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April 1988—March 1994

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Work Performed Under Contract No. DE-FG22-93BC14966

ParaMagnetic Logging, Inc.
Woodinville, Washington

**National Petroleum Technology Office
U.S. DEPARTMENT OF ENERGY
Tulsa, Oklahoma**

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Proof of Feasibility of the Through Casing Resistivity Technology

By
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June 2000

Work Performed Under Contract No DE-FG22-93BC14966

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FOREWORD

ParaMagnetic Logging, Inc. has received a total of four Grants from the U.S. Department of Energy (DOE) that are relevant to the initial discovery and later design, construction and testing of two apparatus versions of the Through Casing Resistivity Tool® (TCRT®). These four DOE Grants are listed below:

First DOE Grant

Grant No. DE-FG06-84ER13294 signed by DOE on 9/27/84
Including Amendments No. M001, A002, M003, M004, A005, M006, M007, M008, M009, and M010
Title: "Validating the Paramagnetic Logging Effect"
Status: All work completed, Final Report accepted, closed-out.

Second DOE Grant

Grant No. DE-FG19-88BC14243 signed by DOE on 5/12/88
Including Amendments No. M001, A002, M003, M004, M005, and M006
Title: "Proof of Feasibility of Thru Casing Resistivity Technology"
Status: All work completed, Final Report accepted, closed-out.

Third DOE Grant

Grant No. DE-FG22-90BC14617 signed by DOE on 2/2/90
Including Amendments No. M001, A002, M003, M004, M005, A006, M007, and M008
Title: "Proof of Concept of Moving Thru Casing Resistivity Apparatus"
Status: All experimental work completed, Final Report submitted, and close-out is in progress.

Fourth DOE Grant

Grant No. DE-FG22-93BC14966 signed by DOE on 3/23/93
Including Amendments No. M001, M002, M003, and M004
Original Title: "Fabrication and Downhole Testing of Moving Through Casing Resistivity Apparatus"
Amended Title: "Proof of Feasibility of the Through Casing Resistivity Technology"
Status: All experimental work completed, Final Report submitted (herein), and close-out is in progress.

In terms of the above definitions, this is the Final Report to DOE for the Fourth DOE Grant.

RESEARCH SUMMARY

Title. "Proof of Feasibility of the Through Casing Resistivity Technology"

Contractor. ParaMagnetic Logging, Inc.

Principal Investigator. W. Banning Vail, Ph.D.

Report Period. April 1988 through March 1994

Objective. To definitively prove that the resistivity of geological formations can be measured from within cased wells and to license the relevant patents and technology to major wireline service companies.

Technical Perspective. Heretofore, it has been impossible to measure the resistivity of adjacent geological formations from within the steel walls of cased boreholes. Resistivity is a particularly important measurement because gas and oil do not conduct electricity but the typically salty connate water present does conduct electricity. In freshly drilled wells, before the casing is set in place, hydrocarbons are typically detected and measured as follows: (a) the porosity is measured to determine the volume in the rock which may be occupied with gas, oil, and connate water; (b) the electrical resistivity of any water present is measured or determined from a nearby non-hydrocarbon, 100% water bearing zone; and (c) the resistivity of the rock present is measured. The data can then be used to determine the total amount gas and oil present. Gas and oil can then be distinguished in the open hole by certain nuclear and other measurements. This overall analysis procedure is sometimes called "open-hole style log analysis" and it is universally used throughout the industry.

In cased wells, the porosity and water salinity can presently be determined from inside casings. Gas and oil can be separated from inside casings with certain nuclear techniques. However, until this work, the resistivity of rock present could not be directly measured. In a particular form of suggested cased-hole log analysis, the use of pulsed neutron tools from inside casing yield "Sigma", and with resistivity measured from within cased wells, "Sigma-Rt Crossplots" can be used to determine the presence of hydrocarbons - provided the porosity is known.

The overall major implication to the industry of this work eventually will be to allow the use of "open-hole style log analysis" to be performed on a routine basis from within steel cased wells and drill pipes. Measuring resistivity through

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casings and drill pipes is important for at least the following reasons: locating bypassed gas and oil; reservoir monitoring; quantitatively measuring hydrocarbon saturations behind pipe; perhaps cement evaluation; perhaps permeability measurements by using injected fluids; perhaps measurements through a non-rotating drill string when the drilling bit is stopped (called "Measurement-While-Drilling-Bit-Stopped™" abbreviated as "MWDS®"); and to allow major changes in the drilling industry to occur perhaps resulting in the development of revolutionary "one-trip-down drilling" for infill drilling purposes.

Results. The research has definitively proved beyond any reasonable doubt that the resistivity of geological formations can be measured from within cased wells. The data obtained at the MWX-2 Well in Rifle, Colorado under the circumstances of a "blind test" provided that proof. The blind test data were obtained under procedures administered by Gas Research Institute and by Western Atlas Logging Services.

The patents and technology involving the Through Casing Resistivity Tool™ (TCRT®) have been licensed to Western Atlas Logging Services and to Schlumberger Technology Corporation and its Licensed Affiliates. PML owns the technology, owns eight patents on this subject that have issued in the United States Patent and Trademark Office, and owns other related foreign patents. The patents and technology have been licensed to Western Atlas Logging Services by PML under the Non-Exclusive Patent and Technology License Agreement finalized during January of 1994 after successful data were obtained from the MWX-2 Well. Following those successful well tests at the MWX-2 Well, the patents and technology were licensed to Schlumberger Technology Corporation and its Licensed Affiliates.

The data at the MWX-2 Well were obtained with a second generation TCRT apparatus designed and built by PML. Data with that second generation apparatus were initially obtained in PML's Test Well in Woodinville, Washington during late 1993. A first generation TCRT apparatus provided data during 1989 and 1990 in a Test Well located in Fort Worth that proved the in-principle efficacy of the TCRT measurement concepts. However, that first generation TCRT apparatus had poor vertical resolution, took an hour to acquire each data point, and had other limitations.

The data obtained to date with all of the instruments show that the methods of analysis set forth in PML's various patents on the subject are completely self-sufficient to provide TCRT logs that substantially agree with various open-hole logs obtained before the casings were set. PML's simple data interpretation scheme using a single Calibration Constant K has proven successful so far in all cases. This method requires simple algebraic analysis

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to generate an immediate wellsite log. First principles calculations of the Calibration Constant K provide substantial agreement with the empirically determined values to typical accuracies of 13%. In the most pertinent and appropriate case, the calculated Calibration Constant K and the empirically determined value agree to the accuracy of 3%.

The use of the Calibration Constant K appears to be a valid approximation at low frequencies provided the formation is relatively thick; the cement causes no difficulties; and provided the TCRT is not near the extreme end of the casing. The cement present in all of the different wells did not cause significant measurement difficulties.

Technical Approach. The general concept for the measurements is briefly described in the one-page explanation of how the device works in Figure 1 of Section II-A that is entitled "Concept of the Through Casing Resistivity Tool™". More complete understanding may be obtained from the patents on the subject assigned to ParaMagnetic Logging, Inc. that include the following U.S. Patent Numbers: 4,820,989 (Vail, 1989a); 4,882,542 (Vail, 1989b); 5,043,669 (Vail, 1991a); 5,043,668 (Vail, 1991b); 5,075,626 (Vail, 1991c); 4,796,186 (Kaufman, 1989); 5,187,440 (Vail, 1993a); and 5,223,794 (Vail, 1993c). Copies are available upon request.

In this technical approach, current is passed from an electrode in electrical contact with the interior of the borehole casing to an electrode on the surface of the earth. Two pairs of voltage measuring electrodes which are in electrical contact with the interior of the casing provide two voltage outputs which are subtracted to provide a differential voltage output which in turn provides a measurement of the "leakage current" conducted into formation. A calibration and nulling procedure is used which minimizes the influence of variations in the thickness of the casing and in variations of electrode placements. Sinusoidal currents typically at the frequency of 1 Hz are used which allow measurements of the resistivities of the adjacent geological formations.

PML presently uses a very simplified form of analysis to obtain apparent resistivity that is briefly described in Figure 2 in Section II-A entitled "Simple TCRT® Data Interpretation Scheme". The potential voltage of the portion of the casing spanned by the two pairs of voltage measurement electrodes is measured with respect to a voltage reference electrode at electrical "infinity". The potential voltage having the units of volts is algebraically divided during analysis by the leakage current having the units of amps to give the value of a resistor having the units of ohms. This is a "resistor to infinity" R_c that is

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connected to the portion of the casing spanned by the two sets of voltage measurement electrodes used by the TCRT. The apparent resistivity in ohm-meters is obtained by multiplying the value of R_C having the units of ohms by PML's Calibration Constant K that has the units of meters.

Project Implications. As a result of the theoretical and experimental work conducted in the course of this project, the technical feasibility of making measurements of formation electrical resistivity through steel casing has been established. Since electrical resistivity is the key indicator of the presence of hydrocarbons in a subsurface rock formation, the technology developed through this project will allow the identification of hydrocarbon zones behind pipe in wells that have already been cased. This includes old wells in which pay zones may have been missed during the initial completion, or in new wells that may need to be cased before open-hole logging in order to preserve the well integrity. In addition, this technology will allow improved gas recovery by providing a method to monitor fluid movement in a reservoir during its production history and ensuring that no localized "pockets" of gas are left behind.

ParaMagnetic Logging, Inc. has entered into licensing agreements with two major service companies who are developing commercial logging services based upon the technology documented in this Final Report. The next step toward the commercial development of this technology is to prove that instrumentation can be developed by these major service companies to make the required downhole measurements at an overall cost low enough to be widely applied in the exploration and production industry.

GRI Project Manager. Dr. Robert W. Siegfried, II who is Principal Technology Manager, Formation Evaluation

PREFACE TO FINAL REPORT

The nearly six years of work performed by ParaMagnetic Logging, Inc. under Contract No. 5088-212-1664 with Gas Research Institute was completed during the period spanning the following particular dates: April 15, 1988 through March 31, 1994. A Confidential First Draft of the Final Report to GRI concerning this work was completed on July 4, 1994. That Confidential First Draft was not publicly distributed. However, that First Draft was reviewed by three reviewers and their reports were forwarded to GRI.

PML is gratified by the comments from the reviewers. All the reviewers had comments concerning the theoretical developments in Section VIII-A and Section VIII-C involving the calculation of the Calibration Constant K from Equation VIII-C-10 for the Through Casing Resistivity Tool™ (TCRT®). In particular, the first reviewer, Professor Liang C. Shen, Well Logging Laboratory, University of Houston, had comments in his August 9, 1994 letter involving a potentially erroneous factor of 2 as it relates to Sections VIII-A and VIII-C. The authors very much appreciated Professor Shen's encouragement to include within this Final Report the simple model calculations for K now appearing in Sections VIII-A and VIII-C. The second reviewer also had comments that amounted to another different factor of 2 as it relates to Sections VIII-A and VIII-C. The authors made changes to Sections VIII-A and VIII-C related to the different factors of 2. The authors believe that Sections VIII-A and VIII-C are presently correct. However, in the end, all of the computed numerical results in Section VIII-C for the Calibration Constant K (Figures VIII-C-2 through VIII-C-22) are precisely the same figures that were submitted in the First Draft. Equation VIII-C-10 was not changed in any way by the factors of 2 discussed above because their respective influence canceled out (although in the First Draft this equation had a different equation number).

The authors wish to express their particular appreciation to the third reviewer, W. David Kennedy, of Mobil Technology Corporation, Dallas, Texas. In his written review dated September 15, 1994, W. David Kennedy states the following regarding the experimenter's original empirical determination of the Calibration Constant K:

'Vail has empirically determined a calibration constant that is fairly robust; i.e., it gives apparent resistivities approximately the same as some open-hole resistivity instruments in many cases - in other cases the apparent responses differ. This should not be construed to mean that one instrument is "right" and the other "wrong" - rather it should be remembered that while we are habituated to

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thinking the instrument response of open-hole resistivity logs is the formation resistivity at the point where the response is read, in fact this is rarely the case: various (sometimes negligible and usually neglected) corrections must be applied to apparent resistivity response to obtain "true" resistivities.'

W. David Kennedy also expressed interest in PML providing the following:

"...departure (or correction) curves which will permit the correction of the observed apparent resistivity response in the presence of cement sheathes,....".

Accordingly, PML has included extensive theoretical sections concerned with the corrections due to the presence of cement (Section VIII-F), corrections due to the end effects of casing (Section VIII-I), and the general formulae to obtain true formation resistivity from TCRT apparent resistivity (Section VIII-J). We very much appreciate the encouragement of W. David Kennedy to include these particular theoretical sections in this Final Report.

This Revised Version of the report to GRI was actually finalized on March 31, 1996. However, all data and all theory presented in this Final Report to GRI was in the possession of PML and known to PML no later than September 30 of 1994. No changes of any type were made to Figures 7 - 88, which are identical to those presented in the First Draft. This Final Report to GRI is to be considered having an effective date of September 30, 1994, with the following exception. Portions of the material in this Final Report have not been published prior to the publication of this work. For the purposes of public disclosure of potentially proprietary information, this document shall have the actual date of publication and release by Gas Research Institute.

It should be noted that this Final Report covers work performed over a period spanning about 6 years, and the preparation of this report also took considerable time and effort.

Because the effective date of this Final Report is September 30, 1994, publications by PML since that date are not referenced in the Bibliography. PML has published the following particularly relevant papers after the date of September 30, 1994:

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Vail, W.B., Momii, S.T., Haines, H., Gould, J.F., and Kennedy, W.D., 1995a, "Formation Resistivity Measurements Through Metal Casing at the MWX-2 Well in Rifle, Colorado", Paper OO, SPWLA 36th Annual Logging Symposium, Paris, France, June 22-29

Vail, W.B., Momii, S.T., and Dewan, J.T., 1995b, "Through Casing Resistivity Measurements and Their Interpretation for Hydrocarbon Saturations", SPE Paper No. 30582, SPE Annual Technical Conference & Exhibition, Dallas, Texas, Oct. 22-26

Vail, W.B., Momii, S.T., and Woodhouse, R., 1995c, "Through Casing Resistivity Tool™ To Locate Bypassed Oil", Special Report in The American Oil & Gas Reporter, pages 70-76, October

It should also be noted that Western Atlas Logging Services has published the following particularly important papers after the date of September 30, 1994:

Zinger, B.Sh. Strack, K.-M., and Tabarovsky, L.A., 1994, "Modeling of Electrical Effects of Borehole Casing Inhomogeneities", SEG, Expanded Abstracts, 64th Annual Meeting, Los Angeles, CA, pages 399-402, October 23-28

Singer, B.Sh., Fanini, O., Strack, K.-M., Tabarovsksy, L.A., and Zhang, X., 1995a, "Through-Casing Resistivity: 2-D and 3-D Distortions and Correction Techniques", Paper PP, SPWLA 36th Annual Logging Symposium, Paris, France, June 26-29

Singer, B.Sh., Fanini, O., Strack, K.-M., Tabarovsky, L.A., and Zhang, X., 1995b, "Measurement of Formation Resistivity Through Steel Casing", SPE Paper No. 30628, SPE Annual Technical Conference & Exhibition, Dallas, Texas, Oct. 22-26

The authors wish to express particular appreciation to Singer, et. al., 1995a and 1995b, for adopting a "tool factor" in their Equations No. 1 and No. 6 which provide equations for data interpretation that are equivalent to the use of PML's Calibration Constant K in the combined form of Equations No. 2 and No. 3 of this Final Report which have been typically used by PML to interpret data acquired with the TCRT. The authors of this Final Report believe that uniform usage of terms in the industry concerning the TCRT will assist the commercialization process of the technology.

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Several major technical articles concerning the TCRT have appeared in the technical press recently, the most important of which are listed as follows:

LeLeux, D., "Through-Casing Electrical Log Can Locate Bypassed Reserves", 1995, World Oil, Vol. 216, No. 11, pages 95-100, November

Bell, S., 1995b, "Operators Convey Optimism in Cased-Hole Resistivity Measurements", Petroleum Engineer International, pages 53-54, December

Other miscellaneous articles and a press release concerning the TCRT have been published after the date of September 30, 1994, several of which are listed as follows:

Bell, S., 1994, "Logging Tool Gives Resistivity Measurements Through Casing", Petroleum Engineer International, Vol. 66, No. 11, page 9, November

Lemmon, R.E., 1995, "Small Company's Novel Idea for Oil, Gas Producers Becoming Government-Industry R&D Success Story", TechLine #3037, a Press Release from the U.S. Department of Energy, Office of Fossil Energy, April 28

Lagiovane, P., 1995, "Through-Casing Logging for Oil/Gas Wells", DOE No. DOE/FE-0328C, in brochure entitled "Meeting the Technology Needs of the Domestic Natural Gas and Oil Industry: Oil Field Equipment and Technologies Developed with Department of Energy Assistance", U.S. Department of Energy, Office of Fossil Energy

Schempf, F.J., 1995, "Through-Casing Logging Tool Licensed to Atlas, Schlumberger", Improved Recovery Week, Vol. 4, No. 20, May 22

Editor, 1995, "New Tool Detects Hydrocarbons Behind Pipe", Oil & Gas Journal, page 58, May 15 (that was corrected under "Industry Briefs" on page 20, May 29)

Bell, S., 1995a, "Advanced Logging Technology Helps Locate Bypassed Reserves", Energy Perspectives, Vol. 2, No. 1, July

Port, O., 1995, "There's Oil Near Them Thar Wells", Business Week, page 140, September 25

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Theoretical activity by others is continuing in this field as evidenced by the following publications:

Schenkel, C.J., 1994, "DC Resistivity Imaging Using a Steel Cased Well", SEG, Expanded Abstracts, 64th Annual Meeting, Los Angeles, CA, pages 403-406, October 23-28

Kaufman, A.A., Karinsky, A.D., and Wightman, W.E., 1996, "Influence of Inductive Effect on Measurements of Resistivity Through Casing", Geophysics, Vol. 61, No. 1, pages 34-42, January-February

A particularly important final report concerning subcontract work performed under this GRI Contract No. 5088-212-1664 is defined as follows:

Klein, J.D. and Martin, P.R., 1994, "The Electrical Resistivity of Cement", Final Report to GRI, Report No. GRI-94/0273, April

The authors wish to express their appreciation to Klein and Martin (1994) for their pioneering work on the resistivity of cement. The results in their final report are important, and have been used by the authors in Section VIII-F to show that corrections to possible effects related to the presence of cement, if any exist at all, will be limited to geological formations having formation resistivities less than about 3 ohm-meters.

With particular relevance to Section II-D entitled "Experiments with Moving Test Jig and the Triboelectric Effect", it should be noted that PML has filed a U.S. Patent Application entitled: "Methods and Apparatus to Produce Stick-Slip Motion of Logging Tool Attached to a Wireline Drawn Upward by a Continuously Rotating Wireline Drum". That Section II-D was written during March of 1996, but has no information in it not available and known to PML as of September 30, 1994.

There shall be no proprietary final report submitted to GRI. Instead, PML shall continue to file necessary U.S. and foreign patent applications to protect the relevant proprietary property developed by PML under the auspices of the work funded by GRI.

PML has licensed its TCRT patents and technology to Western Atlas Logging Services. PML has licensed its TCRT patents and technology to Schlumberger Technology Corporation and its Licensed Affiliates. Hereinafter in this Final Report, these

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shall be called "PML's Licensees". PML has forwarded to PML's Licensees much relevant data, theoretical models, and proprietary information in various proprietary documents not presented in this Final Report to GRI.

In addition, PML has entered into a patent cross-licensing agreement with Atlantic Richfield Corporation involving the TCRT.

Perhaps the importance to the popular press of the research work funded by GRI and DOE on the TCRT can be best summarized by the following quote:

'While no one can deny the importance and the growth potential of 3-D seismic, another weapon of great importance was added to the oil finder's arsenal when ParaMagnetic Logging unveiled the "Through Casing Resistivity Tool" (TCRT) at the 70th Annual Meeting of the SPE. Bypassed reserves that are behind pipe in existing wells are now legitimate targets for the TCRT - time alone will tell if this tool is as cost effective as 3-D seismic for finding additional reserves...' - Warren, J.E., 1995, Journal of Petroleum Technology, page 1031, December

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SECTION I

INTRODUCTION

A. Overall Project Objectives

To definitively prove that the resistivity of geological formations can be measured from within cased wells and to license the relevant patents and technology to a major wireline service company.

B. Brief Description of the Project

Before starting this GRI sponsored project (co-funded with the DOE), two U.S. Patents had previously been filed by PML that issued as U.S. Patent Nos. 4,820,989 (Vail, 1989a) and 4,882,542 (Vail, 1989b). Several successful laboratory experiments had been done previous to GRI funding showing much promise for the technology. GRI was presented this information prior to submission of PML's original Proposal dated December 14, 1987 that served as the starting point of the contractual relationship between PML and GRI. GRI and DOE have since co-funded much of the work resulting in this Final Report.

During the period of co-funded work by GRI and DOE, PML has applied for and been granted patents identified by the following U.S. Patent Nos.: 5,043,669 (Vail, 1991a); 5,043,668 (Vail, 1991b); 5,075,626 (Vail, 1991c); 5,187,440 (Vail, 1993a); and 5,223,794 (Vail, 1993c). During 1990, PML acquired all rights to U.S. Patent No. 4,796,186 (Kaufman, 1989) on this subject. The inventions described in those patents define the Through Casing Resistivity Tool™ and its abbreviation (TCRT®). The work has been reviewed often by GRI, by consultants to GRI, by advisors to GRI, and by DOE personnel. The research directions have periodically been altered in response to meeting certain milestones and in response to certain discoveries made along the way.

The initially co-sponsored work by GRI and DOE resulted in the design and fabrication of a first generation apparatus version of the TCRT based upon PML's patent disclosures. Henceforth, that first generation apparatus device may be called "PML's First TCRT" for brevity. The mechanical portions of that tool were designed with the help of personnel from then Gearhart Industries, Inc. of Fort Worth, Texas. Data was obtained from that First TCRT in the Research Well at Gearhart Industries, Inc.

in Fort Worth. That work resulted in the publication of the paper entitled "Formation Resistivity Measurements Through Metal Casing" having the authors of W.B. Vail, S.T. Momii, R. Woodhouse, M. Alberty and R.C.A. Peveraro, and J.D. Klein that was presented at the 34th Annual Logging Symposium of the SPWLA, June 13-16, 1993 (Vail, et. al., 1993b). While those measurements proved that formation resistivity from within cased wells could be measured in-principle, PML's First TCRT had comparatively poor vertical resolution and took about an hour to take data at each point.

It was subsequently decided that it was necessary to investigate how to design a tool having better vertical resolution and which was capable of rapidly acquiring data. It was originally theorized that a moving tool which continuously moved vertically upward in the well could be designed and fabricated based upon the use of standard wirelines and sophisticated signal processing techniques. PML then designed and built the Moving Test Jig to test those hypotheses in a laboratory prior to designing a new downhole device. However, the laboratory experiments performed with the Moving Test Jig showed that various effects including the Triboelectric Effect generated large noise signals that could mask the borehole casing signal from the TCRT. Those experiments showed that such noise would mask the borehole casing signal if standard 7 conductor wirelines were used that effectively limited the total amount of current that could be sent downhole. Nevertheless, signal processing techniques were developed that are capable of acceptable data acquisition rates suitable for commercial logging. Those signal processing techniques were adopted for the final stage of this research effort.

A second generation apparatus version of the TCRT was designed and built based upon acceptable signal processing techniques. Henceforth, that device may be called "PML's Second TCRT" for brevity. The mechanical portions of PML's Second TCRT provided for increased vertical resolution. Data was acquired with PML's Second TCRT at PML's Test Well in Woodinville, Washington during 1993. Data was then acquired with PML's Second TCRT at the MWX-2 Well in Rifle, Colorado during late 1993 and early 1994.

PML obtained data at the MWX-2 Well in Rifle, Colorado under blind test circumstances administered by Gas Research Institute and by Western Atlas Logging Services. After those measurements had been performed, the above defined "Overall Project Objectives" had been totally reached. PML had definitively proved that the resistivity of geological formations can be measured from within cased wells and had licensed the relevant patents and technology to Western Atlas Logging Services.

C. Rationale for Undertaking the Project

Heretofore, it has been impossible to measure the resistivity of geological formations from within cased wells. Resistivity measurements from open-hole logs (i.e. during drilling phase, before completion) are invaluable to the gas producer, because such information assists in determining the location of gas zones, and provides an assessment of probable production for each gas zone in the field. However, before the advent of this technology, no tool had yet been developed which was capable of providing accurate and reliable through casing resistivity data for production wells, even though such a tool has been much sought by the industry for years. In past years, numerous technical approaches have been conceived by industry researchers, but each new approach has failed due to the inability to overcome environmental factors such as rust and corrosion, the presence of borehole fluids, non-uniform cement sheathing, polarization phenomena, and small signal sizes, to name a few. Industry experts concur on the need for this technology and its applications, and believe that data from such a tool would significantly enhance gas production from existing fields by monitoring production activities and finding bypassed gas.

D. Projected Benefits to Gas Consumers

This technology will be used in the gas industry for at least the following important purposes: locating bypassed gas and for reservoir evaluation. These uses can significantly affect the economics of locating and producing gas from new and existing gas fields. Other potential uses include: significant improvements in casing inspection; precise collar location; the location and detection of fractures; permeability measurements with log-inject-log techniques; perhaps certain types of cement evaluation with different types of TCRT electrode configurations; and perhaps the determination of lithological information.

Measuring the resistivity of formations adjacent to cased boreholes is critical for numerous applications, but especially for reservoir, production, and depletion monitoring. Such measurements will also be invaluable for identifying "missed" or bypassed gas zones in nearly depleted or "workover" wells. A tool which can provide accurate resistivity measurements through casing will, through better interpretation of formation data, significantly improve the efficiency of recovery and development efforts, and will have a profound effect on gas field economics. All of these uses for this technology have the potential to lower production costs for gas producers.

From the perspective of log analysis, before this work it has been impossible to measure the resistivity of adjacent geological formations from within the steel walls of cased boreholes. Resistivity is a particularly important measurement because gas and oil do not conduct electricity but the typically salty connate water present does conduct electricity. In freshly drilled wells, before the casing is set in place, hydrocarbons are typically detected and measured as follows: (a) the porosity is measured to determine the volume in the rock which may be occupied with gas, oil, and connate water; (b) the electrical resistivity of any water present is measured, or determined from a nearby non-hydrocarbon, 100% water bearing zone (or obtained from reservoir data or from water samples); and (c) the resistivity of the rock present is measured. The data can then be used to determine the total amount of gas and oil present. Gas and oil can then be distinguished in the open hole by certain nuclear and other measurements. This overall analysis procedure is sometimes called "open-hole style log analysis" and it is universally used throughout the industry.

In cased wells, the porosity can presently be determined from inside casings. Water salinity can also be presently determined from inside casings (or obtained from reservoir data or from water samples). Oil and gas can be separated from inside casings with certain nuclear techniques. However, until this work, the resistivity of rock present could not be directly measured. In a particular form of suggested cased-hole log analysis, the use of pulsed neutron tools from inside casing yield "Sigma", and with resistivity measured from within cased wells, "Sigma-Rt Crossplots" can be used to determine the presence of hydrocarbons, provided the porosity is known.

The overall major implication to the industry of this work eventually will be to allow the use of "open-hole style log analysis" to be performed on a routine basis from within steel cased wells and drill pipes. This development could have profound and long lasting consequences in other areas of the industry, including in the drilling industry.

For example, it is possible that the technology could be used to perform "open-hole style log analysis" from within a non-rotating drill string when the drilling bit is stopped. This would avoid having to repeatedly pull the drill string out of the well for such purposes that include open-hole logging. PML calls this "Measurement-While-Drilling-(Bit)-Stopped™" or "MWDS®" for short. This approach has most of the advantages of MWD measurements but few of the drawbacks. MWDS would certainly be cheaper than true MWD. The drill pipe would be pulled up and down with the block above the rig floor to prevent sticking as is presently done in practice for other reasons. Mud could be continually circulated during the measurements. Perhaps the mud could instead be used to pump down the tool string in highly deviated wells. The

resistivity of the mud would be measured and perhaps controlled to allow correction of the apparent resistivity obtained from MWDS for the presence of the mud. MWD devices that locate the direction of the drill bit during drilling appear to be very desirable. However, geophysical information obtained from MWD is relatively expensive. If instead equivalent geophysical information could be obtained at lower cost with an MWDS system, there may be significant demand in the future for the development of a practical MWDS system.

In some difficult drilling conditions where open-hole logging is risky, and after the TCRT is routinely commercially available, it could make sense to cement casing in place without performing any open-hole measurements. After the well is cased and cemented in place, all logging would be performed from within the cased well.

This technology could allow yet further changes in the drilling industry to occur perhaps resulting in the development of revolutionary "one-trip-down drilling". This procedure would probably be used initially for infill drilling purposes. Here, the drill bit is attached to the casing and it proceeds downhole just one time in geological areas where the bit lasts long enough to reach the desired depth in one such pass. All logging is done from within the casing after it is set in place using various cementing procedures presently available. Various industry experts have previously suggested this vision for the future. However, with the advent of the TCRT, this vision can be implemented practically. This approach would save the time of repetitively pulling out the drill string and would avoid any open-hole logging whatsoever.

Several of these drilling aspects of the technology may perhaps be overly speculative and therefore subject to controversy. However, the failure to mention any relationship of the technology to drilling would be overly conservative. The point here is that the advent of the Through Casing Resistivity Technology appears to open up many more avenues for advancement in the industry than would be expected from the development of "just one more cased-hole logging tool".

CONTENTS OF SECTION II: TECHNICAL SECTION

- Section II-A: Theory of the Through Casing Resistivity Tool™
- Section II-B: Results from the MWX-2 Well in Rifle, Colorado
- Section II-C: Results from PML's Test Well in Woodinville, Washington
- Section II-D: Experiments with Moving Test Jig and the Triboelectric Effect
- Section II-E: Results from Research Well in Fort Worth, Texas
- Section II-F: Brief Summary of Subcontract Work Under this Project

SECTION II - A

THEORY OF THE THROUGH CASING RESISTIVITY TOOL™

It is the intent of this section to describe the theory for the Through Casing Resistivity Tool as it was actually used in practice most recently at the MWX-2 Well in Rifle, Colorado where successful blind-test measurements were made with the TCRT®.

The authors have tried to make this section readable by the non-specialist in TCRT measurements. Extensive references to the Theoretical Appendices are provided so that experts can further review certain assertions made by the authors.

Please refer to Figure 1 entitled "Concept of the Through Casing Resistivity Tool™" that appears on the next page. It explains how the TCRT works in principle. That figure shows in principle how the current leakage ΔI is measured from inside the casing. That method of operation was actually used to acquire data at the Test Well in Fort Worth, Texas. However, physically balancing for the null output by changing the gain of amplifier A1 is laborious and time consuming. Therefore, certain refinements were used to acquire data at the MWX-2 Well in Rifle, Colorado.

The symbol ΔI herein is used for simplicity in this particular document which stands for the quantity rigorously defined as δi_2 in Equation 28 of U.S. Patent No. 5,075,626 (Vail, 1991c). The symbol ΔI shall henceforth be defined in this Final Report to mean the quantity δi_2 defined in Equation 28 of that patent.

The algebraic equations of U.S. Patent No. 5,075,626 (Vail, 1991c) are used in practice to interpret all data from the TCRT. Several minor typos were made in intermediate equations of that patent when re-typed by the U.S. Patent and Trademark Office which are corrected in Section VIII-E of the Theoretical Appendices that are provided in this Final Report for the convenience of the reader. Equation 28 in Vail (1991c) is the central result of that analysis and is correct as it stands.

Referencing Figure 1, there exist algebraic quantities of particular interest that are conveniently defined in the following. The "Measurement State" herein is that state of the apparatus corresponding to the connection of SW1 to Electrode B (or equivalent). The "Calibration State" herein is that state of the apparatus corresponding to the connection of SW1 to Electrode F (or equivalent).

CONCEPT OF THE THROUGH CASING RESISTIVITY TOOL™ PARAMAGNETIC LOGGING, INC.

FIGURE 1

The Through Casing Resistivity Tool™, TCRT®, developed by ParaMagnetic Logging, Inc. of Woodinville, Washington measures formation resistivity through brine-saturated cement surrounding the borehole casing.

With switch SW1 connected to Electrode B, low frequency AC current introduced on the interior of the casing by Electrode A will flow off the casing and into the formation.

The average current conducted along the casing between Electrodes C and D is I_1 which results in voltage V_1 . Analogously, voltage V_2

is measured between Electrodes D and E. Voltages V_1 and V_2 are subtracted which gives a measure of the net current conducted into the formation between Electrode Pairs C-D and D-E.

The current conducted into the formation gives an accurate indication of the formation resistivity behind the casing because the tool is initially nulled for changes in casing conductance and electrode effects. The tool is initially nulled by connecting switch SW1 to Electrode F and varying the gain of amplifier A1 to achieve a null output voltage between Electrode Pairs C-D and D-E. This compensation corrects for variations in casing conductance and electrode effects to first order.

The following algebraic quantities shall have the following meanings herein:

- V1: Output of Electrode Pair C-D at Surface in volts 0-peak in Measurement State for Current I_T conducted to Electrode A (or to top of well if chosen) that is in-phase with Current I_T .
- V2: Output of Electrode Pair D-E at Surface in volts 0-peak in Measurement State for Current I_T conducted to Electrode A (or to top of well if chosen) that is in-phase with Current I_T .
- V3*: Output of Electrode Pair C-D at Surface in volts 0-peak in Calibration State for current I_N^* conducted along the casing that is in-phase with I_N^* .
- V4*: Output of Electrode Pair D-E at Surface in volts 0-peak in Calibration State for current I_N^* conducted along the casing that is in-phase with I_N^* .
- I_T : The total current in amps 0-peak conducted to the casing in the Measurement State.
- I_N^* : The total current in amps 0-peak conducted to the casing in the Calibration State.

The "value of the current" herein is meant to mean either (a) the zero-to-peak value of a sinusoidal current about its D.C. average or (b) the average of the D.C. value if a D.C. current - whichever is appropriate in the relevant discussion.

The apparatus at the MWX-2 Well in Rifle, Colorado directly measured the following quantities (among others): V1, V3*, V1-V2, V3*-V4*, I_T , and I_N^* .

1. Details Concerning Measurement of the Current Leakage ΔI

The purpose of this section is to describe to the technical specialist what was done at the MWX-2 Well to determine the current leakage in terms of the technical literature. The casual reader is encouraged to skip to the following section.

As explained in rigorous detail in U.S. Patent No. 5,075,626 (Vail, 1991c), Equation 28 depends upon the fact of the equality of currents flowing defined in Equation 27 therein. The equality of currents defined in Equation 27 allows the use of Equation 28 to produce measurements of current leakage ΔI that are unaffected by first or second order errors of measurement which are defined

in U.S. Patent No. 5,075,626 (Vail, 1991c). Equation 27 requires that the currents flowing along the casing between Electrodes C-D are identically the SAME in the Measurement State and in the Calibration State (which means that $V1 = V3$ in that patent). The symbol "*" herein is used to remind the reader that the quantity measured was obtained under conditions where Equation 27 was NOT satisfied.

