CASED HOLE AND PRODUCTION LOG EVALUATION

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PennWell®

Contents

CHAPTER 1 INTRODUCTION **1**

Background 1
Categories of Cased Hole Logs 2
Purpose of This Book 3

CHAPTER 2 THE CASED HOLE LOGGING JOB **5**

The Well 5
The Logging Job 7
Rigging Up for the Job—Naturally Producing Wells 8
Rigging Up—Pumping Wells 10
Rigging Up—High Deviation Angle and Horizontal Wells 11
Points to Remember 14
References 15

CHAPTER 3 LOGGING TOOLS AND THE CASED HOLE ENVIRONMENT **17**

The Cased Hole Environment 17
Factors Affecting Log Response 19
Typical Production Problems 22
Points to Remember 25
References 25

CHAPTER 4 FORMATION EVALUATION: NATURAL GAMMA RAY LOGGING **27**

Conventional Gamma Ray Logging 27
Applications of the Gamma Ray Measurement 28
Natural Gamma Ray Spectrometry Measurements 32
Applications of Spectral Gamma Ray Measurements 34
Points to Remember 40
References 42

CHAPTER 5 FORMATION EVALUATION: PULSED NEUTRON CAPTURE LOGS **43**

Equipment and Applications 43
Principle of Operation 44
Formation Model and Log Response 46
Measurement Technique 51
Chronological Development of Tools and Log Presentations 52
Factors Influencing the Sigma Measurement 61
Interpretation Techniques 64
Applications Arising from Time-Lapse PNC Log Runs 69
Points to Remember 79
References 80
Other Suggested Reading 81

CHAPTER 6 FORMATION EVALUATION: NEUTRON LOGGING **83**

Neutron Logging Overview 83
Single Detector Neutron Tools 83
Compensated Dual Detector Neutron Logs 85
Environmental Effects 88
Pulsed Source Neutron Tools 91
Application Examples of Dual Detector Neutron Logs 92
Points to Remember 95
References 96

CHAPTER 7 FORMATION EVALUATION: CARBON/OXYGEN LOGGING **97**

Typical Applications of Carbon/Oxygen Logging 97
Methods of Operation to get Carbon/Oxygen Ratio 99
Interpretation and Presentation of Carbon/Oxygen Logs 104
Through Tubing Carbon/Oxygen Logging 109
Examples of Carbon/Oxygen Log Applications 115
Points to Remember 121
References 122
Other Suggested Reading 123

CHAPTER 8 FORMATION EVALUATION: SONIC AND ACOUSTIC TECHNIQUES **125**

Sonic Overview 125
Basic Principles 125
Applications of Sonic Measurements 128
Sonic Equipment 129
Measurement Technique and Requirements 132
Acoustic Logs Through Casing—Application Examples 133
Points to Remember 138
References 138

CHAPTER 9 FORMATION EVALUATION: OTHER SERVICES **141**

Introduction 141
Borehole Gravity Survey 141
Points to Remember 146
Density Log 146
Formation Resistivity Through Casing 147
Points to Remember 152
Chlorine Log 152
Cased Hole Wireline Formation Tester 153
Points to Remember 160
References 160

CHAPTER 10 WELL INTEGRITY: ACOUSTIC CEMENT EVALUATION SURVEYS **161**

Overview 161
Cement Bond Log (CBL) Tool Configuration and Operation 162
The Received Signal and Logs Presented 162
CBL Log Presentation 166
Factors Affecting Tool Performance 167
Quantitative Cement Bond Log Evaluation 176

Special and Non-Standard CBL Examples 181
Borehole Compensated Cement Bond Logs 183
Pad Type CBL, The Segmented Bond Tool (SBT) 187
Bond Logs with Directional Receivers 189
Points to Remember 189
References 190
Other Suggested Reading 191

CHAPTER 11 WELL INTEGRITY: ULTRASONIC PULSE ECHO CEMENT EVALUATION 193

Overview 193
Fixed Transducer Pulse Echo Tool Configuration and Operation—The Schlumberger CET 194
The Halliburton PET 201
Miscellaneous Factors 202
CBL/Pulse Echo Comparison 205
The Mobil/Goodwin Technique 207
The Schlumberger Ultrasonic Imaging Tool (USI) 209
Points to Remember 212
References 213

CHAPTER 12 WELL INTEGRITY: DOWNHOLE CASING INSPECTION 215

Overview 215
Mechanical Calipers 216
Electromagnetic Casing Inspection Tools 217
Acoustic Casing Inspection Tools 224
Borehole Videos 227
Casing Potential Surveys for Cathodic Protection 229
Points to Remember 233
References 233

CHAPTER 13 FLUID MOVEMENT: TEMPERATURE SURVEYS 235

Temperature Logging Overview 235
Single Well Temperature Logs 236
Time Lapse Temperature Logging Techniques 242
Locating Fractured and Acidized Zones 244
Other Temperature Log Applications 246
Radial Differential Temperature (RDT) Logging 247
Log Examples 249
Points to Remember 252
References 252

CHAPTER 14 FLUID MOVEMENT: NOISE LOGGING 255

Noise and Fluid Movement Downhole 255
Noise Amplitude and Spectrum 256
Noise Log Presentation and Response 257
Quantitative Considerations in Noise Logging 261
Other Noise Logging Techniques 263
Noise Log Examples 264
Points to Remember 267
References 268

