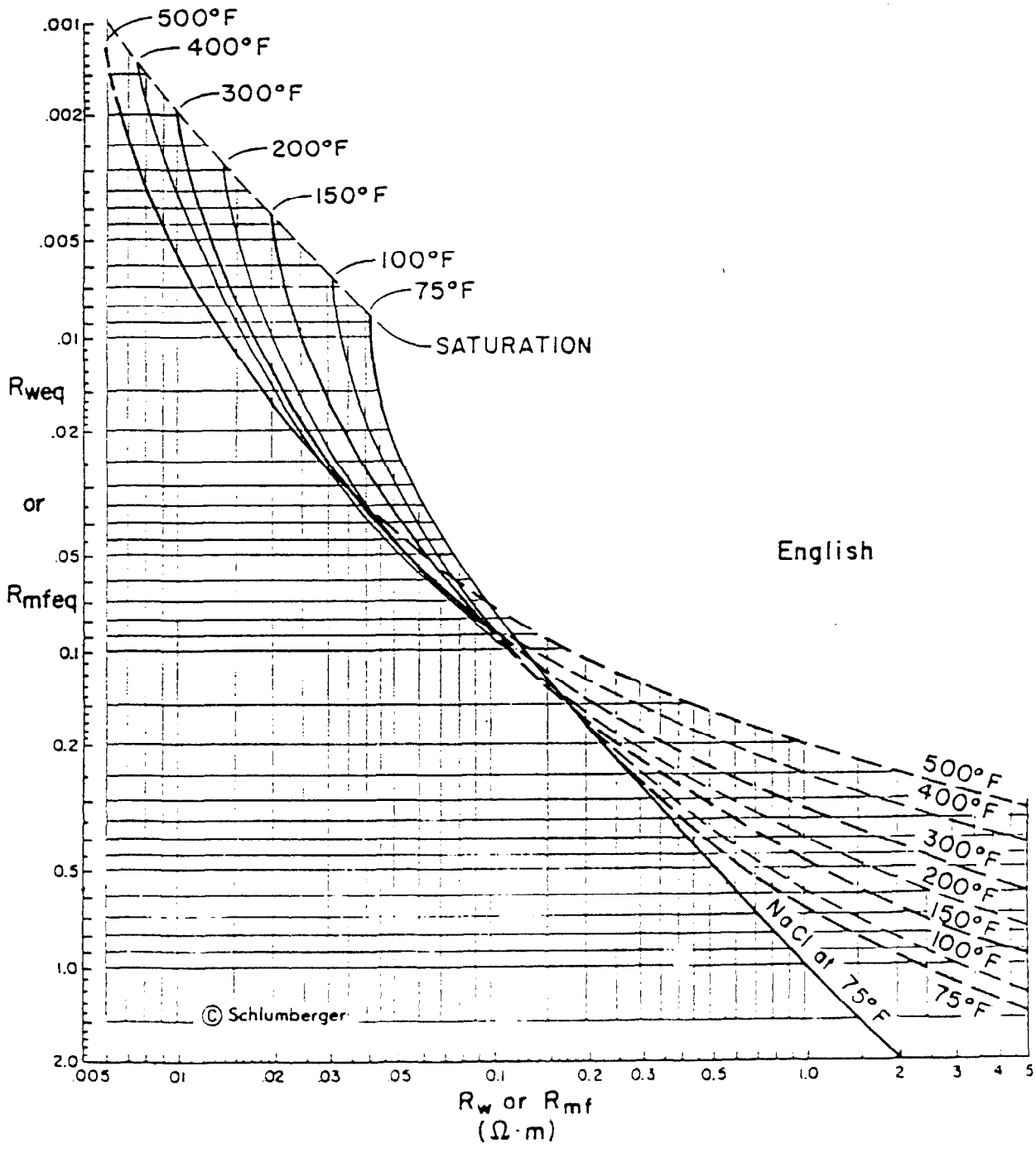


EXAMPLE: BHT is 200°F at 11,000′ (Point A).
Temperature at 8,000′ is 167°F (Point B).

Temperature Gradient Conversions: 1°F/100 ft = 1.823°C/100 m
1°C/100 m = 0.5486°F/100 ft

FIGURE 8 Rw VS Rweq AND FORMATION TEMPERATURE

R_w VERSUS R_{weq} AND FORMATION TEMPERATURE[3]



Use the solid lines of this chart for predominantly NaCl waters. The dashed lines are approximate for "average" fresh formation waters (where effects of salts other than NaCl become significant). The dashed portions may also be used for gyp-base mud filtrates.

EXAMPLE: $R_{weq} = 0.025$ at 150°F. From chart, $R_w = 0.038$

Special procedures for muds containing Ca or Mg in solution are discussed in the reference. Lime-base muds usually have a negligible amount of Ca in solution, and may be treated as regular mud types.