In the event that the conditions for current equality are not met in Equation 27, then Equation 28 must be modified accordingly. Assuming that the apparatus is linear in amplitude and phase response and further assuming that the geophysics is linear, Equation 28 of U.S. Patent No. 5,075,626 (Vail, 1991c) is revised and is presented below as Equation 1 herein in terms of the variables defined in this Final Report.

$$\Delta I = \{ IN* (V1/V3*) \} \times \{ (V1-V2) - (V1/V3*) (V3*-V4*) \} \\ \times \{ D V1 - (V1/V3*) (V3*-V4*) \}^{-1}$$

Equation 1.

Here, D is the reduction in gain or "divider ratio" D that is defined in U.S. Patent No. 5,075,626 (Vail, 1991c). Equation 1 was actually used in practice at the MWX-2 Well in Rifle, Colorado to do all of the data analysis to obtain current leakage. Please notice that the quantity ΔI is NOT dependent upon the absolute gain of the apparatus which was an original design requirement for the instrument.

2. The Potential Voltage V_o

Please refer to Figure 2 appearing on the next page that is entitled "Simple TCRT® Data Interpretation Scheme". That figure shows how the Potential Voltage is V_o is measured. The principles of measuring the potential voltage V_o are adequately described in U.S. Patent Nos. 4,820,989 (Vail, 1989a) and 4,882,542 (Vail, 1989b).

There exists a Characteristic Length for the problem defined in Equation 1 of U.S. Patent No. 5,187,440 (Vail, 1993a). The results of calculations performed in terms of that Characteristic Length appear in U.S. Patent No. 4,820,989 (Vail, 1989a) and are explicitly shown in Figures 6 - 9 of U.S. Patent No. 4,882,542 (Vail, 1989b) for a 1 ohm-meter formation having a Characteristic Length of approximately 320 meters. The Characteristic Length is defined as the length along a given borehole casing where 1/2 the current leaks off the casing. Because these Characteristic

SIMPLE TCRT[®] DATA INTERPRETATION SCHEME

PARAMAGNETIC LOGGING, INC.

FIGURE 2

To determine the apparent resistivity ρ_a , PML uses the simple Calibration Constant K as follows:

$$\rho_a = K R_c$$

This simple concept defined in U. S. Patent Nos. 4,820,989 and 5,075,626 has been used to interpret all TCRT data to date and appears to be a valid approximation provided that the formation under investigation is relatively thick; the cement causes no difficulties; and the TCRT is not near the extreme end of the casing string. K depends primarily on electrode spacing and the O.D. of the casing.

Lengths are well in excess of 100's of meters in typical borehole circumstances, occasional measurements of the potential voltage along the casing provided adequate results to measure apparent resistivity. This has been found to be the case in practice to date and is critically important information necessary to acquire data rapidly.

Additional details concerning the Characteristic Length are found in Section VIII-D of the Theoretical Appendices which shows that PML's Characteristic Length yields results very similar to quantities calculated more recently by several other authors. That Characteristic Length is used in Section VIII-G to calculate the D.C. Driving Impedance of the Casing. The current delivered to the casing times the D.C. Driving Impedance yields the Potential Voltage V_o of the casing.

Detailed methods to measure the Potential Voltage V_o in practice are described in various proprietary documents that have been forwarded to PML's Licensees. The frequencies used to measure the Potential Voltage are also described in detail in various proprietary documents that have been forwarded to PML's Licensees.

3. Determination of Apparent Resistivity ρ_a

Please refer to Figure 2. The electric field on the exterior of the casing results in Potential Voltage V_o causing the leakage current ΔI to flow off the casing to infinity. Therefore, the TCRT can be used to determine the value of an apparent resistor connected between Electrodes C, D, and E to "electrical infinity".

That resistor to electrical infinity carrying the current ΔI has historically been defined as R_c that is so labeled in Figure 2. That resistor R_c is explicitly defined in Equation 8 of U.S. Patent No. 4,820,989 (Vail, 1989a). Section VIII-A of the Theoretical Appendices also provides much additional detail concerning the fundamental meaning of R_c . For the sake of completeness, the value of the resistor to electrical infinity is given by the following:

$$R_c = V_o / \Delta I \quad \text{Equation 2.}$$

U.S. Patent 4,820,989 (Vail, 1989a) sets forth a direct method to calculate apparent resistivity from the value of R_c as defined in Equation 7 of that patent. That calculation shows that the electrode spacing and the O.D. of the casing are of the greatest importance. That calculation in that patent also provides the

basis of the use of PML's Calibration Constant K. Further information is presented in the Theoretical Appendices concerning how to approximately calculate K from first principles for the technical specialist. In particular, the interested reader may wish to refer to Sections VIII-A, VIII-B and VIII-C of the Theoretical Appendices at this point.

PML began using the concept of the Calibration Constant K during 1986 - well before field work began at the Test Well in Fort Worth during 1989. That quantity was finally explicitly defined in the literature in Equation 33 in U.S. Patent 5,075,626 (Vail, 1991c). Apparent resistivity ρ_a at any given well is then given by the following at any depth in the well:

$$\rho_a = K R_C \quad \text{Equation 3(a).}$$

Using Equation 2 for R_C , then Equation 3(a) becomes the following closely related equation:

$$\rho_a = K (V_O / \Delta I) \quad \text{Equation 3(b).}$$

Both equations 3(a) and 3(b) may henceforth be referred together simply as "Equation 3" for brevity.

Before proceeding further, it is first necessary to rigorously define certain variables to be used in the theoretical discussions throughout this Final Report. The following symbols involving resistivity are used throughout the text:

- ρ_a - The apparent resistivity measured by the TCRT from within casing (ohm-meters).
- ρ_t - The "true" formation resistivity obtained from the TCRT by a series of corrections to ρ_a (ohm-meters); see Sections VIII-F, VIII-I, and VIII-J for much additional detail.
- ρ_f - The geologically "correct" formation resistivity (ohm-meters); this symbol is particularly used in formulas where either ρ_a and/or ρ_t appear for the purpose of avoiding any possible confusion.
- ρ - This symbol is used as a simple abbreviation for ρ_f when there is little possibility for confusion about its meaning (ohm-meters); this symbol is often used in very general theoretical discussions where there is assumed to be no differences between any of the above three symbols.

The authors have diligently tried to use the variables ρ_a and ρ_t consistently throughout the text. If any of the symbols ρ_a or ρ_t or ρ_f are used, these symbols are defined above.

If the symbol of simply " ρ " is used in general theoretical arguments, it may be assumed that there are no differences between ρ and ρ_a or ρ_t or ρ_f .

Now that the terms are clearly defined, the very simple physical ideas leading to Equations 3(a) and 3(b) can be discussed. In their simplest form, Equations 3(a) and 3(b) can be assumed to be applicable in the D.C. and low frequency limit where the skin effects of the casing and the skin effects of the geological formation can be neglected, or assumed to produce relatively small effects. Under these circumstances, the starting place is the physical picture that for a given electric field strength existing on the outside of pipe, that such a given electric field will cause a certain current density to flow off the exterior of the pipe in accordance with one of Maxwell's Equations given by the following:

$$J = \sigma E \quad \text{Equation 4.}$$

Here J is the current density in units of amps per unit area; the quantity σ is the conductivity; and E is the electric field strength. In complex situations, the above equation may take on a tensor form. However, the only assumption here whatsoever is that the current flows primarily linearly in response to the electric field strength. As an example, assumptions of linear response to electric field strength results in "Ohm's Law" of resistors. Therefore, the use of Equation 4 begins on very safe theoretical ground.

At a given position on the casing adjacent to a "relatively thick" formation, it is evident that the current leakage ΔI is proportional to the current density J . Therefore, the following is true where g is some constant of proportionality.

$$\Delta I = g J \quad \text{Equation 5.}$$

The constant of proportionality g is related primarily to geometric factors involving integrals, the electrode spacing, the O.D. of the casing, and the distance from the end of the casing if close to the end of the casing string.

At the given position on the casing adjacent to the same "relatively thick" formation, it is evident that the potential voltage V_o is proportional to the electric field strength on the

outside of the casing. Therefore, the following is true where h is another constant of proportionality.

$$V_o = h E \quad \text{Equation 6.}$$

The constant of proportionality h is due to different geometric factors involving integrals, the electrode spacing, the O.D. of the casing, and the distance from the end of the casing if close to the end of the casing string.

Further, the electrical resistivity ρ is related to the conductivity σ as follows:

$$\rho = 1 / \sigma \quad \text{Equation 7.}$$

Therefore, substituting Equations 5, 6 and 7 into Equation 4 results in the following:

$$\rho = (g / h) (V_o / \Delta I) \quad \text{Equation 8.}$$

Consequently, the Calibration Constant K in this analysis herein is defined in terms of the constants of proportionality as follows:

$$K = g / h \quad \text{Equation 9.}$$

Therefore, keeping in mind the above definitions related to resistivity, the apparent resistivity ρ_a measured from inside the cased well is then given by the following equation:

$$\rho_a = K (V_o / \Delta I) \quad \text{Equation 10.}$$

This is Equation 3(b) set forth above.

The assumption in the above is that the constants of proportionality g and h will NOT change significantly vs. depth in a uniform half-space for a given O.D. casing and for a given electrode spacing in a given well. This appears to be a reasonable assumption in the low frequency limit that is assumed for this analysis. Therefore, for a given well, for a given

electrode spacing, and for a given O.D. of casing, and for thick relatively homogenous formations, K is NOT anticipated to be a strong function of depth unless one is very near the end of the casing string. The experience at the Test Well in Fort Worth, Texas, at PML's Test Well in Woodinville, Washington, and at the MWX-2 Well in Rifle, Colorado, provide collaborating evidence that K is not a strong function of depth unless the TCRT is very near the end of a casing string.

Near the end of a casing string, it has been expected by PML that the Calibration Constant K will be substantially unaffected until the last several hundred feet of the casing string. From symmetry arguments, it has been anticipated that the Calibration Constant K will increase monotonically near the end of the casing string, and will achieve about twice its nominal value near the extreme end of the casing string. The Calibration Constant K is expected to increase because extra current flows directly downward below the casing that does not have the cylindrical symmetry required by PML's typical theory of interpretation.

Section VIII-I of the Theoretical Appendices provides PML's simple model to calculate the end effects of casing. A correction parameter $\beta(\text{END})$ is described therein to obtain ρ_t from ρ_a . The interested reader is referred to Section VIII-I for details.

The above derivation also assumes that there are no adverse effects due to the presence of cement. Section VIII-F of the Theoretical Appendices provides PML's simple model to calculate the effects of cement. A correction factor $\beta(\text{CEMENT})$ is described therein to obtain ρ_t from ρ_a . The interested reader is referred to Section VIII-F for details.

It should also be noted that a host of other relatively minor effects have been neglected in the above derivation. Section VIII-J of the Theoretical Appendices shows how to correct ρ_a to obtain ρ_t if a number of these combined corrections are required. Section VIII-J defines a correction factor for a number of such "residual effects" that is called $\beta(\text{REFS})$. Small corrections related to the Characteristic Length that are defined as $\beta(\text{CHARACTERISTIC LENGTH})$ also appear in Section VIII-J. The interested reader is referred to Section VIII-J for the details.

This completes the derivation of use of the Calibration Constant K from elementary ideas and physical pictures. Sections VIII-A, VIII-B and VIII-C of the Theoretical Appendices show how to approximately calculate K from first principles in the low frequency limit.

Analytic formulas are developed in Section VIII-C for the Calibration Constant K which are derived from first principles. Quantitative calculation of the Calibration Constant provides

agreement between theory and experiment to approximately 13%. In one case, agreement is achieved to an accuracy of 3% (see last portion of Section VIII-C-2). Sections VIII-A and VIII-B present necessary developments used in Section VIII-C to obtain the analytic formulae.

Section VIII-A presents the relationship between the Piece-Wise Continuous Resistor Model and the Continuum Model that is necessary for the calculation of the Calibration Constant K. Equation VIII-A-12 of Section VIII-A provides an important result. Section VIII-B reviews the formulae in the literature used to calculate the resistance of cylinders buried in the earth. Those formulae are then used in Section VIII-C to derive approximate analytic formulae for the Calibration Constant K. The principal result is Equation VIII-C-10 of Section VIII-C.

The fact that we can now approximately calculate the Calibration Constant from first principles and that it substantially agrees with what we have used at the Test Well in Fort Worth, Texas, in PML's Test Well in Woodinville, Washington, and at the MWX-2 Well in Rifle, Colorado, shows that we have a rather complete understanding of how the Through Casing Resistivity Tool actually works.

This simple theory presented herein provides additional powerful results. Section VIII-H shows that the assumption of a Calibration Constant K results in the determination of a 50% Radius of Investigation about equal to 23 times the radius of the casing. Section VIII-K shows that this simple theory also provides methods to calculate the approximate signal sizes to be expected at different well sites. Therefore, the initial assumption long ago that a Calibration Constant K should be appropriate for the problem has resulted in many intriguing results based upon this simple theory.

In the end, Section VIII-L entitled "Retrospective on Calibration Constant K" shows that it is now evident, in hind-sight, that the concept for the Calibration Constant K should have been expected to work based upon analogies with other measurements.

4. Comparison of Apparent Resistivity ρ_a with Tabarovsky, et. al. (1994)

It should be noted that the paper entitled "Through-Casing Resistivity (TCR): Physics, Resolution and 3-D Effects" having the authors of L.A. Tabarovsky, M.E. Cram, T.V. Tamarchenko, K.M. Strack and B.S. Zinger of Western Atlas Logging Services given at the 35th Annual SPWLA Symposium in Tulsa, Oklahoma, June 19-22, 1994 (Tabarovsky, et. al., 1994) presented theory that is

relevant to the validity of Equation 10 and to Equation 3(b) herein.

Equation 7 in Tabarovsky, et. al. (1994) states the following:

$$I_r = U / R_{tube}$$

It is the understanding of the authors that Equation 2 herein is obtained from Equation 7 in Tabarovsky, et. al. (1994) provided that the following quantities defined by Tabarovsky, et. al. (1994) are equivalent to those herein in Equations 11, 12, and 13 as follows:

$$R_{tube} = R_C \quad \text{Equation 11.}$$

$$U = V_O \quad \text{Equation 12.}$$

$$I_r = \Delta I \quad \text{Equation 13.}$$

The quantities defined in Tabarovsky, et. al. (1994) are on the left above and those defined herein are on the right. It is further the understanding of the authors that the following is true:

$$R_f = \rho \quad \text{Equation 14.}$$

Equation 9 in Tabarovsky, et. al. (1994) states the following which provides the definition of the parameter L therein as follows:

$$R_{tube} = R_f L$$

Using Equations 11 and 14 above, Equation 9 in Tabarovsky, et. al. (1994) then becomes the following:

$$\rho = R_C / L \quad \text{Equation 15.}$$

However, Equation 15 above is the same equation as Equation 3(a) herein provided the following is true:

$$K = 1 / L \quad \text{Equation 16.}$$

If Equations 11, 12, 13, 14, and 15 are true, then the following is also true:

$$L = 1 / K \quad \text{Equation 17.}$$

It is comforting to find confirmation from Tabarovsky, et. al. (1994) that several of the concepts used by PML appear to agree with their independently derived rigorous theory. It is always possible that the above quantities could be related by some other set of constants that when grouped together into these particular equations give mutual agreement. However, there appears to be a close relationship between the concepts set forth in Tabarovsky, et. al. (1994) and those heretofore used by PML.

(NOTE TO THE TECHNICAL SPECIALIST: THE SYMBOL L USED IN EQUATIONS 15, 16, AND 17 IN THIS SECTION II-A-4 SOLELY MEAN THE PARAMETER "L" DEFINED BY TABAROVSKY, ET. AL. (1994). IT HAS THE DIMENSIONS OF 1/LENGTH. THE SYMBOL L USED ELSEWHERE IN THIS FINAL REPORT MEANS THE LENGTH OF A CYLINDER.)

5. Distinguishing Apparent Resistivity from Other A.C. Effects

U.S. Patent No. 4,882,542 (Vail, 1989b) describes in detail the methods used to determine the suitability of the frequency of operation of the invention. Please refer to a copy of Figure 10 and Figure 11 on the next page.

The following quote is from U.S. Patent No. 4,882,542 (Vail, 1989b). The original text in that patent used the symbol "V₃" to mean the quantity that is rigorously defined as (V₁-V₂) in this Final Report. Keeping in mind here that V₃ is applicable to this section only and to Figure 10, the following is quoted from page 17 of the patent.

"Fig. 10 shows a plot of V₃ vs. the frequency f for several values of the 0-peak current conducted downhole, for I₁ and for I₂. For I₁, f₁ is still in a region dominated by polarization effects, f₃ is the lowest frequency where polarization effects are relatively negligible compared to resistivity effects, f₄ is the center of the frequency band

appropriate for resistivity measurements, f_5 is the uppermost frequency where resistivity effects dominate skin-depth effects of the casing, and f_6 is in a region where skin-depth effects dominate measurements. For current I_1 , resistivity measurements should be performed in the region where V_3 is ideally a relative constant, namely between frequencies f_3 and f_5 . For I_2 , which is a larger current conducted through the formation, the relative shape of the curve can change significantly in the polarization region."

Quoting further from U.S. Patent No. 4,882,542 (Vail, 1989b) it states:

"However, accurate resistivity data can still be taken between frequencies f_3 and f_5 for current I_2 . Figure 11 is nearly the same as Fig. 10 except here the quantity ΔI is plotted vs. the frequency f . However, the major conclusions are all the same."

Polarization effects are rigorously defined in Vail (1989b) on pages 13 to 16. Possible acceptable operational frequencies down to the frequency of .01 Hz are explicitly described in PML's patents on the subject.

Skin depth phenomena are described on page 16 of U.S. Patent No. 4,882,542 (Vail, 1989b). On page 15 and 16 of that patent it further states:

"In general, many polarization phenomena result in non-linear relationships between V_3 or ΔI vs. either V_0 or I . And all other things being equal, polarization phenomena are larger at lower frequencies because such lower frequencies allow polar molecules to orient in applied fields, allow preferential gas build-up on the electrodes, and also allow the time necessary to produce concentration gradients in solution. At higher frequencies on the other hand, the skin effect of the casing interferes with the interpretation of resistivity data."

On page 16 of U.S. Patent No. 4,882,542 (Vail, 1989b) it further states:

"As the frequency of the current I is increased, then eventually a frequency will be reached when most of the current simply flows from electrode A up the inside of the casing to the surface for a return to electrode B. This is caused by the skin effect of the pipe. The skin effect causes an exponential attenuation of the electric field applied across the thickness of the steel casing, where the electric field is attenuated as follows:

$$\xi = \xi_0 e^{-(\tau_1 / \delta)} \quad \text{Eq. 21}$$

The electric field ξ_{OA} is that applied to the inside of the casing by electrode A, ξ is the field immediately outside of the pipe, τ_1 is the thickness of the pipe, and δ is the skin depth given by the following:

$$\delta = (\pi f u \sigma)^{-1/2} \quad \text{Eq. 22}$$

Here, f is the frequency in Hz, u is the magnetic permeability, and σ is the conductivity of the material. (Please refer to 'Fields and Waves In Communication Electronics', Simon Ramo, et. al., Second Edition, John Wiley & Sons, 1984, p. 149.) Typical steel in borehole casing has a relatively permeability of 100, and the resistivity ($1 / \sigma$) of typical steel is 10 micro-ohm-cm. Therefore, the above formula becomes:

$$\delta = (0.62 / f^{1/2}) \text{ inches} \quad \text{Eq. 23}$$

The critical frequency is the frequency where the skin depth equals the thickness of the pipe in question. The critical frequency for a 0.50 inch wall thickness in 1.54 Hz. The critical frequency for a 0.375 inch wall thickness is 2.73 Hz. Typically casing has wall thickness between 0.25 and 0.50 inches. If the frequency of operation is significantly less than the critical frequency, then the results for resistivity measurements need not be corrected for skin depth phenomena. For frequencies above the critical frequency, then the resistivity results need to be corrected for such phenomena. For very high frequencies of operation, then none of the current is conducted through the pipe into the formation but instead goes up the inside of the pipe from electrode A for a return across the earth's surface to electrode B."

The above theory has been used successfully at the Test Well in Fort Worth, Texas; in PML's Test Well in Woodinville, Washington; and at the MWX-2 Well, in Rifle, Colorado.

In all cases, and at each test well, plots similar to Figure 11 have been made at a minimum of one selected depth. Equivalently, apparent resistivity ρ_a vs. frequency is plotted. At a given depth, if a region is found where the apparent resistivity ρ_a vs. frequency is a constant, and does not change with frequency, that is the region where the casing, formation, and the measurement instrument are actually measuring resistive quantities - instead of reactive quantities that appear as distributed inductance and/or distributed capacitance. After

all, we are trying to measure the resistivity of the formation from the determination of resistive quantities.

In laboratory measurements on solely resistive networks, measurements repeated at different frequencies will give the same measurements of the resistors present. We have used exactly the same physical notion since the year of 1987 when U.S. Patent No. 4,882,542 was filed.

The actual frequencies of operation chosen at the MWX-2 Test Well in Rifle, Colorado and why they were chosen are described in various proprietary documents that have been forwarded to PML's Licensees. Additional information and data obtained by PML concerning the measurement of various A.C. Effects have also been forwarded to PML's Licensees in various proprietary documents.

6. Comparison of PML's Work on A.C. Effects with Tabarovsky, et. al. (1994)

PML's work on skin-depth phenomena can be compared with the work in Tabarovsky, et. al. (1994). Therein it states:

"The analysis of Figs. 4 and 5 shows the quantities under comparison are less than 10% if the following condition is satisfied,

$$(\text{Casing-skin-depth}) / (\text{Casing-thickness}) \geq 2$$

(30)"

Therefore, the results in Tabarovsky, et. al. (1994) are in agreement with the statements in U.S. Patent No. 4,882,542 (Vail, 1989b) concerning skin depth phenomena and limitations on the frequency of operation. We are very gratified with the agreement.

7. Definition of Selected Symbols Used to Describe the Experimental Results

Several of the following have already been defined elsewhere but are repeated herein for convenience. Much of the following are defined herein for the first time within this Final Report. The following symbols are used to describe the data in the various Figures.

- V1: Output of Electrode Pair C-D at Surface in volts 0-peak as measured by a Phase Sensitive Detector in the Measurement State for Current I_T conducted to Electrode A (or to top of well if chosen) that is in-phase with I_T .
- V2: Output of Electrode Pair D-E at Surface in volts 0-peak as measured by a Phase Sensitive Detector in the Measurement State for Current I_T conducted to Electrode A (or to top of well if chosen) that is in-phase with I_T .
- V3*: Output of Electrode Pair C-D at Surface in volts 0-peak as measured by a Phase Sensitive Detector in the Calibration State for current I_N^* conducted along the casing that is in-phase with I_N^* .
- V4*: Output of Electrode Pair D-E at Surface in volts 0-peak as measured by a Phase Sensitive Detector in the Calibration State for current I_N^* conducted along the casing that is in-phase with I_N^* .
- I_T : The total current in amps 0-peak conducted to the casing in the Measurement State.
- I_N^* : The total current in amps 0-peak conducted to the casing in the Calibration State.
- V1-V2 (VOP): The output in volts 0-peak at the surface as measured by a Phase Sensitive Detector corresponding to the algebraic quantity $(V1 - V2)$.
- $(V3-V4)^*$ (VOP): The output in volts 0-peak at the surface as measured by a Phase Sensitive Detector corresponding to the algebraic quantity $(V3^* - V4^*)$.
- Apparent Resistivity ρ_a : The apparent resistivity ρ_a in ohm-meters measured by the TCRT from inside the cased well. See the related definitions of ρ , ρ_t and ρ_f in Section II-A-3 entitled "Determination of Apparent Resistivity ρ_a ".
- Depth from Top of Casing: This is the distance from the top of the cased well to Electrode D of the TCRT. Any open-hole data is shifted in depth so that it reads on the same scale. For example, many of the logs state "Open Hole Log: 28.16 feet subtracted from depth". For such open-hole data, in fact 28.16 feet was subtracted from the open-hole depth of that log.
- K: The Calibration Constant K in meters. For all of the data at the MWX-2 Well, $K = 0.489$ meters.

Blind Test: PML was not provided a copy of the open-hole log until after all of the data was acquired during the first and second passes (Pass 1 and Pass 2) in a given logging Zone.

Z1: Abbreviation for Zone One in the MWX-2 Well chosen by Western Atlas Logging Services and GRI.

Z2: Abbreviation for Zone Two in the MWX-2 Well chosen by Western Atlas Logging Services and GRI.

ZX: Abbreviation for Zone X in the MWX-2 Well chosen by PML.

P1: Abbreviation for Pass 1 (the first logging run).

P2: Abbreviation for Pass 2 (the second, or repeat logging run).

Sharp Electrodes: Fresh electrodes were installed at the surface before the logging run.

Dull Electrodes: Old, dull electrodes used during entire logging run.

ILD002: An open-hole deep induction log provided by Schlumberger.

ILM002: An open-hole medium induction log provided by Schlumberger.

INVERTED ILD: The "Inverted ILD" open-hole logs for the MWX-2 Well were provided to PML by Dr. James D. Klein of ARCO Exploration and Production Technology in his June 1, 1994 letter.

COLLAR: The casing collars as located by the TCRT.

% Down: The percentage of the total current IT conducted to the casing that is flowing downward between Electrodes C and D in the Measurement State.

R1: The resistance in micro-ohms of the portion of the casing spanned by Electrodes C-D at a particular depth determined during the Calibration State.

V1 / IT: The ratio of V1 divided by IT (which approximately mimics R1 vs. depth under typical circumstances).

ΔI (AOP): The current leakage ΔI defined in Section II-A in units of amps 0-peak.

Q (Volts/Amp): Various techniques are used to measure the Potential Voltage V_o . As implemented at the MWX-2 Well, Q is the ratio of the Potential Voltage V_o divided by the current causing the generation of the Potential Voltage.

DC: Q measured using certain D.C. techniques that are described in detail in various proprietary documents that have been forwarded to PML's Licensees.

AC: Q measured using certain A.C. techniques that are described in detail in various proprietary documents that have been forwarded to PML's Licensees.

NEAR: The Potential Voltage using the "Near Potential Voltage Reference Electrode G".

FAR: The Potential Voltage using the "Far Potential Voltage Reference Electrode G".

V_o (VOP): The Potential Voltage V_o determined in volts 0-peak. Mathematically: $V_o = (Q) (IT)$.

R_c : The resistor R_c to infinity defined in Section II-A that is measured with the TCRT.

3 pt Smooth: Data smoothed with Harvard Graphics "3 Point Moving Average" program.

5 pt Smooth: Data smoothed with Harvard Graphics "5 Point Moving Average" program.

A:Top of Casing - Top of the well is energized during the Measurement State.

A:Electrode A - Electrode A of the TCRT is energized during the Measurement State.

No Back Loading - Certain type of movement of TCRT described in various proprietary documents that have been forwarded to PML's Licensees.

NBL - Abbreviation for "No Back Loading".

()^{*} = ()^{*} These expressions are equivalent in the text and on the Figures.

(See all "Rules" on next page for clarity)

Rule A: If the measured apparent resistivity ρ_a is less than 0 ohm-meters, or if the measured apparent resistivity ρ_a is greater than 400 ohm-meters, then set the value of the apparent resistivity ρ_a on the graph equal to the value of 400 ohm-meters.

Rule B: If the measured apparent resistivity ρ_a is less than 0 ohm-meters, or if the measured apparent resistivity ρ_a is greater than 300 ohm-meters, and the TCRT is within +/- 2 feet from a collar, then do not plot the point on the graph.

If the measured apparent resistivity ρ_a is less than 0 ohm-meters, or if the measured apparent resistivity ρ_a is greater than 400 ohm-meters, and the TCRT is not within +/- 2 feet from a collar, then set the value of the apparent resistivity ρ_a on the graph equal to the value of 400 ohm-meters.

Rule C: If the measured apparent resistivity ρ_a is less than 0 ohm-meters, or if the measured apparent resistivity ρ_a is greater than 300 ohm-meters, and the TCRT is within +/- 2 feet from a collar, then do not plot the point on the graph.

If the measured apparent resistivity ρ_a is less than 0 ohm-meters, or if the measured apparent resistivity ρ_a is greater than 1000 ohm-meters, and the TCRT is not within +/- 2 feet from a collar, then set the value of the apparent resistivity ρ_a on the graph equal to the value of 1000 ohm-meters.

SECTION II - B

RESULTS FROM THE MWX-2 WELL IN

RIFLE, COLORADO

The purpose of Section II-B is to summarize the results obtained from the MWX-2 Well located in Rifle, Colorado. Certain data and results are stated in the text. On occasion, the authors wish to make certain comments to clarify matters or to make a point. When such extended comments are made concerning the data, the authors have tried to explicitly begin a paragraph with the phrase "Comments:". The data presented are our experimental results and the data are correct. The "Comments" are marked accordingly so as not to be confused with the hard data.

It should be noted that the data herein corresponding to Zone 1 and Zone 2 were paid for by the Contract between GRI and PML. The data in Zone X was acquired by PML at its own expense, much of which was initially provided to GRI and to Western Atlas Logging Services at no additional cost (but the rights to publish that data from Zone X, with suitable recognition of PML, was later acquired by GRI and Western Atlas Logging Services after suitable payments were made to PML). The data is presented in the relative order of importance to the understanding of the technology, and not in chronological order.

PML designed and built the second generation apparatus version of the Through Casing Resistivity Tool™ (TCRT®) whose ultimate purpose was to acquire the data from the MWX-2 Well that is presented herein in Section II-B. It is shown in Figure 4 that is entitled "TCRT For MWX-2 Well". That second generation apparatus shall hereinafter be called "PML's Second TCRT" in the text for brevity.

Referring to Figure 4, the tool sections are evident. Electrodes A, C, D, E, J, and F of the TCRT are identified in Figure 4. The minimum O.D. of PML's Second TCRT is presently 5 1/4 inches O.D. (However, it can be retrofitted with simple mechanical parts that would make it 4 5/8 inches O.D. and with suitable effort, it be made as small as 4 1/4 inches O.D.). PML's Second TCRT is presently configured to work in 7 inch O.D. cased wells. (However, it can be retrofitted to work in any well ranging from 5 1/2 inches O.D. to 9 5/8 inches O.D.)

The electronics is designed to operate at 125 degrees C. However, it has only been tested to 80 degrees C to date.

The temperature at approximately 5,000 feet in the MWX-2 Well registered 66 degrees C on a "Templabel".

Unless otherwise specifically stated to the contrary, "the depth" means the distance from the top of the cased well to the position of Electrode D of the TCRT.

The pertinent distances between electrodes are given as follows:

- Distance from Electrode A to Electrode C: 60 5/8 inches
- Distance from Electrode C to Electrode D: 19 13/16 inches
- Distance from Electrode D to Electrode E: 19 13/16 inches
- Distance from Electrode E to Electrode J: 19 13/16 inches
- Distance from Electrode J to Electrode F: 59 9/16 inches

PML's Second TCRT used in the MWX-2 Well is approximately 80.35 feet long. The distance from the top of the rubber bushing protruding from the cable head to the make-up slot of Bowspring Centralizer #1 is 2.93 feet. The distance from the make-up slot of Bowspring Centralizer #1 to Electrode D of the TCRT is 24.82 feet. The distance from Electrode D to the make-up slot of the Lower Pressure Housing is 28.33 feet. The distance from the make-up slot of the Lower Pressure Housing to the Bull Plug is 24.27 feet. The sum of all of these distances is 80.35 feet.

The weight hanging in air of PML's Second TCRT used in the MWX-2 Well is approximately 1800 lbs according to a 3047 Weight Indicator manufactured by Western Atlas Logging Services. PML wishes to express its gratitude to Western Atlas Logging Services for providing that weight indicator to PML for the work at the MWX-2 Well. As a further check on the weight of the tool, the tool weighed approximately 1900 lbs according to an old hydraulic Martin Decker gage in the cab of PML's Mack Logging Truck.

Each individual Sinker Bar is 30.4 inches long; weighs approximately 133 lbs; is 4.25 inches O.D.; and is made from ferromagnetic 41L42 material. Sinker Bars #1, #2, #3, #4 and #5 have a total weight of about 665 lbs and a combined length of 12.67 feet.

Figure 5 shows the "Electrode Locations at MWX-2 Wellsite, Rifle, Colorado". The distances shown there are in feet.

Several other wells are located in the area that are called the MWX-1, MWX-3, and SHCT-1 Wells. The relative orientations of those wells to the MWX-2 Well are shown in Figure 5.

The legal description of the MWX-2 Well is as follows that is quoted from the metal sign attached to the well:

CER CORPORATION
MWX #2 RULISON FIELD
SEC. 34 T6S R.94W
GARFIELD COUNTY, COLO.
701' FWL 2134' FNL
ELEV. 5351' G.L.

Figures 1 and 2 define the meanings of Electrodes B and G in the following.

Electrode B was most often attached to the "Culvert" that was located approximately 1475 feet from the MWX-2 Well. Electrode B is the "current return electrode" used during the Measurement State.

Electrode G is designated as the Potential Voltage Reference Electrode. We had two each different such electrodes at the MWX-2 Well. As shown in Figure 5, the "Near Reference Plate" was located about 336 feet from the MWX-2 Well and the "Far Reference Plate" was located about 667 feet away from the MWX-2 Well.

Each Potential Voltage Reference Electrode was fabricated from one each 6 foot wide, 19 foot long, 1/4 inch thick completely rusty scrap metal plates that happened to have groves stamped in them. Approximately 10 each "V" groves were stamped perpendicular to the long side of each plate. Each "V" grove was about 2 inches wide and 1.5 inches deep. There was no particular reason for the "V" groves, they simply came with the scrap steel plates located in a local junk yard. Two each steel rods having an O.D. of 5/8 inches were welded to each of the rusty steel plates for later electrical contact with wires at the surface. A pit about 48 inches deep was bulldozed. About 100 pounds of rock salt was mixed in mud about 12 inches deep in the bottom of the pit that was allowed to cure for 24 hours. The rusty steel plate was then lower into the pit. Thereafter, about 100 pounds of rock salt was mixed with in mud, and the plate was covered with this mixture to 18 inches above the plate. That mix was allowed to cure for 24 hours. Another 100 pounds of rock salt was thrown on top of the cured mixture which was then covered with a plastic sheet on the top so as to prevent salt from leaching into the grass above the plate. The pit was then back-filled with clean soil to the surface. The pit was watered frequently and allowed to cure for about 30 days before use for measurements. These detailed facts are reported for the record, and such large plates are not necessary.