CHAPTER 15 FLUID MOVEMENT: RADIOACTIVE TRACER LOGGING 269

Introduction to Radioactive Tracer Logging 269
Radioactive Tracer Tools and Isotopes 270
Calculating Flow Rates with Tracers 274
RA Tracer Techniques for Fluid Movement 276
Tagging Materials Downhole, Multiple Tracers, RotaScan 284
Tracer Log Examples 287
Points to Remember 292
References 292

CHAPTER 16 FLUID MOVEMENT: OXYGEN ACTIVATION AND OTHER PULSED NEUTRON APPLICATIONS 295

Overview 295
Water Movement Detection Using Oxygen Activation 295
Identification of Borehole Fluids 302
Special PNC Applications for Fluid Movement 306
Points to Remember 309
References 309

CHAPTER 17 FLUID MOVEMENT: BULK FLOW RATE MEASUREMENT 311

Types of Flowmeters 311
Spinner Response 313
Computing Downhole Flow Velocity from Log Data 316
Computation of Bulk Flow Rate from the Spinner Velocity 320
Spinner Logging in Multiphase Inclined Flow 321
Other Flowmeter Techniques 324
Log Examples 325
Points to Remember 328
References 328

CHAPTER 18 FLUID MOVEMENT: FLUID IDENTIFICATION AND MULTIPHASE FLOW 331

Downhole Flow Conditions 331
Phase Holdup and Cut 332
Fluid Identification Devices 335
Computing Two-Phase Holdup, Slip, and Flow Rates 340
Three-Phase Flow 343
Examples of Multiphase Logs 344
Points to Remember 347
References 348

CHAPTER 19 FLUID MOVEMENT: PRODUCTION LOGGING IN HORIZONTAL WELLS 349

The Tools and Equipment of Horizontal Wells 349
Configuration of a Horizontal Well 349
Production Logging Tool Response in Horizontal Flows 353
Conclusion 357
Points to Remember 359
References 359

Preface

The topic of cased hole logging encompasses a very broad spectrum of applications. These include formation evaluation for shows of hydrocarbons, assurance of well integrity, and the mapping of fluid movement downhole. For these applications, many technologies have been and continue to be developed. This book is an attempt to provide a somewhat complete and grand overview of such technologies and examples of their application.

The text is presented to maximize the reader's physical sense of how tools work and why they work. The interpretation models are presented in a concise and logical manner. The discussion focuses on the basic computational techniques and on higher order effects where such effects may be useful for new and novel measurements.

The present state of the industry comprises the range from basic analog technologies to highly sophisticated computer modeling and imaging techniques. This book covers the full spectrum, with emphasis on the tools and their uses. This book is up-to-date with discussion of the newest tools available today. Since this book is published only in black and white, many of the new full color imaging presentations cannot be shown, and the interested reader is advised to request examples from the service companies. Older tools which may no longer be used, and which often occur in well files, are also covered.

Certain types of cased hole logs are not discussed in this book. These include the gravel pack evaluation logs and the so-called stuck point or free point indicators. Also, nonlogging wireline apparatus, such as perforating equipment, casing cutters, and the like are not covered.

The author would like to thank the wireline service companies for their assistance and contributions to this book. They have been extremely helpful in proofreading various sections and supplying technical information requested. The wireline business is very competitive. The author has attempted to avoid any bias or preference among service companies or their hardware, and has tried to show examples originating from numerous service company sources. The names of the companies are used throughout the book. The author would also like to thank his many friends at major oil companies for their comments and assistance.

Certain people deserve special thanks, for they have been pivotal in the author's path of life leading to this document. First and most recently, the author would like to thank Fred Bradburn of Shell Internationale Petroleum Maatschappij B.V., Group Training, in the Netherlands. Fred reviewed training materials used in a course and provided strong initial prodding to write this book. The author would like to thank the late Bob Kudrle of Schlumberger. Bob many years ago provided the vision necessary for me to remain on the technical course which ultimately led to this book. Dr. Antoni K. Oppenheim, of the University of California at Berkeley, deserves special thanks. He, like a surrogate father, provided me a direction when my long term objectives appeared to vacillate day to day. And, of course, my family's patience through this period is greatly appreciated.

It would be the author's greatest delight for this book to open the reader's minds to new ideas and applications for cased hole logging techniques not previously used in their areas. As production declines in many producing provinces, these techniques hold the key to stemming the decline and restoring production. Just as one would not have surgery without a proper diagnosis, the cased hole logs are the diagnostic tools for producing reservoirs and wells. Their maintenance and workover should not be done without the use of cased hole logs.

Chapter 1

INTRODUCTION

BACKGROUND

Why run cased hole logs? They are run to assess well integrity, improve reservoir management, and scan the well for bypassed production before plugging and abandoning. These services are also key diagnostic tools for workover planning and operations.

In new wells, cased hole logs are run to establish that the primary cement job has been accomplished properly. Is there cement over the interval to be completed? Is such cement adequate to provide a reasonable assurance of zonal isolation? Is the well integrity adequate to complete the well as planned? Is a squeeze cement job needed and where should it be done?