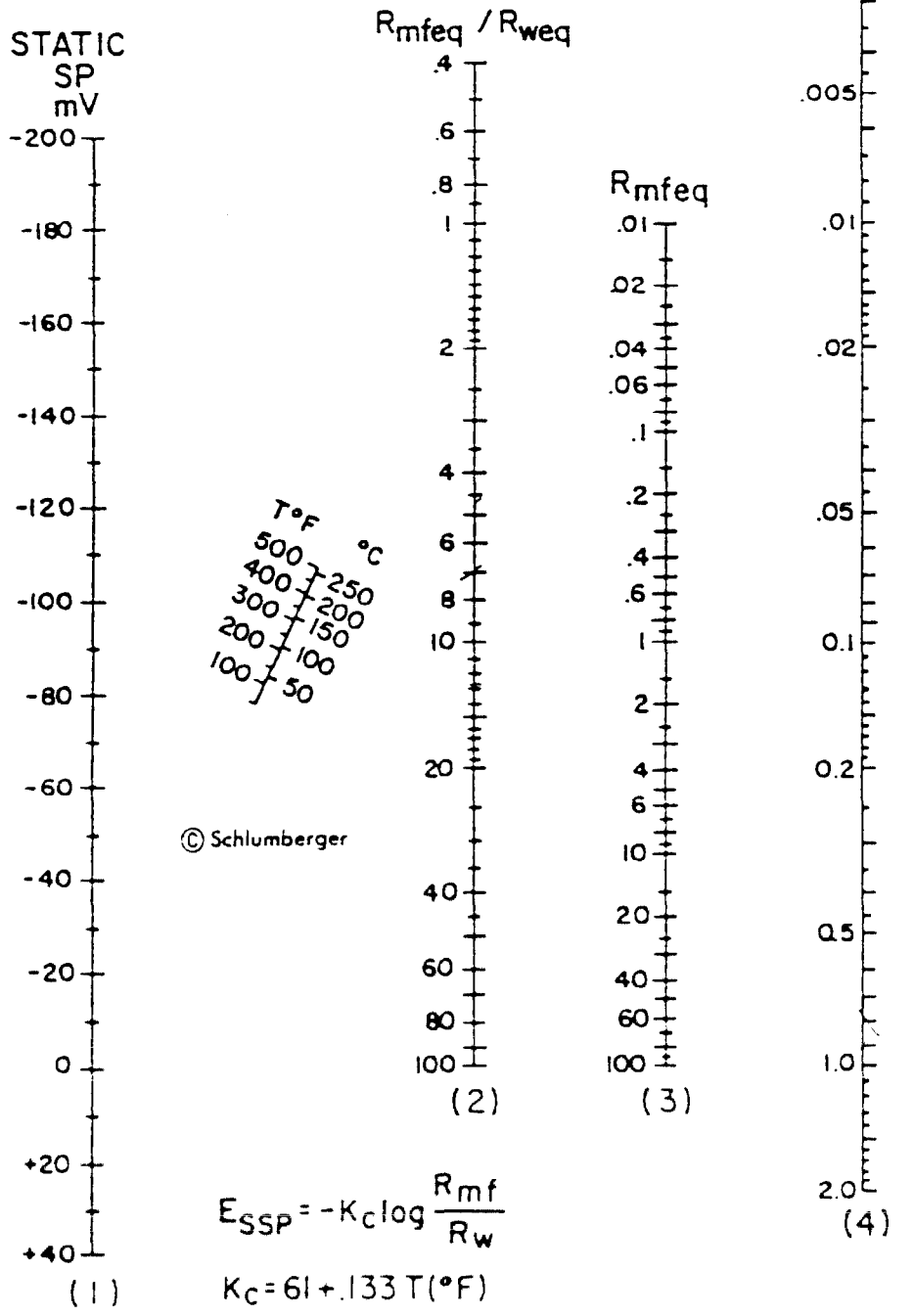
FIGURE 9 Rweq DETERMINATION FROM THE SSP

R_{weq} DETERMINATION FROM THE SSP
(CLEAN FORMATIONS)

For predominantly sodium chloride muds determine R_{mfeq} as follows:

a. If R_{mf} at 75°F (24°C) is greater than 0.1 Ω·m, correct R_{mf} to formation temperature using Gen-9, and use $R_{mfeq} = 0.85\ R_{mf}$.

b. If R_{mf} at 75°F (24°C) is less than 0.1 Ω·m, use SP-2 to derive a value of R_{mfeq} at formation temperature.



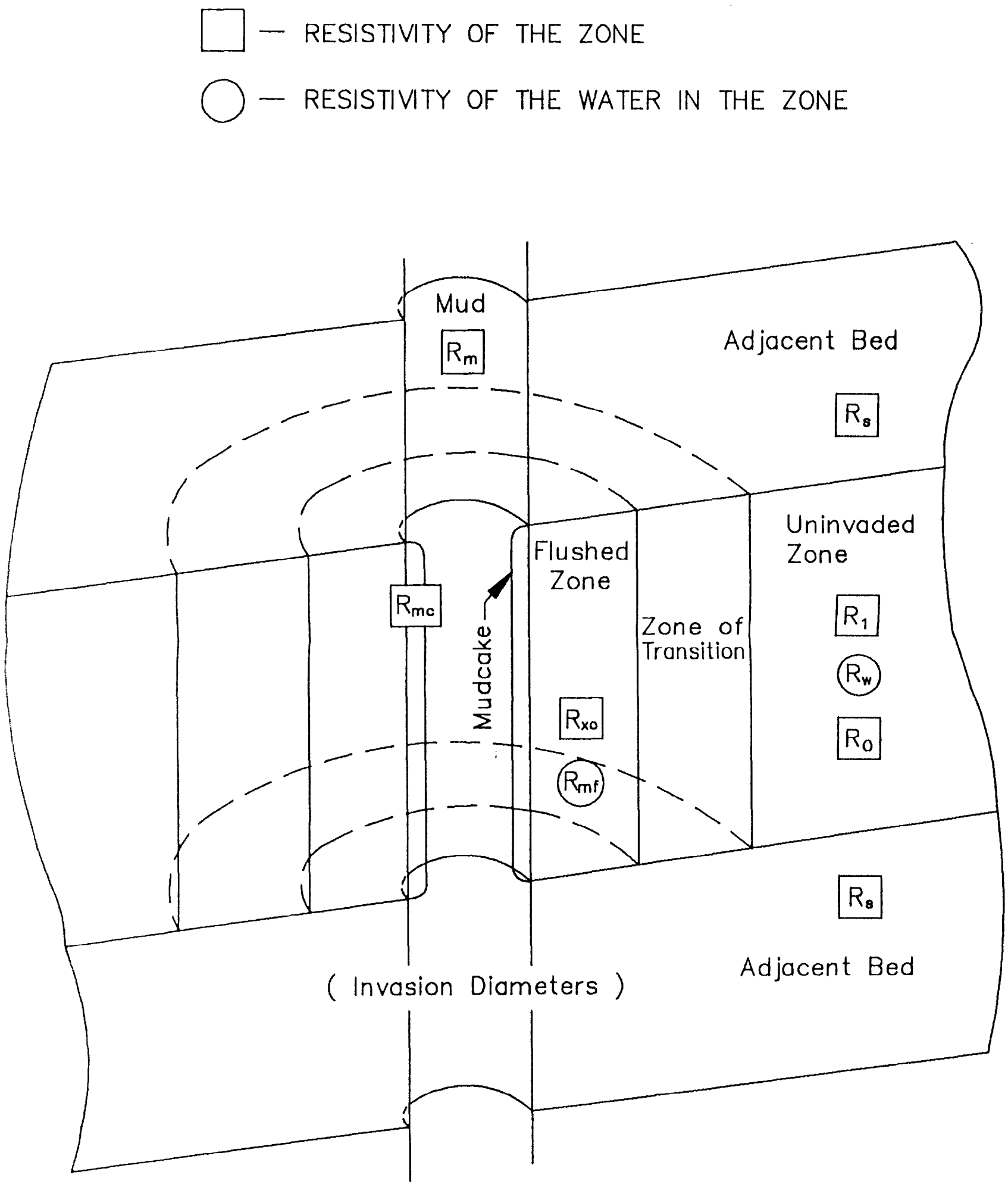
$$E_{SSP} = -K_C \log \frac{R_{mf}}{R_w}$$