Various experiments were performed involving many different positions of the electrodes in relation to Figure 5 for the purposes of determining tool design parameters. However, those

results are reported in various proprietary documents that have been forwarded to PML's Licensees. It is worth while stating here that those experiments proved that it was not necessary to use the large Potential Voltage Reference Plates described above and that nearby well heads and other structures can be used as the Potential Voltage Reference Electrodes and those experiments are described in further detail in various proprietary documents that have been forwarded to PML's Licensees. The above details are only reported herein to provide a complete record of what was actually done at the MWX-2 Well.

For the remaining purposes in Section II-B, Electrode B was always attached to the Culvert and Electrode G was attached to one of the two Potential Voltage Reference Plates.

Figure 6 presents the "MWX-2 Wellbore, Rifle, Colorado". The depths used in Figure 6 are measured from the top of the cased well. The types of casing used and their location are specified in Figure 6.

The frequency of operation chosen and the reasons for doing so at the MWX-2 Well are summarized in various proprietary documents that have been forwarded to PML's Licensees. It is sufficient to state here that the procedure described in Section II-A in "5. Distinguishing Apparent Resistivity from Other A.C. Effects" was used to double check the validity of the data obtained from the MWX-2 Well. The data presented herein corresponds to a frequency between f_3 and f_5 shown in Figure 11 of U.S. Patent No. 4,882,542 (Vail, 1989b).

The Calibration Constant K used at the MWX-2 Well was obtained as follows:

K used for data herein =

(K used in Fort Worth) x

{(new electrode spacing)/(Fort Worth electrode spacing)}

K used for data herein = 1.407 meters

x (19 13/16 inches / 57 inches)

K used for data herein = .489 meters

Equation 18.

(Note: An electrode spacing of 56 7/8 inches is reported in Vail, et. al. (1993b) for the electrode spacing used in Fort Worth. This separation would make K equal to .490 meters instead. No attempt was made to correct for this very minor change.)

It should be noted here that no correction was made in the above Calibration Constant K for the different sized casings. The casing at Fort Worth was 8 5/8 inches O.D. The casing at the MWX-2 Well in Rifle, Colorado and at PML's Test Well in Woodinville, Washington was 7 inches O.D. Since the electrode spacing affects K more dramatically than the O.D. of the casing, the above choice for K is the crudest first order choice available to the authors. For simplicity, the authors chose to use this value of $K = .489$ meters for the experimental plots which follow.

1. Zone 2, Pass 1

Figures 7 through 25 describe data obtained from Zone 2 ("Z2"), Pass 1 ("P1") of the MWX-2 Well. Zone 2, Pass 1 was a blind test of the technology. GRI and Western Atlas Logging Services withheld the open-hole logs from PML until all data had been acquired from Pass 1 (and Pass 2) in Zone 2.

Unless stated otherwise herein, the top of the casing was energized for these measurements. While energizing the top of the casing, and with reference to Figure 1, Switch SW1 is connected to Electrode B in the Measurement State, and the other output from the "Power Amplifier" is connected to the top of the casing (instead of to Electrode A of the TCRT). Measurements were also performed using Electrode A of the TCRT and those measurements appear later.

Comments: It should be noted that current can be used to energize the top of the casing during the Measurement State, provided that the TCRT is otherwise used as shown in Figures 1 and 2 in the Calibration State. This fact has been verified at the MWX-2 Well in Rifle, Colorado, at PML's Test Well in Woodinville, Washington, and in the Research Well in Fort Worth, Texas.

Figure 7 shows the Apparent Resistivity vs. Depth for Zone 2, Pass 1. The results from PML's Second TCRT are shown with the boxes. The diamond shapes show the locations of the collars determined from other measurements as described later. Here depth means the "Depth from the Top of the Casing" in feet. That depth is the distance from the top of the casing to Electrode D. Also plotted are the ILD002 and ILM002 open-hole Schlumberger logs.

Mr. Harvey Haines of GRI reviewed these open-hole Schlumberger logs. As a result of that review, he provided the following quote for this report:

"Two Induction log runs were recorded in the well over the interval of concern, run 3 on February 29, 1982 and run 4 on March 5, 1982. Both runs used a Schlumberger Dual Induction Spherically Focused Log. The MWX#2 was drilled with oil based mud resulting in a meaningless focused log and as result the focused log was not recorded. Only deep and medium induction logs were recorded. The March 5 induction log was apparently recorded with an incorrect sonde error and was corrected at a later date. The induction data included in this report are from the February 29 induction log, which is the log recommended by the operator of the well, the CER Corporation."

It is clear that the Apparent Resistivity obtained with PML's Second TCRT agrees substantially with the open-hole logs obtained before the casing was set. It is also clear that the vertical resolution of PML's Second TCRT is much better than the vertical resolution of the ILM or of the ILD.

Figure 8 plots % Down of IT vs. Depth in Zone 2, Pass 1. The % Down of IT is the percentage of the total current IT conducted to the casing in the Measurement State that is flowing downward between Electrodes C and D. It is defined in Part 7 of Section II-A. For example, at 4900 feet deep, there was approximately 27% of the total current IT conducted to the top of the casing that was flowing downward between Electrodes C and D during Pass 1 of Zone 2.

Figure 9 plots V1-V2 vs. Depth in Zone 2, Pass 1. The quantity V1-V2 is defined in Part 7 of Section II-A. Put another way, it is the difference in voltage at the surface in the Measurement State between the voltage output of Electrode Pair C-D and the voltage output of Electrode Pair D-E. It is evident that the collars can be located from this data by inspection.

Figure 10 plots V1-V2 vs. Depth in Zone 2, Pass 1, on an expanded scale to see detail in the range from approximately 4,800 to 4,830 feet. It is worthwhile to notice that there is no obvious correlation between this quantity in this depth range and with the Apparent Resistivity in Figure 7 over the same depth range.

Figure 11 plots (V3-V4)* vs. Depth in Zone 2, Pass 1. The quantity (V3-V4)* is defined in Part 7 of Section II-A. Put another way, it is the difference at the surface in the Calibration State between the voltage output of Electrode Pair C-D and the voltage output of Electrode Pair D-E. It is evident that the collars can be located from this data by inspection.

Figure 12 plots (V3-V4)* vs. Depth in Zone 2, Pass 1 on an expanded scale to see detail in the range from approximately

4,800 to 4,830 feet. It is worthwhile to notice again that there is no obvious correlation between this quantity in this depth range and with the Apparent Resistivity in Figure 7 over the same depth range.

Comments: Figures 7, 10, and 12 prove one central point. The lack of correlation between the quantities measured in Figures 10 and 12 with the corresponding Apparent Resistivity in Figure 7 shows that the Equation 28 used to calculate the current leakage in U.S. Patent No. 5,075,626 (Vail, 1991c) really works astoundingly well. The reason that we generated Figures 10 and 12 is to graphically demonstrate this point. The reason that the Apparent Resistivity is not evident from Figures 10 and 12 is because of the existence of First and Second Order Errors of measurement defined in Equation 14 of U.S. Patent No. 5,075,626 (Vail, 1991c) that are typically larger than the quantity of interest. The quantity V_1-V_2 defined herein is given by Equation 9 in that patent (and said quantity is named V_M in the patent). The quantity $(V_3-V_4)^*$ defined herein is given by Equation 4 of that patent (and said quantity is named V_N in that patent). The final point here is that U.S. Patent No. 5,075,626 (Vail, 1991c) presents methods of correcting for First and Second Order Errors of measurement and the theory set forth in that patent works in practice to accomplish that objective. The authors wish to note the quote in Tabarovsky, et. al. (1994) that states: "The calibration technique proposed in the literature (Vail, 1991) works well, although it does not completely eliminate the effects of casing inhomogeneities like collars, perforations, and corrosion." The authors believe that Figures 7, 10, and 12 herein show why PML's calibration (or compensation) technique "works well".

Figure 13 presents the quantity V_1 / IT vs. Depth for Zone 2, Pass 1. That quantity is defined in Part 7 of Section II-A. It is related to the resistance per unit length of the casing, IT , and tends to mimic R_1 in typical situations.

Figure 14 presents the resistance of the casing R_1 vs. Depth for Zone 2, Pass 1. The TCRT obviously locates the collars directly from measurements of R_1 . The positions of the collars are denoted therein and were located from discontinuities in the resistance of the casing. Please notice that there was a change in casing weight at about 4838 feet. Nobody knew there was different weight casing in this string.

Comments: At approximately 4838 feet in Figure 14, the weight change in the casing did not produce unreasonable effects in the measurement of the Apparent Resistivity at the same depth in Figure 7. The authors wish to draw the conclusion that the methods to eliminate First and Second Order Errors of measurement in U.S. Patent No. 5,075,626 (Vail, 1991c) really do work well in practice. It is evident that the TCRT in general provides high

resolution casing inspection data that can be used for at least the following purposes: (a) locating collars; (b) locating different weight casings in the casing string; (c) measuring the amount of casing remaining between Electrodes C-D in the presence of casing corrosion.

Figure 15 presents a plot of ΔI vs. Depth for Zone 2, Pass 1. As in all work done at the MWX-2 Well, the quantity ΔI is computed from Equation 1 of Part 1 of Section II-A.

Figure 16 presents a plot of Q (Volts/Amp) vs. Depth for Zone 2, Pass 1. The quantity Q is defined in Part 7 of Section II-A. Other details concerning the measurement of Q are presented in various proprietary documents that have been forwarded to PML's Licensees.

Figure 17 presents a plot of the Potential Voltage V_o vs. Depth for Zone 2, Pass 1. The small discontinuities observed at 4,807 feet and 4,868 feet are related to unknown errors of measurement done on different days.

Figure 18 presents a plot of the quantity R_c vs. Depth for Zone 2, Pass 1. The quantity R_c is given by Equation 2 in Section II-A.

Figure 19 presents a 3 Point Moving Average of the Apparent Resistivity measured with PML's Second TCRT vs. Depth in Zone 2, Pass 1.

Comments: It appears that $K = 0.489$ meters is too large if the Apparent Resistivity is to overlap the ILD002 or the ILM002.

Figure 20 presents a 5 Point Moving Average of the Apparent Resistivity measured with PML's Second TCRT in Zone 2, Pass 1.

Comments: It again appears that $K = 0.489$ meters is too large if the Apparent Resistivity is to overlap the ILD002 or the ILM002.

Figure 21 presents R_1 vs. Depth for Zone 2, Pass 1. The actual measurements are shown as boxes in Figure 21. The heavy solid line connects the boxes together on the basis of a straight line between adjacent points. We shall call that the "First Model for R_1 ".

Comments: That First Model for R_1 can be used to calculate other observables to test the theory of operation of the tool.

Figure 22 presents $(V_3 - V_4) \cdot$ vs. Depth for Zone 2, Pass 1. The actual measurements are shown as boxes in Figure 22. The heavy solid line however is from the Model Calculation using the First Model for R_1 . The First Model for R_1 was used to calculate

$(V3-V4)^*$ from Equation 4 in U.S. Patent No. 5,075,626 (Vail, 1991c). There is obviously good agreement between the model calculation and the data.

Figure 23 presents $(V3-V4)^*$ vs. Depth for Zone 2, Pass 1 on an expanded scale in the depth range from about 4,800 feet to 4,830 feet. The actual measurements are shown as boxes in Figure 23. The heavy solid line however is from the Model Calculation using the First Model for R1. The First Model for R1 was used to calculate $(V3-V4)^*$ from Equation 4 in U.S. Patent No. 5,075,626 (Vail, 1991c). There is obviously good agreement between the model calculation and the data even on this expanded scale.

Comments: Because there is good agreement between the data and the above model calculation, we know that Equation 4 in U.S. Patent 5,075,626 (Vail, 1991c) is valid. That patent states that variations in the casing resistance and variations in separations of electrode spacings will give variations in R1 and R2 which when multiplied by the current flowing along the pipe will mask the signal due to current leakage. Put another way, "Term B" that is the First Order Error Term in Equation 14 of U.S. Patent 5,075,626 (Vail, 1991c) masks "Term A" that has the current leakage information in it. It should be noted that the quantity $(V3-V4)^*$ defined herein is equal to the quantity V_N defined in Equation 4 of the patent. The current I_N shown in Equation 4 in that patent was obtained from the data at the MWX-2 Well. Here, approximately three amps 0-peak were passed along the casing in the Calibration Step as was typically the case at the MWX-2 Well. It is further evident from these results that the quantity $(V3-V4)^*$ can be used to locate the collars using at least one of the following different signatures: (a) where it first crosses zero provided that there is a strong maximum of one sign on one side of the zero and a strong maximum of the opposite sign on the other side of the zero; (b) 1/2 way between two strong maxima of opposite signs; or (c) just "large excursions" in $(V3-V4)^*$. It should be stated that the effect from the collars on the quantities $V1-V2$ or $(V3-V4)^*$ produce antisymmetric excursions about the center of the collar. (Here antisymmetric, means one sign of voltage on one side of the center line of the collar and the opposite sign of voltage on the other side of the center line of the collar. Symmetric would mean having the same sign on either side of the center line of the collar.) It should also be stated that the antisymmetric shape of the discontinuities in $V1-V2$ and $(V3-V4)^*$ used by PML to identify collars are not related to the shape of the discontinuities in current leakage at the collars as shown in Figure 9 in Tabarovsky, et. al. (1994). Those discontinuities in leakage current near collars predicted by Tabarovsky, et. al. (1994) appear to be symmetric in shape about the center of the collar.

Figure 24 presents R1 vs. Depth for Zone 2, Pass 1. The actual measurements are shown as boxes in Figure 24. Mr. Steven

T. Momii constructed the "Second Model for R1" that is the solid line on Figure 24.

Figure 25 presents $(V3-V4)^*$ vs. Depth for Zone 2, Pass 1. The actual measurements are shown as boxes in Figure 25. The heavy solid line however is from the Second Model Calculation using the Second Model for R1. The Second Model for R1 was used to calculate $(V3-V4)^*$ from Equation 4 in U.S. Patent No. 5,075,626 (Vail, 1991c). There is obviously reasonable agreement between the model calculation and the data keeping in mind the assumptions made.

Comments: The First Model Calculation shown in Figures 21, 22 and 23 provide better results than the Second Model Calculation because the First Model for R1 is much better than the approximate Second Model for R1.

2. Zone 2, Pass 2

Figures 26 through 37 describe data obtained from Zone 2 ("Z2"), Pass 2 ("P2") of the MWX-2 Well. Zone 2, Pass 2 was a blind test of the technology. It was the "repeat log" for Zone 2, Pass 1. GRI and Western Atlas Logging Services withheld the open-hole logs from PML until all data had been acquired from Pass 1 (and Pass 2) in Zone 2.

Figure 26 presents the Apparent Resistivity vs. Depth for Zone 2, Pass 2. The point reading 1,000 ohm-meters comes from one reading at 4881 feet where the leakage current ΔI becomes essentially zero (74 micro-amps 0-peak) and Rule C is applied.

Comments: This basically repeats the data from Figure 7. Much, but not all, of the fine structure in Figure 7 is reproduced in Figure 26.

Figure 27 presents the % Down of IT vs. Depth for Zone 2, Pass 2. It basically repeats the data from Figure 8.

Figure 28 presents $V1-V2$ vs. Depth for Zone 2, Pass 2. It basically repeats the data from Figure 9.

Figure 29 presents $(V3-V4)^*$ vs. Depth for Zone 2, Pass 2. It basically repeats the data from Figure 11. Comparing Figures 29 and Figure 11, there is good agreement.

Figure 30 presents $V1 / IT$ vs. Depth for Zone 2, Pass 2. It basically repeats the data from Figure 13.

Figure 31 presents R1 vs. Depth for Zone 2, Pass 2. It basically repeats the data from Figure 14.

Comments: From visual comparison of Figures 14 and 31, it appears as though R_1 repeats absolutely to $(+/-)$ (0.2) micro-ohms. This means that measurements of R_1 absolutely repeat from one run to another to an absolute accuracy of $(+/-)$ 1%. Such accuracy is adequate for many casing inspection applications.

Figure 32 presents the current leakage ΔI vs. Depth for Zone 2, Pass 2. It basically repeats the data from Figure 15.

Figure 33 presents Q vs. Depth for Zone 2, pass 2. It basically repeats the data from Figure 16.

Figure 34 presents the Potential Voltage V_o vs. Depth for Zone 2, Pass 2. Please note the discontinuities at 4818 and 4860 feet. These discontinuities are related to unknown errors related to measurements done on different days.

Figure 35 presents R_c vs. Depth for Zone 2, Pass 2. The scale in Figure 35 is dramatically different than that used in Figure 18 because of the large value of R_c at 4881 feet.

Figure 36 presents a 3 Point Moving Average of the Apparent Resistivity measured with PML's Second TCRT vs. Depth in Zone 2, Pass 2.

Comments: With the exception of the large excursion at about 4882 feet in Figure 36, the 3 Point Moving Averages in Figures 36 and 19 agree reasonably well. However, it appears that the value of $K = 0.489$ meters is too large if the Apparent Resistivity is to overlap the ILD002 or the ILM002 in those two figures.

Figure 37 presents a 5 Point Moving Average of the Apparent Resistivity measured with PML's Second TCRT in Zone 2, Pass 2.

Comments: With the exception of the large excursion at about 4882 feet in Figure 37, the 5 Point Moving Averages in Figures 37 and 20 agree reasonably well. However, it appears that the value of $K = 0.489$ meters is too large if the Apparent Resistivity is to overlap the ILD002 or the ILM002 in those two figures.

3. Zone X, Pass 2, 4,708 feet to 4,616 feet Energizing Top of the Casing

Mr. John F. Gould, Jr., Petrophysical Advisor, Mobil Exploration & Producing U.S., Inc., participated in the data acquisition process for this data. The data in this section was acquired while energizing the top of the casing during the Measurement State.

Figure 38 presents the Apparent Resistivity vs. Depth in Zone X, Pass 2.

Comments: There is much general agreement between the Apparent Resistivity and the open-hole logs. However, PML's Second TCRT has much better vertical resolution than shown in the ILM002 and ILD002. Please notice that the perforations present at the depth interval of 4692 to 4694 feet did not cause any major problems - either in interpretation of the data or mechanically with the tool.

Figure 39 presents the % Down of IT vs. Depth in Zone X, Pass 2.

Figure 40 presents V1-V2 vs. Depth in Zone X, Pass 2.

Figure 41 presents (V3-V4)* vs. Depth in Zone X, Pass 2.

Figure 42 presents V1 / IT vs. Depth in Zone X, Pass 2.

Figure 43 presents R1 vs. Depth in Zone X, Pass 2.

Figure 44 presents ΔI vs. Depth in Zone X, Pass 2.

Figure 45 presents Q vs. Depth in Zone X, Pass 2.

Figure 46 presents V_o vs. Depth in Zone X, Pass 2.

Figure 47 presents R_c vs. Depth in Zone X, Pass 2.

Figure 48 presents the 3 Point Moving Average of the Apparent Resistivity vs. Depth in Zone X, Pass 2.

Figure 49 presents the 5 Point Moving Average of the Apparent Resistivity vs. Depth in Zone X, Pass 2.

4. Zone X, Pass 1, 4,618 feet to 4,570 feet Energizing Top of the Casing

There is only a short run of about 50 feet over Zone X, Pass 1. Here, the top of the casing was energized during the Measurement State. That is the meaning of "A:Top of Casing" on each of the figures herein. The purpose of this short run was to compare to Pass 2 over this section where Electrode A of the tool would be energized.

Figure 50 presents the Apparent Resistivity vs. Depth for Zone X, Pass 1.

Figure 51 presents the % Down of IT vs. Depth for Zone X, Pass 1.

Figure 52 presents V1-V2 vs. Depth for Zone X, Pass 1.

Figure 53 presents (V3-V4)* vs. Depth for Zone X, Pass 1.

Figure 54 presents V_I / I_T vs. Depth for Zone X, Pass 1.

Figure 55 presents R_I vs. Depth for Zone X, Pass 1.

Figure 56 presents ΔI vs. Depth for Zone X, Pass 1.

Figure 57 presents Q vs. Depth for Zone X, Pass 1.

Figure 58 presents V_O vs. Depth for Zone X, Pass 1.

Figure 59 presents R_C vs. Depth for Zone X, Pass 1.

Figure 60 presents the 3 Point Moving Average of the Apparent Resistivity vs. Depth for Zone X, Pass 1.

Figure 61 presents the 5 Point Moving Average of the Apparent Resistivity vs. Depth for Zone X, Pass 1.

Comments: Figures 50, 60, and 61 suggest that the Calibration Constant K chosen to be $K = 0.489$ meters is providing reasonable agreement with the open-hole logs.

5. Zone X, Pass 2, 4,616 feet to 4,565 feet Energizing Electrode A of TCRT

Here, the TCRT was operated in the more typical fashion where Electrode A of the TCRT was energized during the Measurement State. The data here are to be compared to that in Part 4 above where the top of the casing was energized during the Measurement State. Mr. John F. Gould, Jr., Petrophysical Advisor, Mobil Exploration & Producing U.S., Inc., participated in the data acquisition.

Figure 62 presents the Apparent Resistivity vs. Depth for Zone X, Pass 2.

Comments: The data in Figure 50 is very similar to that in Figure 62 with one major exception. That exception concerns the relative constant open-hole resistivity between 4,600 feet to 4,612 feet. The Apparent Resistivity in Figure 50 provides substantial agreement with that constant open-hole portion of the log. However, the Apparent Resistivity in Figure 62 is providing readings below that constant section.

Figure 63 presents the % Down of I_T vs. Depth for Zone X, Pass 2.

Comments: Figure 63 shows the % Down of I_T being equal to between 49.4 to 49.6%. Of the current introduced on the casing by Electrode A, about 1/2 the current is going up the casing and

about 1/2 is going down the casing. This makes sense because at this depth Electrode A is near the mid-point of the casing. However, Figure 51 shows a decreasing fraction of the current remaining on the casing with increasing depth which makes sense if the top of the casing is energized.

Figure 64 presents V_1-V_2 vs. Depth for Zone X, Pass 2.

Figure 65 presents $(V_3-V_4)^*$ vs. Depth for Zone X, Pass 2.

Comments: Figure 65 basically repeats Figure 53 because the measurements have been done exactly the same on successive passes over the well. The Calibration States are the same for both figures.

Figure 66 presents V_1 / I_T vs. Depth for Zone X, Pass 2.

Comments: Figure 66 is different than Figure 54 because the currents flowing on the casing are significantly different in the two cases.

Figure 67 presents R_1 vs. Depth for Zone X, Pass 2.

Comments: Figure 67 repeats Figure 55 because the resistance of the casing is being measured on two successive passes.

Figure 68 presents ΔI vs. Depth for Zone X, Pass 2.

Comments: Figure 68 is different than Figure 56 because the Potential Voltage V_0 is different and the currents flowing on the casing are different in the two cases.

Figure 69 presents Q vs. Depth for Zone X, Pass 2.

Comments: Q in Figure 69 is different than Q in Figure 57 because the Potential Voltages resulting from driving Electrode A and driving the top of the casing are different.

Figure 70 presents the Potential Voltage V_0 vs. Depth for Zone X, Pass 2.

Comments: The Potential Voltage V_0 in Figure 70 and Figure 58 are different because the Potential Voltages resulting from driving Electrode A and driving the top of the casing are different.

Figure 71 presents R_c vs. Depth for Zone X, Pass 2.

Figure 72 presents the 3 Point Moving Average of the Apparent Resistivity vs. Depth for Zone X, Pass 2.

Figure 73 presents the 5 Point Moving Average of the Apparent Resistivity vs. Depth for Zone X, Pass 2.

Comments: The moving averages appear to give better agreement with the open-hole logs than provided in Figure 62. The 5 Point Moving Average at 4605 feet gives about 60 ohm-meters from Figure 73. However, the ILD002 in this same region is about 70 ohm-meters. This data suggests that the Calibration Constant K should be increased for this data by about 16% if the Apparent Resistivity is to agree with the ILD002. Part 2 of Section VIII-C in fact predicts from first principles theory that the Calibration Constant K at the MWX-2 Well should have been chosen to be 13% larger than the value of 0.489 meters (ie, it should have been $K(\text{THEORY}) = .553$ meters). It is not known whether this result is fortuitous or not. It is known that the theory set forth in Section VIII-C would be most applicable to energizing Electrode A rather than energizing the top of the casing because of the surface effects and the relatively larger remnant A.C. effects when energizing the top of the casing. The theory set forth in Section VIII-C to calculate the Calibration Constant K does not take into account any surface effects or the influence of remnant A.C. effects.

6. Zone 1, Pass 1

Zone 1, Pass 1 was logged while energizing the top of the casing in the Measurement State. Historically, this was the first data acquired at the MWX-2 Well that bore a resemblance to the open-hole resistivity. However, we had not learned at that time that having sharp electrodes was crucial to obtain highly reproducible data. In fact, at that time, the electrodes on this tool had been used to log much of the PML's Test Well in Woodinville, Washington. Perhaps those electrodes were used to log up to 300 feet of PML's Test Well. These same electrodes had been used to log another 200 to 300 feet of the MWX-2 Well before this logging run. Therefore, these figures are labeled with "Dull Electrodes". The electrodes were not changed before this particular logging run.

Figure 74 presents the Apparent Resistivity vs. Depth for Zone 1, Pass 1.

Figure 75 presents the 3 Point Moving Average of the Apparent Resistivity vs. Depth for Zone 1, Pass 1.

Figure 76 presents the 5 Point Moving Average of the Apparent Resistivity vs. Depth for Zone 1, Pass 1.

Figure 77 presents R1 vs. Depth for Zone 1, Pass 1.

Comments: Please notice the peculiar "sloping" to the curves when compared to other plots of R1. We do not know if poor electrical contact is responsible for this behavior.

Figure 78 presents Q vs. Depth for Zone 1, Pass 1.

7. Zone 1, Pass 2

The electrodes were not changed after Pass 1 above.

Figure 79 presents the Apparent Resistivity vs. Depth for Zone 1, Pass 2.

Comments: Please notice that the data here is much "spikier" in appearance than that in Figure 74. It is surmised that this is due to the fact that the electrodes are duller for Pass 2 than for Pass 1.

Figure 80 presents the 3 Point Moving Average of the Apparent Resistivity vs. Depth for Zone 1, Pass 2.

Figure 81 presents the 5 Point Moving Average of the Apparent Resistivity vs. Depth for Zone 1, Pass 2.

Figure 82 presents R1 vs. Depth for Zone 1, Pass 2.

Comments: Please notice that R1 in Figure 82 substantially repeats R1 from Figure 77. The peculiar "sloping" to the curves described in Figure 77 is repeated in Figure 82.

Figure 83 presents Q vs. Depth for Zone 1, Pass 2.

8. Comparison with Inverted ILD

Dr. James D. Klein from ARCO Exploration and Production Technology, Plano, Texas provided inverted ILD logs in his June 1, 1994 letter. The authors wish to express their sincere appreciation to Dr. Klein for these logs.

The first paragraph from that letter is quoted herein for reference: "I have inverted the ILD logs from the MWX#2 in order to improve the resolution of the thin beds. The software that I used is named ILMEM, and is based on maximizing the entropy of the log. I thought that you might like to see the results, and compare to your logs."

Figures 84 through 88 compare our logs to the Inverted ILD.

Figure 84 is similar to Figure 7, except the Inverted ILD is also plotted.

Figure 85 is similar to Figure 26, except the Inverted ILD is also plotted.

Figure 86 is similar to Figure 38, except the Inverted ILD is also plotted.

Figure 87 is similar to Figure 50, except the Inverted ILD is also plotted.

Figure 88 is similar to Figure 62, except the Inverted ILD is also plotted.

The interested reader having questions concerning the Inverted ILD is encouraged to call Dr. James D. Klein, Arco Exploration and Production Technology in Plano, Texas.

9. Log for MWX-2 Well

A typical looking paper "Log" for Zone 2 and Zone X has been prepared by Mr. Steven T. Momii using LISTOOLS, a program purchased by PML from III Oaks Software. A copy of this Log is available from PML upon request. On the 4 cycle resistivity trace, "ILM", "ILD", "TCRT", and "REP1" are shown.

"ILM" is the open-hole ILM002 data provided by Schlumberger.

"ILD" is the open-hole ILD002 data provided by Schlumberger.

"TCRT" is the first logging run in a given zone from the Through Casing Resistivity Tool. "REP1" is the first repeat of the data from the Through Casing Resistivity Tool in the zone.

The lower trace of the Log shows typical natural gamma-ray data identified by "GR". The Casing Resistance R1 during the first logging run in a given zone is shown in the lower trace as "CR1". The repeat measurements of Casing Resistance R1 in the zone is labeled in the lower trace as "CR2".

PML is now capable of providing such a paper "Log" at the wellsite during future operations.

FIGURE 4
TCRT For MWX-2 Well
ParaMagnetic Logging, Inc.

7/4/94

FIGURE 5
ELECTRODE LOCATIONS
AT MWX-2 WELLSITE
RIFLE, COLOARDO

FIGURE 6
MWX-2 WELLBORE
RIFLE, COLORADO

**ZONE 2, PASS 1
FIGURES 7 - 25
MWX-2 WELL
RIFLE, COLORADO**

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure 7; Rule C; Sharp Electrodes
Printed Out 7/4/94; K = 0.489 meters; Blind Test
Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure 8; Sharp Electrodes
Printed Out 7/4/94
Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure 9; Sharp Electrodes

Printed Out 7/4/94

Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure 10; Sharp Electrodes
Printed Out 7/4/94
Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure 11; Sharp Electrodes
Printed Out 7/4/94
Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure 12; Sharp Electrodes
Printed Out 7/4/94
Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure 13; Sharp Electrodes

Printed Out 7/4/94

Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure 14
Printed Out 7/4/94; Sharp Electrodes

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

□ TCRT Z2 P1 ◇ COLLAR

Figure 15; Sharp Electrodes
Printed Out 7/4/94
Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

+ TCRT Z2 P1 DC NEAR □ TCRT Z2 P1 DC FAR ○ TCRT Z2 P1 AC NEAR △ TCRT Z2 P1 AC FAR

Figure 16
Printed Out 7/4/94

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

□ TCRT Z2 P1 DC FAR + TCRT Z2 P1 DC NEAR △ TCRT Z2 P1 AC FAR ○ TCRT Z2 P1 AC NEAR ◇ COLLAR

Figure 17; Sharp Electrodes

Printed Out 7/4/94

Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure 18; Rule C; Sharp Electrodes
Printed Out 7/4/94
Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

◇ COLLAR □ 3 pt Smooth TCRT Z2 P1 — ILD002 ··· ILM002

Figure 19; Rule C; Sharp Electrodes

K = 0.489 meters; Printed Out 7/4/94

Smoothing with 3 Point Moving Average; Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure 20; Rule C; Sharp Electrodes
K = 0.489 meters; Printed Out 7/4/94
Smoothing with 5 Point Moving Average; Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure 21; Sharp Electrodes
Printed Out 7/4/94

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure 22; Sharp Electrodes

Printed Out 7/4/94

Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
Paramagnetic Logging, Inc.

Figure 23; Sharp Electrodes
Printed Out 7/4/94
Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure 24; Sharp Electrodes
Printed Out 7/4/94

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure 25; Sharp Electrodes
Printed Out 7/4/94

**ZONE 2, PASS 2
FIGURES 26 - 37
MWX-2 WELL
RIFLE, COLORADO**

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure 26; Rule C; Sharp Electrodes
Printed Out 7/4/94; K = 0.489 meters; Blind Test
Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure 27; Sharp Electrodes
Printed Out 7/4/94
Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure 28; Sharp Electrodes
Printed Out 7/4/94
Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure 29; Sharp Electrodes
Printed Out 7/4/94
Open Hole Log: 28.16 feet subtracted from depth

Figure 30: Sharp Electrodes
Printed Out 7/4/94
Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure 31; Sharp Electrodes
Printed Out 7/4/94

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure 32; Sharp Electrodes
Printed Out 7/4/94
Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

+ TCRT Z2 P2 DC NEAR □ TCRT Z2 P2 DC FAR

Figure 33

Printed Out 7/4/94

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

□ TCRT Z2 P2 DC FAR + TCRT Z2 P2 DC NEAR ◇ COLLAR

Figure 34; Sharp Electrodes

Printed Out 7/4/94

Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure 35; Rule C; Sharp Electrodes
Printed Out 7/4/94
Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure 36; Rule C; Sharp Electrodes
K = 0.489 meters; Printed Out 7/4/94
Smoothing with 3 Point Moving Average; Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure 37; Rule C; Sharp Electrodes

K = 0.489 meters; Printed Out 7/4/94

Smoothing with 5 Point Moving Average; Open Hole Log: 28.16 feet subtracted from depth

**ZONE X, PASS 2
FIGURES 38 - 49
ENERGIZING TOP OF CASING
MWX-2 WELL
RIFLE, COLORADO**

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure 38; Rule C; Sharp Electrodes; NBL; A:Top of Casing
K = 0.489 meters; John Gould Participated in Data Acquisition; Printed Out 7/4/94
Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure 39; Sharp Electrodes; A: Top of Casing
Printed Out 7/4/94
Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure 40; Sharp Electrodes; A: Top of Casing
Printed Out 7/4/94
Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure 41; Sharp Electrodes; A: Top of Casing
Printed Out 7/4/94
Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
 ParaMagnetic Logging, Inc.