In most older producing wells, cased hole logs are all that can be run. Traditional reasons include diagnosing the illness of old wells, wells which may now produce excessive amounts of water. How can the water production be reduced and hydrocarbon production increased? Cased hole logs shed light on the sources of water and hydrocarbon production downhole and offer hope that such production restorations may be possible.

Wells need not be sick or exhibit production changes to be candidates for cased hole logs. Indeed, logs are frequently run in casing to monitor the reservoir so that changes in production can be anticipated and planned for. Such monitoring is commonly done to detect movement of water-oil or gas-oil contacts during production in individual wells and thereby help manage overall reservoir production among a number of wells. Saturation changes at unanticipated locations may dictate selectively perforating new intervals to assure proper reservoir depletion.

Cased hole logs are extremely important in secondary or tertiary recovery programs. Typically water (or other fluid) is injected into certain wells and produced along with hydrocarbons at other wells in the field. Injection and production profiles are run to detect anomalous injection/production, i.e., is the flow going in or coming out near the top or bottom of the formation? What must be done to assure that the flood front is uniform and prevent operations from simply circulating water between wells?

Sometimes, old wells are logged for the purpose of detecting bypassed producible zones, typically uphole from current or recently produced zones. This occurs when old wells do not have a good suite of open hole logs available, or such bypassed production was not detectable using older logging or interpretation techniques. Perhaps such upper zones are gas and were not of interest at the time of initial completion. Locating such bypassed production will provide new reserves to a company from assets thought to be depleted and worthless.

Due to the increased use of Logging While Drilling (LWD) operations, cased hole logs are frequently used as supplemental sources of information on formation lithology and hydrocarbon saturation. If the day comes where wells will be routinely drilled using coiled tubing units with turbine drill bits, cased hole logs will then have come of age. It is anticipated that such operations would utilize the coil tubing as the production casing string and virtually no open hole logs would be available. The only logging information would be that obtainable through casing.

Cased hole logs are the diagnostic tools for efficient reservoir management and production. Problems must be properly defined before they can be corrected. Virtually no workover operation or step taken to optimize or improve production would not be helped in some way by cased hole logs. This text will examine a wide variety of logging tools and types of services. The previous examples are only a tiny fraction of the applications of such services. This text is designed to highlight the operation and application of logging tools. Emphasis is on the physical sense of what each tool does and how it does it. It is hoped that this approach will provide the reader with the kind of information which stimulates creative thinking in applying these logs to solve both traditional as well as new problems in oilfield operations.

CATEGORIES OF CASED HOLE LOGS

For purposes of this text, cased hole logs may be placed into the following four categories:

1. Formation Evaluation
2. Wellbore Integrity
3. Fluid Movement During Production/Injection
4. Other

A description of each category follows:

Formation Evaluation

Logging tools in this category are designed to evaluate formation properties. Included are formation shale content, clay type, and vertical definition of zones which are clean and shale free. Logging services in this category are also capable of determining the type of rock (sand, lime, etc.), the type of hydrocarbon, i.e., gas or oil, and its saturation. Other information available includes mechanical properties of the rock, to mineralogy, its permeability, skin damage, pressure, natural fractures, and even samples of formation fluids.

Wellbore Integrity

This category of logs includes the wide variety of logs to evaluate the cement sheath around the casing. Cement top location, fraction of annular fill, and cement compressive strength can be measured. This information provides some assurance of hydraulic isolation. Casing condition in terms of depth and extent of damage may also be evaluated. Certain tools even discriminate damage on the inner wall from that on the outer surface of the casing.

Fluid Movement During Production/Injection

This category includes tools which detect channels behind pipe in both injection and production wells. Such tools furthermore detect zones of fluid injection, location of pumped-in materials such as fracture fluid or proppant, and even can directionally detect the orientation of certain injected particulates. Flow profiles in both injection and production may be evaluated along with the contributions of each phase of produced fluid on a zone by zone basis. Combined with pressure information, these contributions may be the basis for determining a zone by zone inflow performance relationship (IPR).

Other

This category is a catch-all for services whose application or environment may be unusual. For example, the gravel pack logs are designed to evaluate the presence of gravel outside of a wire wrapped or slotted liner, a condition which is neither in casing nor out of it. Another grouping in this catch-all category are the stuck point or free point indicator tools. These are typically not closely related to reservoir management and are of a more immediate operational concern. These surveys are not covered in this text.

Operational Considerations

Cased hole logging tools are typically run on wireline. This line may be either armored electrical cable or "slick line." Units using electrical cable transmit data to the surface and data is gathered in real time. Most cased hole tools are run on a cable with a single conductor, i.e., a monocable, although some services may be run on multiconductor cable. With slick line units, data is gathered and recorded downhole and retrieved when the tool string is brought to the surface.

In highly deviated and horizontal wells, various tricks must be done to get the tools into and moving across the interval of interest. Such operations are typically done with coiled tubing units where the electric wireline is inside of the coiled tubing to which the tool string is rigidly attached. The tubing is used to push or pull the tool across the interval to be logged. Units without electric cable and using downhole recorders are also available. Alternatively, pump down techniques in which the tool string with wireline attached is pumped down through tubing to the end of the horizontal section, then pulled back. Needless to say, this technique would only work using a nuclear tool which sees through the tubing.