$$K_C = 61 + .133\,T(°F)$$

$$K_C = 65 + .24\,T(°C)$$

FIGURE 10 RESISTIVITY SYMBOLS USED IN LOG INTERPRETATION

FIGURE 10



KEN E. DAVIS ASSOCIATES

RESISTIVITY SYMBOLS USED IN LOG INTERPRETATION

DATE: 12/14/87	CHECKED BY: M/J	JOB NO.: 30-956
DRAWN BY: D. T.	APPROVED BY: M/J	DWG. NO.: 30-956-1

APPENDICES

APPENDIX 1

EXAMPLE 1 - CALCULATION OF TDS USING RP AND SP METHODS

APPENDIX 1

CASE HISTORY - CLASS I DISPOSAL WELL
BRAZORIA COUNTY, TEXAS

Well Log Heading Data

BHT 294°F
TD 15000 ft
Mud Weight 11.4 ppg
Rm = 4.8 ohm - m @ 75°F
Rmf = not listed

I. 1) Calculate TDS concentration at the suspected USDW, from the clean sandstone interval between 1300 - 1360 ft

A) RP Method

1) Determine Porosity from Crossplot

$$\phi = 36\% = 0.36$$

2) Determine Formation Temperature Using Figure 7

Tf = 99°F (with assumed surface temperature of 80F)

3) Determine formation factor using Humble equation or Figure 2

$$F = 0.62/\phi^{2.15}$$

$$= \frac{0.62}{(.36)^{2.15}} = \underline{5.57}$$

4) Pick Ro from deep Electric Log

Ro = 3.1 ohm - m

5) Determine Rw using equation 2

$$Rw = \frac{Rt}{F}$$

$$Rw = \frac{3.1 \text{ ohm - m}}{5.57} = 0.56 \text{ ohm - m}$$

6) Determine TDS concentration using Figures 1 or 9

TDS = 7700 ppm

II. B) SP Method

1) Determine formation temperature using Figure 6

$Tf = 99^{o}F$

2) Determine Rm at formation temp. using Figure 1 and Rm value listed on log heading

Rm = 3.7 ohm - m @ $99^{o}F$

3) Determine Rmf at formation temp. using Figure 6

Rmf = 2.9 ohm - m

4) Pick a value for SSP (maximum deflection from shale baseline)

SSP = -50 millivolts

5) Determine Rmfeq using equations in Figure 9

Rmfeq = 0.85 Rmf

= 0.85 (2.9 ohm - m)

= 2.5 ohm - m

6) Determine Rweq using Figure 9

$\frac{Rmfeq}{Rweq} = 4.5$

Rweq = 0.57 ohm - m

7) Determine Rw from Rweq using Figure 8

Rw = .57 ohm - m

8) Determine TDS concentration using Figure 1 or 2

TDS = 7500 ppm

APPENDIX 2

SUBSTANTIATING INFORMATION FOR SECTION 4.0

WEST-PAINE Laboratories INC.
7979 GSRI AVE. • BATON ROUGE, LA 70820

Lake Charles, Louisiana

May 27, 1985

Sample: _____

Parameter	Results	Quality Assurance Actual/Found	Date/Time Analyst
Chloride (mg/L Cl)	4,050	50.0/50.5	05-23/0830/DT
Color (APHA Units) (True/Apparent)	25/100	50/50	05-23/1500/DT
Iron (mg/L Fe)	2.3	0.50/0.49	05-24/RM
Manganese (mg/L Mn)	0.06	0.250/0.250	05-24/RM
Odor (T.O.N.)	No Odor Detected	Positive	05-23/1500/DT
Sulfate (mg/L SO_4)	7.9	10.0/9.1	05-24/0900/DT
Total Dissolved Solids (mg/L)	7,020	5,000/5,120	05-24/0800/KA
ilica (mg/L SiO_2)	21	5.0/5.0	05-24/1500/RG
Calcium (mg/L Ca)	52	0.250/0.248	05-24/RM
Magnesium (mg/L Mg)	21	0.250/0.247	05-24/RM
Sodium (mg/L Na)	2,890	5.0/4.7	05-24/RM
Potassium (mg/L K)	7.5	5.0/4.8	05-24/RM
Total Phosphate (mg/L P)	0.26	0.50/0.47	05-25/1400/RG
Total Organic Carbon (mg/L C)	5	25/23	05-23/0730/MS
Total Organic Halogen (mg/L Cl)	0.47	0.100/0.095	05-27/NB
Specific Gravity	1.01	1.00/1.00	05-24/1100/RG