Figure 42; Sharp Electrodes; A: Top of Casing
 Printed Out 7/4/94
 Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure 43; Sharp Electrodes; A:Top of Casing
Printed Out 7/4/94
Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure 44; Sharp Electrodes; A:Top of Casing
Printed Out 7/4/94
Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure 45; Sharp Electrodes; A:Top of Casing
Printed Out 7/4/94
Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

□ TCRT ZX P2 DC FAR + TCRT ZX P2 DC NEAR △ TCRT ZX P2 AC FAR
○ TCRT ZX P2 AC NEAR ◇ COLLAR ■ PERFORATIONS

Figure 46; Sharp Electrodes; A:Top of Casing
Printed Out 7/4/94
Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure 47; Rule C; Sharp Electrodes; A:Top of Casing

Printed Out 7/4/94

Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure 48; Rule C; Sharp Electrodes; NBL; A:Top of Casing
K = 0.489 meters; Printed Out 7/4/94; John Gould Participated in Data Acquisition
Smoothing with 3 Point Moving Average; Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure 49; Rule C; Sharp Electrodes; NBL; A:Top of Casing

K = 0.489 meters; Printed Out 7/4/94; John Gould Participated in Data Acquisition

Smoothing with 5 Point Moving Average; Open Hole Log: 28.16 feet subtracted from depth

**ZONE X, PASS 1
FIGURES 50 - 61
ENERGIZING TOP OF CASING
MWX-2 WELL
RIFLE, COLORADO**

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure 50; Rule C; Sharp Electrodes; NBL; A:Top of Casing

K = 0.489 meters; Printed Out 7/4/94

Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure 51; Sharp Electrodes; A: Top of Casing
Printed Out 7/4/94
Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure 52; Sharp Electrodes; A:Top of Casing
Printed Out 7/4/94
Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure 53; Sharp Electrodes; A: Top of Casing
Printed Out 7/4/94
Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure 54; Sharp Electrodes; A: Top of Casing
Printed Out 7/4/94
Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure 55; Sharp Electrodes; A:Top of Casing
Printed Out 7/4/94
Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

□ TCRT ZX P1 ◇ COLLAR

Figure 56; Sharp Electrodes; A:Top of Casing
Printed Out 7/4/94
Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure 57; Sharp Electrodes; A: Top of Casing
Printed Out 7/4/94
Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure 58; Sharp Electrodes; A:Top of Casing
Printed Out 7/4/94
Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure 59; Rule C; Sharp Electrodes; A: Top of Casing
Printed Out 7/4/94
Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure 60; Rule C; Sharp Electrodes; NBL; A:Top of Casing

K = 0.489 meters; Printed Out 7/4/94

Smoothing with 3 Point Moving Average; Open Hole Log: 28.16 feet subtracted from depth

**ZONE X, PASS 2
FIGURES 62 - 73
ENERGIZING ELECTRODE A
MWX-2 WELL
RIFLE, COLORADO**

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure 62; Rule C; Sharp Electrodes; NBL; A:Electrode A
K = 0.489 meters; Printed Out 7/4/94; John Gould Participated in Data Acquisition
Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure 63; Sharp Electrodes; A:Electrode A
Printed Out 7/4/94
Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure 64; Sharp Electrodes; A: Electrode A
Printed Out 7/4/94
Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure 65; Sharp Electrodes; A:Electrode A
Printed Out 7/4/94
Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure 66; Sharp Electrodes; A:Electrode A
Printed Out 7/4/94
Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure 67; Sharp Electrodes; A:Electrode A
Printed Out 7/4/94
Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure 68; Sharp Electrodes; A:Electrode A
Printed Out 7/4/94
Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

□ TCRT ZX P2 DC FAR + TCRT ZX P2 DC NEAR ◇ COLLAR

Figure 69; Sharp Electrodes; A:Electrode A

Printed Out 7/4/94

Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

□ TCRT ZX P2 DC FAR + TCRT ZX P2 DC NEAR ◇ COLLAR

Figure 70; Sharp Electrodes; A:Electrode A

Printed Out 7/4/94

Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure 71; Rule C; Sharp Electrodes; A:Electrode A
Printed Out 7/4/94
Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure 72; Rule C; Sharp Electrodes; NBL; A:Electrode A
K = 0.489 meters; Printed Out 7/4/94; John Gould Participated in Data Acquisition
Smoothing with 3 Point Moving Average; Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
Paramagnetic Logging, Inc.

Figure 73; Rule C; Sharp Electrodes; NBL; A:Electrode A
K = 0.489 meters; Printed Out 7/4/94; John Gould Participated in Data Acquisition
Smoothing with 5 Point Moving Average; Open Hole Log: 28.16 feet subtracted from depth

ZONE 1, PASS 1
FIGURES 74 - 78
MWX-2 WELL
RIFLE, COLORADO

MWX-2, RIFLE, CO.
 ParaMagnetic Logging, Inc.

Figure 74; Rule C; Dull Electrodes
 K = 0.489 meters; Printed Out 7/4/94
 Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure 75; Rule C; Dull Electrodes
K = 0.489 meters; Printed Out 7/4/94
Smoothing with 3 Point Moving Average; Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

◇ COLLAR □ 5 pt Smooth TCRT Z1 P1 — ILD002 ··· ILM002

Figure 76; Rule C; Dull Electrodes

K = 0.489 meters; Printed Out 7/4/94

Smoothing with 5 Point Moving Average; Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure 77
Printed Out 7/4/94
Dull Electrodes

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure 78
Printed Out 7/4/94

**ZONE 1, PASS 2
FIGURES 79 - 83
MWX-2 WELL
RIFLE, COLORADO**

MWX-2, RIFLE, CO.
 ParaMagnetic Logging, Inc.

Figure 79; Rule C; Dull Electrodes
 K = 0.489 meters; Printed Out 7/4/94
 Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure 80; Rule C; Dull Electrodes
K = 0.489 meters; Printed Out 7/4/94
Smoothing with 3 Point Moving Average; Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure 81; Rule C; Dull Electrodes

K = 0.489 meters; Printed Out 7/4/94

Smoothing with 5 Point Moving Average; Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure 82
Printed Out 7/4/94
Dull Electrodes

MWX-2, RIFLE, CO.
 ParaMagnetic Logging, Inc.

+ TCRT Z1 P2 DC NEAR □ TCRT Z1 P2 DC FAR ○ TCRT Z1 P2 AC NEAR △ TCRT Z1 P2 AC FAR

**COMPARISON OF TCRT DATA
TO INVERTED ILD
FIGURES 84 - 88
MWX-2 WELL
RIFLE, COLORADO**

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure 84; Rule C; Sharp Electrodes
K = 0.489 meters; Blind Test; Printed Out 7/4/94
Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure 85; Rule C; Sharp Electrodes
K = 0.489 meters; Blind Test; Printed Out 7/4/94
Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure 86; Rule C; Sharp Electrodes; NBL; A:Top of Casing
K = 0.489 meters; John Gould Participated in Data Acquisition; Printed Out 7/4/94
Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure 87; Rule C; Sharp Electrodes; NBL; A:Top of Casing
K = 0.489 meters; Printed Out 7/4/94
Open Hole Log: 28.16 feet subtracted from depth

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure 88; Rule C; Sharp Electrodes; NBL; A:Electrode A
K = 0.489 meters; John Gould Participated in Data Acquisition; Printed Out 7/4/94
Open Hole Log: 28.16 feet subtracted from depth

SECTION II - C

RESULTS FROM PML'S TEST WELL

IN WOODINVILLE, WASHINGTON

PML's Test Well in Woodinville, Washington was drilled and logged specifically to calibrate PML's second generation apparatus version of the TCRT. The open-hole well was logged by Schlumberger Well Services. This well has 7 inch O.D. casing, 0.362 inch wall thickness, 26 pounds/foot, Type K-55 casing installed to a depth of 303 feet. Very short "casing nipples" were used having lengths of approximately 13 feet long for assembly under a low overhead clearance. No cement exists behind the casing over the particular interval logged by the TCRT.

Figure 89 shows representative data from PML's Test Well in Woodinville, Washington. The curves denoted by boxes show apparent resistivity measured with the TCRT at a frequency of operation of 1.25 Hz; diamonds show the position of the collars, with data deleted two feet on either side of the collars. The TCRT shows reasonably good agreement with the open-hole SFLU up to perhaps 200 ohm-meters. The TCRT also shows reasonable agreement with the open-hole LLS up to perhaps 100 ohm-meters. Evidently, the vertical resolution of the TCRT is similar to that of the SFLU.

Figure 90 shows representative data from the TCRT compared to the open-hole ILD. Obviously, the vertical resolution of the TCRT is superior to that of the ILD.

Figures 89 and 90 specifically reference "Method B". "Method B" is a method of operation of the TCRT that is similar to the method of operation shown in Figure 1 where amplifier A3 is physically located downhole within the pressure housing of TCRT. Another method of measurement, "Method C", was used to acquire data that looks very similar to that shown in Figures 89 and 90.

In Method C, amplifier A3, or its conceptual equivalent, is located on the surface of the earth. Therefore, similar experimental results were obtained using different downhole electronics and different algebraic analyses, further corroborating TCRT measurements and their interpretation.

Data from Method C in PML's Test Well has been provided to PML's Licensees in various proprietary documents. However, data from Method C is not shown here. Much additional data using Method B beyond the final apparent resistivity has also been provided to PML's Licensees in various proprietary documents.

PML'S TEST WELL, WOODINVILLE, WA.
ParaMagnetic Logging, Inc.

Figure 89
K = 0.489 meters
TCRT Data Deleted +/- 2 ft from Collars

PML'S TEST WELL, WOODINVILLE, WA.
ParaMagnetic Logging, Inc.

Figure 90
K = 0.489 meters
TCRT Data Deleted +/- 2 ft from Collars

SECTION II - D

EXPERIMENTS WITH MOVING TEST JIG AND THE TRIBOELECTRIC EFFECT

1. Historical Perspective

The initially co-sponsored work by GRI and DOE resulted in the design and fabrication of a first generation apparatus version of the TCRT based upon PML's patent disclosures. Henceforth, that first generation apparatus device may be called "PML's First TCRT" for brevity. The mechanical portions of that tool were designed with the help of personnel from then Gearhart Industries, Inc. of Fort Worth, Texas. Data was obtained from that First TCRT in the Research Well at Gearhart Industries, Inc. in Fort Worth. That work resulted in the publication of the paper entitled "Formation Resistivity Measurements Through Metal Casing" having the authors of W.B. Vail, S.T. Momii, R. Woodhouse, M. Alberty and R.C.A. Peveraro, and J.D. Klein that was presented at the 34th Annual Logging Symposium of the SPWLA, June 13-16, 1993 (Vail, et. al., 1993b). While those measurements proved that formation resistivity from within cased wells could be measured in-principle, that First PML TCRT had relatively poor vertical resolution and took about an hour to take data at each point.

It was subsequently decided that it was necessary to investigate how to design a tool having better vertical resolution and which was capable of rapidly acquiring data. It was originally theorized that a moving tool which continuously moved vertically upward in the well could be designed and fabricated based upon the use of standard wirelines and sophisticated signal processing techniques. PML then designed and built the Moving Test Jig to test those hypotheses in a laboratory prior to designing a new downhole device. However, the laboratory experiments performed with the Moving Test Jig showed that various effects including the Triboelectric Effect generated large noise signals that could mask the borehole casing signal from the TCRT. Those experiments showed that such noise would mask the borehole casing signal if standard 7 conductor wirelines were used that effectively limited the total amount of current that could be sent downhole (typically about 6 amps).

The purpose of this Section II-D is to briefly review these experiments involving the Triboelectric Effect and the development of new measurement techniques to overcome related effects.

As a result of these experiments, signal processing techniques were developed that are capable of acceptable data acquisition rates suitable for commercial logging. Those signal processing techniques were adopted for the final stage of this research effort. As a result, a second generation apparatus version of the TCRT was designed and built based upon acceptable signal processing techniques. Henceforth, that device may be called "PML's Second TCRT" for brevity. The mechanical portions of PML's Second TCRT provided for increased vertical resolution. Data was acquired with PML's Second TCRT at PML's Test Well in Woodinville, Washington during 1993. Data was then acquired with PML's Second TCRT at the MWX-2 Well in Rifle, Colorado during late 1993 and early 1994 under the circumstances of a "blind test".

2. Desirable Operational Specifications for the TCRT

Mr. Richard Woodhouse established the standards of accuracy to be achieved for a TCRT to be used in the Prudhoe Bay Oil Field. On the low resistivity end, the TCRT for use in Prudhoe Bay should measure 3 ohm-meters to an accuracy of plus/minus 1 ohm-meter. In the mid range of required resistivities, the TCRT for use in Prudhoe Bay should measure a 30 ohm-meter formation to an accuracy of plus/minus 5 ohm-meters. For work in Prudhoe Bay, measurements beyond 100 ohm-meters are not extremely important. These standards of accuracy have been referred to as the so-called "Woodhouse Specifications".

Further, in Prudhoe Bay itself, very slow logging speeds would result in limited use of the TCRT. However, it is desirable if the TCRT could operate at an average logging speed of about 2 feet per minute. General agreement was reached that a logging speed of 5 feet per minute would result in widespread standard commercial usage throughout the industry.

General agreement was also reached concerning the desirable vertical resolution. An electrode spacing from Electrode C-D (and D-E) of about 2 feet will result in a TCRT that will read the 100% correct resistivity over approximately the middle 1/3 portion of a 5 foot thick resistive bed buried in an otherwise less resistive half-space without any shoulder-bed corrections. It was generally agreed to that an electrode spacing from Electrode C-D (or D-E) of about two feet will result in a acceptable vertical resolution.

Any TCRT having the accuracy of the "Woodhouse Specifications", which also has an average logging speed of 2 feet per minute, and that also has an electrode spacing of about 2 feet and the corresponding vertical resolution, shall hereinafter be defined as a TCRT having "Acceptable Performance Specifications".

As an example, we spent considerable time and effort to determine a specific operational specifications desirable for a TCRT which could meet the detailed requirements found in the Prudhoe Bay Oil Field. These specific requirements are listed in Part 8 of this section that is entitled 'Anticipated Performance Specifications of the Prudhoe Bay Through Casing Resistivity Tool ("PBTCRT"), November 12, 1992'.

3. Moving Test Jig

The Moving Test Jig was originally designed and built to determine the experimental difficulties that would be involved with designing and building a continuously moving tool which would meet the commercially desirable specifications defined in Part 2 of this section. Please refer to Figure 91 that shows the Moving Test Jig and PML's Test Pipe. In the end, this system was used to test various different proposed measurement systems. Basically, measurement systems were tested to verify that the proposed system would perform measurements according to the above defined "Acceptable Performance Specifications".

The Test Pipe is a rusty piece of casing that is 20 feet long. The Test Pipe is 7 inch O.D. with 0.362 inch wall thickness. It is believed that the type casing is N-80.

The Moving Test Jig is pulled through the Test Pipe. The Moving Test Jig has rotating cutter electrodes which are spring-loaded against the inside of the rusty casing. The Moving Test Jig has front-end amplifiers mounted on the Moving Test Jig allowing measurement of the required voltage signals.

In Figure 91, please notice the resistor bank attached to the center of the Test Pipe. This is to simulate the presence of a relatively conducting formation in an otherwise insulating half-space. The resistor bank shown in Figure 91 has a particular configuration where all the resistors are connected. In general, and depending upon the experimental arrangement, one or more of the resistors can be disconnected and the currents flowing through the resistors can be modified to suit the desired experimental measurement situation.

Figure 92 shows results from a continuously moving Test Jig. The average speed for this data is approximately 1 foot per minute. At the position "0", 100 milliamps (zero-to-peak at 1 Hz) are actually injected on the casing. We measured that 100 milliamp amplitude injected current to an accuracy of plus/minus 11 milliamps. Figure 92 shows Runs 1 and 2 which were done at slightly different logging speeds.

Figure 92 shows that at one foot per minute, we can measure about 11 milliamps leaking from the casing. It turns out that level of

accuracy is acceptable to meet the first of the so-called Woodhouse Specifications, namely the ability to measure a 3 ohm-meter formation to an accuracy of plus/minus 1 ohm-meter.

However, the second Woodhouse Specification involving the measurement of a 30 ohm-meter formation to an accuracy of plus/minus 5 ohm-meters turns out to require the measurement of current leakage to an accuracy of about 1 milliamp 0-peak. Even at one foot per minute, the Moving Test Jig could not obtain data to that level of accuracy while continuously moving.

Figure 92 shows that if very large currents are conducted to the casing, then a continuously moving TCRT can be designed and built. However, for most 7 conductor wirelines presently in use, each typical wire can handle a little over 1 amp, so that with 6 such wires, about 6 amps can be routinely conducted to cased wells with standard industry wirelines now in existence. With such small currents, it would be very difficult and time consuming to do continuously moving measurements with the TCRT.

It is logical to question what gives raise to the relatively large noise observed when the TCRT moves. As an example, please refer to Figure 93. Here, 10 milliamps 0-peak are conducted along the casing. Before the time of 3 seconds, the Moving Test Jig is stationary in the Test Pipe. However, after the time of 3 seconds, the Moving Test Jig is pulled forward by a "stroke distance" that is typically between 8 to 10 inches. It takes some time for the transients to die out. Thereafter, the Moving Test Jig is stationary. We spent considerable time determining what causes the noise in Figure 93. The cause of that noise is the Triboelectric Effect.

4. Triboelectric Effect

A long series of experiments were completed involving the noise from moving electrodes of the Moving Test Jig which showed the following:

- a. The noise coming from continuously moving electrodes is not due to the details of the design of the front-end instrumentation amplifiers.
- b. The noise coming from continuously moving electrodes is not affected by the AC or DC coupling of the amplifiers.
- c. The noise coming from continuously moving electrodes is not related to the type of active devices used in the instrumentation amplifiers.
- d. The noise coming from continuously moving electrodes is not related to bias currents nor offset voltages which are intrinsic to all amplifiers including our front-end amplifiers.

- e. The noise coming from continuously moving electrodes is not related to the change in amplifier characteristics upon shorting the input.
- f. The noise coming from continuously moving electrodes is not due to any type of microphonic problem.
- g. The noise coming from continuously moving electrodes is not due to any magnetic pick-up problem.
- h. The noise coming from continuously moving electrodes is not due to any type of grounding interference.
- i. The noise coming from continuously moving electrodes at a given speed is dependent upon the pressure of electrode contact. For a given geometry of cutter electrode, too little pressure will not allow contact with the metal through the surface layer of rust. Increasing pressure allows continuous contact. Increasing the pressure beyond that point substantially increases the noise from the electrodes.
- j. The noise coming from continuously moving electrodes is dependent upon electrode geometry. That geometry involves both the number of "teeth" on the circumference and the "height" of each tooth. If the teeth are too numerous, no metal contact is made. If the teeth are too few, they do not roll and they can scratch the casing. Therefore, the geometry of our rolling cutter electrodes is one reasonable choice that will not damage the casing and which provides good electrical contact.
- k. The noise coming from continuously moving electrodes is dependent upon the speed. The faster the electrode speed, the greater the noise observed.
- l. The noise coming from the continuously moving electrodes is not coming from the rotation of the cutter electrodes in their respective metallic mounts. Wiring the cutters in place, thus preventing their rotation while dragging the apparatus, and other experiments with graphite lubricants, have conclusively shown that the noise is coming from the casing-teeth contact, not from the electrical contact of the cutter electrodes in their mounts of the Moving Test Jig. Different spring washers, and washers with different materials have also demonstrated that the noise is coming from the casing-teeth contact and not from the mounts.
- m. Annealed cutter electrodes resulted in less noise than hard, new, and sharp cutter electrodes at a given speed and given pressure. But such improvements are not sufficient to achieve the measurement accuracy required.

n. Using RC filters on the electrodes did not improve the noise coming from the electrodes.

o. Simultaneously conducting current of a different frequency from the cutter electrodes into the pipe while moving the cutter electrodes made the noise much worse coming from the electrodes.

The conclusion to the above work is that there is a real voltage noise generated by the contact of two metals which are in relative motion. As it turns out, this effect has a name - the "Triboelectric Effect".

The dictionary describes "triboelectricity" as "an electrical charge produced by friction between two objects". Several authors seem to imply that triboelectricity is primarily related to effects involving insulating materials, such as rubbing plastic rods with cat's fur in elementary physics demonstrations. Such is the case implied in a section from a handbook of Linear Technology, Inc. (the "1990 Linear Databook", pages 15-25).

However, it is known that metal contacts in motion act as a voltage sources. Quoting from an article available from Beckman Instruments entitled "Electrical Noise in Wire-Wound Potentiometers" by Irving J. Hogan dated August 28, 1952 presented at the West Coast I.R.E. Convention: 'When two dissimilar metals are rubbed together, a potential difference of constant polarity is developed between them. This has been named the "tribo effect" or "tribo emf" (from a Greek word meaning "to rub"). Very little is known about the origin and mechanics of the tribo emf; some investigators have identified it with the thermocouple effect, but others have denied this. The magnitude of the tribo emf encountered in precision wire-wound potentiometers is usually quite small, being on the order of tens or hundreds of micro-volts, and depends on the relative velocity between the two metals, the contact force, the composition of the metals, the surface condition of the metals, and probably other, unknown factors.' Maximum noise voltages from this effect quoted in that article range up to 200 to 300 micro-volts. The basic size of the physical effect is quoted as ranging from micro-volts to millivolts depending on circumstances.

In the article entitled "Sliding Contacts to Transmit Small Signals" by Billy M. Horton, The Review of Scientific Instruments, Volume 20, Number 12, December, 1949, page 930 (Horton, 1949) the following quote is repeated herein: "But even when practically no current is flowing through a sliding contact, electrical noise impulses still are generated by the sliding. Only this generated noise is considered here. Its origin will not be discussed except to say that is due partially to thermoelectric pulses from hot spots created by frictional heating and partially to effects of semi-conducting and

insulating films. Its magnitude depends upon the materials used, the conditions of their surfaces, speed of sliding, normal force, and the number of contacts in parallel." Even with very clean, ideal gold and silver electrodes, noise voltages on the order of 300 nano-volts were observed.

Despite additional efforts, we were not able to locate more current publications related to measuring the Triboelectric Effect involving metals.

5. Simple Demonstration of the Triboelectric Effect

We devised a small table top experiment which demonstrates the Triboelectric Effect involving various different metals. Please refer to Figure 94. In Figure 94, one probe is in electrical contact with the metal, is held stationary, and is called here in the text the "Reference Electrode". In Figure 94, the other probe is also in electrical contact with the metal, but is in motion, and is called here in the text the "Moving Electrode". The Moving Electrode is dragged along the surface of the metal. Figure 94 identifies the Moving Electrode with the velocity vector "V". The commercially purchased electronic probes are constructed from hardened steel materials of unknown compositions that are ground to have sharp ends. Using steel as the "Given Material" so labeled in Figure 94, such an experimental procedure typically generates a negative 200 micro-volt D.C. signal (referenced to the input of the amplifier). Using copper as the "Given Material" and using this experimental procedure typically generates a positive 20 micro-volt D.C. signal (referenced to the input of the amplifier). Results for other materials are also shown in the table appearing in Figure 94.

These voltages are much larger than the potential voltages seen between a first stationary probe in electrical contact with one point of the steel metal surface and a second stationary probe in electrical contact with another point of the same steel surface (which range no larger than 3 to 4 micro-volts on a typical sample of steel, referenced to the input of the amplifier). The general point to be made here is that two dissimilar metals in contact, and in motion, generate a D.C. voltage which varies in time and which masks the 20 nano-volt resolution we are trying to achieve referenced to the input of the amplifier. Here, the two metals are respectively the Moving Electrode and the metal surface of the "Given Material". Random noise is also created during dragging one metal over another, but the most striking phenomenon is the existence of the net D.C. voltage. This random noise could instead be defined as fluctuations in the net D.C. voltage. If both probes are simultaneously dragged over the metal surface, there is some tendency to cancel the net D.C. voltages coming from both, but fluctuations in the combined D.C. voltage levels still completely mask the 20 nano-volt resolution we are trying to achieve.

As another separate matter, the iron oxide layer seems to the authors to function only as a relative electrical insulator, which unto itself does not apparently generate much additional noise when the electrodes break through it. This is anecdotal information that should be verified with additional experiments in the future.

The fact that a D.C. voltage is generated while the metals are in continuous contact and in continuous motion is very difficult to justify based upon the different work functions of different materials. Fundamental discussions of the physics responsible for work functions and their measurement are discussed in Zisman (1932) and in the paper by Patai and Pomerantz (1951). Also see the undated book entitled Solid State Physics, having the author of A.J. Dekker, published by Prentice-Hall, Inc., New Jersey, in Section "9-10" on pages 230-232. Once the materials are shorted out with solid metallic contact, the Fermi levels should become equal, which should therefore cause the electric field between two dissimilar metals to vanish. Hence, the potential difference between the materials should also vanish. In fact, probing around the metal surface yields very little D.C. voltage from stationary point to stationary point (about 3 to 4 micro-volts on steel) which substantiates this point. The movement of the materials is the important issue here.

The point herein is that Triboelectric Effect produces voltages that are many orders of magnitude larger than the 20 nano-volt resolution we are seeking. Their variation cause noise in our detection bandwidth centered at 1 Hz. The existence of the Triboelectric Effect caused a complete reassessment of our measurement requirements. Therefore, the "Slider Method of Measurement" that provides measurements during stick-slip motion was devised to overcome Triboelectric Effects.

6. Slider Method of Measurement

We implemented the "Slider Method of Measurement" in experiments involving the Moving Test Jig. That "Slider Method of Measurement" relies upon the following events transpiring in sequence involving the Moving Test Jig located inside the rusty Test Pipe: (a) the Moving Test Jig is jerked forward about 10 inches in about 2 seconds causing much electrical noise; (b) the massive noise is limited with a voltage limiter; (c) it takes about 2 seconds for the electronics to recover; and then (d) two measurements are performed using a time constant typically of 1 second (or sometimes 3 seconds). This sequence of events has shown that the Slider Method of Measurement can provide TCRT measurements that meet the "Acceptable Performance Specifications".

As an example of the many logging runs performed by PML using this Slider Method of Measurement, some data is presented here that was originally sent to Mr. Harvey Haines in PML's Report to GRI dated March 18, 1992. Current leakage is measured through the resistor bank shown in Fig. 91.

Figure 95 shows the usual demonstration of current leakage using the simulated Slider Method of Measurement. The total size of the "bump" centered at around 130 inches corresponds to about 12 milliamps 0-peak leaking from the laboratory Test Pipe into a simulated resistive bed. Therefore, measurements here are accurate to about plus/minus 1 milliamp 0-peak that is required by the most stringent of the Woodhouse Specifications. Only "counter-flowing" currents are used here which are exactly in-balance. Here, the average rate of travel of the Moving Test Jig within the Test Pipe is 3.2 feet/minute. Figure 96 shows a repeat run obtained on a different day.

Figure 97 shows the same measurement as in Figures 95 and 96, except there is an additional 50 ma 0-peak simultaneous "out-of-balance current" at 1 Hz flowing along the casing, and a simultaneous additional 30 ma 0-peak calibration current at 3 Hz flowing along the casing. These extra currents simulate what we expect to see downhole under typical circumstances - if multiple frequencies of measurement are to be employed (one frequency for the Measurement State and another for the Calibration State). The measurement clearly shows that we can still measure the 12 milliamps 0-peak leaking from the laboratory Test Pipe to an accuracy of about 1 milliamp 0-peak at the average speed of 3.2 feet per minute. The extra "wings" on the data below 60 inches and above 200 inches are caused by the fact that in these primitive measurements, we were not then able to compensate for thickness variations with the laboratory Test Pipe. Later measurements were performed with proper compensation for thickness variations, but these measurements described here are particularly informative and were shown to many visitors to PML so we used these measurements as the examples cited here.

The data shown in Figure 97 signified the passage of a major milestone. That data proves, in principle, that we can measure the TCRT signal of interest in the presence of the numerous and confusing background signals expected downhole at the average logging speed of 3 feet per minute to the level of accuracy defined by the "Acceptable Performance Specifications".

Figure 98 is similar to Figures 95 and 96, except that the Moving Test Jig is pulled forward within the laboratory Test Pipe at much closer intervals to obtain a finer resolution. Here, a total of 11 resistors span a length of 60 inches which simulates the presence of a conducting formation inserted in an otherwise insulating half-space.

Figure 99 is similar to Figure 98, except here the center most 3 resistors have been disconnected within the 60 inch interval. Therefore, disconnecting 3 resistors opens up a 24 inch-wide section of the 60 inches. The separation of voltage measuring electrodes is 18 inches. The response shows that the vertical resolution is somewhere between one electrode spacing and two electrode spacings - regardless of what reasonable definition you may wish to choose to define "vertical resolution".

Figure 100 is similar to Figures 95 and 96 except here, proper account is taken for the thickness variations of the casing. In Figure 100, the leakage current is properly measured. The current leakage is measured with TCRT processing techniques by the Moving Test Jig within the Test Pipe to be about 0.33 milliamps/inch near the center of the "bump" in Figure 100. This compares very favorably with the current leakage per unit length determined to be physically flowing through the resistor bank on the outside of the casing in Figure 91 (0.333 millimaps/inch). In this particular data run, the current leakage in the Measurement State at the frequency of 1.25 Hz is determined in the presence of simultaneously flowing Calibration Current at the frequency of 3.75 Hz. This is another example of multi-frequency TCRT operation. (However, the TCRT at the MWX-2 Well obtained data using current of the same frequency by altering between the Measurement State and the Calibration State.) It should also be noted that the good numerical agreement between the current leakage measured with the Moving Test Jig and the calculated value is dependent on the validity of an appropriate form of Equation VIII-A-10 in the Theoretical Appendices.

It should also be stated that experiments were conducted at the MWX-2 Well with the PML's Second TCRT which showed that the Slider Method of Measurement actually works in practice, although at slower logging speeds than 3 feet per minute. However, the principle of measurement was demonstrated in the MWX-2 Well during late 1993 and early 1994.

In the case of a downhole tool, upward force on the wireline results in overcoming any sticking friction of a particular tool located in the well, and the tool subsequently lurches forward until it stops again. Such motion can be called "stick-slip motion". Further, the logging tool may be operated in a stick-slip fashion while the wireline drum on the surface undergoes continuous rotation.

If the wireline drum rotates continuously at the surface, the industry normally associates that continuous rotation with a "continuously moving logging tool". In general, the wireline logging industry desires "continuously moving tools" - meaning that the wireline is continuously wound up on the wireline drum.

A TCRT can be designed and built that has all the desirable features of a continuously moving logging tool, which overcomes the problems of the Triboelectric Effect, and which acquires TCRT measurements meeting the "Acceptable Performance Specifications". Therefore, what is required by the practicality of the situation are the following operational features: (a) a continuously rotating wireline drum that continuously winds the wireline on the drum located on the logging truck at the surface; and (b) means to cause the TCRT to execute periodic, stick-slip motion to log a well at different vertical portions, where the TCRT alternatively lurches upward in the well between durations of time when the tool otherwise remains stationary in the well, during which stationary times the TCRT makes measurements of the resistivity of geological formations from within the cased well. This is the implementation of The Slider Method of Measurement defined above.

The period of the periodic motion can be described as the sum of the times during which the tool is stationary and the time during which the tool moves upward in the well. The period equals the sum of the following: (a) the average duration of time when the tool is stationary and is sticking in place (i.e, the "stick time"); and (b) the average duration when it is slipping upward within the well (i.e, the "slip time"). The period therefore equals the average duration of time for the "stick-slip" motion within the well.

A spring inserted into the tool string can provide one means to adjust the period of the "stick-slip" motion. For example, a suitable spring could, in principle, be inserted between the lower end of the Mass Isolator #2 and the top of the Bowspring Centralizer #2 in Figure 4. Such a spring inserted into the tool string can be described as one example of a Slider Mechanism to implement the Slider Method of Measurement. Many other means can be implemented to cause such "stick-slip" motion.

Relevant information concerning the Slider Method of Measurement has been forwarded to PML's Licensees in various proprietary documents.

7. Higher Frequencies of Measurement & Demonstration of Inductive Effects of Casing

We have performed experiments related to current leakage at higher frequencies. For example, we could meet the Woodhouse Specifications if we could operate at 10 Hz. Therefore, we looked again at the possibility of running at higher frequencies.

We measured the voltages generated at the midpoint of the Test Pipe shown in Figure 91 from electrodes separated by 18 inches located on inside and outside of the Test Pipe. Please refer to

Figure 101 that shows the results. These results were forwarded to Mr. Harvey Haines in PML's Report to GRI having the date of September 11, 1991. Please notice that measurements inside and outside of the pipe are the same until about 3 Hz. Thereafter, they are substantially different.

The dot is for inside the Test Pipe, the "x" for outside of the Test Pipe, and the circle was from a control experiment. To simplify interpretation, we would prefer to remain in a frequency range where the pipe acts mostly like a resistor - namely below 3 Hz. Therefore, from these measurements, we are restricted to working below about 3 Hz in accordance with theory and our prior test results at Fort Worth.

The difference between the measurements performed inside and outside of the casing in Figure 101 are due to the A.C. inductive effects of the casing itself. Much detail on this subject has been forwarded to PML's Licensees in the form of various proprietary documents.

8. Anticipated Performance Specifications
of the Prudhoe Bay Through Casing Resistivity Tool ("PBT CRT")
November 12, 1992

(Note: This document was a portion of the Report to GRI
dated February 1, 1993 and addressed to Mr. Harvey Haines.)

Nominal O.D. with Electrodes
in "Closed Position": 3 3/8 inches O.D.

Fraction of Wells in Prudhoe Bay Accessible to a 3 3/8 inch
O.D. tool: approximately 80%

Maximum Working Temperature of Electronics: 125 degrees C
(257 degrees F)

Two Mechanical Configurations Possible:

- (A) With Slider Mechanism, Continuous Moving Tool Possible
- (B) Without Slider Mechanism, Fast Station-to-Station

Minimum Continuous Logging Speed with
Slider Mechanism: 2 feet per minute

Maximum Continuous Logging Speed
with Slider Mechanism: 5 feet per minute

Without Slider Mechanism, Time Required for Measurement
After Halt: no longer than 15 seconds

Absolute Minimum Accuracy to be Achieved at Continuous Logging
Speeds ("The Woodhouse Specifications"):

- (A) Low Range - 3 ohm-meters +/- 1 ohm-meter
- (B) High Range - 30 ohm-meters +/- 5 ohm-meters

Absolute Minimum Repeatability of Measurements if Halted:

- (A) 0.5 to 100 ohm-meters: better than +/- 5%
- (B) 100-200 ohm-meters: better than +/- 12%

Accuracy of Measurement obtained with a time constant of 1 second
if PBT CRT Stopped due to sum of thermal and environmental noise
in range of 0.5 to 200 ohm-meters: better than +/- 1%

Systematic Errors Caused by Presence of Cement in Prudhoe Bay:

- (A) Low Range - 3 ohm-meter formation - influence of cement negligible because resistivity of cement is about 3 ohm-meters from measurements at ARCO
- (B) High Range - 30 ohm-meter formation - influence of cement causes lower apparent reading of 26.7 ohm-meters for example for 7 inch O.D. casing and 3 ohm-meter cement which is 2 inches thick
- (C) Conclusion: Systematic Errors due to Presence of Cement in Prudhoe Bay will not exceed requirements of "The Woodhouse Specifications"

Vertical Resolution: 100% correct reading of resistivity
over center 20 inch section of a
5 foot thick bed

Wireline Required: Standard 7 wire wireline

Communication Protocol: Analog current-loop

Type Uphole and Downhole Electronics Used: Same as developed
for PML's Second
TCRT

Preferable Maximum Limit of Current in any
Wire of Wireline: 1 amp

Hydraulics: Downhole hydraulic pump allows
arms attached to Fauskatrons to open and close
repetitively on command from the surface.

Pressure: Up to 20,000 P.S.I.

Anticipated Length of PBTCRT: No longer than 40 feet

Maximum Length of any one tool section: No longer than 10 feet

Basic Mechanical Components: Gearhart 17 pin tool joints;
3 3/8 inch O.D. Gearhart cablehead;
3 3/8 inch Gearhart Mass Isolators;
3 3/8 inch O.D. pressure housings;
and other custom parts

Operates in following O.D.'s of Casing: 5 1/2 inches O.D. to
9 5/8 inches O.D.

Field-Changeable Modifications to PBTCRT allow Operation
in Following Liners Found in Prudhoe Bay: 5.5 inches O.D.
7 inches O.D.
7.625 inches O.D.
9.625 inches O.D.