In most cases tool diameter is important since it is the deciding factor between "through tubing" or "in casing" operations. The former requires little well preparation and is least expensive in terms of lost production and other required operations. The latter typically is done at the time of completion or later. After completion and production, such operations require shutting in the well and removing the tubing and packer at great expense.

PURPOSE OF THIS BOOK

This book is written to present in one place a grand overview of virtually all of the cased hole logging tools available today. This is increasingly important since certain types of equipment are often used for cross discipline purposes. Most notable are the pulsed neutron capture tools which are primarily used for porosity, water saturation, and gas detection. In recent years these have been used for water flow measurement, gas entry detection, and phase holdup evaluation. Such comments, however, also apply to the natural gamma ray, compensated neutron, ultrasonic, and other tools. A basic understanding of such cross-applications hopefully will provide the basis for creative solutions to complex downhole diagnostic problems.

This text attempts to provide the reader with a physical sense of what the tools do, how they do it, and why they do what they do. Modern tools as well as certain older generation tools are reviewed since all are likely to be present in well files. A wide variety of applications if not discussed in the text will be shown in the log examples at the end of each chapter.

Can the Log Be Run through Tubing?

Refer to Figure 2.1. The last piece of piping installed in the well is the tubing string. This string is necessary if the well is to be producing while logging. Some logs are run through tubing, some not. This may or may not be a problem depending upon when in the life of the well the logging job occurs.

If the tubing has not yet been installed and the casing not perforated, then it is convenient to run certain surveys. For example, this is the ideal time to run a cement evaluation type of log such as a cement bond log (CBL). Also, logs for depth correlation such as gamma ray and collar locator are run during this time.

Once the tubing has been installed and the well is producing, then it is most desirable to run logs through tubing. Such surveys are characterized by small diameter tools, typically 1 11/16 in. (4.3 cm). After appropriate rigging up at the surface, the tools can be run directly down into the well through the tubing and measurements made across the producing interval. Operations performed in this manner do not necessarily require shutting in the well, although the flow may be stopped or reduced when running in. Therefore, there is no or little loss of production. Surveys run for monitoring saturation changes in the formation or for locating water or other production sources are most often run through tubing.

Sometimes the logging tool is too large to run through tubing. This may occur if a casing inspection tool is required or a larger diameter carbon/oxygen tool is required to evaluate formation water saturations. To run a larger diameter tool, the tubing must be removed and the well killed. This results in a loss of production, excessive rig time costs, and the risk that production will not resume at its earlier rates. So, when considering running cased hole logs, it is important to determine the maximum tool size that can be run and to try to select those surveys which can be run through tubing if such are available to do the job.

RIGGING UP FOR THE JOB—NATURALLY PRODUCING WELLS

Rigging Up at the Wellsite

The equipment necessary at the wellsite for a typical cased hole logging job through tubing in a naturally producing well is shown on Figure 2.2.[3] The numbered descriptions correspond to the figure.

1. The logging truck. The cable, winch, surface computers, and logging personnel are in this truck.
2. The mast truck. This unit has a mast which folds or tele-scopes up to the position shown and back for movement off location.
3. The wellhead with valves and flowlines connected to it.
4. Lubricator or riser pipe. This pipe is used to store the tool before running into the hole. The lubricator is mounted atop the wellhead and the pressure in the lubricator is equalized to that of the wellhead before logging. Note that a number of riser pipe sections may be connected to accommodate longer tool strings.
5. Cable. This cable is usually a single conductor (monocable) armored cable. The cable is wound onto the winch of the logging truck for storage.
6. Pressure bleed-off hose to relieve pressure from the riser pipe after the logging job.
7. Grease line to main grease seal.
8. Grease pump and reservoir for grease seal.
9. Grease seal. These seals assure hydraulic seal around the cable even when running the cable in and out of the hole.
10. Instrument truck. This unit typically may or may not be needed depending on the services run. Most modern trucks are fully contained and this unit is usually not necessary.
11. Pressure being released from the lubricator through the bleed-off hose.
12. Upper sheave wheel. Note also the lower sheave wheel chained to the wellhead.

	SURVEY	REGION OF INVESTIGATION I	II	III	IV
FLUID FLOW	TEMPERATURE	●	○	○	○
	DIFFERENTIAL TEMPERATURE	●	○	○	○
	NOISE (STATIONARY)	●	○	○	
	NOISE (CONTINUOUS)	●	○	○	
	RADIOACTIVE TRACER	●	○	○	○
	OXYGEN ACTIVATION WATER FLOW	●	○	○	
	CONTINUOUS SPINNER	●	○		
	FLOW DIVERTING SPINNER	●			
	HORIZONTAL SPINNER	●	○		
	FLUID IDENTIFICATION	●	○		
	FLUID SAMPLER	●			
WELL INTEGRITY	BOW SPRING CALIPER		●		
	MULTIFINGER CALIPER		●		
	ELECTROMAGNETIC (PAD TYPE)		●		
	ELECTROMAGNETIC (PHASE SHIFT)		●		○
	ACOUSTIC PULSE ECHO SURVEY	○	●		
	BOREHOLE VIDEO CAMERA	○	●		
	CASING POTENTIAL SURVEY	○	●	○	○
	COLLAR LOCATOR		●		
	ACOUSTIC BOND LOG	○	○	●	○
	PULSE ECHO BOND LOG	○	○	●	○
	PAD TYPE BOND LOG	○	○	●	
	RADIAL DIFFERENTIAL TEMPERATURE	○	○	●	○
FORMATION EVALUATION	GAMMA RAY AND SPECTRAL GR	○	○	○	●
	DIRECTIONAL GR (ROTASCAN)	○	○	○	●
	CHLORINE LOG	○	○	○	●
	NEUTRON-COMPENSATED NEUTRON LOG	○	○	○	●
	PULSED NEUTRON CAPTURE	○	○	○	●
	CARBON/OXYGEN (INDUCED GR)	○	○	○	●
	DENSITY	○	○	○	●
	ACOUSTIC	○	○	○	●
	GRAVIMETER				●
	PRESSURE	○			●
	FORMATION TESTER			○	●