WEST-PAINE Laboratories INC.
7979 GSRI AVE • BATON ROUGE, LA 70820

Lake Charles, Louisiana
May 27, 1985

Sample: _____

Parameter	Results	Quality Assurance Actual/Found	Date/Time Analyst
pH (Units)	7.59	Analyzed In Field	
Specific Conductivity (K)	13.5	Analyzed In Field	
Temperature (^{o}C)	25.3	Analyzed In Field	
Arsenic (mg/L As)	0.06	0.050/0.048	05-23/VM
Barium (mg/L Ba)	1.6	2.50/2.36	05-24/RM
Cadmium (mg/L Cd)	0.011	0.250/0.250	05-23/VM
Chromium (mg/L Cr)	<0.01	0.50/0.50	05-24/RM
Lead (mg/L Pb)	<0.04	2.50/2.50	05-24/RM
Mercury (mg/L Hg)	<0.0002	0.0100/0.0105	05-23/VM
Selenium (mg/L Se)	0.33	0.050/0.048	05-23/VM
Silver (mg/L Ag)	<0.01	0.50/0.50	05-23/VM
Nitrate (mg/L N)	0.03	0.20/0.20	05-24/0800/MS
Fluoride (mg/L F)	1.0	0.50/0.50	05-25/1030/RG
Total Coliform (colonies/100 ml)	3.0	Positive	05-23/1500/DT
Turbidity (NTU)	20	100/100	05-23/1500/DT
Endrin (mg/L)	<0.0002	------	05-24/CL
Lindane (mg/L)	<0.004	------	05-24/CL
Toxaphene (mg/L)	<0.005	------	05-24/CL
Methoxychlor (mg/L)	<0.100	------	05-24/CL
2,4-D (mg/L)	<0.100	------	05-24/CL
2,4,5-TP Silvex (mg/L)	<0.010	------	05-24/CL
Radium (pCi/L)	5.41 ± 0.42	Not Applicable	Not Applicable
Gross Alpha (pCi/L)	2.16 ± 1.94	Not Applicable	Not Applicable
Gross Beta (pCi/L)	13.24 ± 4.28	Not Applicable	Not Applicable
Carbonate Alkalinity (mg/L $CaCO_3$)	<1.0	100/108	05-24/1400/DT
Bicarbonate Alkalinity (mg/L $CaCO_3$)	550	100/108	05-24/1400/DT

85-1889

Schlumberger

LITHO DENSITY

A CSU* Service

COMPANY

EXHIBIT NO. 1

WELL U.I.C. MONITOR WELL

FIELD DISPOSAL

COUNTY CALCASIEU STATE LOUISIANA

LOCATION 1817' FSL & 988' FEL OF SEC. 32

API SERIAL NO	SEC	TWP	RANGE

Other Services:

COUNTY CALCASIEU
FIELD DISPOSAL
LOCATION U.I.C. MONITOR WELL
WELL
COMPANY

Permanent Datum: GL ; Elev.: 20.0
Log Measured From RKB 9.5 Ft. Above Perm. Datum
Drilling Measured From SAME

Elev.: K.B. 29.5
D.F. 28.5
G.L. 20.0

Date	5-9-85			
Run No	ONE			
Depth Driller	2255			
Depth Logger (Schl)	2255			
Btm Log Interval	2252			
Top Log Interval	64			
Casing Driller	12 @ 55	@	@	@
Casing Logger	64			
Bit Size	9 7/8			
Type Fluid in Hole	QUICK-GEL			
Dens / Visc	9.7 / 36	/	/	/
pH / Fluid Loss	7.0 / ml	/ ml	/ ml	/ ml
Source of Sample	PIT			
Rm @ Meas Temp	5.63 @ 76 °F	@ °F	@ °F	@ °F
Rmf @ Meas Temp	5.5 @ 77 °F	@ °F	@ °F	@ °F
Rmc @ Meas Temp	8.45 @ 76 °F	@ °F	@ °F	@ °F
Source Rmf / Rmc	M / C	/	/	/
Rm @ BHT	4.817 @ 90 °F	@ °F	@ °F	@ °F
TIME Circulation Stopped	1730/5-9			
TIME Logger on Bottom	2130/5-9			
Max. Rec. Temp.	≈ 90 °F	°F	°F	°F
Equip / Location	8107 / ICOH	/	/	/
Recorded By	BISESI			
Witnessed By	MESSRS. WEBB-CONGER			

FOLD HERE

The well name, location and borehole reference data were furnished by the customer.