Well Deviation: Designed to work in any deviation of the well
from vertical to horizontal

Materials: Must conform to NACE Specifications in MRO175-91

Method of Fielding PBTCRT: Operation initially looks like
leased-line operation

Visual Presentation of Data on CRT
at Well Site: Updated every 30 seconds from "real time"

Hard Copy Presentation of Data
at Well Site ("the log"): 4 cycle semi-logarithmic plot of
resistivity vs. depth

Standard Data Format for data on 9-track
magnetic tapes: LIS Data Format

Other Standard Formats Immediately Available: CWLS ASCII
AMOCO "A"

Natural Gamma Ray available in typical log format accompanying
4 cycle semi-logarithmic plot of resistivity vs. depth

Casing Collar Location also available in log format accompanying
4 cycle semi-logarithmic plot of resistivity vs. depth

FIGURE 91
TEST PIPE
WITH MOVING TEST JIG
EXPERIMENTAL SETUP

TEST PIPE, WOODINVILLE, WA.
ParaMagnetic Logging, Inc.

Figure 92
Printed Out 7/4/94
Data Collected: 7/23/91

TEST PIPE, WOODINVILLE, WA.
ParaMagnetic Logging, Inc.

Figure 93, Jerk & Hold with 10 mAOP on Test Pipe
Printed Out 7/4/94
Data Collected: 11/7/91, Run #1

FIGURE 94
DEMONSTRATION OF THE
TRIBOELECTRIC EFFECT

TEST PIPE, WOODINVILLE, WA.
ParaMagnetic Logging, Inc.

Figure 95
1 Hz, 3.2 ft/min, 3 pts, TC=1s
Data Collected: 1/24/92 Run #1

TEST PIPE, WOODINVILLE, WA.
ParaMagnetic Logging, Inc.

Figure 96
1 Hz, 3.2 ft/min, 3 pts, TC=1s
Data Collected: 2/5/92 Run #4

TEST PIPE, WOODINVILLE, WA.
ParaMagnetic Logging, Inc.

Figure 97
1 Hz, 3.2 ft/min, 3 pts, TC=1s, Data Collected: 2/5/92 Run #5
1 & 3 Hz Common Mode Currents

TEST PIPE, WOODINVILLE, WA.
ParaMagnetic Logging, Inc.

Figure 98
1 Hz, 3 pts, TC=1s
Data Collected: 2/6/92 Run #2

TEST PIPE, WOODINVILLE, WA.
ParaMagnetic Logging, Inc.

Figure 99
1 Hz, 3 pts, TC = 1s, Data Collected: 2/6/92 Run #3
3 Middle Resistors Removed

TEST PIPE, WOODINVILLE, WA.
ParaMagnetic Logging, Inc.

Figure 100

LEAKAGE (20 mAOP, 1.25 Hz), CALIBRATION (30 mAOP, 3.75 Hz), NO OUT-OF-BALANCE, TC=1s

Sigma T/Inch Calculated = 0.333 mAOP/Inch, Data Collected: 9/25/92 Run #1

TEST PIPE, WOODINVILLE, WA.
ParaMagnetic Logging, Inc.

Figure 101
Printed Out 7/4/94

SECTION II - E

RESULTS FROM RESEARCH WELL IN FORT WORTH, TEXAS

This work resulted in the first known accurate measurements of formation resistivity obtained from within a cased well. This pioneering work was co-sponsored by GRI and DOE.

The mechanical portions of that experimental apparatus, called PML's First TCRT, were designed with the help of personnel from then Gearhart Industries, Inc. of Fort Worth, Texas. Data was obtained from that First TCRT in the Research Well at Gearhart Industries, Inc. Final Reports on this work were submitted respectively to Gas Research Institute (Vail and Momii, 1990a) and to the U.S. Department of Energy (Vail and Momii, 1990b).

The work at Fort Worth also resulted in the publication of the paper entitled "Formation Resistivity Measurements Through Metal Casing" having the authors of W.B. Vail, S.T. Momii, R. Woodhouse, M. Alberty and R.C.A. Peveraro, and J.D. Klein that was presented at the 34th Annual Logging Symposium of the SPWLA, June 13-16, 1993 (Vail, et. al., 1993b).

For a review the body of work at the Research Well in Fort Worth, the interested reader is referred to the two Final Reports (Vail and Momii, 1990a and 1990b) and particularly to Vail, et. al. (1993b). However, the authors wish to review in detail one pivotal result of that work - the empirical determination of the Calibration Constant K.

With reference to Figure 3 from Vail, et. al. (1993b), the authors wish to quote the particularly relevant portion of that paper on page 5 which states:

"The Calibration Constant K used for all the figures was obtained as follows. At approximately 275 feet, the open-hole LL3, Medium Induction Log, and the Deep Induction Log all substantially overlap. There had been significant discussion involving which of the three logs to which to compare the TCRA experimental results. However, since these logs overlap at the depth of 275 feet, choosing the Calibration Constant K at that depth appears reasonable regardless of which log the data is to be compared. The Calibration Constant K was chosen to make the TCRA readings at 275 feet in Figure 3 overlap the open-hole, smoothed, LL3. This choice results in $K = 1.407$ meters. All of the data in Figures 2, 3, 4, 5, and 6 have used this single value for the Calibration Constant."

Here, "TCRA" is an abbreviation for "Through Casing Resistivity Apparatus". PML's First TCRT is another name used in this Final Report for the TCRA. A copy of Figure 3 from Vail, et. al. (1993b) follows this page. In Figure 3, "Old Data" and "New Data" were obtained approximately one year apart.

The Calibration Constant K is substantially dependent upon the Electrode Spacing "ELECTSP" that is the distance of separation between Electrodes C-D (or D-E) of the TCRT. The empirical determination of $K = 1.407$ meters was appropriate for PML's First TCRT that had an ELECTSP = $56 \frac{7}{8}$ inches.

Equation 18 on page II-B-4 shows how this first value of K that was obtained from PML's First TCRT was used to determine the new value of K for PML's Second TCRT that had a different ELECTSP = $19 \frac{13}{16}$ inches. That new $K = 0.489$ meters was used to interpret ALL experimental results obtained with PML's Second TCRT at PML's Test Well in Woodinville, Washington (Section II-C of this Final Report). Further, that new $K = 0.489$ meters was used to interpret ALL experimental results obtained with PML's Second TCRT at the MWX-2 Well in Rifle, Colorado (Section II-B of this Final Report).

Therefore, one single measurement obtained at the depth of approximately 275 feet deep at the Research Well in Forth Worth, Texas has been sufficient to provide an empirically determined Calibration Constant K that has yielded highly successful formation resistivity measurements at three different wells to date.

A copy of Figure 5 from Vail, et. al. (1993b) accompanies this section. This is another interval logged at the Research Well in Forth Worth.

A copy of Figure 7 from Vail, et. al. (1993b) also accompanies this section. This is an example of a procedure that may be used within any cased well to determine the acceptable frequency of operation for the TCRT. That data was obtained using methods discussed in detail in this Final Report in Section II-A "5. Distinguishing Apparent Resistivity from Other A.C. Effects".

For additional details, the interested reader is referred to Vail and Momii (1990a), Vail and Momii (1990b), and Vail, et. al. (1993b).

FIGURE 3
THROUGH CASING RESISTIVITY
DATA FROM THE RESEARCH WELL

FIGURE 5
THROUGH CASING RESISTIVITY
DATA FROM THE RESEARCH WELL

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FIGURE 7
APPARENT FORMATION RESISTANCE R_c
VS FREQUENCY FROM TCRA

Mode A: Energize Electrode A
Mode B: Energize Top of Casing
Depth = 245 feet

SECTION II - F

BRIEF SUMMARY OF SUBCONTRACT

WORK UNDER THIS PROJECT

The three formal subcontracts under this work resulted in their own respective formal final reports. The related final reports are listed as follows in alphabetical order of the lead author:

Kaufman, A.A., 1993b, "Electric Logging Through Casing",
Final Report to ParaMagnetic Logging, Inc.,
Colorado School of Mines Project No. 4-49515,
September

Klein, J.D. and Martin, P.R., 1994, "The Electrical Resistivity
of Cement", Final Report to GRI, Report No. GRI-94/0273, April

Morrison, H.F., and Schenkel, C.J., 1991a, "Final Report to
ParaMagnetic Logging, Inc. for Numerical Analysis of D.C.
Logging Through Metal Casing" (a private report), Engineering
Geoscience, College of Engineering, University of California,
Berkeley, California, November 22

Morrison, H.F., and Schenkel, C.J., 1991b, "Numerical Analysis of
D.C. Logging Through Metal Casing", Final Report to
ParaMagnetic Logging, Inc. under Contract Number UCB Eng-7724
for Gas Research Institute (a revised form of above private
report that is Morrison and Schenkel 1991a), Engineering
Geoscience, College of Engineering, University of
California, Berkeley, California, November 22
(Revised on May 4, 1992)

During the work performed under GRI Contract No. 5088-212-1664, many consultants, fabricators, and suppliers were used to provide work to PML, many of which were subject to various agreements and contractual arrangements with PML. However, to PML's knowledge, the above list presents all work done for PML on the basis of formal subcontracts under GRI Contract No. 5088-212-1664. The respective final reports are described separately below. Particular emphasis is placed on the results of the final reports as they relate to PML's actual field work.

1. Kaufman (1993b)

This was one of the theoretical studies performed for PML on a subcontract basis under GRI Contract No. 5088-212-1664. Much of

the work appearing in this final report to PML, which is the reference defined as Kaufman, A.A., 1993b in the Bibliography, actually appeared in the paper entitled "A Transmission-line Model for Electrical Logging Through Casing", Geophysics, Vol. 58, No. 12 which is the reference defined as Kaufman, A.A., and Wightman, W.E., 1993a in the Bibliography.

No credit is given to PML or to GRI for the work that appeared in Kaufman, A.A. and Wightman, W.E., 1993a. For the record, none of the equations appearing in Kaufman, A.A. and Wightman, W.E., 1993a or in Kaufman, A.A., 1993b, were used to interpret any TCRT data obtained by PML during any field work under GRI Contract No. 5088-212-1664.

2. Morrison and Schenkel (1991a and 1991b)

This was the another theoretical study performed for PML on a subcontract basis under GRI Contract No. 5088-512-1664. Theoretical studies are presented in their final reports which show that PML's Calibration Constant K calculated from the first principles application of Maxwell's Equations turns out to be a very good approximation for data interpretation. In particular, please see Figure 3 on page 25, Figure 5 on page 27, and Figure 6 on page 28 of Morrison and Schenkel (1991a and 1991b).

These final reports were completed at a time after the results were obtained with PML's First TCRT in Fort Worth, Texas but before the logs were obtained with PML's Second TCRT in PML's Test Well in Woodinville, Washington and at the MWX-2 Well in Rifle, Colorado. It was reassuring to the experimenters at PML to obtain confirmation at that time that the use of the Calibration Constant K was a very good approximation under the theoretical conditions studied. PML is grateful to Professor Morrison and Dr. Schenkel for their work presented in their final reports to ParaMagnetic Logging, Inc.

Analysis is also presented in their final reports showing how PML's approach contrasts with the approach chosen by Kaufman (1990). Morrison and Schenkel (1991a and 1991b) have carefully studied this issue. Professor Morrison and Dr. Schenkel provide a quote on page 5 of their final reports related to certain fundamental assumptions made in Kaufman (1990) resulting in equations (13) and (14) in their final reports which are crucial to Kaufman (1990) obtaining resistivity from the analysis presented by Kaufman (1990). Morrison and Schenkel (1991a and 1991b) state on page 5 in relation to those equations (13) and (14) used in Kaufman (1990): "It is not obvious that equations (13) and (14) are valid." They further state in relation to the conclusions of Kaufman (1990): "With no theoretical evidence to support equation (14), this expression

for sufficient distance appears to be an accommodating relation to obtain the formation resistivity directly from the transverse resistance."

Nevertheless, Professor Morrison and Dr. Schenkel go on to show on pages 5, 6 and 7 of their final reports to PML that if (a) the physics described in Kaufman (1990) is correct and (b) the use of PML's Calibration Constant K is correct, and that if (a) and (b) are BOTH SIMULTANEOUSLY CORRECT, then they derive equation (24) in their final reports showing that PML's Calibration Constant K should be approximately equal to the TCRT's Electrode Spacing (ELECTSP). This equality has proven to be approximately true experimentally at three cased wells so far and has been shown in Section VIII-C herein to be a good approximation based upon theoretical grounds developed in Section II-A and in the Theoretical Appendices.

Consequently, it is reasonable to conclude that PML's use of the Calibration Constant K and the developments in Kaufman (1990) are apparently approximately equivalent at some fundamental level. The authors of this Final Report to GRI believe that this subject should be further investigated. In any event, the authors of this Final Report are gratified in the continuing interest in this field shown by Professor A.A. Kaufman and his esteemed colleagues.

For the record, however, no equation of Kaufman (1990) was used to interpret any TCRT data obtained by PML during any field work under GRI Contract No. 5088-212-1664.

3. Klein and Martin (1994)

The final report to GRI entitled "The Electrical Resistivity of Cement" by J.D. Klein and P.R. Martin completed in 1994 provides very important experimental data on the resistivity of cement. The results in that final report are important, and have been used by the authors in Section VIII-F to show that corrections for possible effects related to the presence of cement, if any exist at all, will be limited to geological formations having formation resistivities less than about 3 ohm-meters.

PML's previous anecdotal information dating back to 1986 concerning the resistivity of cement and previous theoretical models turned out to be correct. However, it was gratifying for the experimenters at PML to find corroboration in first rate research confirming that the previous anecdotal information turned out to be correct. Based on this work, and on the previous anecdotal information, no corrections for cement were applied to the data obtained at the MWX-2 Well in Rifle, Colorado.

SECTION III

MAJOR ACHIEVEMENTS OF THE PROJECT

PML invented new theory from scratch to perform measurements of resistivity from inside cased wells. Electronic measurement techniques were invented from scratch to measure nano-volt signals on the inside of cased wells in the presence of large interfering signals that implemented that new theory. Several apparatus versions of the Through Casing Resistivity Tool® were built from scratch which performed the first accurate measurements of resistivity from inside cased wells. This record of technical achievement was accomplished with just three full time employees over a number of years: Ms. Marilyn L. Vail, Office Manager; Mr. Steven T. Momii, Vice President, Electronic Systems; and W. Banning Vail, Ph.D., inventor, and President & COO of PML. The major achievement of the entire project is the definitive demonstration that the Through Casing Resistivity Technology actually works.

SECTION IV

MAJOR TECHNICAL PROBLEM AREAS ENCOUNTERED

We encountered no problems that were insoluble.

The existence of the Triboelectric Effect does affect the design of a continuously moving tool if standard wirelines and currents are to be used. However, a TCRT can be effectively designed wherein the drum of the logging truck rotates at a constant speed during logging operations with the TCRT. Such a tool would use standard wirelines and typically acceptable currents. As verified by certain laboratory experiments, particular varieties of TCRT's can be designed and fielded which have most of the important attributes of a "moving tool". Please refer to Section II-D-6 entitled "Slider Method of Measurement" for additional information on this particular point.

It took much time and effort to develop the detailed measurement techniques and front-end amplifier designs to measure nano-volt signals from the current leakage in the presence of large interfering voltages. Much time and effort was devoted to building two different logging tool strings from scratch using the available personnel. Lack of personnel drove PML to invent and develop the use of "Fauskatrons" so that we did not have to design and build inherently more mechanically complex downhole pump systems. Learning by experiment how to properly measure the Potential Voltage V_o took significant time and effort. Learning by experiment how to identify the signatures of certain adverse interfering effects also took much time and effort.

The prevailing wisdom of most industry experts in this area in the 1980's was that no tool could be designed to measure resistivity from inside cased wells. However, the technology works. Otherwise, making an almost endless list of problems we had to overcome to make the technology work and the equally long list of objections that most of the industry experts had to this technology would be a waste of time. For the record, the authors are particularly grateful to the precious few scientists, engineers, technical managers, and corporate managers who were open to new ideas of any type.

SECTION V

CONCLUSIONS

This work has definitely proven beyond any reasonable doubt that the resistivity of geological formations can be measured from within cased wells.

Successful resistivity measurements were obtained within cased wells with apparatus versions of the Through Casing Resistivity Tool™ (TCRT®) at the Research Well in Fort Worth, Texas; at PML's Test Well in Woodinville, Washington; and at the MWX-2 Well in Rifle, Colorado. Data were obtained in portions of the MWX-2 Well in Rifle, Colorado under blind test circumstances administered by the Gas Research Institute and by Western Atlas Logging Services. Those data provided definitive and conclusive results.

As a result of the data obtained at the MWX-2 Well in Rifle, Colorado, PML licensed its patents and technology to Western Atlas Logging Services in January 1994 under the auspices of the Non-Exclusive Patent and Technology License Agreement. Thereafter, PML licensed its TCRT patents and technology to Schlumberger Technology Corporation and its Licensed Affiliates.

It has been determined from data in real wells that the TCRT actually works in practice in accordance with the theory described in PML's various patents on the subject. The data show that the theory set forth in those patents is completely self-sufficient to provide TCRT logs which substantially agree with various open-hole logs obtained before the casings were set. PML's simple data interpretation scheme using a single Calibration Constant "K" has proven successful so far in all cases. This method requires only simple algebraic analysis to generate an immediate wellsite log and therefore should be of considerable utility to the industry. First principles calculations of the Calibration Constant K provide substantial agreement with the empirically determined values of K obtained in three different wells to date.

Earlier patents on the TCRT had been filed before the beginning of this project funded by GRI. Earlier experiments in a tank proving the efficacy of the relevant TCRT measurement techniques to the authors of this report had been completed prior to the beginning of this project funded by GRI. However, it can be safely stated that the entire science of measuring resistivity from inside casings has been proven during this project which GRI has co-funded with DOE.

The Contract with GRI is entitled "Proof of Feasibility of the Through Casing Resistivity Technology". The goals of that Contract have been completely satisfied.

SECTION VI

RECOMMENDATIONS

As of the date of publication of this Final Report to GRI during March of 1996, PML's TCRT has provided the only known accurate measurements of formation resistivity obtained from within cased wells. Accordingly, the authors believe that items no. 1, 2 and 3 in particular should be carefully considered by the industry. Our recommendations are listed as follows.

1. Request PML to log a low resistivity formation with the TCRT to determine if the resistivity of cement is a problem or if any other unanticipated problems exist in such a low resistivity formation. The low resistivity formation should have beds with resistivities less than 1 ohm-meter.
2. Request PML to log a well having both gas and oil bearing zones to demonstrate how the TCRT may be used to monitor reservoir conditions. Perhaps an attempt could be made to identify bypassed gas or oil zones during any such test. Perhaps the DOE could participate in that test. Perhaps a well could be provided under the direction of Mr. John F. Gould, Jr., Mobil Exploration & Producing U.S., Midland, Texas.
3. In the event that the TCRT is not rapidly commercialized by PML's Licensees, assist PML to systematically log a group of wells to demonstrate to the industry that the technology will solve real problems. Perhaps this project could be overseen by Mr. John F. Gould, Jr., and perhaps this project could follow successful results from items no. 1 and 2 above.
4. Compare PML's approximate calculation of the Calibration Constant K with other model calculations. It is earnestly hoped that Professor Liang C. Shen of the Well Logging Laboratory of the University of Houston will choose to compare his model calculations against the predictions of PML's Calibration Constant K for various electrode spacings, casings, formation resistivities, etc.
5. Request a theoretician to prepare in an unbiased fashion a comparison between the formulation of the problem of measuring formation resistivity from inside cased wells proposed in the literature respectively by the lead authors of L.A. Tabarovksy; B.Sh. Singer; C.J. Schenkel; A.A. Kaufman; and W.B. Vail. The results should be presented in some organized fashion useful to the industry. Meaningful differences appear to exist between the theories proposed by these lead authors.

SECTION VII

BIBLIOGRAPHY

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Through Casing Resistivity Tool™ (TCRT®)
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SECTION VIII - A

RELATIONSHIP OF PIECE-WISE CONTINUOUS RESISTOR

MODEL TO CONTINUUM MODEL & CONSEQUENCES

The purpose of this section is to lay the ground work to provide an approximate calculation of the Calibration Constant K from first principles using standard equations in the literature. Before doing so, however, it is first necessary to precisely determine the meaning of "current leakage".

The "current leakage" for the Piece-Wise Continuous Resistor Model of the earth gives one set of equations in U.S. Patent No. 5,075,626 (Vail, 1991c). Those equations are correct for the Piece-Wise Continuous Resistor Model of the earth. The "current leakage" determined from the equations in that patent are mathematically correct in terms of the Piece-Wise Continuous Resistor Model of the earth. Please refer to Figure VIII-A-1 entitled "Piece-Wise Continuous Resistor Model".

In the real case, current continuously leaks off the portion of the casing spanned by Electrodes C, D, and E. Therefore, the real case corresponds to a continuum model of the earth. Please refer to Figure VIII-A-2 entitled "Continuum Model". The "Total Real Current Leakage" for the real case is different than the "current leakage" calculated for a Piece-Wise Continuous Resistor Model. Therefore, it is necessary to consider at this point how the "Total Real Current Leakage" in the real case is related to the "current leakage" determined from the Piece-Wise Continuous Resistor Model.

As stated in the second paragraph of SECTION II-A, the quantity δi_2 defined in U.S. Patent No. 5,075,626 (Vail, 1991c) is re-named in this Final Report to be the variable ΔI and both quantities are the "current leakage" determined from the Piece-Wise Continuous Resistor Model of the earth. Therefore, we use the following definition herein:

$$\delta i_2 = \Delta I \quad \text{Equation VIII-A-1}$$

Therefore, the quantity ΔI in this Final Report is defined by Equation 7 in U.S. Patent No. 5,075,626 (Vail, 1991c) as follows:

$$I_E = I_M - \Delta I \quad \text{Equation VIII-A-2}$$

FIGURE VIII-A-1
"PIECE-WISE CONTINUOUS
RESISTOR MODEL"

FIGURE VIII-A-2
"CONTINUUM MODEL"

There are several observations at this point. First of all, Equation 28 in U.S. Patent No. 5,075,626 (Vail, 1991c) is used to actually determine ΔI . That equation is true if and only if Equation 27 is also true in U.S. Patent No. 5,075,626 (Vail, 1991c) that calls for keeping I_M fixed and equal to a predetermined fixed current I_0 that is also the magnitude of the current caused to flow through R_1 in other modes of the tool for the purpose of the minimization of certain first and second order errors defined in that patent.

Please refer to Figure VIII-A-1 that shows the Piece-Wise Continuous Resistor Model. The definition of I_C is that current flowing downward immediately below Electrode C and after the current loss labeled " i_c ". In this model, I_M is the current flowing along the section of the casing spanned by R_1 , and from this model, no current leaks off the pipe until ΔI leaks into the resistor R_C that is located opposite Electrode D. Therefore, in this Piece-Wise Continuous Resistor Model, $I_C = I_M$. The definition of I_E is that current flowing downward into the point of contact of Electrode E before any current loss labeled " i_e ". Therefore, in this model I_E is the current flowing along the section of the casing spanned by R_2 and from this model, no current leaks off the pipe until the current i_e flows off the pipe opposite Electrode E as shown in Figure VIII-A-1. By virtue of this model and the mathematics used in U.S. Patent No. 5,075,626 (Vail, 1991c), ΔI and R_C are determined using this particular Piece-Wise Continuous Resistor Model. Please notice that if Electrodes C, D, and E of the TCRT are positioned as shown in Figure VIII-A-1, the currents i_c and i_e are not determined from the measurements.

Please refer to Figure VIII-A-2 entitled the "Continuum Model". This is the real case. As above, the definition of I_C is that current flowing downward immediately below Electrode C. As above, the definition of I_E is that current flowing downward into the point of contact of Electrode E. However, in this model, current continuously leaks off the pipe between Electrodes C, D, and E. The Total Real Current Leakage hereinafter abbreviated herein as "TRCL" is the total real current flowing into the formation between Electrodes C, D, and E. From Figure VIII-A-2, that quantity is given by the following:

$$\text{TOTAL REAL CURRENT LEAKAGE} = \text{TRCL} = \delta i_{cd} + \delta i_{de}$$

Equation VIII-A-3

Question: How is TRCL related to ΔI above? The following logic provides an answer to this question. Please refer to Figure VIII-A-3 for reference in the following.

FIGURE VIII-A-3
 AVERAGE CURRENT FLOW
 IN CONTINUUM MODEL
 ASSUMING UNIFORM CURRENT
 LEAKAGE

The difference in voltage across Electrodes C and D "Vcd" in the Continuum Model is related to the average of the current flowing along CD times the resistance R1 that gives voltage Vcd as follows:

$$V_{cd} = \{ I_C - (\delta_{icd} / 2) \} R_1$$

Equation VIII-A-4

The difference in voltage across Electrodes D and E that is the quantity "Vde" in the Continuum Model is related to the average of the current flowing along DE times the resistance R2 that gives voltage Vde as follows:

$$V_{de} = \{ I_C - \delta_{icd} - (\delta_{ide} / 2) \} R_2$$

Equation VIII-A-5

Suppose the current leakage is uniform as follows:

$$\delta_{ide} = \delta_{icd}$$

Equation VIII-A-6

Further assuming $R_1 = R_2$, then the difference in voltage between Vcd and Vde is:

$$V_{cd} - V_{de} = \delta_{icd} R_1$$

Equation VIII-A-7

But from Equation VIII-A-3 and Equation VIII-A-6 then:

$$\delta_{icd} = TRCL / 2$$

Equation VIII-A-8

Therefore, Equation VIII-A-7 becomes:

$$V_{cd} - V_{de} = (TRCL / 2) R_1$$

Equation VIII-A-9

The point of this is that the difference in voltage between Electrode Pairs CD and DE is related to ONE HALF THE TOTAL REAL CURRENT LEAKAGE "TRCL" as measured with the TCRT as set forth in U.S. Patent No. 5,075,626 (Vail, 1991c).

Therefore, the following is true from this analysis:

$$\text{TRUE REAL CURRENT LEAKAGE} = \text{TRCL} = \{ 2 \Delta I \}$$

Equation VIII-A-10

Put in operational terms, the quantity ΔI is measured using the techniques defined in U.S. Patent 5,075,626 (Vail, 1991c). Then, the total real current leaking into the formation between Electrodes C, D, and E is given by the quantity $2 \Delta I$.

What does this particular matter involving the total real current leaking into formation have do to the rest of the mathematics set forth in U.S. Patent No. 5,075,626 (Vail, 1991c)? Answer - Nothing.

However, suppose one wants to know the value of the "real resistor to infinity in ohms that connects the portion of the casing spanned by Electrodes C, D, and E to electrical infinity". We will call that resistor $R(\text{REAL})$.

The relationship between $R(\text{REAL})$, V_o , and TRCL is given by Ohm's Law as follows:

$$R(\text{REAL}) = V_o / \text{TRCL}$$

Equation VIII-A-11

The relationship between R_c , V_o , and ΔI is given by Equation 2 and it is repeated as follows:

$$R_c = V_o / \Delta I$$

Combining Equation 2, Equation VIII-A-10, and Equation VIII-A-11 results in the following relationship:

$$R(\text{REAL}) = R_c / 2$$

Equation VIII-A-12

This means that the "real resistor to infinity in ohms that connects the portion of the casing spanned by Electrodes C, D, and E to electrical infinity" is obtained by dividing R_c by 2.

Put in operational terms, the quantity R_c is measured using the techniques defined in U.S. Patent 5,075,626 (Vail, 1991c). Then, the total real resistor connecting the portion of the casing spanned by Electrodes C, D, and E to electrical infinity is given by the following quantity: $(R_c / 2)$.

There is yet another way to verify the basic validity of Equation VIII-A-12. Please refer to Figure VIII-A-4 that shows the "Extended Piece-Wise Continuous Resistor Model". Here, Electrode D of the TCRT is placed at "position number 3" along the casing. At position number 3, the TCRT measures resistor $R_c(3)$. Moving down one electrode spacing from the position shown, the TCRT would then measure $R_c(4)$. Again translating down one more position, the TCRT would then measure $R_c(5)$. This process would continue until n resistors would be measured up to value of $R_c(n)$.

It is evident from inspection of Figure VIII-A-4, that there is one resistor R_c connecting each portion of the casing having the length of ONE ELECTRODE SPACING to infinity. Therefore, there are two such resistors in general connecting a portion of the casing spanned by Electrodes C, D, and E to infinity.

For example in Figure VIII-A-4, it would be logical to compute $R(\text{REAL at position 3})$ as follows using the parallel resistor formula and assuming for simplicity that resistors $R_c(3)$ and $R_c(4)$ are associated with position 3:

$$\{ 1 / R(\text{REAL at position 3}) \} = 1 / R_c(3) + 1 / R_c(4)$$

Equation VIII-A-13

Assuming that all of the values of the above resistors are equal to R_c , then the following is true:

$$R(\text{REAL at position 3}) = R_c / 2$$

Equation VIII-A-14

Equations VIII-A-14 and VIII-A-12 are the same for the purposes herein. The above logic can be extended to use portions of the resistors symmetrically about Electrode D, but the results are the same.

FIGURE VIII-A-4
EXTENDED PIECE-WISE CONTINUOUS
RESISTOR MODEL

Therefore, the principal conclusion of Section VIII-A is as follows:

The "real resistor to infinity in ohms that connects the portion of the casing spanned by Electrodes C, D, and E to electrical infinity" is obtained by dividing R_c by 2 where R_c is measured with the TCRT.

Question: Does any of this herein regarding R(REAL) change any equation in U.S. Patent No. 5,075,626? Answer - No.

Note: It should be further stated that the conclusions herein concerning the true real current leakage "TRCL" and the true resistor to infinity R(REAL) have also been independently confirmed with experiments involving PML's Moving Test Jig used within a test casing located at PML's laboratory. Resistors simulating R(REAL) attached to the test casing provide true real current leakage "TRCL". Measurements of ΔI and R_c from within the test casing with the Moving Test Jig are used to calculate R(REAL) and "TRCL". Agreement is found providing further confirmation of the proper operation of the equipment, the basic theory of operation, and the method of interpretation of the results.

The relationship between the Piece-Wise Continuous Resistor Model and the Continuum Model does have immediate implications concerning how to use standard equations in the literature to approximately calculate the Calibration Constant K from first principles. Towards that end, the next section provides a brief review of the relevant formulas in the literature that are used thereafter to provide an approximate analytical formula for K.

SECTION VIII - B

BRIEF REVIEW OF EQUATIONS IN LITERATURE TO CALCULATE RESISTANCE OF CYLINDERS BURIED IN THE EARTH

1. Equations from Tagg (1964)

(A.) Equation 6.6 on page 96 in Tagg (1964) presents the "resistance of a driven rod" as follows:

$$R = \left\{ \rho / 2 \pi L \right\} \left\{ \ln [4 L / d] \right\}$$

Here R is the electrical resistance to current flow off the cylinder; ρ is the average resistivity of the half-space; L is the length of the cylinder; and d is the diameter of the cylinder. The prior discussion on page 94 of Tagg (1964) shows that the equation above is an approximation that derives from assuming the rod is really an ellipsoid of revolution where the length of the major axis is much longer than that of the minor axis. Therefore, this equation is an approximation at best.

(B.) Equation 6.8 on page 97 in Tagg (1964) presents the "alternative formula" for the resistance of the driven rod as follows:

$$R = \left\{ \rho / 2 \pi L \right\} \left\{ \ln [8 L / d] - 1 \right\}$$

This is derived assuming a uniform charge per unit length and assuming that all higher order terms in (d / L) are small. Page 98 of Tagg (1964) states that the resistance calculated here is generally slightly smaller than that calculated from the previous equation in part (A.) above.

2. Equations from Sunde (1949)

(A.) Equation 3.24 on page 75 in Sunde (1949) presents the resistance of a cylindrical conductor as follows on the next page, with the definition of X provided here to simplify the expression.

Let $X = \{ 1 + (a / 2 L)^2 \}^{1/2}$; and then

$$R_1 = \{ \rho / 2 \pi L \} \{ \ln [(2 L / a) (1 + X)] + a / 2 L - X \}$$

Here, R_1 is the resistance to current flow off the cylinder; ρ is the resistivity of the medium of infinite extent in all directions; L is the length of the cylinder; and a is the radius of the cylinder.

(B.) Equation 3.24 above simplifies when a is much smaller than L to the following approximation given by Equation 3.25 on page 75 in Sunde (1949):

$$R_1 = \{ \rho / 2 \pi L \} \{ \ln [4 L / a] - 1 \}$$

With $d = 2a$, then this becomes:

$$R_1 = \{ \rho / 2 \pi L \} \{ \ln [8 L / d] - 1 \}$$

This is the same equation as Equation 6.8 on page 97 in Tagg (1964).

3. Summary

It is clear that Equation 3.24 on page 75 in Sunde (1949) should be used for short cylinders. For cylinders where (d / L) is very small, then any of the above approximations appear to give similar results.

SECTION VIII - C

QUANTITATIVE CALCULATION OF CALIBRATION CONSTANT K FROM FIRST PRINCIPLES & COMPARISON WITH DATA

1. Basic Formulae

Part 2 in Section VIII-B reviewed Equation 3.24 on page 75 in Sunde (1949) that gives the resistance R_1 of a cylindrical conductor buried in the earth as follows:

$$\text{Let } X = \{ 1 + (a / 2 L)^2 \}^{1/2}$$

Equation VIII-C-1

Then;

$$R_1 = \{ \rho / 2 \pi L \} \{ \ln [(2 L / a) (1 + X)] + a / 2 L - X \}$$

Equation VIII-C-2

It is further convenient to define the following:

$$\{\text{SUNDE}\} = \{ \ln [(2 L / a) (1 + X)] + a / 2 L - X \}$$

Equation VIII-C-3

Then R_1 from Sunde (1949) becomes the following:

$$R_1 = \{ \rho / 2 \pi L \} \{\text{SUNDE}\}$$

Equation VIII-C-4

The quantity R_1 in Sunde (1949) is the total resistance to electrical infinity of the buried cylinder. In terms of Section VIII-A, R_1 is called $R(TOTAL)$ in this Final Report. Therefore, in terms of the variables herein:

$$R(TOTAL) = \{ \rho / 2 \pi L \} \{ SUNDE \}$$

Equation VIII-C-5

Here the quantity L is the total length of the cylinder buried into the earth. It is important to note that this length L corresponds to the entire length between Electrodes C, D, and E. That entire length L leaks current into the formation in the Continuum Model. Therefore, it is necessary to define the following:

$$ONE \text{ ELECTRODE SPACING} = "ELECTSP"$$

$$= \text{DISTANCE BETWEEN ELECTRODES C \& D}$$

$$= \text{DISTANCE BETWEEN ELECTRODES D \& E}$$

Equation VIII-C-6

The variable with the long name "ELECTSP" cannot be confused with the length L between Electrodes C, D, and E. Therefore:

$$L = 2 (ELECTSP)$$

Equation VIII-C-7

Therefore, L has been properly defined. Now it is necessary to return to the task of obtaining an explicit approximate analytical formula for the Calibration Constant K .