Figure 3.2 Generic names of cased hole logging services

tool's response. Certain tools are seriously affected by borehole fluids as well, especially gas, which is present in the figure. There is, however, one bit of good news. Unless channeling is present, there should be no formation invasion provided the log is run adequately long after circulating cement.

Other factors of the environment relate to tool ratings of temperature and pressure. Each service company's equipment is rated to slightly different limits and they should be closely consulted as temperature and/or pressure become high. Hostile high temperature equipment is available for some types of tools. The presence of H_2S requires special attention and knowledge of it is critical not only to the measurement but to the safety of the personnel on the job site.

Logs Showing Spectral Gamma Ray Applications

The following annotated log examples highlight the applications listed below:

- Source rock/false shale having production potential
- Location of water producing perforations
- Radioactive scaling within reservoir rock
- Effect of muds/wellbore fluids containing potassium
- Natural fracture identification
- CSNG* detects changes in wellbore hardware

Source Rock/False Shale with Production Potential (Figure 4.7). The total counts gamma ray log shows what at first glance appears to be two shale sections above and below the relatively clean and tight Buda limestone. The Del Rio shale below 4,218 ft (1,285.6 m)

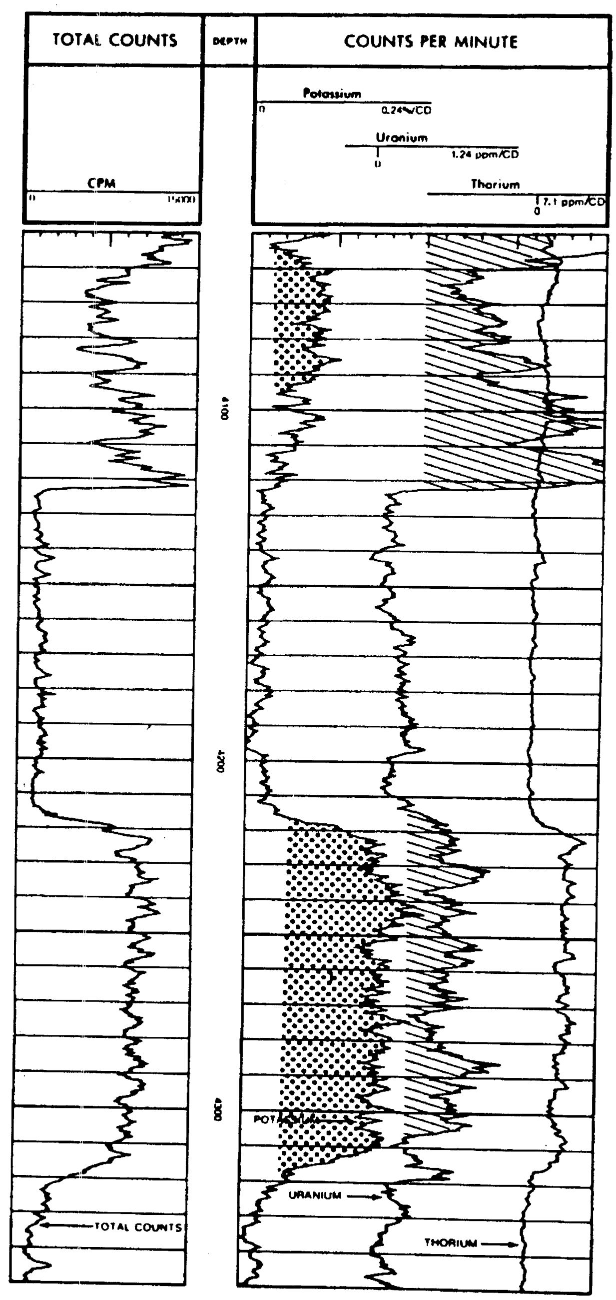

Figure 4.7 Source rock/false shale with production potential (Courtesy Western Atlas and Copyright SPE, Ref. 9)