AL /

SCALE CHANGES			
Type Log	Depth	Scale Up Hole	Scale Dc

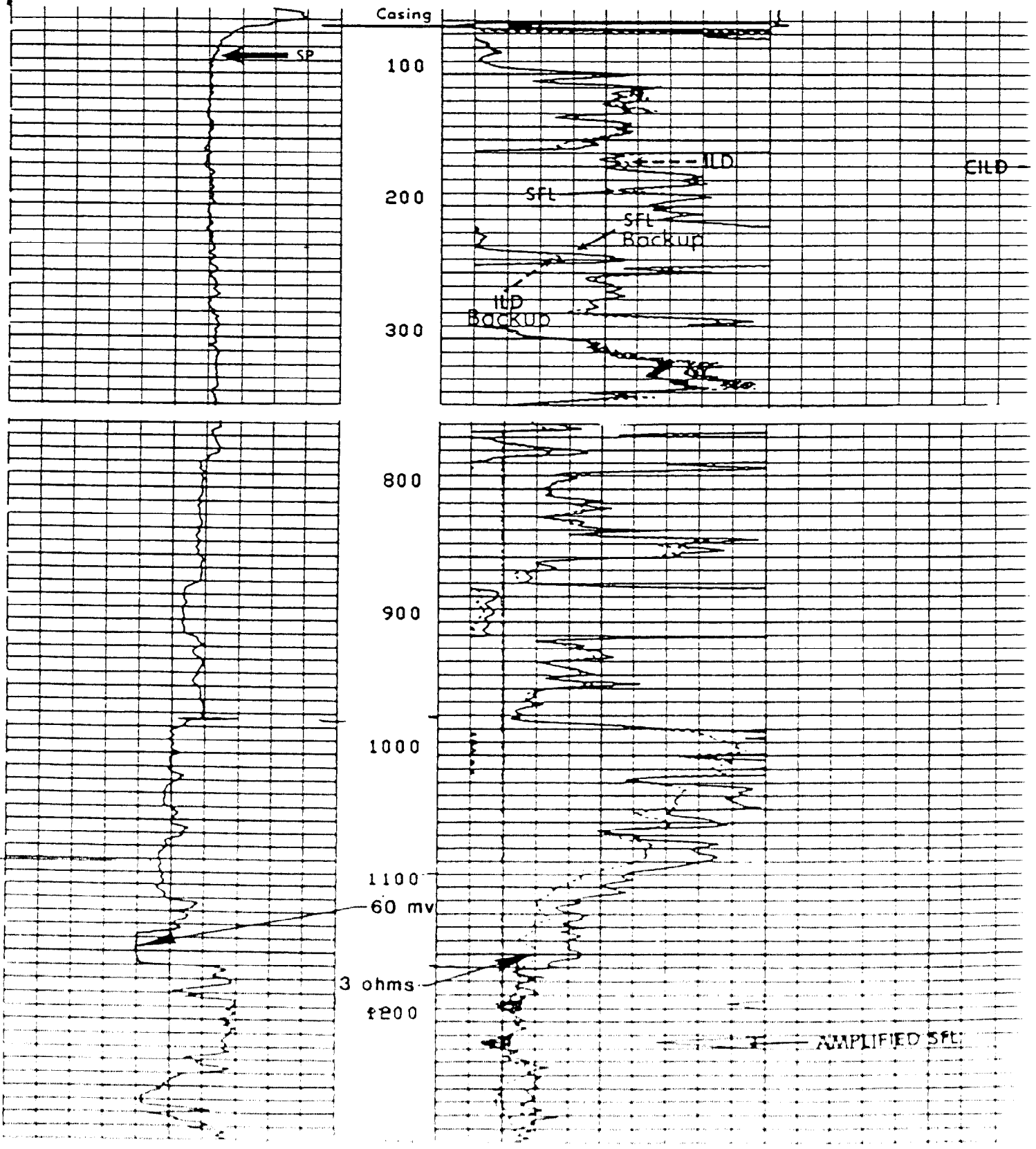
REMARKS

MONITOR WELL FOR UNDERGROUND DRINKING WATER.
DRILLING MEASURES TRC FROM GL. LOGGING MEASURES TRC RKB. 100 DEG. THERMOMETER USED NOT REGISTER.

RUN NO.	ONE																						
Service Order No.	453423																						
Fluid Level																							
Salinity, PPM CL.																							
Speed - F.P.M.																							
EQUIPMENT DATA																							
IE Module				AB-269																			
Ind. Cartridge				DA-526																			
Ind. Sonde				EC-560																			
IND. PANEL NO.				BC-154																			
TELEMETRY CART. NO.				A-202																			
Dens. Skid.																							
Dens. Sonde				B-3743																			
Dens. Source				J-7208																			
Dens. Calibrator				D-1863																			
Neut. Cart.																							
Neut. Source																							
Neut. Calibrator																							
GR Cart.				SA-717																			
SBR																							
S. O.:																							

SP (MV)		ILD (OHMM)	
		0.0 10.000	
		SFLA(OHMM)	
		0.0 2.0000	
		SFLA(OHMM)	CILD(MMHO)
-160.0 40.000		0.0 10.000	4000.0

FILE 7 09-MAY-85 22:44



APPENDIX 3

SINCLAIR VARIABLE MULTIPLIERS

An example of this method using water-quality data for the Red River Formation in a North Dakota well is illustrated in table 1. The water analysis is listed with the appropriate multiplier for each ionic constituent (Desai and Moore, 1969). The last column in the table lists the product of ppm and the multiplier. The sum of the products is the concentration of an equivalent NaCl solution in ppm. Resistivity of this solution can be determined from nomograph 1-4 in Dresser Atlas (1979). The formula from Dresser-Atlas (1979),

$$Rw = 0.0123 + \frac{3647.5}{[\text{NaCl ppm}]^{0.955}},$$

can be used to calculate Rw, when the total ppm as NaCl is less than 100,000 ppm. The calculated resistivity in table 1 differs from the measured value by about 9 percent. In most cases the difference between the calculated and the measured resistivities will be less than plus or minus 10 percent, and should be within plus or minus 5 percent according to Desai and Moore (1969).

Table 1.—*Analysis of water from drill-stem tests in a North Dakota well*

Constituent	Concentration (ppm)	Sinclair variable multiplier	Resultant (ppm)
Calcium	7,640	0.349	2,666
Magnesium	1,420	-.652	-926
Sodium	66,056	1.0	66,056
Bicarbonate	60	.100	6
Sulfate	1,235	.200	247
Chloride	118,600	1.0	118,600
Dissolved solids calculated	194,880	-----	-------
Equivalent NaCl	-------	-----	186,649

Specific gravity	1.129 g/cc
Measured resistivity	0.056 ohm-meters
Calculated resistivity (from nomograph, Dresser-Atlas, 1979)	0.051 ohm-meters

APPENDIX 4

HINGLE CROSS PLOT

HINGLE CROSSPLOT

INTRODUCTION

In the late 1950's, Hingle proposed a method based on resistivity and porosity log data which allows the percent water saturation to be determined directly from a crossplot. The method is based on the well-known Archie equation, which in a rearranged form is plotted on special grid-type graph paper.

The basic mathematical manipulation includes:

$$F = a/\phi^m$$

$$R_o = F \times R_w$$

$$R_o = S_w^n \times R_t$$

$$\phi = (a/F)^{1/m}$$

$$\phi = [(a \times R_w)/R_o)]^{1/m}$$

$$\phi = [(a \times R_w)/(S_w^n \times R_t)]^{1/m}$$

$$\phi = [(a \times R_w)/S_w^n]^{1/m} \times R_t^{1/m} \qquad (1)$$

Equation 1 will describe a set of straight lines fanning-out from a common point or origin when plotting porosity, ϕ, vs resistivity, R_t, the latter on a special grid (i.e., $R_t^{-1/m}$). Special graph paper is required (Figures 23.2 and 23.3) for sandstones (where $F = 0.62 \times \phi^{-2.15}$) and carbonates (where m = 2.0).