At this point it is necessary to obtain a relationship between $R(TOTAL)$ and R_c . $R(TOTAL)$ is NOT equal to $R(REAL)$ given by Equation VIII-A-14. This is so because the above equation VIII-C-5 INCLUDES the resistance into formation from the two end-caps of the short cylinder, whereas $R(REAL)$ defined in Equation VIII-A-14 does NOT.

There is a crude approximation to handle this problem. Please refer to Figure VIII-C-1 that shows a short buried cylinder.

FIGURE VIII-C-1
CYLINDRICAL ELECTRODE
OF LENGTH L & ELECTRODES C , D , AND E

Equation VIII-A-12 and the Equation VIII-A-14 both show that for calculation purposes, the value of R_C attached between Electrodes C-D to infinity and another such value of R_C attached between Electrodes D-E to infinity can be used to calculate currents flowing off a long pipe. Therefore, to calculate $R(TOTAL)$ from a short buried cylinder, imagine that a first resistor R_C connects the portion of the short cylinder spanned by Electrodes C-D to infinity; that a second resistor R_C connects the portion of the short cylinder spanned by Electrodes D-E to infinity; that a third resistor R_C connects the top end of the short cylinder to infinity; and that a final fourth resistor R_C connects the bottom end of the short cylinder to infinity. Therefore, there are four resistors having the value of R_C connected in parallel to infinity, and using this approximation, we obtain the following:

$$R(TOTAL) = R_C / 4 \quad \text{Equation VIII-C-8}$$

Using Equation VIII-C-8, Equation VIII-C-5 then becomes:

$$\rho = [\pi L / 2 \{SUNDE\}] R_C \quad \text{Equation VIII-C-9}$$

Using the definition of the Calibration Constant K from Equation 3, the Calibration Constant K is finally given as follows:

$$K = \pi L / 2 \{SUNDE\} \quad \text{Equation VIII-C-10}$$

To summarize, K is to be calculated with Equation VIII-C-10. The quantity $\{SUNDE\}$ is given by Equation VIII-C-3; X is needed for the calculation of $\{SUNDE\}$ that is defined in Equation VIII-C-1; and L is defined in Equation VIII-C-7.

This is the principle result of most of the work to this point in Sections VIII-A, VIII-B, and herein. The next task is to use that formula to calculate the Calibration Constant K for different cases.

2. Calculation of the Calibration Constant K for
the MWX-2 Well in Rifle, Colorado and for
PML's Test Well in Woodinville, Washington

For both of these wells, the O.D. of the casing was 7 inches.
Therefore, the radius a is given as follows:

$$a = 3.5 \text{ inches} = .0889 \text{ meters}$$

The Electrode Spacing between C and D is 19 13/16 inches. The
Electrode Spacing between D and E is 19 13/16 inches. Therefore,
One Electrode Spacing "ELECTSP" is 19 13/16 inches. Therefore, L
is given as follows:

$$L = 2 \text{ (ELECTSP)} = 39.625 \text{ inches} = 1.006 \text{ meters}$$

Various other quantities of interest may now be calculated as
follows:

$$a / 2 L = .04418$$

$$2 L / a = 22.632$$

$$X = 1.00098$$

$$\{\text{SUNDE}\} = 2.856$$

Therefore,

$$K = .550 L$$

Using the value of L above in meters,

$$K = .553 \text{ meters}$$

This is the theoretical calculation of K, and therefore:

$$K(\text{THEORY}) = .553 \text{ meters}$$

The value of K actually used at the Test Well in Woodinville, Washington and at the MWX-2 Well in Rifle, Colorado was .489 meters. Therefore,

$$K(\text{USED AT MWX-2 WELL}) = .489 \text{ meters}$$

It is evident that:

$$\{ K(\text{THEORY}) \} / \{ K(\text{USED AT MWX-2 WELL}) \} = 1.13$$

Therefore, the theory set forth in this Final Report is able to calculate the approximate quantitative value of the Calibration Constant K used at the MWX-2 Well and at PML's Test Well in Woodinville, Washington to an accuracy of about 13%.

Here, K from theory is about 13% greater than the value of K used at the MWX-2 Well and at PML's Test Well in Woodinville, Washington.

This has the appearance of stunning agreement between first principles calculations set forth in this Final Report and the prior theory and measurements appearing in PML's U.S. patents on the subject as defined above.

The Calibration Constant K here is calculated particularly assuming that Electrode A of the TCRT is driven. Figure 73 shows the results of such measurements at the MWX-2 Well. The 5 Point Moving Average at 4605 feet gives about 60 ohm-meters from Figure 73. However, the ILD002 in this same region is about 70 ohm-meters. Therefore, this data suggests that the Calibration Constant K should be increased for this data by 16.67% if the Apparent Resistivity is to agree with the ILD002. Therefore, that data suggests that K should have been chosen equal to approximately .571 meters. Therefore:

$$\text{Corrected K (For Data in Figure 73)} = .571 \text{ meters}$$

The above theory shows that $K(\text{THEORY}) = .553$ meters. Therefore, the Corrected K (For Data in Figure 73) and $K(\text{THEORY})$ agree to approximately 3% in this case.

It is known that the theory set forth in Section VIII-C would be most applicable to energizing Electrode A rather than energizing the top of the casing. There are several reasons for this fact. Any calculations of the Calibration Constant K here neglect surface effects which might be more important if the top of the casing is driven. Furthermore, certain A.C. effects are accentuated if the top of the casing is driven because the phase of the driving current is assumed to be in-phase with the Potential Voltage V_0 at depth at the frequency of measurement. The theory set forth in Section VIII-C to calculate the Calibration Constant K does not take into account any surface effects or remnants of A.C. effects. It is therefore to be expected that the theory and experiment would agree better if the Electrode A is driven. That appears to be the case here.

3. Calculation of the Calibration Constant K for the Research Well in Fort Worth, Texas

The dimensions used for the well herein may be found in Vail, et. al. (1993b).

The O.D. of the casing was 8 5/8 inches. Therefore, the radius a is given as follows:

$$a = 4.3125 \text{ inches} = .1095 \text{ meters}$$

The Electrode Spacing between C and D is 56 7/8 inches. The Electrode Spacing between D and E is 56 7/8 inches. Therefore, One Electrode Spacing "ELECTSP" is 56 7/8 inches. Therefore, L is given as follows:

$$L = 2 \text{ (ELECTSP)} = 113.75 \text{ inches} = 2.8893 \text{ meters}$$

Various other quantities of interest may now be calculated as follows:

$$a / 2 L = .01895$$

$$2 L / a = 52.773$$

$$X = 1.00018$$

$$\{\text{SUNDE}\} = 3.6780$$

Therefore,

$$K = .427 L$$

Using the value of L above in meters,

$$K = 1.233 \text{ meters}$$

This is the theoretical calculation of K, and therefore:

$$K(\text{THEORY}) = 1.233 \text{ meters}$$

The value of K actually empirically determined at the Research Well in Forth Worth, Texas was 1.407 meters. Therefore,

$$K(\text{USED IN FORT WORTH}) = 1.407 \text{ meters}$$

It is evident that:

$$\{ K(\text{THEORY}) \} / \{ K(\text{USED IN FORT WORTH}) \} = .876$$

Therefore, the theory set forth in this Final Report is able to calculate the approximate quantitative value of the Calibration Constant K used at the Research Well in Forth Worth, Texas to an accuracy of about 13%.

Here, K from theory is about 13% less than K empirically determined at the Test Well in Forth Worth, Texas.

This again has the appearance of reasonable agreement between first principles calculations set forth in this Final Report and the prior theory and measurements appearing in PML's U.S. patents on the subject as defined above.

4. Future Study of PML's Calibration Constant K

The authors hope that the encouraging agreement between theory and experiment in this Section VIII-C of the Final Report would encourage further serious study of PML's Calibration Constant K.

5. Various Sets of Model Calculations & the Parameter γK

The authors have calculated a set of curves for the Calibration Constant for various electrode spacings and for various pipe O.D.'s.

It is convenient to use the symbol γK as follows:

$$\gamma K = K / (\text{ELECTSP}) \quad \text{Equation VIII-C-11}$$

The quantity γK is the ratio of the Calibration Constant K in meters to the Electrode Spacing in meters. Therefore, the quantity γK is a dimensionless quantity.

Mr. Steven T. Momii has used Math Cad to calculate the following figures involving γK .

SET A: For a Chosen O.D. of the Casing, Plot γK vs. ELECTSP

Figure VIII-C-2, O.D. = 4 1/2 inches

Figure VIII-C-3, O.D. = 5 1/2 inches

Figure VIII-C-4, O.D. = 7 inches

Figure VIII-C-5, O.D. = 7 5/8 inches

Figure VIII-C-6, O.D. = 8 5/8 inches

Figure VIII-C-7, O.D. = 9 5/8 inches

Figure VIII-C-8, O.D. = 13 3/8 inches

These curves will can be used in practice to obtain K for a given O.D. of the casing.

For example, Figure VIII-C-4 shows that γK for 7 inch O.D casing appropriate for the MWX-2 Well. For an ELECTSP of 19 13/16 inches, γK is approximately unity from inspection of Figure VIII-C-4. K actually used for 7 inch O.D. casing at the MWX-2 Well was .489 meters or 19.25 inches. Therefore, the theory predicts a γK near unity that matches the experimental results (19.25 inches / 19 13/16 inches = 0.97).

As another example, Figure VIII-C-6 shows that γK for 8 5/8 inch O.D casing appropriate for The Research Well in Fort Worth,

Texas. For an ELECTSP near $56 \frac{7}{8}$ inches, γK is approximately 0.9 from inspection of Figure VIII-C-6. K actually used for the $8 \frac{5}{8}$ inch O.D. casing was 1.407 meters or about 55.4 inches. Therefore, the theory predicts a γK near .9 that approximately matches the experimental results ($55.4 \text{ inches} / 56 \frac{7}{8} \text{ inches} = 0.97$).

SET B: For a Chosen Electrode Spacing (ELECTSP), Plot γK vs. O.D. of the Casing

Figure VIII-C-9, ELECTSP = $19 \frac{13}{16}$ inches

Figure VIII-C-10, ELECTSP = $56 \frac{7}{8}$ inches

Certain mechanical designs of the Through Casing Resistivity Tool provide for fixed electrode separation that works in variable O.D. casings. For example, a tool with $19 \frac{13}{16}$ inch separation of electrodes could be designed to work in casings having the ranges of 5.5 inches O.D. to $8 \frac{5}{8}$ inches O.D. Figure VIII-C-9 would then give K for different O.D. of casings.

SET C: Calculations Relevant to Extremely Large Limits of the O.D. of the Casings

Figure VIII-C-11, for ELECTSP = $19 \frac{13}{16}$ inches, γK vs. O.D. is plotted for O.D. up to 10,000 inches.

Figure VIII-C-12, for ELECTSP = $56 \frac{7}{8}$ inches, γK vs. O.D. is plotted for O.D. up to 10,000 inches.

These figures show that for very large O.D., K is approximately linear with O.D. These curves are only useful to the specialist studying extreme mathematical values of K.

SET D: Calculations Relevant to Extremely Large Electrode Spacings

Figure VIII-C-13, for ELECTSP = 10,000 inches, γK vs. O.D. of the casing is plotted.

Figure VIII-C-14, for ELECTSP = 100,000 inches, γK vs. O.D. of the casing is plotted.

Figure VIII-C-15, for ELECTSP = 1,000,000 inches, γK vs. O.D. of the casing is plotted.

It is the intent of the authors to compare these extreme limits with analytical limits of the equations at a later date. These curves in SET D are only useful to the specialist studying extreme mathematical values of K.

SET E: Topics Related to Understanding the Physics of γK

Figure VIII-C-16, lines of constant γK are plotted on a graph having the O.D. as the ordinate and the ELECTSP as the abscissa. Each curve is labeled with constant γK for values of $\gamma K = 1.0, 1.5, \text{ and } 2.0$. Both the O.D. and ELECTSP are in units of inches.

Figure VIII-C-17, sets of curves of γK vs. ELECTSP are plotted for different O.D. of casings. The curves are plotted with an increasing parameter of the O.D. of the casing, spanning the range from an O.D. of $1/8$ inch to $15 \frac{1}{8}$ inches. Both the O.D. and ELECTSP are in units of inches.

These plots can be useful to understand the physics of γK . However, these curves in SET E are primarily useful to the specialist for tool design purposes and to the theoretician comparing functional dependencies.

SET F: Topics Related to Determining Extreme Limits of γK for Large Values of ELECTSP to Investigate Mathematical Convergence of γK

Figure VIII-C-18, sets of curves of γK vs. ELECTSP are plotted for values of ELECTSP spanning 10 inches to 10,000 inches.

Figure VIII-C-19, sets of curves of γK vs. ELECTSP are plotted for values of ELECTSP spanning 10 inches to 1,000,000 inches.

It is the intent of the authors to compare these extreme limits with analytical limits of the equations at a later date. These curves in SET F are only useful to the specialist studying extreme mathematical values of K.

SET G: For a Chosen Electrode Spacing (ELECTSP) of 0.5, 1.0, and 2.0 Meters, Plot γK vs. O.D. of the Casing

Figure VIII-C-20, ELECTSP = 0.50 meters

Figure VIII-C-21, ELECTSP = 1.0 meters

Figure VIII-C-22, ELECTSP = 2.0 meters

Certain theoretical calculations have been performed in the literature assuming an ELECTSP of 1.0 meters. The purpose of these curves is to provide the specialist easy and rapid comparison with the calculations of γK herein.

6. Inapplicability of Coaxial Transmission Line Models to Calculate K

The quantity K cannot be calculated using the cylindrical model described in Section VIII-F. While the Leaky Capacity Model can provide reasonable answers for radii relatively close to the casing, it is subject to giving infinite answers at the radius of infinity. This is the "infinity problem" typically found in cylindrical geometries at great radii. For example, allowing the radius "c" defined on page VIII-F-1 go to infinity in Equation VIII-F-4 gives an infinite answer for the apparent resistance (in ohms). Therefore, this approach cannot be used to numerically calculate K.

In the authors' opinion, an analogous problem was encountered by Kaufman (1990). A very important equation, which has no number that follows Equation (51) on page 36 of Kaufman (1990), is central to the method set forth in that paper to obtain apparent resistivity from TCRT type measurements. In that non-numbered extremely important equation, the natural log of the ratio of outer to inner cylindrical radii is arbitrarily set equal to the number of 2π . That equation is quoted as follows from Kaufman (1990):

$$2\pi = \ln \frac{b}{a} \quad \begin{array}{l} \text{non-numbered equation} \\ \text{in Kaufman (1990)} \end{array}$$

Here, "a" is the radius of the casing and "b" is the radius to a "...cylindrical surface with zero potential..." located at "...a sufficient distance from the borehole" quoting from Kaufman (1990). In the opinion of the authors, this is a device used by Kaufman (1990) to get around the above defined "infinity problem".

In their final reports to ParaMagnetic Logging, Inc., Morrison and Schenkel (1991a and 1991b) have carefully studied Kaufman (1990) and the above non-numbered equation. Professor Morrison and Dr. Schenkel provide a quote on page 5 of their final reports related to certain fundamental assumptions made in Kaufman (1990) resulting in equations (13) and (14) in their final reports which are crucial to Kaufman (1990) obtaining resistivity from the above non-numbered equation presented by Kaufman (1990). Morrison and Schenkel (1991a and 1991b) state on page 5 in relation to those equations (13) and (14) used in Kaufman (1990): "It is not obvious that equations (13) and (14) are valid." They further state in relation to the conclusions of Kaufman (1990) relating to the above non-numbered equation: "With no theoretical evidence to support equation (14), this expression for sufficient distance appears to be an accommodating relation to obtain the formation resistivity directly from the transverse resistance." Therefore, Morrison and Schenkel (1991a and 1991b) apparently corroborate the opinion of the authors stated the previous paragraph concerning the non-numbered equation appearing in Kaufman (1990).

The authors wish to make the following point here concerning the calculation of K. If Kaufman (1990) were hypothetically used to calculate K based on the use of the above defined non-numbered equation that was criticized by Morrison and Schenkel (1991a and 1991b), the value of K so determined would depend upon the arbitrary number chosen by Kaufman (1990) which is the natural logarithm of the ratio of the outer radius to the "cylindrical surface with zero potential" to the inner radius of the casing. Therefore, Kaufman (1990) cannot be used to calculate K unless such problems involving arbitrarily chosen numbers are addressed in some other fundamental way.

Further, the rigorous form of the solution to a true coaxial transmission model of the casing problem cannot be used to calculate K. In the rigorous form of the coaxial transmission line model, the outer boundary is set equal to some particular radius. The value of K calculated from a coaxial transmission line model would necessarily depend upon the exact value of that radius. Further, if that radius were allowed to go to infinity, the usual "infinity problem" typically found in cylindrical geometries would appear. To the extent that Kaufman and Wightman (1993a) is based on coaxial transmission line equations, that work cannot be used to accurately calculate K for the same reasons.

There are ways to calculate K. The authors have set forth a very simple approximate method in the earlier portions of this Section. Further, Morrison and Schenkel (1991a and 1991b) show that K can be calculated from first principles. It is the understanding of the authors that certain forms of the methods

set forth in Tabarovsky, et. al. (1994) could also be used to calculate K. Any valid solution to Maxwell's Equations which properly takes into account current flow at infinity can be used to calculate K.

However, if any coaxial model is chosen that has an arbitrarily chosen outer radius, any such coaxial model cannot by itself be used to accurately calculate K. Instead, some other relationship would be needed in addition to the coaxial transmission line model to determine the actual resistance in ohms to infinity such as that which resulted in the author's determination of K in Equation VIII-C-10 based upon Sunde (1949).

As a final note, the authors do not wish to minimize the utility of certain results based upon coaxial transmission line models. The influence of certain A.C. phenomena can be approximately calculated from such models. The authors use coaxial transmission line models for the calculation of certain A.C. phenomena. However, rigorous coaxial transmission line models by themselves cannot be used to calculate K without some other additional feature added to the coaxial models.

CALIBRATION CONSTANT K
KCAL.MCD 7/8/94

$i := 0, 1 \dots 1024$

$ELECTSP_i := \left(6 + \frac{i}{16}\right)$ ELECTRODE SPACING IN INCHES

$L_i := 2 \cdot ELECTSP_i \cdot 0.0254$ L IN METERS

$OD := 4 + \frac{1}{2}$ OD OF CASING IN INCHES

$a := \frac{OD \cdot 0.0254}{2}$ RADIUS OF CASING IN METERS

$X_i := \sqrt{1 + \left[\frac{a}{(2 \cdot L_i)}\right]^2}$

$SUNDE_i := \ln \left[\left(2 \cdot \frac{L_i}{a}\right) \cdot (1 + X_i) \right] + \frac{a}{2 \cdot L_i} - X_i$

$K_i := \frac{\pi \cdot L_i}{2 \cdot SUNDE_i}$

$\gamma K_i := \frac{K_i}{(ELECTSP_i \cdot 0.0254)}$

FIGURE VIII-C-2

CALIBRATION CONSTANT K
KCAL.MCD 7/8/94

$i := 0, 1 \dots 1024$

$ELECTSP_i := \left(6 + \frac{i}{16}\right)$ ELECTRODE SPACING IN INCHES

$L_i := 2 \cdot ELECTSP_i \cdot 0.0254$ L IN METERS

$OD := 5 + \frac{1}{2}$ OD OF CASING IN INCHES

$a := \frac{OD - 0.0254}{2}$ RADIUS OF CASING IN METERS

$X_i := \sqrt{1 + \left[\frac{a}{(2 \cdot L_i)}\right]^2}$

$SUNDE_i := \ln \left[\left(2 \cdot \frac{L_i}{a}\right) \cdot (1 + X_i) \right] + \frac{a}{2 \cdot L_i} - X_i$

$K_i := -\frac{\pi \cdot L_i}{2 \cdot SUNDE_i}$

$\gamma K_i := \frac{K_i}{(ELECTSP_i \cdot 0.0254)}$

FIGURE VIII-C-3

CALIBRATION CONSTANT K
KCAL.MCD 7/8/94

$i := 0, 1 \dots 1024$

$ELECTSP_i := \left(6 + \frac{i}{16}\right)$ ELECTRODE SPACING IN INCHES

$L_i := 2 \cdot ELECTSP_i \cdot 0.0254$ L IN METERS

$OD := 7$ OD OF CASING IN INCHES

$a := \frac{OD - 0.0254}{2}$ RADIUS OF CASING IN METERS

$X_i := \sqrt{1 + \left[\frac{a}{(2 \cdot L_i)}\right]^2}$

$SUNDE_i := \ln \left[\left(2 \cdot \frac{L_i}{a}\right) \cdot (1 + X_i) \right] + \frac{a}{2 \cdot L_i} - X_i$

$K_i := -\frac{\pi \cdot L_i}{2 \cdot SUNDE_i}$

$\gamma K_i := \frac{K_i}{(ELECTSP_i \cdot 0.0254)}$

FIGURE VIII-C-4

CALIBRATION CONSTANT K
KCAL.MCD 7/8/94

$i := 0, 1 \dots 1024$

$ELECTSP_i := \left(6 + \frac{i}{16}\right)$ ELECTRODE SPACING IN INCHES

$L_i := 2 \cdot ELECTSP_i \cdot 0.0254$ L IN METERS

$OD := 7 + \frac{5}{8}$ OD OF CASING IN INCHES

$a := \frac{OD \cdot 0.0254}{2}$ RADIUS OF CASING IN METERS

$X_i := \sqrt{1 + \left[\frac{a}{(2 \cdot L_i)}\right]^2}$

$SUNDE_i := \ln \left[\left(2 \cdot \frac{L_i}{a}\right) \cdot (1 + X_i) \right] + \frac{a}{2 \cdot L_i} - X_i$

$K_i := \frac{\pi \cdot L_i}{2 \cdot SUNDE_i}$

$\gamma K_i := \frac{K_i}{(ELECTSP_i \cdot 0.0254)}$

FIGURE VIII-C-5

CALIBRATION CONSTANT K
KCAL.MCD 7/8/94

$i := 0, 1 \dots 1024$

$ELECTSP_i := \left(6 + \frac{i}{16}\right)$ ELECTRODE SPACING IN INCHES

$L_i := 2 \cdot ELECTSP_i \cdot 0.0254$ L IN METERS

$OD := 8 + \frac{5}{8}$ OD OF CASING IN INCHES

$a := \frac{OD \cdot 0.0254}{2}$ RADIUS OF CASING IN METERS

$X_i := \sqrt{1 + \left[\frac{a}{(2 \cdot L_i)}\right]^2}$

$SUNDE_i := \ln \left[\left(2 \cdot \frac{L_i}{a}\right) \cdot (1 + X_i) \right] + \frac{a}{2 \cdot L_i} - X_i$

$K_i := -\frac{\pi \cdot L_i}{2 \cdot SUNDE_i}$

$\gamma K_i := \frac{K_i}{(ELECTSP_i \cdot 0.0254)}$

FIGURE VIII-C-6

CALIBRATION CONSTANT K
KCAL.MCD 7/8/94

$i := 0, 1 \dots 1024$

$ELECTSP_i := \left(6 + \frac{i}{16}\right)$ ELECTRODE SPACING IN INCHES

$L_i := 2 \cdot ELECTSP_i \cdot 0.0254$ L IN METERS

$OD := 9 + \frac{5}{8}$ OD OF CASING IN INCHES

$a := \frac{OD \cdot 0.0254}{2}$ RADIUS OF CASING IN METERS

$$X_i := \sqrt{1 + \left[\frac{a}{(2 \cdot L_i)}\right]^2}$$

$$SUNDE_i := \ln \left[\left(2 \cdot \frac{L_i}{a}\right) \cdot (1 + X_i) \right] + \frac{a}{2 \cdot L_i} - X_i$$

$$K_i := -\frac{\pi \cdot L_i}{2 \cdot SUNDE_i}$$

$$\gamma K_i := \frac{K_i}{(ELECTSP_i \cdot 0.0254)}$$

FIGURE VIII-C-7

CALIBRATION CONSTANT K
KCAL.MCD 7/8/94

$i := 0, 1..1024$

$ELECTSP_i := \left(6 + \frac{i}{16}\right)$ ELECTRODE SPACING IN INCHES

$L_i := 2 \cdot ELECTSP_i \cdot 0.0254$ L IN METERS

$OD := 13 + \frac{3}{8}$ OD OF CASING IN INCHES

$a := \frac{OD \cdot 0.0254}{2}$ RADIUS OF CASING IN METERS

$X_i := \sqrt{1 + \left[\frac{a}{(2 \cdot L_i)}\right]^2}$

$SUNDE_i := \ln \left[\left(2 \cdot \frac{L_i}{a}\right) \cdot (1 + X_i) \right] + \frac{a}{2 \cdot L_i} - X_i$

$K_i := -\frac{\pi \cdot L_i}{2 \cdot SUNDE_i}$

$\gamma K_i := \frac{K_i}{(ELECTSP_i \cdot 0.0254)}$

FIGURE VIII-C-8

$$j := 0, 1, \dots, 111$$

$$\text{ELECTSP} := 19 + \frac{13}{16}$$

ELECTRODE SPACING IN INCHES

$$L := 2 \cdot \text{ELECTSP} \cdot 0.0254$$

L IN METERS

$$\text{OD}_j := \frac{1}{8} + \frac{j}{8}$$

OD OF CASING IN INCHES

$$a_j := \frac{\text{OD}_j \cdot 0.0254}{2}$$

RADIUS OF CASING IN METERS

$$X_j := \sqrt{1 + \left[\frac{a_j}{(2 \cdot L)} \right]^2}$$

$$\text{SUNDE}_j := \left[\ln \left[\left(2 \cdot \frac{L}{a_j} \right) \cdot (1 + X_j) \right] + \frac{a_j}{(2 \cdot L)} \right] - X_j$$

$$K_j := \frac{\pi \cdot L}{2 \cdot \text{SUNDE}_j}$$

$$\gamma K_j := \frac{K_j}{(\text{ELECTSP} \cdot 0.0254)}$$

FIGURE VIII-C-9

$$j := 0, 1 \dots 111$$

$$\text{ELECTSP} := 56 + \frac{7}{8}$$

$$L := 2 \cdot \text{ELECTSP} \cdot 0.0254$$

$$\text{OD}_j := \frac{1}{8} + \frac{j}{8}$$

$$a_j := \frac{\text{OD}_j \cdot 0.0254}{2}$$

$$X_j := \sqrt{1 + \left[\frac{a_j}{(2 \cdot L)} \right]^2}$$

$$\text{SUNDE}_j := \left[\ln \left[\left(2 \cdot \frac{L}{a_j} \right) \cdot (1 + X_j) \right] + \frac{a_j}{(2 \cdot L)} \right] - X_j$$

$$K_j := \frac{\pi \cdot L}{2 \cdot \text{SUNDE}_j}$$

$$\gamma K_j := \frac{K_j}{(\text{ELECTSP} \cdot 0.0254)}$$

ELECTRODE SPACING IN INCHES

L IN METERS

OD OF CASING IN INCHES

RADIUS OF CASING IN METERS

FIGURE VIII-C-10

$$j := 0, 1 \dots 999$$

$$\text{ELECTSP} := 19 + \frac{13}{16}$$

ELECTRODE SPACING IN INCHES

$$L := 2 \cdot \text{ELECTSP} \cdot 0.0254$$

L IN METERS

$$\text{OD}_j := 10 + j \cdot 10$$

OD OF CASING IN INCHES

$$a_j := \frac{\text{OD}_j \cdot 0.0254}{2}$$

RADIUS OF CASING IN METERS

$$X_j := \sqrt{1 + \left[\frac{a_j}{(2 \cdot L)} \right]^2}$$

$$\text{SUNDE}_j := \left[\ln \left[\left(2 \cdot \frac{L}{a_j} \right) \cdot (1 + X_j) \right] + \frac{a_j}{(2 \cdot L)} \right] - X_j$$

$$K_j := - \frac{\pi \cdot L}{2 \cdot \text{SUNDE}_j}$$

$$\gamma K_j := \frac{K_j}{(\text{ELECTSP} \cdot 0.0254)}$$

FIGURE VIII-C-11

$$j := 0, 1 \dots 999$$

$$\text{ELECTSP} := 56 + \frac{7}{8}$$

ELECTRODE SPACING IN INCHES

$$L := 2 \cdot \text{ELECTSP} \cdot 0.0254$$

L IN METERS

$$\text{OD}_j := 10 + j \cdot 10$$

OD OF CASING IN INCHES

$$a_j := \frac{\text{OD}_j \cdot 0.0254}{2}$$

RADIUS OF CASING IN METERS

$$X_j := \sqrt{1 + \left[\frac{a_j}{(2 \cdot L)} \right]^2}$$

$$\text{SUNDE}_j := \left[\ln \left[\left(2 \cdot \frac{L}{a_j} \right) \cdot (1 + X_j) \right] + \frac{a_j}{(2 \cdot L)} \right] - X_j$$

$$K_j := -\frac{\pi \cdot L}{2 \cdot \text{SUNDE}_j}$$

$$\gamma K_j := \frac{K_j}{(\text{ELECTSP} \cdot 0.0254)}$$

FIGURE VIII-C-12

$$j := 0, 1, \dots, 111$$

$$\text{ELECTSP} := 10000$$

$$L := 2 \cdot \text{ELECTSP} \cdot 0.0254$$

$$\text{OD}_j := \frac{1}{8} + \frac{j}{8}$$

$$a_j := \frac{\text{OD}_j \cdot 0.0254}{2}$$

$$X_j := \sqrt{1 + \left[\frac{a_j}{(2 \cdot L)} \right]^2}$$

$$\text{SUNDE}_j := \left[\ln \left[\left(2 \cdot \frac{L}{a_j} \right) \cdot (1 + X_j) \right] + \frac{a_j}{(2 \cdot L)} \right] - X_j$$

$$K_j := - \frac{\pi \cdot L}{2 \cdot \text{SUNDE}_j}$$

$$\gamma K_j := \frac{K_j}{(\text{ELECTSP} \cdot 0.0254)}$$

ELECTRODE SPACING IN INCHES

L IN METERS

OD OF CASING IN INCHES

RADIUS OF CASING IN METERS

FIGURE VIII-C-13

$j := 0, 1 \dots 111$

ELECTSP := 100000

ELECTRODE SPACING IN INCHES

$L := 2 \cdot \text{ELECTSP} \cdot 0.0254$

L IN METERS

$\text{OD}_j := \frac{1}{8} + \frac{j}{8}$

OD OF CASING IN INCHES

$a_j := \frac{\text{OD}_j \cdot 0.0254}{2}$

RADIUS OF CASING IN METERS

$X_j := \sqrt{1 + \left[\frac{a_j}{(2 \cdot L)} \right]^2}$

$\text{SUNDE}_j := \left[\ln \left[\left(2 \cdot \frac{L}{a_j} \right) \cdot (1 + X_j) \right] + \frac{a_j}{(2 \cdot L)} \right] - X_j$

$K_j := -\frac{\pi \cdot L}{2 \cdot \text{SUNDE}_j}$

$\gamma K_j := \frac{K_j}{(\text{ELECTSP} \cdot 0.0254)}$

FIGURE VIII-C-14

$$j := 0, 1, \dots, 111$$

$$\text{ELECTSP} := 1000000$$

$$L := 2 \cdot \text{ELECTSP} \cdot 0.0254$$

$$\text{OD}_j := \frac{1}{8} + \frac{j}{8}$$

$$a_j := \frac{\text{OD}_j \cdot 0.0254}{2}$$

ELECTRODE SPACING IN INCHES

L IN METERS

OD OF CASING IN INCHES

RADIUS OF CASING IN METERS

$$X_j := \sqrt{1 + \left[\frac{a_j}{(2 \cdot L)} \right]^2}$$

$$\text{SUNDE}_j := \left[\ln \left(2 \cdot \frac{L}{a_j} \cdot (1 + X_j) \right) + \frac{a_j}{(2 \cdot L)} \right] - X_j$$

$$K_j := - \frac{\pi \cdot L}{2 \cdot \text{SUNDE}_j}$$

$$\gamma K_j := \frac{K_j}{(\text{ELECTSP} \cdot 0.0254)}$$

FIGURE VIII-C-15

KCAL01.MCD

i:=0,1..64

ELECTSP_i:=6+i

j:=0,1..15

OD_j:= $\frac{1}{8}+j$

$$f(\text{ELECTSP}, \text{OD}) := \frac{\pi}{\ln \left[\frac{2 \cdot 2 \cdot \text{ELECTSP} \cdot 0.0254}{\left(\frac{\text{OD} \cdot 0.0254}{2} \right)} \cdot \left[1 + \sqrt{1 + \left(\frac{\frac{\text{OD} \cdot 0.0254}{2}}{2 \cdot 2 \cdot \text{ELECTSP} \cdot 0.0254} \right)^2} \right] + \frac{\frac{\text{OD} \cdot 0.0254}{2}}{2 \cdot 2 \cdot \text{ELECTSP} \cdot 0.0254} \cdot \left[1 + \sqrt{1 + \left(\frac{\frac{\text{OD} \cdot 0.0254}{2}}{2 \cdot 2 \cdot \text{ELECTSP} \cdot 0.0254} \right)^2} \right] \right]}$$

$\gamma K_{i,j} := f(\text{ELECTSP}_i, \text{OD}_j)$

FIGURE VIII-C-16

KCAL01.MCD

i := 0, 1..64

ELECTSP_i := 6 + i

j := 0, 1..15

OD_j := $\frac{1}{8} + j$

$$f(\text{ELECTSP}, \text{OD}) := \frac{\pi}{\ln \left[\frac{2 \cdot 2 \cdot \text{ELECTSP} \cdot 0.0254}{\left(\frac{\text{OD} \cdot 0.0254}{2} \right)} \right] \left[1 + \sqrt{1 + \left(\frac{\text{OD} \cdot 0.0254}{2 \cdot 2 \cdot \text{ELECTSP} \cdot 0.0254} \right)^2} \right] + \frac{\text{OD} \cdot 0.0254}{2 \cdot 2 \cdot \text{ELECTSP} \cdot 0.0254} \left[1 + \sqrt{1 + \left(\frac{\text{OD} \cdot 0.0254}{2 \cdot 2 \cdot \text{ELECTSP} \cdot 0.0254} \right)^2} \right]}$$

$\gamma K_{i,j} := f(\text{ELECTSP}_i, \text{OD}_j)$

FIGURE VIII-C-17

0

ELECTSP
(INCHES)