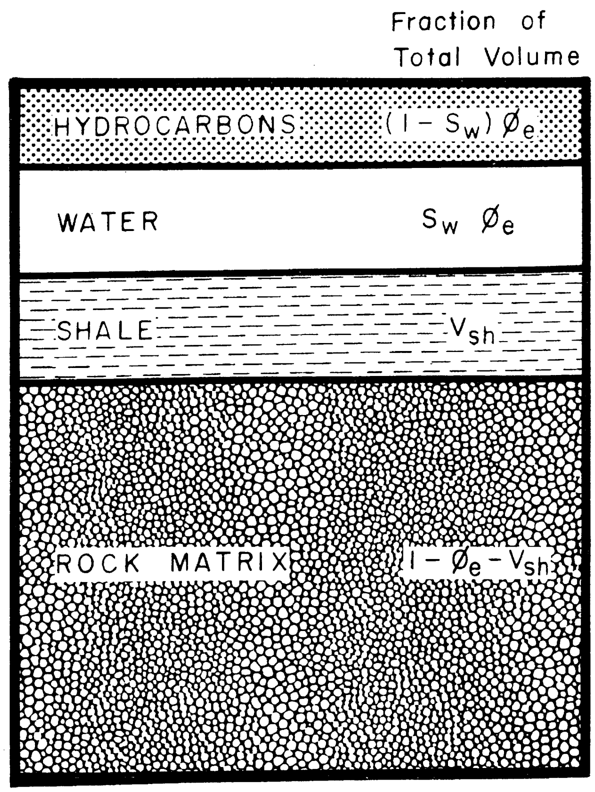

Figure 5.4 Formation model for PNC analysis (Courtesy Schlumberger, Ref. 9)

Applying this equation for Gulf Coast conditions of $\phi_e = .30$ $\Sigma_M = 10.0$ c.u., $\Sigma_H = 21.0$ c.u., and $\Sigma_W = 58.0$ c.u.(100,000 ppm NaCl), water (S_w=1), oil (S_w=.20) and gas (S_w=.20) zone responses are calculated as follows:

Water Zone—S_w = 1.0

$$\Sigma_{LOG} = (1.0-.30) \times 10.0 + .30 \times (1.0-1.0) \times 21.0 + .30 \times 1.0 \times 58.0 =$$

$$7.0 \text{ c.u.} + 0.0 \text{ c.u.} + 17.4 \text{ c.u.} = 24.4 \text{ c.u.}$$

matrix hydrocarbon water

Oil Zone—S_w = .20

$$\Sigma_{LOG} = (1.0-.30) \times 10.0 + .30 \times (1.0-.20) \times 21.0 + .30 \times .20 \times 58.0 =$$

$$7.0 \text{ c.u.} + 5.04 \text{ c.u.} + 3.48 \text{ c.u.} = 15.5 \text{ c.u.}$$

Gas Zone—S_w = .20, Σ_g = 8.0 c.u.

$$\Sigma_{LOG} = (1.0-.30) \times 10.0 + .30 \times (1.0-.20) \times 8.0 + .30 \times .20 \times 58.0 =$$

$$7.0 \text{ c.u.} + 1.92 \text{ c.u.} + 3.48 \text{ c.u.} = 12.4 \text{ c.u.}$$

A PNC log run over these intervals would look like the heavy capture cross section curve of Figure 5.5. The water, oil, and gas zones are clearly identifiable over this interval. The water-oil contact (WOC) and gas-oil contact (GOC) can easily be found. The bed boundaries at the shales stand out.

The typical PNC tool is said to have an error bar (plus or minus one standard deviation of measured capture cross section in c.u.) of +/–.5 c.u., for a total range of one c.u. The range between a water and oil zone is 24.4–15.5 = 8.9 c.u. This means a resolution of saturation of about 1 part in 10. Clearly, this is a useful measurement in such an environment.

INTERPRETATION TECHNIQUES

Sigma-Porosity Cross Plot—Clean Formation

The sigma porosity cross plot for a clean formation is defined by three points: the capture cross sections of the matrix, water, and hydrocarbon.[34-37] These points define a triangular area as shown in Figure 5.19. The basic equation on which this analysis is based is equation 5.2, a linear equation for the model of Figure 5.4. The uppermost line of Figure 5.19 connects the matrix point at zero porosity with the water point at 100% porosity or ϕ_e =1.0. If these were the only two formation constituents present, at any porosity a PNC log would indicate a sigma defined by this line. Hence, this is the S_w =1.0 line. If only matrix and hydrocarbon were present, with no connate water, the lowermost line could similarly be constructed. At zero porosity the logging tool would indicate sigma matrix while at 100% porosity the tool would read Σ_h, i.e., about 21.0 c.u. for oil and less than 10 for a gas. For any intermediate porosity, a PNC log would read a sigma defined by this line if only hydrocarbon and matrix were present. This would be the S_w =0.0 line.

Once the triangular area has been defined, any combination of matrix, water, and hydrocarbon would define a point within this area. For a given porosity, the sigma read by a PNC logging tool would fall between the water (S_w=1) and hydrocarbon (S_w=0) lines. Since the system is linear, the distance between the water and hydrocarbon lines could be divided into four equal segments, separated by three lines corresponding to S_w=.25, .50, and .75 as shown on Figure 5.19. So, if at 30 percent porosity a PNC log read Σ A', this would be a point 100% water saturated. If at 25 percent porosity it read Σ_B, this point would be 25% water saturated, i.e., a hydrocarbon point.