Figure 23.1 shows the basic principles of the Hingle plot. Lines of constant S_w values originate at the matrix point where porosity ϕ = 0% and $R_t = \infty$, provided formation water salinity stays constant over the interval under study.

The water line (S_w = 1.0) can be drawn from the matrix point through the most northwesterly points on the crossplot. The slope of this water line defines R_w, which can be calculated by:

$$R_w = R_o/F \qquad (2)$$

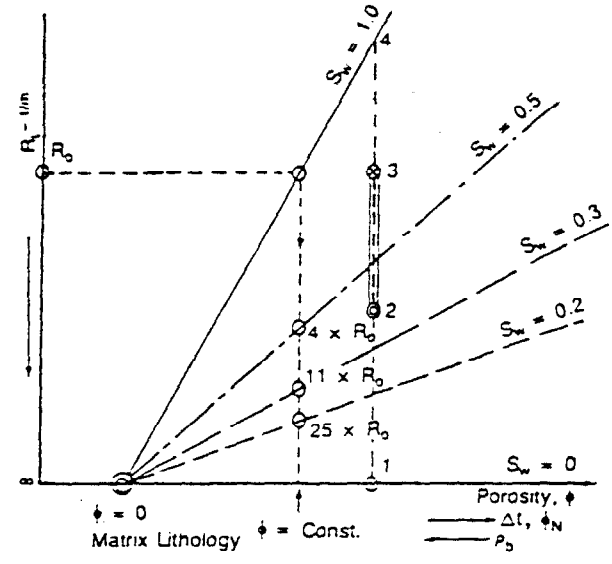
anywhere along the water line (S_w = 1.0).

S_w lines other than for 1.0 can be determined based on the Archie equation:

$$R_t = R_o/S_w^2 \qquad (3)$$

For example, 4 × R_o corresponds to the line of S_w = 0.5, 11 × R_o corresponds to S_w = 0.3, 25 × R_o to 0.2, etc. (Fig. 23.1)

Any of the three porosity logs (acoustic, density, neutron) can be used with any deep-reading resistivity device (induction, laterolog, etc.). Further, if an R_{xo} device is available, the amount of movable oil (MOP) can also be determined graphically. For the crossplot, the R_{xo} value has to be corrected for the resistivity contrast between formation water (R_w) and filtrate (R_{mf}). This normalization is obtained by (R_{xo}) × (R_w/R_{mf}). The latter value is then entered into the crossplot.



Where:

Carbonates: $F = \phi^{-m} = \phi^{-2}$

Sandstones: $F = 0.62 \times \phi^{-2.15}$

$\overline{12} = S_w$ $\quad$ $\overline{13} - \overline{12}$ = Movable Oil (MOP)

$\overline{13} = S_{xo}$ $\quad$ $\overline{14} - \overline{13}$ = Residual Oil (ROS)

FIGURE 23.1
Hingle plot principles.

The basic response of the three porosity logs is well-known and has been discussed many times in well logging literature. These tool responses have to be kept in mind when using the Hingle plot. Figure 23.4 shows the generalized effects which may influence any interpretative results.

Plotting procedure is outlined as follows:

1. Select proper crossplot paper. (Fig. 23.2 or 23.3)

2. Scale the x-axis in linear fashion for raw logging parameters (Δt, ρ_b) and establish porosity scale. Porosity will be zero at the matrix point and increases to the right. Make sure the scale is selected