70

KCAL01.MCD

i := 0, 1..100

ELECTSP_i := 10 + 100·i

j := 0, 1..15

OD_j := $\frac{1}{8} + j$

$$f(\text{ELECTSP}, \text{OD}) := \frac{\pi}{\ln \left[\frac{2 \cdot 2 \cdot \text{ELECTSP} \cdot 0.0254}{\left(\frac{\text{OD} \cdot 0.0254}{2} \right)} \cdot \left[1 + \sqrt{1 + \left(\frac{\text{OD} \cdot 0.0254}{2 \cdot 2 \cdot \text{ELECTSP} \cdot 0.0254} \right)^2} \right] + \frac{\text{OD} \cdot 0.0254}{2 \cdot 2 \cdot \text{ELECTSP} \cdot 0.0254} \cdot \left[1 + \sqrt{1 + \left(\frac{\text{OD} \cdot 0.0254}{2 \cdot 2 \cdot \text{ELECTSP} \cdot 0.0254} \right)^2} \right] \right]}$$

$\gamma K_{i,j} := f(\text{ELECTSP}_i, \text{OD}_j)$

FIGURE VIII-C-18

i := 0, 1..100 KCAL01.MCD

ELECTSP_i := 10 + 10000 · i

j := 0, 1..15

OD_j := $\frac{1}{8} + j$

$$f(\text{ELECTSP}, \text{OD}) := \frac{\pi}{\ln \left[\frac{2 \cdot 2 \cdot \text{ELECTSP} \cdot 0.0254}{\left(\frac{\text{OD} \cdot 0.0254}{2} \right)} \cdot \left[1 + \sqrt{1 + \left(\frac{\frac{\text{OD} \cdot 0.0254}{2}}{2 \cdot 2 \cdot \text{ELECTSP} \cdot 0.0254} \right)^2} \right] + \frac{\frac{\text{OD} \cdot 0.0254}{2}}{2 \cdot 2 \cdot \text{ELECTSP} \cdot 0.0254} \cdot \left[1 + \sqrt{1 + \left(\frac{\frac{\text{OD} \cdot 0.0254}{2}}{2 \cdot 2 \cdot \text{ELECTSP} \cdot 0.0254} \right)^2} \right] \right]}$$

$\gamma K_{i,j} := f(\text{ELECTSP}_i, \text{OD}_j)$

FIGURE VIII-C-19

$$j := 0, 1, \dots, 111$$

$$\text{ELECTSP} := 0.5$$

ELECTRODE SPACING IN METERS

$$L := 2 \cdot \text{ELECTSP}$$

L IN METERS

$$\text{OD}_j := \frac{1}{8} + \frac{j}{8}$$

OD OF CASING IN INCHES

$$a_j := \frac{\text{OD}_j \cdot 0.0254}{2}$$

RADIUS OF CASING IN METERS

$$X_j := \sqrt{1 + \left[\frac{a_j}{(2 \cdot L)} \right]^2}$$

$$\text{SUNDE}_j := \left[\ln \left[\left(2 \cdot \frac{L}{a_j} \right) \cdot (1 + X_j) \right] + \frac{a_j}{(2 \cdot L)} \right] - X_j$$

$$K_j := \frac{\pi \cdot L}{2 \cdot \text{SUNDE}_j}$$

$$\gamma K_j := \frac{K_j}{(\text{ELECTSP})}$$

FIGURE VIII-C-20

$$j := 0, 1, \dots, 11$$

$$\text{ELECTSP} := 1.0$$

ELECTRODE SPACING IN METERS

$$L := 2 \cdot \text{ELECTSP}$$

L IN METERS

$$\text{OD}_j := \frac{1}{8} + \frac{j}{8}$$

OD OF CASING IN INCHES

$$a_j := \frac{\text{OD}_j \cdot 0.0254}{2}$$

RADIUS OF CASING IN METERS

$$X_j := \sqrt{1 + \left[\frac{a_j}{(2 \cdot L)} \right]^2}$$

$$\text{SUNDE}_j := \left[\ln \left[\left(2 \cdot \frac{L}{a_j} \right) \cdot (1 + X_j) \right] + \frac{a_j}{(2 \cdot L)} \right] - X_j$$

$$K_j := -\frac{\pi \cdot L}{2 \cdot \text{SUNDE}_j}$$

$$\gamma K_j := \frac{K_j}{(\text{ELECTSP})}$$

FIGURE VIII-C-21

$$j := 0, 1, \dots, 111$$

$$\text{ELECTSP} := 2.0$$

$$L := 2 \cdot \text{ELECTSP}$$

$$\text{OD}_j := \frac{1}{8} + \frac{j}{8}$$

$$a_j := \frac{\text{OD}_j \cdot 0.0254}{2}$$

$$X_j := \sqrt{1 + \left[\frac{a_j}{(2 \cdot L)} \right]^2}$$

$$\text{SUNDE}_j := \left[\ln \left[\left(2 \cdot \frac{L}{a_j} \right) \cdot (1 + X_j) \right] + \frac{a_j}{(2 \cdot L)} \right] - X_j$$

$$K_j := -\frac{\pi \cdot L}{2 \cdot \text{SUNDE}_j}$$

$$\gamma K_j := \frac{K_j}{(\text{ELECTSP})}$$

ELECTRODE SPACING IN METERS

L IN METERS

OD OF CASING IN INCHES

RADIUS OF CASING IN METERS

FIGURE VIII-C-22

SECTION VIII - D

QUANTITATIVE CALCULATION OF THE CHARACTERISTIC LENGTH (CL) FROM FIRST PRINCIPLES

1. Basic Theory of PML's Characteristic Length (CL)

In Section II, the importance of the Characteristic Length (CL) was simply stated. The Characteristic Length for the problem is defined in Equation 1 of U.S. Patent No. 5,187,440 (Vail, 1993a). The results of calculations performed in terms of that Characteristic Length appear in U.S. Patent No. 4,820,989 (Vail, 1989a) and are explicitly shown in Figures 6 - 9 of U.S. Patent No. 4,882,542 (Vail, 1989b) for a 1 ohm-meter formation having a Characteristic Length of approximately 320 meters. The Characteristic Length is defined as the length along a given borehole casing where 1/2 the current leaks off the casing.

Section VIII-E provided certain corrections to various equations appearing in PML's Patents. The correct equation corresponding to Equation 1 of U.S. Patent No. 5,187,440 (Vail, 1993a) is given by Equation VIII-E-2 that is restated herein as follows:

$$(CL) (r) = \rho \{ \ln [4 (CL) / d] \} / 2 \pi (CL)$$

Equation VIII-E-2

Here, the underlines showing changes have been removed that were present in the original form of this equation in Section VIII-E.

Here, CL is the Characteristic Length; r is the average resistance per unit length for the casing; ρ is the resistivity of a uniform formation; and d is the diameter of the casing. Equation VIII-E-2 is a transcendental equation that must be solved numerically.

This equation makes sense to calculate the Characteristic Length of the problem. As defined in the above references, the Characteristic Length is the distance along the casing it takes in a given uniform formation to leak 1/2 the current off the casing and into the formation. The resistance to current flow along the casing during a distance of CL is (CL) (r). The

resistance to current flow off of the casing of length CL into the formation is given by Equation 6.6 in Tagg (1964) that is presented in part 1.(A.) of Section VIII-B.

2. Calculation of the Characteristic Length for the MWX-2 Well in Rifle, Colorado

We will now calculate the Characteristic Length for the MWX-2 Well in Rifle, Colorado. From Figure 14, the average resistance per unit length of casing found at the MWX-2 Well in Rifle, Colorado was approximately 20 micro-ohms per Electrode Spacing.

Therefore:

$$\begin{aligned} r &= 20 \text{ micro-ohms} / \text{One Electrode Spacing} \\ &= 20 \text{ micro-ohms} / (19 \frac{13}{16} \text{ inches}) \\ &= 20 \text{ micro-ohms} / 1.651 \text{ feet} \\ &= 12.11 \text{ micro-ohms} / \text{foot} \end{aligned}$$

The square boxes on Figure VIII-D-1 show the results. Obtaining values from inspection of the figure, in a 1 ohm-meter uniform formation, the Characteristic Length for this case is about 600 feet. In a 10 ohm-meter formation it is about 2,000 feet. And in a 100 ohm-meter formation, it is about 7,000 feet.

3. Simplified Analytical Solution for PML's Characteristic Length (CL)

A simplified analytical solution to Equation VIII-E-2 was determined by Mr. Steven T. Momii over the resistivity range from .1 ohm-meter to 1,000 ohm-meters. Over this range, the solution to reasonable accuracy is given by the following approximation:

$$CL = (10 \rho / 2 \pi r)^{1/2} \quad \text{Equation VIII-D-1}$$

The exact solution and the simplified solution are plotted together on Figure VIII-D-2. It is evident that this analytical

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Figure VIII-D-1; 7" OD Casing; 19 13/16" Electrode Spacing
20 Micro-ohm Casing Resistance/ Electrode Spacing
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solution over the range from .1 ohm-meters to 1,000 ohm-meters is reasonable. After the evaluation of the relevant constants, Equation VIII-D-1 becomes:

$$CL = 1.26 \left(\rho / r \right)^{1/2} \quad \text{Equation VIII-D-2}$$

4. Comparison of PML's Characteristic Length with the Transmission Line Parameter α in Kaufman, et. al. (1993a)

Kaufman, et. al. (1993a) states that "within the intermediate zone the casing and borehole behave as a transmission line in a medium with cylindrical interfaces". A parameter α is determined, "where α is the parameter of the transmission line" that is Equation 3 in Kaufman, et. al. (1993a) that is given as follows:

$$\alpha = 1 / (ST)^{1/2}$$

Equation 5 in Kaufman, et. al. (1993a) concludes that the following is approximately true:

$$T = \rho$$

Equation 4 in Kaufman, et. al. (1993a) states the following where σ_c is the conductivity of the casing:

$$S = \sigma_c \ 2 \ \pi \ a \ \Delta a$$

If ρ_c is the resistivity of the casing, then the following relationship is true:

$$\sigma_c = 1 / \rho_c$$

Ohm's Law is used to calculate r , the resistance per unit length, as follows:

$$r = \rho_c / (2 \ \pi \ a \ \Delta a) \quad \text{Equation VIII-D-3}$$

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Figure VIII-D-2; 7" OD Casing; 19 13/16" Electrode Spacing
20 Micro-ohm Casing Resistance/ Electrode Spacing
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Then:

$$S = 1 / r$$

Equation VIII-D-4

Equation VIII-D-4 gives S herein; Equation 5 from Kaufman, et. al. (1993a) gives T; so that Equation 3 in Kaufman, et. al. (1993a) becomes the following using the variables defined herein:

$$\alpha = (r / \rho)^{1/2}$$

Equation VIII-D-5

The parameter α has the dimension of 1 / length. Therefore, the inverse of α is finally given as follows:

$$1 / \alpha = \text{"A LENGTH FROM TRANSMISSION LINE PARAMETER } \alpha \text{"}$$

$$= (\rho / r)^{1/2}$$

Equation VIII-D-6

The phrase "A LENGTH FROM TRANSMISSION LINE PARAMETER α " is a phrase defined herein in this Final Report. However, it is evident to the authors of this Final Report from the work in Kaufman, et. al. (1993a) that the parameter α is related to a fundamental length in the problem.

Please notice that the above defined "LENGTH FROM TRANSMISSION LINE PARAMETER α " in Equation VIII-D-6 agrees with PML's Characteristic Length in Equation VIII-D-2 to an accuracy of about 26%. This agreement is considered to be adequate considering the approximations used from both independent derivations. However, Kaufman, et. al. (1993a) does not state what fraction of current would leak off in the distance defined herein nor does Kaufman, et. al. (1993a) use the above terminology to describe the physics of the situation.

This agreement is further confirmation of the utility of PML's Characteristic Length and the theoretical consequences set forth in PML's various patents on this subject that use the concept of the Characteristic Length.

5. Comparison of PML's Characteristic Length with the
"Characteristic Length of the Problem" in
Tabarovsky, et. al. (1994)

Tabarovsky, et. al. (1994) names a theoretical section on page 2 as the "Characteristic Length of the Problem". On page 3 therein it states the following:

"If we define

$$z_c = 2 / \alpha = 2 (S R_f L_D)^{1/2} \quad (23)$$

we can see from Eq. (22) that 86.5% of the current leaks into formation from the casing at interval of $2 z_c$."

Tabarovsky, et. al. (1994) on page 3 further states:

"The precise analysis of the L_D factor will be performed later. Usually, it is of order 1 so that the assumption L_D (is approximately equal to) 1 is acceptable for obtaining estimates."

Therefore, for the remaining analysis in this section:

$$L_D = 1 \quad \text{Equation VIII-D-7}$$

Tabarovsky, et. al. (1994) uses the R_f for the formation resistivity that is called ρ herein. Therefore, for the remaining analysis in this section:

$$R_f = \rho \quad \text{Equation VIII-D-8}$$

From the remaining equations in Tabarovsky, et. al. (1994) and the equations used herein, we make the following correspondence between the casing conductance S and the resistance per unit length r herein:

$$S = 1 / r \quad \text{Equation VIII-D-9}$$

Substituting Equations VIII-D-7, VIII-D-8, and VIII-D-9 into Equation 23 from Tabarovsky, et. al. (1994) we obtain the following:

$$z_c = 2 (\rho / r)^{1/2} \quad \text{Equation VIII-D-10}$$

This equation has the same basic functional relationship of the variables as set forth in Equation VIII-D-2 above.

6. Summary of Relevant Equations

(A.) PML's Characteristic Length (CL)

PML's Characteristic Length wherein 50% of the current leaks off the casing (Vail 1989a, 1989b, and 1993a) is given by Equation VIII-D-2 above that is repeated herein as follows:

$$CL = 1.26 (\rho / r)^{1/2} \quad \text{Equation VIII-D-2}$$

(B.) A LENGTH FROM TRANSMISSION LINE PARAMETER α , where α is defined in Kaufman, et. al. (1993a)

This length is given by Equation VIII-D-6 above that is repeated herein as follows:

$$\begin{aligned} 1 / \alpha &= \text{"A LENGTH FROM TRANSMISSION LINE PARAMETER } \alpha \text{"} \\ &= (\rho / r)^{1/2} \end{aligned} \quad \text{Equation VIII-D-6}$$

(C.) The "Characteristic Length of the Problem" defined in Tabarovsky, et. al. (1994)

The Characteristic Length of the Problem z_c defined by Tabarovsky, et. al. (1994) is given by Equation VIII-D-10 above that is repeated herein as follows:

$$z_c = 2 (\rho / r)^{1/2}$$

Equation VIII-D-10

Here, 86.5% of the current leaks into formation from the casing in the casing interval $2 z_c$.

Summary: It is evident that all of the different approaches to this problem lead to essentially the same physical result. From the approximations involved in all of the different derivations, the authors of this Final Report consider the agreement between the various approaches to be acceptable.

SECTION VIII - E

CORRECTIONS TO SELECTED FORMULAE

IN PML'S TCRT PATENTS

It is first necessary to state that there are two sources of errors. An Error of the First Type is an error committed by Dr. Vail as the inventor. An Error of the Second Type is committed at the United States Patent and Trademark Office (USPTO) during typing. The USPTO completely re-types the entire patent after prosecution, and the inventor is never allowed to proof that document before it is issued by the USPTO. Sometimes, the inventor issues a Certificate of Correction.

1. U.S. Patent No. 4,820,989 - Vail (1989a)

Equation 6 on page 4 presently reads:

$$R_C = \rho \ln (\underline{4} L / d) / (4 \pi L)$$

Equation 6 on page 4 should read instead:

$$R_C = \rho \ln (\underline{8} L / d) / (4 \pi L)$$

Equation VIII-E-1

This is an Error of the First Type. The underlined portions of the equations show the errors and corrections.

Errors of the Second Type had already been corrected in the Certificate of Correction for this U.S. Patent. This Error of the First Type has not been corrected in the Certificate of Correction.

This equation needs to be similarly corrected in two other of PML's U.S. Patents on this subject as follows: Equation 6 in U.S. Patent No. 4,882,542 (Vail, 1989b) and Equation 6 in U.S. Patent No. 5,043,668 (Vail, 1991b). This error was discovered some time ago and does not appear in U.S. Patent No. 5,075,626 (Vail, 1991c); nor does it appear in U.S. Patent No. 5,223,794 (Vail, 1993c).

2. U.S. Patent No. 5,075,626 - Vail (1991c)

(A.) Equation 12 on page 10 is an intermediate equation having the following erroneous algebraic product in that equation: $(R_A \Delta R_2)$

The product identified above should instead read as the following algebraic sum: $(R_A + \Delta R_2)$

This is an Error of the Second Type. Professor Liang Shen pointed this error out in his letter dated July 20, 1993. The authors are grateful to Professor Shen for pointing out this error.

(B.) The line above Equation 22 on page 11 erroneously states the following condition: $(a_1 = a_1 = A)$.

Instead, the line above Equation 22 on page 11 should read as follows: $(a_1 = a_2 = A)$.

This is an Error of the First Type. Professor Liang Shen pointed this error out in his letter dated July 20, 1993. The authors are grateful to Professor Shen for pointing out this error.

The authors wish to express their appreciation to Dr. Liang Shen, Professor and Director of the Well Logging Laboratory at the University of Houston for his study of the algebraic equations in U.S. Patent No. 5,075,626. We are pleased that no other algebraic errors were found during his study. The authors are grateful that Professor Shen took the time and effort to study the equations in this patent and for his July 20, 1993 letter.

3. U.S. Patent No. 5,187,440 - Vail (1993a)

Equation 1 on page 9 now reads:

$$(CL) (r) = \rho \{ \ln [2 (LC) / d] \} / 2 \pi (LC)$$

Equation 1 on page 9 should read:

$$(CL) (r) = \rho \{ \ln [4 (CL) / d] \} / 2 \pi (CL)$$

Equation VIII-E-2

These are all Errors of the First Type. The underlined portions of the equations show the errors and corrections. Dr. Vail made typos inverting the letters CL and LC in the application originally submitted to the USPTO. The factor of 2 mathematical error comes from the corrections in U.S. Patent No. 4,820,989 (Vail, 1989a) above.

4. Copies of First Pages from U.S. Patents
Concerning the TCRT Owned by
ParaMagnetic Logging, Inc.

A convenient list of the TCRT Patents that have issued in the U.S. Patent and Trademark Office and which have been assigned to PML is provided in the one page document on the next page entitled "THROUGH CASING RESISTIVITY TOOL™ PATENTS", "Patent Information Summary Sheet". That Summary Sheet defines PML's TCRT Patents in terms of an internal identification number. Consequently, PML's TCRT Patents are internally referred to as PML's Patent #5, #7, #10, #14, #16, #18, #21, and #22. PML has patents on other subjects, so there are gaps in the numbering system. These internal numbers refer to the chronological order in which these particular patents became important at PML.

After the one page Patent Information Summary Sheet follows copies of the first pages only from PML's U.S. Patents concerning the TCRT in the order of PML's internal patent numbering system.

ParaMagnetic Logging, Inc.

THROUGH CASING RESISTIVITY TOOLTM PATENTS

Patent Information Summary Sheet

PML No.	U.S. Pat. No.	Issue Date	Filing Date	Serial No.	Comments
5	4,820,989	04/11/89	11/04/86	06/927,115	
7	4,882,542	11/21/89	08/26/87	07/089,697	C.I.P. PML Patent No. 5
10	5,043,669	08/27/91	11/16/89	07/438,268	C.I.P. PML Patent No. 7
14	5,075,626	12/24/91	11/13/89	07/434,886	C.I.P. PML Patent No. 7
16	5,043,668	08/27/91	10/30/89	07/435,273	Continuation - PML Patent No. 7
18	4,796,186	01/03/89	07/30/86	06/891,951	Inventor: A.A. Kaufman
21	5,187,440	02/16/93	08/23/91	07/749,136	C.I.P. PML Patent No. 16
22	5,223,794	06/29/93	09/04/91	07/754,965	Divisional - PML Patent No. 14

Print Out Date: July 12, 1993

Location: PAT-GEN\TCRT.02

- [54] METHODS AND APPARATUS FOR MEASUREMENT OF THE RESISTIVITY OF GEOLOGICAL FORMATIONS FROM WITHIN CASED BOREHOLES

[75] Inventor: William B. Vail, III, Bothell, Wash.

[73] Assignee: ParaMagnetic Logging, Inc.,
Woodinville, Wash.

[21] Appl. No.: 927,115

[22] Filed: Nov. 4, 1986

[51] Int. Cl.⁴ G01V 3/02

[52] U.S. CL 324/368

[58] **Field of Search** 324/323, 332, 333, 334,
324/347, 354, 357, 358, 360, 363, 364, 366, 368,
370, 373, 375

[56] **References Cited**

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Primary Examiner—Reinhard J. Eisenzopf

Assistant Examiner—Warren S. Edmonds

Attorney, Agent, or Firm—Flehr, Hohbach & Test

[57] ABSTRACT

Methods and apparatus are disclosed which allow measurement of the resistivity of a geological formation through borehole casing which may be surrounded by brine saturated cement. A.C. current is passed from an electrode in electrical contact with the interior of the borehole casing to an electrode on the surface of the earth. The A.C. voltage difference is measured between two additional vertically disposed electrodes on the interior of the casing which provides a measure of the resistivity of the geological formation. A calibration and nulling procedure is presented which minimizes the influence of variations in the thickness of the casing. The procedure also minimizes the influence of inaccurate placements of the additional vertically disposed electrodes.

22 Claims, 3 Drawing Sheets

- [54] METHODS AND APPARATUS FOR MEASUREMENT OF ELECTRONIC PROPERTIES OF GEOLOGICAL FORMATIONS THROUGH BOREHOLE CASING
- [75] Inventor: William B. Vail, III, Bothell, Wash.
- [73] Assignee: ParaMagnetic Logging, Inc., Bothell, Wash.
- [21] Appl. No.: 89,697
- [22] Filed: Aug. 26, 1987

Related U.S. Application Data

- [63] Continuation-in-part of Ser. No. 927,115, Nov. 4, 1986, Pat. No. 4,820,989.
- [51] Int. Cl.⁴ G01V 3/02
- [52] U.S. Cl. 324/368
- [58] Field of Search 324/347-375

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Primary Examiner—Reinhard J. Eisenzopf
Assistant Examiner—Warren S. Edmonds
Attorney, Agent, or Firm—Flehr, Hohbach, Test, Albritton & Herbert

[57] ABSTRACT

Methods and apparatus are provided for measuring electronic properties of geological formations and cement layers adjacent to cased boreholes including resistivities, polarization phenomena and dielectric constants. Current is passed from an electrode in electrical contact with the interior of the borehole casing to an electrode on the surface of the earth. At least three voltage measuring electrodes in electrical contact with the interior of the casing measure the voltage at various points thereon. The voltage differences between discrete pairs of the voltage measuring electrodes provide a measurement of differential current conducted into formation in the vicinity of those electrodes. These measurements facilitate calculation of the resistivities of the adjacent geological formations as well as an indication of whether cement is present. Measurements of the differential voltage response to transient currents provide a measurement of the polarization phenomena in formation as well as the capacitance of the casing in contact with the formation which is useful for determining whether oil and gas are present. Lithological characteristics of the formation such as the presence or absence of clay can also be determined. A calibration procedure is provided for minimizing errors induced by variations in the casing. The device also may be placed within the pipe attached to a drill bit while drilling open holes.

80 Claims, 26 Drawing Sheets

- [54] METHODS AND APPARATUS FOR MEASUREMENT OF THE RESISTIVITY OF GEOLOGICAL FORMATIONS FROM WITHIN CASED WELLS IN PRESENCE OF ACOUSTIC AND MAGNETIC ENERGY SOURCES

- [75] Inventor: William B. Vail, III, Bothell, Wash.
[73] Assignee: Para Magnetic Logging, Inc.,
Woodinville, Wash.

- [*] Notice: The portion of the term of this patent subsequent to Apr. 11, 2006 has been disclaimed.

- [21] Appl. No.: 438,268

- [22] Filed: Nov. 16, 1989

Related U.S. Application Data

- [63] Continuation-in-part of Ser. No. 89,697, Aug. 26, 1987, Pat. No. 4,882,542, which is a continuation-in-part of Ser. No. 927,115, Nov. 4, 1986, Pat. No. 4,820,989.

- [51] Int. Cl.⁵ G01V 3/26

- [52] U.S. Cl. 324/368

- [58] Field of Search 324/347-375

[56] **References Cited**

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4,837,518	6/1989	Gard et al.	324/368

4,882,542	11/1989	Vail, III		324/368
4,901,023	2/1990	Vail, III		324/368 X

FOREIGN PATENT DOCUMENTS

56026 11/1939 U.S.S.R. .

Primary Examiner—Kenneth A. Wieder
Assistant Examiner—Warren S. Edmonds

[57] ABSTRACT

Methods and apparatus are provided for measuring the acoustically modulated electronic properties of geological formations and cement layers adjacent to cased boreholes. Current is passed from an electrode in electrical contact with the interior of the borehole casing to an electrode on the surface of the earth. Voltage measuring electrodes in electrical contact with the interior of the casing measure the voltage at various points thereon. The voltage differences between discrete pairs of the voltage measuring electrodes provide a measurement of the leakage current conducted into formation in the vicinity of those electrodes. Simultaneously subjecting the casing and formation to an acoustic source acoustically modulates the leakage current measured thereby providing a measure of the acoustically modulated electronic properties of the adjacent formation. Similarly, methods and apparatus are also described which measure the leakage current into formation while simultaneously subjecting the casing to an applied magnetic field which therefore allows measurement of the magnetically modulated electronic properties of the casing and the adjacent formation.

14 Claims, 9 Drawing Sheets

- [54] ELECTRONIC MEASUREMENT APPARATUS MOVABLE IN A CASED BOREHOLE AND COMPENSATING FOR CASING RESISTANCE DIFFERENCES
- [75] Inventor: William B. Vail, III, Bothell, Wash.
- [73] Assignee: ParaMagnetic Logging, Inc., Woodinville, Wash.
- [*] Notice: The portion of the term of this patent subsequent to Aug. 27, 2008 has been disclaimed.
- [21] Appl. No.: 434,886
- [22] Filed: Nov. 13, 1989

Related U.S. Application Data

- [63] Continuation-in-part of Ser. No. 89,697, Aug. 26, 1987, Pat. No. 4,882,542, which is a continuation-in-part of Ser. No. 927,115, Nov. 4, 1986, Pat. No. 4,820,989.
- [51] Int. Cl.⁵ G01V 3/24
- [52] U.S. Cl. 324/368; 324/371
- [58] Field of Search 324/347-375; 364/422

[56] References Cited

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4,837,518	6/1989	Gard et al.	324/368
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Primary Examiner—Gerard R. Strecker

Assistant Examiner—Warren S. Edmonds

[57] ABSTRACT

Methods of operation of an apparatus having at least two pairs of voltage measurement electrodes vertically disposed in a cased well to measure the resistivity of adjacent geological formations from inside the cased well. During stationary measurements with the apparatus at a fixed vertical depth within the cased well, the invention herein discloses methods of operation which include a measurement step and subsequent first and second compensation steps respectively resulting in improved accuracy of measurement. The invention also discloses multiple frequency methods of operation resulting in improved accuracy of measurement while the apparatus is simultaneously moved vertically in the cased well. The multiple frequency methods of operation disclose a first A.C. current having a first frequency that is conducted from the casing into formation and a second A.C. current having a second frequency that is conducted along the casing. The multiple frequency methods of operation simultaneously provide the measurement step and two compensation steps necessary to acquire accurate results while the apparatus is moved vertically in the cased well.

21 Claims, 6 Drawing Sheets

- [22] Filed: Oct. 30, 1989

[58] **Field of Search** 324/347-375;
364/422

2.729.784	1/1956	Fearon .	
2.891.215	6/1959	Fearon .	
4.796.186	1/1989	Kaufman	324/368 X
4.820.989	4/1989	Vail, III	324/368
4.837.518	6/1989	Gard et al.	324/368
4.882.592	11/1989	Vail, III	324/368
4.901.023	2/1990	Vail, III	324/368

Assistant Examiner—Warren S. Edmonds

Methods and apparatus are provided for measuring electronic properties of geological formations and cement layers adjacent to cased boreholes including resistivities, polarization phenomena and dielectric constants. Current is passed from an electrode in electrical contact with the interior of the borehole casing to an electrode on the surface of the earth. At least three voltage measuring electrodes in electrical contact with the interior of the casing measure the voltage at various points thereon. The voltage differences between discrete pairs of the voltage measuring electrodes provide a measurement of the differential current conducted into formation in the vicinity of those electrodes. These measurements facilitate calculation of the resistivities of the adjacent geological formations as well as an indication of whether cement is present. Measurements of the differential voltage response to transient currents provide a measurement of the polarization phenomena in formation as well as the capacitance of the casing in contact with the formation which is useful for determining whether oil and gas present. Lithological characteristics of the formation such as the presence or absence of clay can also be determined. A calibration procedure is provided for minimizing errors induced by variations in the casing. The device also may be placed within the pipe attached to a drill bit while drilling open holes.

76 Claims, 26 Drawing Sheets

- [54] CONDUCTIVITY DETERMINATION IN A FORMATION HAVING A CASED WELL
- [75] Inventor: Alexander A. Kaufman, Lakewood, Colo.
- [73] Assignee: Oil Logging Research, Inc., Denver, Colo.
- [21] Appl. No.: 891,951
- [22] Filed: Jul. 30, 1986

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Related U.S. Application Data

- [63] Continuation-in-part of Ser. No. 740,734, Jun. 3, 1985, abandoned.
- [51] Int. Cl.⁴ G01R 27/02; G01V 3/20
- [52] U.S. Cl. 364/422; 324/368; 73/151.5
- [58] Field of Search 364/420, 421, 422; 324/366, 368, 367, 333; 73/151.5, 152, 155

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Primary Examiner—Jerry Smith

Assistant Examiner—Kim Thanh Tbui

Attorney, Agent, or Firm—Sheridan, Ross & McIntosh

[57] ABSTRACT

Methods and apparatuses for determining conductivity of a subterranean formation traversed by a well, particularly a cased well are provided. Variations in casing conductivity and/or electrode placement, arising from, e.g. thermal stress or expansion or corrosion, are compensated for. Compensation involves obtaining voltages developed in response to current flowing between relatively closely spaced current electrodes, and using these voltages to provide compensation for voltages developed in response to current flowing between more remotely positioned current electrodes. Modifications are described to permit conductivity measurements in partially cased or uncased wells, or wells being actively drilled.

50 Claims, 5 Drawing Sheets

[54] MEASURING RESISTIVITY CHANGES FROM WITHIN A FIRST CASED WELL TO MONITOR FLUIDS INJECTED INTO OIL BEARING GEOLOGICAL FORMATIONS FROM A SECOND CASED WELL WHILE PASSING ELECTRICAL CURRENT BETWEEN THE TWO CASED WELLS

[75] Inventor: William B. Vail, III, Bothell, Wash.

[73] Assignee: Para Magnetic Logging, Inc., Woodinville, Wash.

[*] Notice: The portion of the term of this patent subsequent to Aug. 27, 2008 has been disclaimed.

[21] Appl. No.: 749,136

[22] Filed: Aug. 23, 1991

Related U.S. Application Data

[63] Continuation-in-part of Ser. No. 435,273, Oct. 30, 1989, Pat. No. 5,043,668, which is a continuation of Ser. No. 89,697, Aug. 26, 1987, Pat. No. 4,882,542, which is a continuation-in-part of Ser. No. 927,115, Nov. 4, 1986, Pat. No. 4,820,989.

[51] Int. Cl.³ G01V 3/20

[52] U.S. Cl. 324/372; 324/368

[58] Field of Search 324/368, 372, 357, 354, 324/348, 370, 371

[56] References Cited

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Mitchell, "Using Resistivity Measurements to Determine Distance Between Wells", *Journal of Petroleum Technology*, Jun. 1972, pp. 723-740.

Primary Examiner—Gerard R. Strecker

Assistant Examiner—Warren S. Edmonds

[57] ABSTRACT

A.C. current is conducted through geological formations separating two cased wells in an oil field undergoing enhanced oil recovery operations such as water flooding operations. Methods and apparatus are disclosed to measure the current leakage conducted into a geological formation from within a first cased well that is responsive to fluids injected into formation from a second cased well during the enhanced oil production activities. The current leakage and apparent resistivity measured within the first cased well are responsive to fluids injected into formation from the second cased well provided the distance of separation between the two cased wells is less than, or on the order of, a Characteristic Length appropriate for the problem.

9 Claims, 6 Drawing Sheets

US005223794A

United States Patent [19]

[11] Patent Number: 5,223,794

Vail, III

[45] Date of Patent: Jun. 29, 1993

[54] METHODS OF OPERATION OF APPARATUS MEASURING FORMATION RESISTIVITY FROM WITHIN A CASED WELL HAVING ONE MEASUREMENT AND TWO COMPENSATION STEPS

[75] Inventor: William B. Vail, III, Bothell, Wash.

[73] Assignee: Para Magnetic Logging, Inc., Woodinville, Wash.

[21] Appl. No.: 754,965

[22] Filed: Sep. 4, 1991

Related U.S. Application Data

[60] Division of Ser. No. 434,886, Nov. 13, 1989, Pat. No. 5,075,626, which is a continuation-in-part of Ser. No. 89,697, Aug. 26, 1987, Pat. No. 4,882,542, which is a continuation-in-part of Ser. No. 927,115, Nov. 4, 1986, Pat. No. 4,820,989.

[51] Int. Cl.⁵ G01V 3/20

[52] U.S. Cl. 324/368; 324/370

[58] Field of Search 324/368, 347-367, 324/369-375

[56] References Cited

U.S. PATENT DOCUMENTS

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Primary Examiner—Gerard R. Strecker

Assistant Examiner—Warren S. Edmonds

[57]

ABSTRACT

Methods of operation of an apparatus having at least two pairs of voltage measurement electrodes vertically disposed in a cased well to measure the resistivity of adjacent geological formations from inside the cased well. During stationary measurements with the apparatus at a fixed vertical depth within the cased well, the invention herein discloses methods of operation which include a measurement step and subsequent first and second compensation steps respectively resulting in improved accuracy of measurement. First and second order errors of measurement are identified, and the measurement step and two compensation steps provide methods to substantially eliminate their influence on the results. A multiple frequency apparatus adapted to movement within the well is described which simultaneously provide the measurement and two compensation steps.

2 Claims, 6 Drawing Sheets

SECTION VIII - F

LEAKY CAPACITOR MODEL PROVIDES SIMPLE QUANTITATIVE CORRECTIONS FOR THE PRESENCE OF CEMENT - β (CEMENT)

1. The "Leaky Capacitor Model"

Referring to Figure VIII-F-1:

a	=	radius of outside surface of casing
b	=	average outer radius of layer of cement
c	=	outer radius of "Leaky Capacitor Model"
L	=	length of Leaky Capacitor
ρ_f	=	formation resistivity in ohm-meters
ρ_c	=	average resistivity of cement in ohm-meters
ρ_a	=	apparent resistivity from TCRT in ohm-meters
ρ_{app}	=	different symbol for ρ_a used in complex equations
r	=	radius of differential volume for integration purposes
dr	=	differential change in radius
x	=	lower boundary condition during integration
y	=	upper boundary condition during integration
S	=	symbol for integration
Ln	=	natural log
R	=	resistance in ohms to current flow from casing at radius a to "ground" located at radius c
R_f	=	resistance in ohms to current flow caused entirely by the geological formation as if <u>no</u> cement is present
R_{app}	=	"apparent resistance" in ohms to current flow in response to both the presence of the formation and the layer of cement

This model is called the "Leaky Capacitor Model" because it resembles a laboratory capacitor that has become "leaky". Such a leaky capacitor has a D.C. resistance to current flow (and not just capacitance). This "Leaky Capacitor Model" is used to calculate D.C. effects related to the presence of cement.