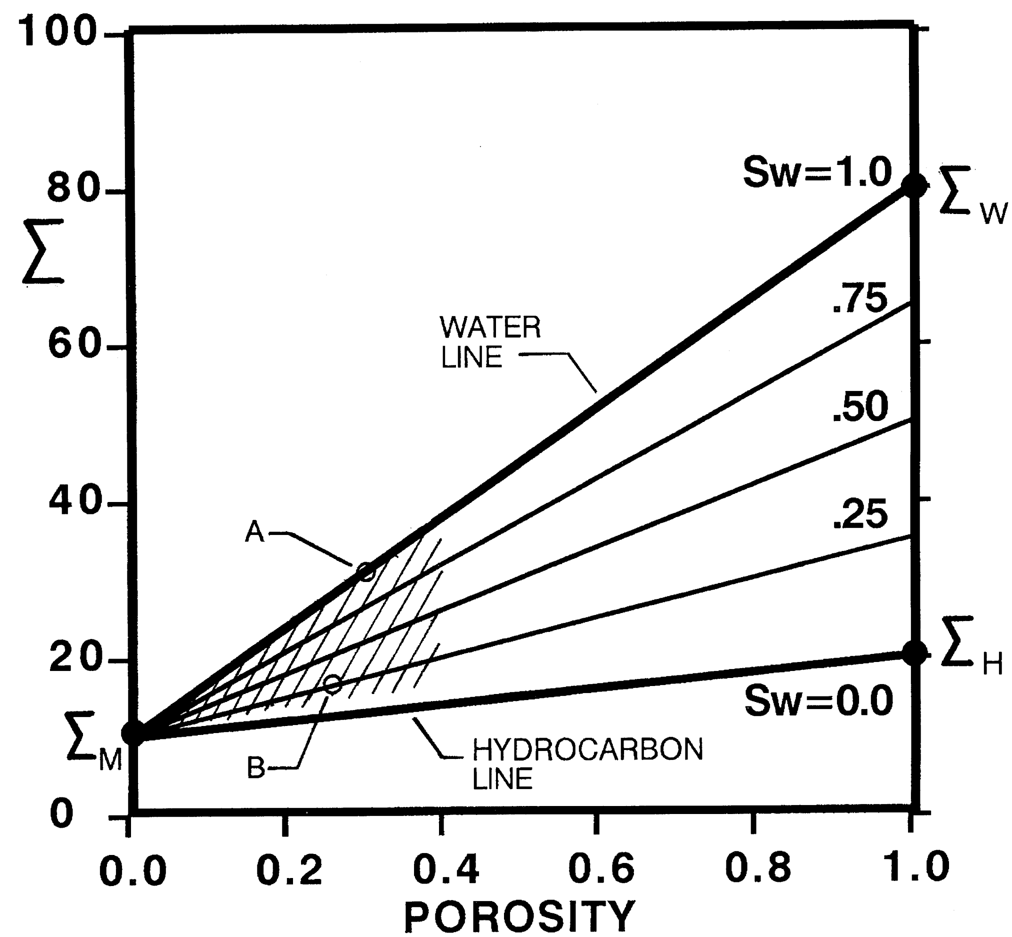

Figure 5.19 Layout for sigma-porosity cross plot showing water and hydrocarbon lines

LOG DATA					COMPUTED DATA				RESULTS	
#	DEPTH	Σ_{LOG}	ϕ_T	GR	Σ_{WA}	S_{wb}	S_{wt}	ϕ_e	S_w	
A	X697	14.0	34.0	32.0	25.6	.00	.08	34.0	.08	OIL
B	X705	14.5	32.5	33.5	29.0	.03	.11	31.5	.08	OIL
C	X796	22.5	25.0	55.0	66.0	.50	.66	12.5	.32	OIL
D	X816	25.0	28.0	55.0	68.7	.50	.72	12.5	.44	OIL?
E	X856	21.0	27.0	58.0	56.1	.57	.45	11.6	.00	OIL
F	X921	27.0	30.0	32.0	71.3	.00	1.00	30.0	1.00	WATER
	X772	33.0	29.0	78.0	94.2	1.00				SHALE
GR_{cl}=32.0				GR_{sh}=78.0			$SIGMA_{ma}$=8.0 c.u.			

Figure 5.30 Values picked from log or computed for depths A–F on the log of Figure 5.22 for the dual-water model