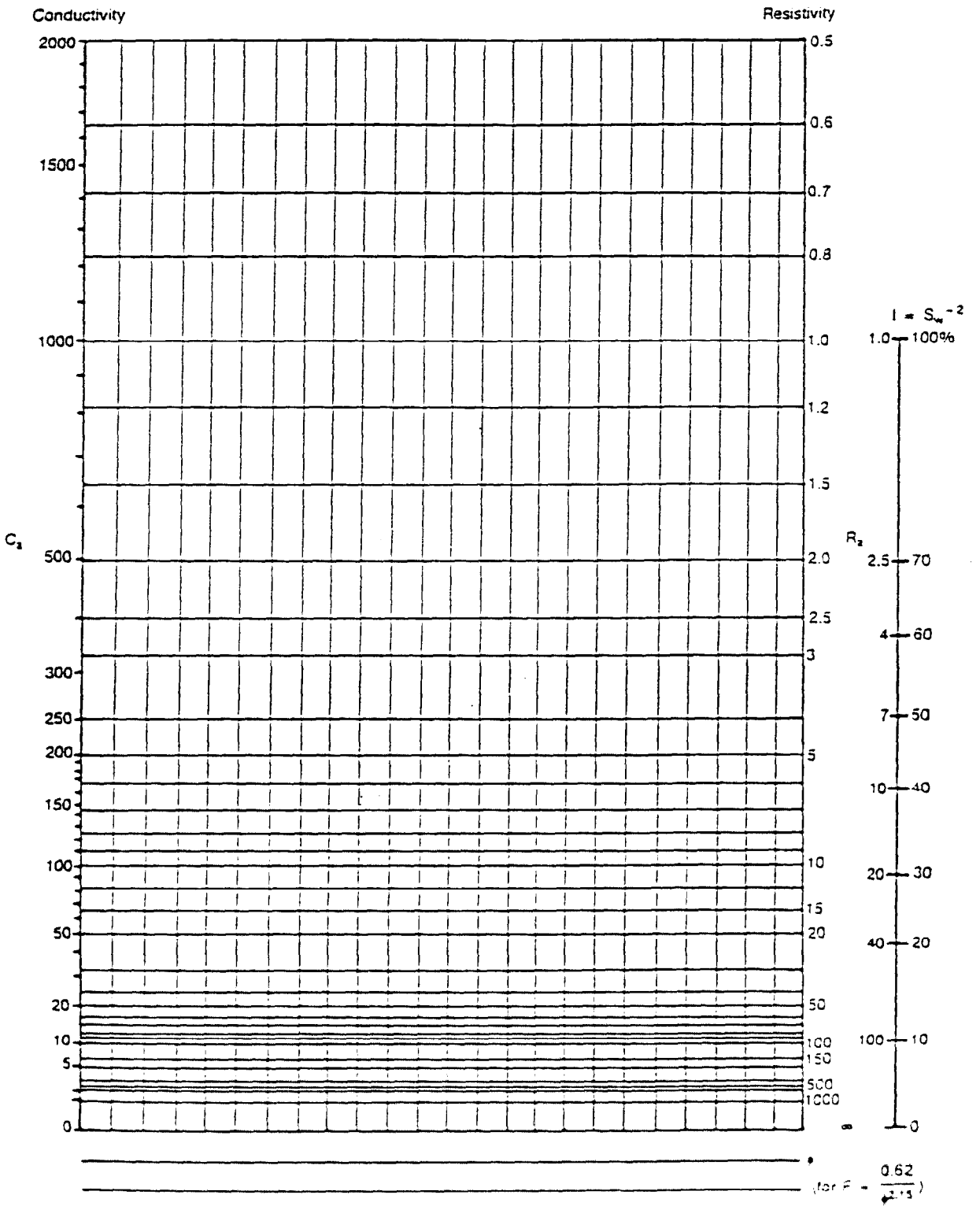


FIGURE 23.2
Resistivity/Porosity crossplots for sandstone

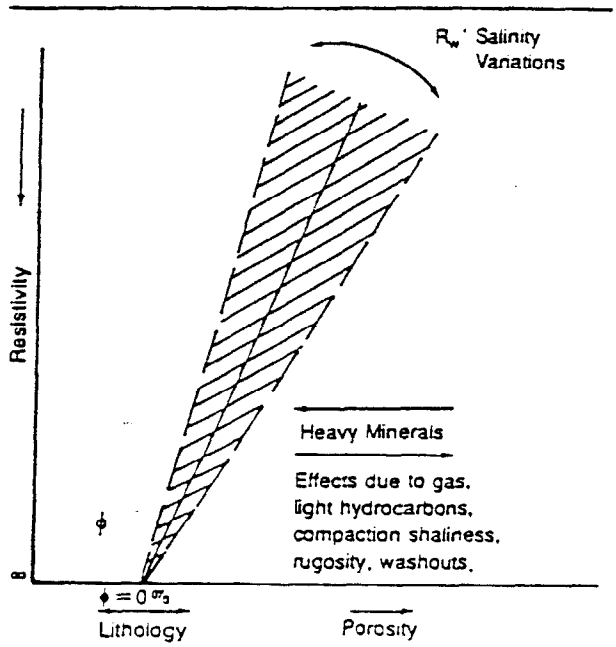


FIGURE 23.4
Generalized effects.

properly so the highest expected porosity values will still plot on the graph paper.

3. Plot the resistivity (R_t) vs log data (Δt, ρ_b, ϕ_N). The resistivity scale can be changed by any order of magnitude to fit the log data. This is done without changing the validity of the graph paper grid.

4. The straight line drawn through the most northwesterly points defines $S_w = 1.0$. Extrapolate this to the intersection with x-axis ($\phi = 0$, $R_t = \infty$).

5. At the intersection determine the matrix value (Δt_{ma} or ρ_{ma}) for a proper porosity scaling of the x-axis.

6. Calculate R_w from any corresponding set of ϕ and R_o data along the water line such as $R_w = R_o/F$.

7. Determine lines of constant S_w values based on $R_t = R_o/S_w^2$ (for any given ϕ-value). Keep in mind that all these lines have to converge at the matrix point ($\phi = 0$, $R_t = \infty$).

8. Read and evaluate S_w values for all points plotted on the crossplot. Make sure points are numbered to avoid confusion, particularly if very long sections are analyzed.

9. As an extension of this method, in case R_{xo} data are also available, the movable oil (MOP) can be determined since

$$S_w = (F \times R_w)/R_t, \; [S_{xo} = (F \times R_{mf})/R_{xo}],$$

$$MOP = S_{xo} - S_w$$

However, R_{xo} values have first to be normalized by multiplying R_{xo} by the ratio R_w/R_{mf} before being plotted on the crossplot graph. The comparison of the computed S_{xo} and S_w values is then indicative of the amount of movable hydrocarbons.

FIELD EXAMPLES

Example 1

Table 23.1 lists pertinent logging data in a well drilled through carbonate rocks in south Texas. Since hard-rock conditions prevail, the data have to be plotted on the proper grid with m = 2.0.

TABLE 23.1

DENSITY — RESISTIVITY CROSSPLOT

No.	Depth, ft	ρ_b, g/cc	R_t, Ωm
1	7,160	2.57	28.0
2	68	2.51	11.0
3	74	2.52	16.0
4	80	2.53	7.0
5	85	2.58	4.5
6	99	2.53	20.0
7	7,212	2.60	19.0
8	30	2.57	20.0
9	41	2.53	15.0
10	47	2.55	16.0
11	64	2.52	6.3
12	69	2.52	2.0
13	75	2.52	9.0

Figure 23.5 shows the graphical display of the density and resistivity logging data. The following conclusions can be drawn:

- The calculated points 5, 12 and 13 define the water-line, i.e. $S_w = 100\%$.
- The calculated value of R_w at, for example, $R_o = 2.5$ and $\phi = 10\%$ ($F = 100\%$), yields 0.025. This value compares favorably with drillstem test data at 7,211 ft; where on the recovered water sample the measured R_w was 0.028 Ω-m at formation temperature.
- Intersection of the water-line with the x-axis (porosity) in the matrix point ($\phi = 0$) defines the presence of a limestone interval exhibiting a density of 2.71 g/cc.
- Properly scaled lines of constant S_w can be drawn, all of which originate in the matrix point.

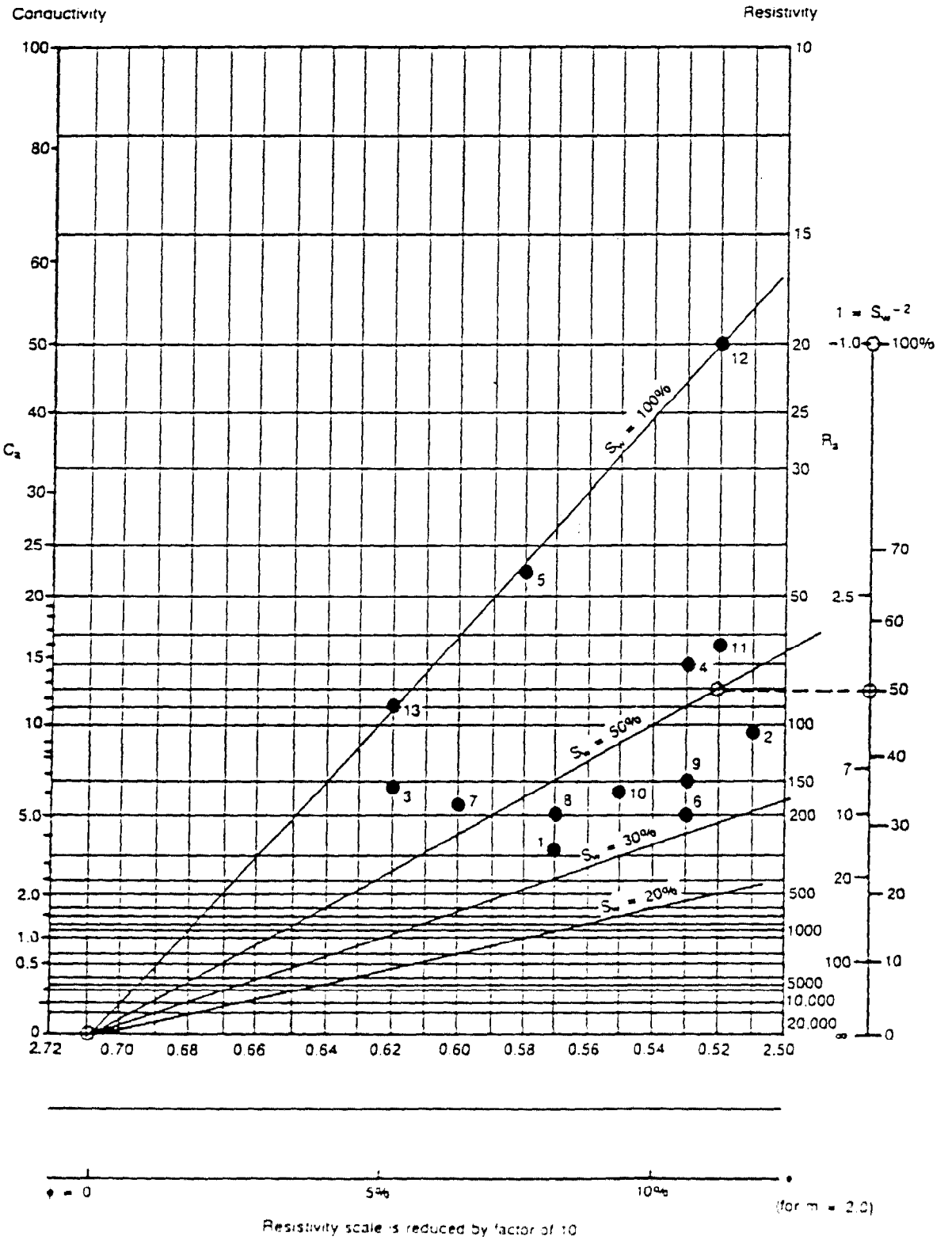


FIGURE 23.5
Resistivity/Porosity Crossplot (RPCP).

- As can be seen in the crossplot, only intervals 1, 2, 6, 8, 9 and 10 fall below the 50% S_w line.

Example 2

Table 23.2 lists pertinent logging data in a well drilled with fresh mud in the Rocky Mountain area. The target formation is known to be a dolomite (V_{ma} =

TABLE 23.2

(Well Location: Rocky Mountain Area)

No.	Depth, ft	R_t, Ωm	R_{xo}, Ωm	Δt μ sec/ft	Φ, %	S_w, %	S_{xo}, %	MOP S_{xo} − S_w, %
1	x524	20.0	13.0	58	10.0	33	46	13
2	28	9.5	8.0	59	11.0	42	54	12
3	31	18.0	12.0	57	9.5	35	53	18
4	33	50.0	35.0	55	8.0	25	35	10
5	x536	30.0	16.0	56	9.0	29	47	18

23,000 ft/sec), and R_w = 0.02 Ωm and R_{mf} = 0.28 Ωm at formation conditions.

Knowledge of the above parameters is sufficient to omit plotting the logging data, since a straight forward application of the Archie equation gives both S_w and S_{xo}: the water saturations in the uninvaded and flushed regions around the wellbore.

$$S_w = (F \times R_w)/R_t$$

$$S_{xo} = (F \times R_{mf})/R_{xo}$$

Furthermore, close inspection of the data in Table 23.2 clearly shows that reservoir porosity extends over a very small range, which would make crossplots of such data crowded and less advantageous. In other words, logging data should be looked at prior to blindly starting out with a particular crossplot technique.

CONCLUSION

The Hingle crossplot technique is a powerful crossplotting technique which allows a long section of well logs to be analyzed in a minimum of time. Similar to any other formation evaluation technique the Hingle method has several advantages and limitations.

Advantages include:

1. A matrix value does not have to be assumed. It is determined from the crossplot.

2. R_w value can be computed from the graph.

3. Quantitative S_w presentation, including visual quick-look at potential pay sections.

4. Minimum calculations.

5. Well adapted for fresh and salt-mud logging.

6. With R_{xo} data a typical MOP evaluation is possible.

Limitations include: a relatively large range of porosity is required; and shaly sands, unconsolidated formations, gas effects, etc. require certain logging suites and precautions. Also, formation water salinity (i.e., R_w), lithology, and degree of mud filtrate invasion have to stay fairly constant over the interval of interest. Finally, a water zone has to be present or a reliable R_w value has to be known.

BIBLIOGRAPHY

Hingle, A. T. The Use of Logs in Exploration Problems, *Transactions, Society of Exploration Geophysicists*, Los Angeles: 1959.