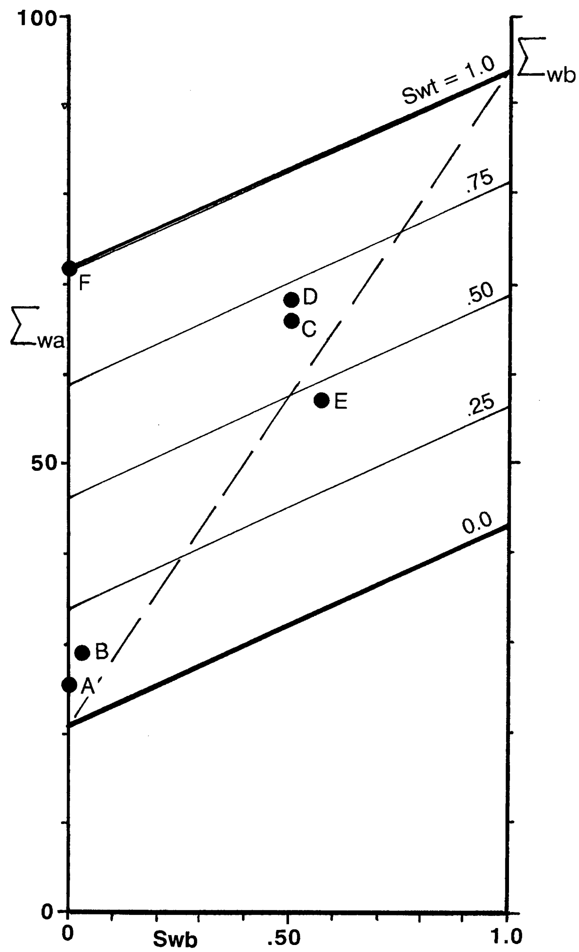

Figure 5.31 Dual water model cross plot for data from Figures 5.22 and 5.30

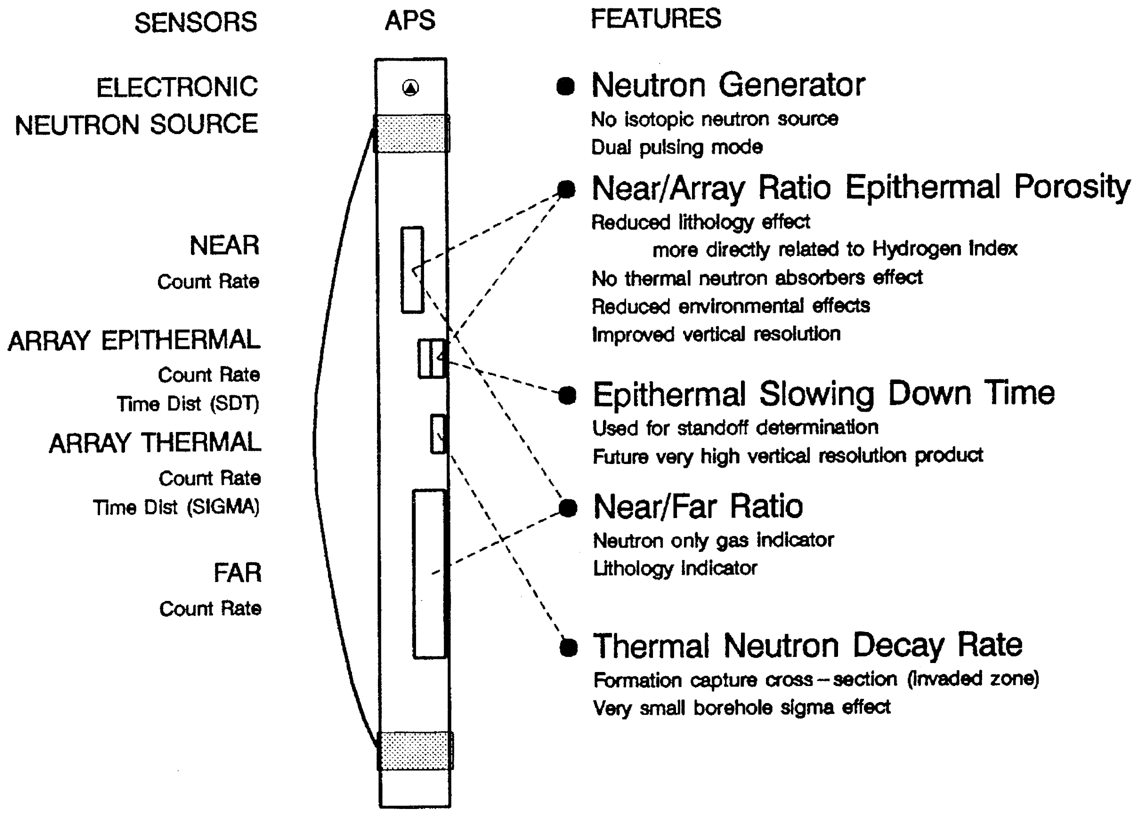

Figure 6.9 Schlumberger Array Porosity Sonde (APS) (Courtesy Schlumberger, Ref. 18)

detectors are shielded from the borehole to minimize its effects. While the measurement of epithermal neutrons has not been useful in cased holes, this sonde uses a pulsed source. This source puts out about 10 times more neutrons than a AmBe chemical source. As a result, it may be possible that sufficient counts are available for cased hole use. This sonde is 3 5/8 in. (9.21 cm) in diameter.

APPLICATION EXAMPLES OF DUAL DETECTOR NEUTRON LOGS

Effect of Invasion

Figure 6.10 shows porosity in the right hand track. Here is an open hole density porosity, ϕ_D, and open hole CNL porosity, ϕ_{OH}.[19] The interval from 6,438 to 6,442 is a low pressure gas zone of about 20–25% porosity. This well was drilled with a heavy mud and significant invasion was expected and indicated from the resistivity logs. The neutron density overlay shows the characteristic crossover indicating a gas zone, apparently a result of residual gas saturation.

A cased hole CNL was run 30 days later and is shown overlaying the open hole CNL over most of the interval. The cased hole log reads a significantly lower porosity, ϕ_{CH}, over the gas interval, indicating that the invaded fluid had largely dissipated.[19]

Monitoring of Gas Movement

The logs of Figure 6.11 show a series of CNL logs run in Alaska for the purpose of monitoring gas cap movement and gas encroachment under shale layers.[20] The gamma ray in the left track shows shale breaks at about 9,395, 9,430, and 9,580. Production perforations are shown below about 9,610. On the right are neutron logs to monitor gas movement. The open hole CNL was run in July of 1979, and based on the open hole data of that time,