For the purposes of these calculations, the length of the Leaky Capacitor L can be taken to be equal to the spacing between Electrodes C and E of the TCRT. Therefore:

$$L = 2 \text{ (ELECTSP)} \quad \text{Equation VIII-C-7}$$

This is the same as equation VIII-C-7 on page VIII-C-2 and is marked accordingly.

From the nature of cylindrical geometry in Figure VIII-F-1:

$$dR = \rho \, dr / (2 \pi r L) \quad \text{Equation VIII-F-1}$$

Doing the integral:

$$R = (1 / 2 \pi L) \int_x^y \rho \, dr / r \quad \text{Equation VIII-F-2}$$

If no cement is present, then the integral in Equation VIII-F-2 becomes:

$$R_f = (1 / 2 \pi L) \rho_f \ln (c/a) \quad \text{Equation VIII-F-3}$$

If the layer of cement is present, then the integral in Equation VIII-F-2 becomes:

$$R_{app} = (1 / 2 \pi L) \{ \rho_c \ln (b/a) + \rho_f \ln (c/b) \} \quad \text{Equation VIII-F-4}$$

Therefore, the ratio of (R_f / R_{app}) which includes the influence of cement to R_{app} that solely due to the formation is given as follows:

$$R_f / R_{app} = \{ \rho_f \ln (c/a) \} / \{ \rho_c \ln (b/a) + \rho_f \ln (c/b) \} \quad \text{Equation VIII-F-5}$$

An apparent resistivity ρ_{app} is then calculated using the single Calibration Constant K of the TCRT as follows:

$$\rho_{app} = K R_c \quad \text{Equation 3}$$

However, we want the formation resistivity, ρ_f , not the apparent resistivity which might be influenced by the presence of cement around the casing. It is evident that:

$$\rho_f / \rho_{app} = R_f / R_{app} \quad \text{Equation VIII-F-6}$$

Substituting Equation VIII-F-6 into Equation VIII-F-5, we get:

$$\rho_f / \rho_{app} = \{ \rho_f \ln (c/a) \} / \{ \rho_c \ln (b/a) + \rho_f \ln (c/b) \} \quad \text{Equation VIII-F-7}$$

Solving for ρ_f :

$$\rho_f = [\{ \rho_{app} \ln (c/a) \} - \{ \rho_c \ln (b/a) \}] / \ln (c/b) \quad \text{Equation VIII-F-8}$$

2. Obtaining Correct Formation Resistivity from Apparent Resistivity Corrected for Cement Effects

Figures VIII-F-2 through VIII-F-7 are plots of ρ_f as a function of ρ_{app} for three choices of b, the average outer radius of layer of cement. a, the radius of outside surface of casing, is fixed at 3 1/2 inches and c, the outer radius of "Leaky Capacitor Model", is fixed at 192 inches. ρ_c , the average resistivity of cement in ohm-meters, is different for each figure.

For Figure VIII-F-2, ρ_c is equal to 1 ohm-m.

For Figure VIII-F-3, ρ_c is equal to 2 ohm-m.

For Figure VIII-F-4, ρ_c is equal to 3 ohm-m.

For Figure VIII-F-5, ρ_c is equal to 4 ohm-m.

For Figure VIII-F-6, ρ_c is equal to 8 ohm-m.

For Figure VIII-F-7, ρ_c is equal to 16 ohm-m.

Please notice the interesting progression of the corrections due to cement from the lowest to the highest values of cement resistivities. At very low cement resistivities, no corrections are required due to its presence. As is evident from these set of curves, for cement resistivities less than about 8 ohm-meters, no substantial corrections are required to obtain true resistivities - provided the apparent resistivities are in excess of about 3 ohm-meters. This is an important fact. Klein, et. al. (1993) found that the maximum resistivity of cement anticipated to be typically encountered in actual reservoir conditions is about 8 ohm-meters. Therefore, in routine field conditions, it is anticipated that provided the apparent resistivity determined is in excess of about 3 ohm-meters, no corrections will be necessary to compensate for the presence of cement.

It is further expected that after many years pass, that the resistivity of cement will become equal to that of the adjacent geological formation. If this actually proves to be the case in general, then few corrections to apparent resistivities obtained with the TCRT will be required under real field conditions.

3. $\beta(\text{CEMENT})$

$\beta(\text{CEMENT})$ is defined as a dimensionless number (a multiplicative correction factor) that corrects ρ_{app} for cement effects. If NO other corrections are needed to ρ_{app} give the true formation resistivity, ρ_f , then:

$$\beta(\text{CEMENT}) = \rho_f / \rho_{\text{app}} \quad \text{Equation VIII-F-9}$$

Substituting Equation VIII-F-7 into Equation VIII-F-9, we get:

$$\beta(\text{CEMENT}) = \{ \rho_f \ln (c/a) \} / \{ \rho_c \ln (b/a) + \rho_f \ln (c/b) \}$$

$$\text{Equation VIII-F-10}$$

Figures VIII-F-8 through VIII-F-13 are plots of $\beta(\text{CEMENT})$ as a function of ρ_{app} for three choices of b, the average outer radius of layer of cement. a, the radius of outside surface of casing, is fixed at 3 1/2 inches and c, the outer radius of "Leaky Capacitor Model", is fixed at 192 inches. ρ_c , the average resistivity of cement in ohm-meters, is different for each figure.

For Figure VIII-F-8, ρ_c is equal to 1 ohm-m.
For Figure VIII-F-9, ρ_c is equal to 2 ohm-m.
For Figure VIII-F-10, ρ_c is equal to 3 ohm-m.
For Figure VIII-F-11, ρ_c is equal to 4 ohm-m.
For Figure VIII-F-12, ρ_c is equal to 8 ohm-m.
For Figure VIII-F-13, ρ_c is equal to 16 ohm-m.

One question that may be raised is the potential sensitivity of the parameter $\beta(\text{CEMENT})$ to the position of the outer boundary c of the Leaky Capacitor Model. That boundary is set at some value to avoid the artificial "infinity" typical of problems having cylindrical geometry. To answer this question, please refer to the following figures that show plots of $\beta(\text{CEMENT})$ vs. the position of the outer boundary c .

For Figure VIII-F-14, $\beta(\text{CEMENT})$ vs. c is plotted, $\rho_f = 1$ ohm-m.
For Figure VIII-F-15, $\beta(\text{CEMENT})$ vs. c is plotted, $\rho_f = 10$ ohm-m.
For Figure VIII-F-16, $\beta(\text{CEMENT})$ vs. c is plotted, $\rho_f = 100$ ohm-m.

It is evident from these figures that provided the outer boundary of the Leaky Capacitor Model is set beyond about 10 feet, that the parameter $\beta(\text{CEMENT})$ is relatively invariant to where that boundary is exactly located between 10 feet to 100 feet. For more on this subject, please refer to Section VIII-H entitled "50% Radius of Investigation - L50%".

To summarize, if corrections prove to be necessary to TCRT data due to the presence of cement, it is the opinion of the authors that such corrections can be done accurately by using the parameter $\beta(\text{CEMENT})$. This parameter is particularly useful, because if no corrections are necessary, it has the value of unity. Departures from unity only occur if the presence of cement affects the accuracy of TCRT measurements.

FIGURE VIII-F-1
LEAKY CAPACITOR MODEL

CEMENT CORRECTION PLOT

ParaMagnetic Logging, Inc.

Figure VIII-F-2

Printed Out 9/8/94

a = 3.5 inches; c = 192 inches; cement resistivity = 1 Ohm-m

CEMENT CORRECTION PLOT

ParaMagnetic Logging, Inc.

— $b = 3.5$ inches - - $b = 4.5$ inches - - - $b = 5.5$ inches

Figure VIII-F-3
Printed Out 9/8/94
 $a = 3.5$ inches; $c = 192$ inches; cement resistivity = 2 Ohm-m

CEMENT CORRECTION PLOT

ParaMagnetic Logging, Inc.

Figure VIII-F-4

Printed Out 9/8/94

$a = 3.5$ inches; $c = 192$ inches; cement resistivity = 3 Ohm-m

CEMENT CORRECTION PLOT

ParaMagnetic Logging, Inc.

Figure VIII-F-5

Printed Out 9/8/94

$a = 3.5$ inches; $c = 192$ inches; cement resistivity = 4 Ohm-m

CEMENT CORRECTION PLOT

ParaMagnetic Logging, Inc.

Figure VIII-F-6
 Printed Out 9/8/94
 $a = 3.5$ inches; $c = 192$ inches; cement resistivity = 8 Ohm-m

CEMENT CORRECTION PLOT

ParaMagnetic Logging, Inc.

Figure VIII-F-7
 Printed Out 9/8/94
 $a = 3.5$ inches; $c = 192$ inches; cement resistivity = 16 Ohm-m

$\beta(\text{CEMENT})$ PLOT
ParaMagnetic Logging, Inc.

Figure VIII-F-8

Printed Out 9/8/94

$a = 3.5$ inches; $c = 192$ inches; cement resistivity = 1 Ohm-m

$\beta(\text{CEMENT})$ PLOT
ParaMagnetic Logging, Inc.

— $b = 3.5$ inches - - $b = 4.5$ inches - · - $b = 5.5$ inches

Figure VIII-F-9

Printed Out 9/8/94

$a = 3.5$ inches; $c = 192$ inches; cement resistivity = 2 Ohm-m

$\beta(\text{CEMENT})$ PLOT
ParaMagnetic Logging, Inc.

Figure VIII-F-10

Printed Out 9/8/94

$a = 3.5$ inches; $c = 192$ inches; cement resistivity = 3 Ohm-m

$\beta(\text{CEMENT})$ PLOT
ParaMagnetic Logging, Inc.

Figure VIII-F-11

Printed Out 9/8/94

$a = 3.5$ inches; $c = 192$ inches; cement resistivity = 4 Ohm-m

$\beta(\text{CEMENT})$ PLOT
ParaMagnetic Logging, Inc.

Figure VIII-F-12
Printed Out 9/8/94
 $a = 3.5$ inches; $c = 192$ inches; cement resistivity = 8 Ohm-m

$\beta(\text{CEMENT})$ PLOT
ParaMagnetic Logging, Inc.

Figure VIII-F-13

Printed Out 9/8/94

$a = 3.5$ inches; $c = 192$ inches; cement resistivity = 16 Ohm-m

VALIDITY CHECK OF LEAKY CAPACITOR MODEL ParaMagnetic Logging, Inc.

Figure VIII-F-14

Printed Out 5/24/95

a = 3.5 inches; b = 4.5 inches; formation resistivity = 1 Ohm-m

VALIDITY CHECK OF LEAKY CAPACITOR MODEL ParaMagnetic Logging, Inc.

Figure VIII-F-15
 Printed Out 5/24/95
 a = 3.5 inches; b = 4.5 inches; formation resistivity = 10 Ohm-m

VALIDITY CHECK OF LEAKY CAPACITOR MODEL ParaMagnetic Logging, Inc.

Figure VIII-F-16
 Printed Out 5/24/95
 a = 3.5 inches; b = 4.5 inches; formation resistivity = 100 Ohm-m

SECTION VIII-G

QUANTITATIVE CALCULATION OF D.C. DRIVING

IMPEDANCE OF CASING

The Characteristic Length is given by Equation VIII-D-2 that is repeated below:

$$CL = 1.26 \left(\rho / r \right)^{1/2} \quad \text{Equation VIII-D-2}$$

Here, ρ is the average resistivity of the half-space and r is the resistance per unit length of the casing.

The average resistivity of the formation at the MWX-2 Well, which is averaged over a Characteristic Length of the well spanning the center of the well, is calculated to be approximately $\rho = 38$ ohm-meters.

The particular type casing at the MWX-2 Well is 7 inch O.D., 29 pound/foot, N-80 type casing that has an average wall thickness of about 0.408 inches. Inspecting Figure 14 for example, the typical measured resistance per unit length is about 20 micro-ohms per ELECTSP (19 13/16 inches) that gives $r = 39.8$ micro-ohms/m.

Therefore, for the above values of r and ρ , from Equation VIII-D-2, or from Figure VIII-D-2, the Characteristic Length for the casing present at the MWX-2 Well is approximately 5,000 feet.

The Characteristic Resistance "Roo" of one piece of pipe having a length equal to the Characteristic Length is defined as follows:

$$R_{oo} = r \quad CL \quad \text{Equation VIII-G-1}$$

Using Equation VIII-D-2, then Equation VIII-G-1 becomes:

$$R_{oo} = 1.26 \left(r \rho \right)^{1/2} \quad \text{Equation VIII-G-2}$$

For the above value of r , the solid line in Figure VIII-G-1 shows a plot of R_{oo} for the MWX-2 Well vs. average formation resistivity ρ . For the average formation resistivity of

38 ohm-meters present in the middle of the well, R_{oo} for the MWX-2 Well is determined to be about 49.0 milli-ohms. Other values of R_{oo} for different assumed wall thicknesses are also plotted in Figure VIII-G-1.

If Electrode A drives the center of the MWX-2 Well, then the D.C. Center Driving Impedance, $ZC(D.C.)$, is expected to be approximately given by driving the parallel combination of R_{oo} to infinity as follows:

$$ZC(D.C.) = R_{oo} / 2 \quad \text{Equation VIII-G-3}$$

Therefore, $ZC(D.C.)$ is expected from this model to be about 49.0 milli-ohms / 2 = 24.5 milli-ohms. If this model is valid, this should be about equal to Q at D.C.

From Figure 69 that corresponds to energizing Electrode A at the MWX-2 Well near the physical center of the well, $Q = 18$ milli-ohms. Therefore, this very simple model gives results that are accurate within 40% for the D.C. Center Driving Impedance observed at the MWX-2 Well. It should be noted that the actual D.C. Center Driving Impedance at the well should be lower, as observed, because this calculation did not take into account the much heavier surface casing present at the MWX-2 Well.

If instead the top of the MWX-2 is energized with current, then the D.C. Top Driving Impedance, $ZT(D.C.)$, is expected to be approximately given by driving just one Characteristic Resistor R_{oo} to infinity as follows:

$$ZT(D.C.) = R_{oo} \quad \text{Equation VIII-G-4}$$

The value of R_{oo} is calculated to be 49 milli-ohms from above. The value of Q actually measured at D.C. by energizing the top of the well is 25 milli-ohms which is about 1/2 the value calculated in Equation VIII-G-4. This discrepancy may be due to the following factors: (a) the calculation does not take into account the heavy large diameter surface casings (see Figure 6); (b) the calculation does not take into account the relatively higher formation resistivity typically near the surface of the earth; and (c) the calculation does not take into account possible distortion of the potential voltage measurements due to currents flowing near the surface and near the Potential Voltage Reference Electrodes (either the Far Reference Plate or the Near Reference Plate in Figure 5).

It may ultimately prove to be the case that this very simplistic model for the Characteristic Resistance R_{oo} only gives values

within plus or minus a factor of 2 or so for the D.C. Driving Impedance of different wells in different geological formations. However, this information is sufficient to determine the approximate signal sizes to be expected from the TCRT while energizing a particular well, with a particular amount of current, in a particular manner (top, middle, bottom of well). Such information is extremely valuable for a variety of purposes.

Data obtained at the MWX-2 Well by PML involving measurements of a variety of AC phenomena, and the models for those AC phenomena, have been forwarded to PML's Licensees. For example, data concerning the AC Driving Impedance and the relevant models have been forwarded to PML's Licensees in various proprietary documents.

MWX-2, RIFLE, CO.
ParaMagnetic Logging, Inc.

Figure VIII-G-1; 7" OD Casing
Resistivity of Casing based on Measurements at the MWX-2 Well
Printed Out 4/28/94

SECTION VIII - H

50% RADIUS OF INVESTIGATION - L50%

The starting point is Equation 3(a) from Section II-A that is repeated below as follows:

$$R_c = \rho_a / K$$

For the purposes herein, let's assume that no corrections are needed for cement, end effects, etc. so that for the purposes of this section, ρ_a is equal to the correct formation resistivity ρ_f .

Repeating Equation VIII-F-3 here, where c is the outer radius of the Leaky Capacitor Model, and a is the radius of the pipe:

$$R_f = (1 / 2 \pi L) \rho_f \ln (c/a) \quad \text{Equation VIII-F-3}$$

Clearly, the "50% Radius of Investigation - L50%" is given by the particular value of " c " such that the real resistor $R(\text{REAL})$ to infinity becomes half of its true value (in ohms). From EQUATION VIII-A-12, that happens when:

$$R_f = R(\text{REAL}) / 2 = R_c / 4 \quad \text{Equation VIII-H-1}$$

Setting " c " = L50%, using Equation VIII-H-1, Equation 3, and Equation VIII-F-3, we obtain the following:

$$\ln (L50\% / a) = \pi L / 2 K \quad \text{Equation VIII-H-2}$$

For the Leaky Capacitor Model, L is chosen such that:

$$L = 2 (\text{ELECTSP}) \quad \text{Equation VIII-C-7}$$

Using Equation VIII-C-7, Equation VIII-H-2 becomes:

$$\ln (L50\% / a) = \pi (\text{ELECTSP}) / K \quad \text{Equation VIII-H-3}$$

The body of work in Section VIII-C shows that PML's Calibration Constant K is approximately equal to ELECTSP for typical electrode spacings of the TCRT and for typical casing sizes.

Therefore, if the following approximation is valid,

$$K = (\text{ELECTSP}) \quad \text{Equation VIII-H-4}$$

then:

$$\ln (L50\% / a) = \pi \quad \text{Equation VIII-H-5}$$

Under this circumstance, then:

$$L50\% = 23.14 a \quad \text{Equation VIII-H-6}$$

This shows that the typical "50 percent response point" of the TCRT appropriate for 7 inch O.D. casing is:

$$\begin{aligned} L50\%(7 \text{ inch O.D. casing}) &= (23.14) (7 \text{ inches} / 2) \\ &= 80.99 \text{ inches} \\ &= 6.75 \text{ feet} \end{aligned}$$

This is a reasonable result. This also shows why it is important to set the value of c to values exceeding 10 feet for the Leaky Capacitor Model in Section VIII-F.

This result is consistent with calculations performed involving the Pseudogeometrical Factor (J) vs. Invasion Diameter in Fig 7-17 on page 7-12 of the volume entitled "Schlumberger Log Interpretation, Principles/Applications" having the date of 1989 on the cover, Schlumberger Educational Services, Houston, Texas, 3rd Printing. That figure shows that for J = 0.5 ("the 50% response point" in the language used herein), the radii of investigation for the LL3 and LL7 type devices are on the order of about 60 inches. For LLD devices, the radius of investigation is much deeper.

In general, Equation VIII-H-4 is only an approximation. Equation VIII-C-11 is repeated below as follows:

$$\gamma K = K / (\text{ELECTSP})$$

Equation VIII-C-11

The quantity γK is the ratio of the Calibration Constant K in meters to the Electrode Spacing in meters. The quantity γK is a dimensionless quantity. Therefore, in general, Equation VIII-H-3 becomes:

$$\ln (L50\% / a) = \pi / \gamma K$$

Equation VIII-H-7

However, using this equation to determine L50% is calculationally more intensive than using the simplified form that appears in Equation VIII-H-6.

Similar results for L50% can be obtained from the equations developed by J.E. Owen and W.J. Greer which are presented in their paper entitled "The Guard Electrode Logging System" (Owen and Greer, 1951). The TCRT in a cased well can be thought of as a Guard Logging Tool having extremely long guards where the casing segments on either side of Electrodes C-D-E act like very long guards.

SECTION VIII-I

CORRECTIONS FOR THE END EFFECTS OF

CASING - β (END)

This section presents an approximate model to provide quantitative corrections for casing end effects.

Away from the ends of casings, current conducted to the casing by the current conducting electrodes of the TCRT generates an electric field E on the outside of the casing that is approximately perpendicular to the casing itself. This causes the current leakage ΔI to leak into the formation between Electrodes C-D-E. Equation 3 applies to this situation.

At the surface of the earth, no current can flow up into the air. Therefore, even though the casing terminates near the surface of the earth, cylindrical symmetry is still preserved. Since current cannot be conducted up into the air above the casing, the electric field E on the outside of the casing near the surface of the earth is still perpendicular to the casing. Equation 3 also applies to this situation.

However, at the end of a casing string, the current ΔI is not only conducted radially into the formation, but some additional current is physically conducted down below the casing and into the earth below the casing. In this case, additional current conducted into the rock from the portion of the casing spanned by Electrodes C-D-E is conducted into the rock below the end of the casing string. In this case, Equation 3 needs to be corrected.

Away from the bottom end of the casing, then Equation 3 is applicable without any substantial corrections for end effects as follows:

$$\rho_f = \rho_a = K R_c$$

Here, the formation resistivity ρ_f is equal to the apparent resistivity ρ_a measured with the TCRT away from the bottom of the casing.

However, near the bottom end of the casing, the apparent resistivity must be corrected to obtain the formation resistivity as follows:

$$\rho_f = \beta(\text{END}) \rho_a = \beta(\text{END}) K R_c$$

Equation VIII-I-1

The quantity $\beta(\text{END})$ is a function that takes on the value of unity at all places along the casing except near the bottom end of the casing string. To determine $\beta(\text{END})$, it is useful to use Equation 2 to substitute for R_c as follows:

$$\rho_f = \beta(\text{END}) K V_o / \Delta I$$

Equation VIII-I-2

Here, ΔI is the total current leaking into formation that is measured with the TCRT. The problem is that near the very end of the casing string, ΔI includes not only radially outward flowing current from the portion of the casing spanned by Electrodes C-D-E, but an additional amount of current flowing downward below the casing from the portion of the casing spanned by these electrodes.

What do we basically expect to happen near the very end of the casing? If a given potential voltage V_o , say 50 milli-volts, were generated near the middle of the pipe by conducting a specific amount of current to the middle of the pipe, Equation VIII-I-2 would be used with $\beta(\text{END}) = 1.00$, and the amount of current leaking radially into the earth would be ΔI_o .

If near the end of the casing, a current was conducted to the casing with the TCRT such that the resulting Potential Voltage V_o was again 50 milli-volts, then approximately the same amount of current ΔI_o would be flowing radially outward as in the middle of the casing. However, an additional amount of current would flow downward into the earth below the casing. From the basic symmetry of the situation, there is about an equal solid angle for current to flow radially outward as there is a solid angle for current to flow downward. Therefore, by symmetry, the amount of current flowing downward should also be about ΔI_o . Consequently, Equation VIII-I-2 would become at the end of the casing string:

$$\rho_f(\text{END}) = \beta(\text{END}) K V_o / (2 \Delta I_o)$$

Equation VIII-I-3

Because the model assumes a uniform half-space, the formation resistivity at the end of the casing is the same as elsewhere. Therefore the parameter $\beta(\text{END})$ must obviously take on the value of 2.00 near the end of the casing to get the same value of ρ_f . The following definitions are useful at this point:

ΔI_o - current conducted radially into formation
away from bottom end of casing in
absence of casing end effects

$\Delta I_T(Z)$ - total current conducted into formation
in all directions (radially and downward)
as a function of distance Z up from the
end of the casing string

Evidently then, for different distances Z up from the end of the casing string, the parameter $\beta(\text{END})$ must satisfy the following condition:

$$\beta(\text{END}, Z) / \Delta I_T(Z) = 1.00 / \Delta I_o$$

Equation VIII-I-4

Therefore:

$$\beta(\text{END}, Z) = \Delta I_T(Z) / \Delta I_o$$

Equation VIII-I-5

For a constant voltage V_o in all cases, the ratio of these currents is simply related to the inverse ratio of the respective resistive loads to infinity.

Away from the bottom of the casing, and in the absence of casing end effects, Equation VIII-A-12 shows what the real resistive load to infinity is for the TCRT, namely:

$$R(\text{REAL}) = R_c / 2$$

Equation VIII-A-12

Please refer to Figure VIII-I-1 that describes the situation at the very end of the casing string. The resistive load to infinity due to radial current flow is $R_c / 2$. However, because of the earlier symmetry arguments, an equal amount of current flows downward through the formation below the casing. Therefore, evidently, the model for the resistive load of the TCRT at the very end of the casing string is shown in Figure VIII-I-1.

For different vertical positions, see Figure VIII-I-2. Here, at different vertical positions away from the end of the casing, the resistivity load changes. This very simple model assumes that for every distance of translation equal to L50%, then an extra

resistor $R_c / 4$ is inserted into the net resistive load for downward flowing current. The value of this resistor being equal to $R_c / 4$ comes from the arguments already presented in Section VIII-H entitled "50% Radius of Investigation - L50%" (see Equation VIII-H-1 for example). Therefore, using the very simple model shown in Figure VIII-I-2 gives the following result:

$$\beta(\text{END}, Z) = \beta(\text{END}, N) = (N + 4) / (N + 2)$$

$$\text{And where: } Z = (N) (L50\%)$$

Equation VIII-I-6

Therefore, Equation VIII-I-6 gives the values of $\beta(\text{END}, Z)$ at different distances Z up from the end of the casing string, where Z is given by N times L50%. The quantity in Equation VIII-I-6 is defined to be $\beta(\text{END}, Z)$ so as to explicitly remind the reader that the calculated quantity is a function of Z . For simplicity, however, the figures refer to " $\beta(\text{END}, Z)$ " simply as " $\beta(\text{END})$ ".

Figure VIII-I-3 shows a plot of $\beta(\text{END})$ vs. N from Equation VIII-I-6. Please notice that within 100 each L50% distances from the end of the casing, that there is very little correction from the quantity $\beta(\text{END})$.

Equation VIII-H-6 presents an approximate value of L50% in terms of the radius of the casing. For 7 inch O.D. casing appropriate for the MWX-2 Well, then Equation VIII-I-6 becomes:

$$\beta(\text{END}, Z) = \beta(\text{END}, N) = (N + 4) / (N + 2)$$

$$Z = (N) (L50\%) = 23.14 \text{ a } N$$

Equation VIII-I-7

Figure VIII-I-4 shows the results for 7 inch O.D. casing. Equation VIII-I-7 is used to plot $\beta(\text{END})$ vs. Z . Please notice that 100 feet up from the end of the casing string requires corrections on the order of about 10%. By 300 feet, the corrections are on the order of about 5% from this model.

It not known at this time whether this admittedly crude model will provide corrections sufficiently accurate for routine field work. Perhaps one could argue that the solid angles for outward and downward current flow near the end of the casing are not the same, but some other relative fraction, which would therefore change the above detailed numbers. However, the basic physics presented herein is essentially correct. Near the end of the

pipe, and for a given Potential Voltage V_o , the TCRT will measure additional currents flowing downward into the rock below the end of the casing and simple corrections are needed to compensate for this effect.

FIGURE VIII-I-1
CORRECTION FOR END EFFECTS
AT BOTTOM OF CASED WELL

FIGURE VIII-I-2
CORRECTION FOR END EFFECTS
AT OTHER POSITIONS IN CASSED WELL

$\beta(\text{END})$ PLOT
ParaMagnetic Logging, Inc.

$\beta(\text{END})$ PLOT
ParaMagnetic Logging, Inc.

Figure VIII-I-4
Printed Out 9/21/94
L50% = 6.75 ft for 7" OD Casing

SECTION VIII-J

FINAL GENERAL FORMULAE TO OBTAIN TRUE

FORMATION RESISTIVITY ρ_t FROM TCRT

APPARENT RESISTIVITY MEASUREMENTS & β (REFS)

It is worthy to repeat the following herein that are used in practice to obtain the apparent resistivity from TCRT measurements. First, the raw experimental data is used to determine R_c as follows:

$$R_c = V_o / \Delta I \quad \text{Equation 2}$$

Then, using PML's Calibration Constant K, we immediately obtain the apparent resistivity ρ_a from the TCRT measurements as follows:

$$\rho_a = K R_c \quad \text{Equation 3(a)}$$

Under certain circumstances, the apparent resistivity ρ_a must be corrected for various effects to obtain the true formation resistivity ρ_t from the TCRT. A distinction is to be made between ρ_t that is the "true formation resistivity" obtained from a series of logical corrections to TCRT data, and ρ_f that is the "formation resistivity" which is the geologically correct resistivity of the formation (however that is determined). It presently appears that such corrections can be performed in accordance with the following equation:

$$\rho_t = \beta(\text{REFS}) \beta(\text{CEMENT}) \beta(\text{END}) \rho_a$$

$$\text{Equation VIII-J-1}$$

Here, ρ_a is the apparent resistivity measured with the TCRT; $\beta(\text{END})$ is a dimensionless number that corrects for end effects of the casing as presented in Section VIII-I; $\beta(\text{CEMENT})$ is a dimensionless number that corrects for the presence of cement as developed in Section VIII-F; and $\beta(\text{REFS})$ is a dimensionless

number that corrects for various "residual effects" (abbreviated "REFS") of the TCRT including for the effects of collars; for D.C. effects related to the Characteristic Length of a given cased well; for the frequency of operation and for various AC effects related to the frequency of operation, to the types of casing present, and to the nature of the geological formations present; for fractures; and for other minor "tool effects".

All of the different " β 's" have the same feature in common: if no correction is required for a particular effect, the particular " β " takes on the value of 1.00. For example, if the TCRT is far away from the end of the casing, then Section VIII-I shows that $\beta(\text{END}) = 1.00$. As another example, if no corrections are required for the presence of cement, then Section VIII-F shows that $\beta(\text{CEMENT}) = 1.00$. And similarly, if no corrections are required for the host of residual effects listed above, then $\beta(\text{REFS}) = 1.00$.

The quantity $\beta(\text{REFS})$ may in general have other components that are given by the following, where the definitions of each is obvious in light of the description provided in the last paragraph beginning on the previous page:

$$\begin{aligned} \beta(\text{REFS}) = & \beta(\text{COLLAR}) \beta(\text{CHARACTERISTIC LENGTH}) \\ & \beta(\text{A.C.}) \beta(\text{FRACTURES}) \beta(\text{MINOR TOOL EFFECTS}) \end{aligned}$$

Equation VIII-J-2

All of these new β 's defined above here have the common feature that in the absence of necessary corrections, their values are all unity.

It should be noted that all of the β 's have additional hidden variables. For example, it is obvious that the parameter $\beta(\text{COLLAR})$ would only be significantly different than the quantity 1.00 near a collar. Therefore, $\beta(\text{COLLAR})$ must be a function of the depth. Further, $\beta(\text{COLLAR})$ must also be a function of the geometry of the collar itself, the type casing present, and the frequency of operation.

Similarly, $\beta(\text{FRACTURES})$ will only be significantly different in regions where fractures exist, so it too will be a function of depth. At any given depth, the size of the fractures, the geometry of the fractures, and the resistivity of water filling the fractures will also affect $\beta(\text{FRACTURES})$.

The general conclusion of this discussion is that while many variables are hidden in Equations VIII-J-1 and VIII-J-2, the

basic concept of using β 's to describe corrections to ρ_a to obtain ρ_t is a reasonable way to approach this problem.^a This approach is also particularly efficient because the β 's only depart from unity when substantial corrections are required, thereby conceptually simplifying a very complex situation.

Data obtained at the MWX-2 Well by PML involving measurements of a variety of AC phenomena, and the models developed at the MWX-2 wellsite by PML for those AC phenomena have a direct bearing on calculations of β (REFS). This data and those particular wellsite models have been forwarded to PML's Licensees in various proprietary documents.

There are other corrections to be applied to TCRT data which are typical for open-hole log interpretation of the LL3. Equation 3 assumes that the geological formation itself adjacent to the casing is a thick formation, meaning it is about 3 times thicker than the Electrode Spacing of the TCRT. For thin beds, analogous corrections to TCRT measurements are required as those which are now presently done for thin bed LL3 corrections.

Similarly, Equation 3 assumes horizontal beds and a vertical well. For inclined beds, or non-vertical wells, analogous corrections to TCRT measurements are required as those now done for inclined bed LL3 corrections.

It is well known that irregular holes also affect LL3 interpretation. If irregular holes around the casing are filled with cement, then analogous corrections are necessary for the TCRT based on experience with the LL3 and using the ideas already set forth in Section VIII-F involving the corrections for the presence of cement.

SECTION VIII-K

SIMPLE ALGEBRAIC FORMULAE TO DETERMINE APPROXIMATE SIGNAL SIZES AT DIFFERENT WELLSITES

The purpose of this section is to provide simple algebraic equations that may be readily used to provide estimated TCRT signal sizes at various wellsites.

Assume that Electrode A of the TCRT is disposed within a deep cased well in a half-space having a uniform resistivity ρ_o . From Equations VIII-G-2 and VIII-G-3 of Section VIII-G, we obtain:

$$ZC(D.C.) = 1.26 (r \rho_o)^{1/2} / 2 \quad \text{Equation VIII-K-1}$$

From Section VIII-G, $ZC(D.C.)$ is the "D.C. Center Driving Impedance" (in ohms) and r is the average resistance per unit length of the casing (in ohms/meter).

If I_T is the total current (in amps 0-peak) conducted to the casing in the Measurement State, then the Potential Voltage V_o (in volts 0-peak) is given by the following:

$$V_o = 1.26 I_T (r \rho_o)^{1/2} / 2 \quad \text{Equation VIII-K-2}$$

From Equation 3(b), we have:

$$\rho_o = K (V_o / \Delta I) \quad \text{Equation 3(b)}$$

Therefore, ΔI is given as follows:

$$\Delta I = K V_o / \rho_o \quad \text{Equation VIII-K-3}$$

Substituting V_o from Equation VIII-K-2 into Equation VIII-K-3 yields the following:

$$\Delta I = K \ 1.26 \ I_T \ (r \ \rho_o)^{1/2} / (2 \ \rho_o)$$

Equation VIII-K-4

The body of work in Section VIII-C shows that PML's Calibration Constant K is approximately equal to ELECTSP for typical electrode spacings of the TCRT and for typical casing sizes. Therefore, the same approximation is used in Equation VIII-H-4 that is repeated here as follows:

$$K = \text{ELECTSP}$$

Equation VIII-H-4

Substituting Equation VIII-H-4 into Equation VIII-K-4, and simplifying, yields:

$$\Delta I = 1.26 \ I_T \ (\text{ELECTSP}) \ (r / \rho_o)^{1/2} / 2$$

Equation VIII-K-5

Equation VIII-K-5 can be used to determine the anticipated current leakage ΔI at wellsites which is unaffected by first and second order measurement errors described in Vail (1991c).

For example, to estimate signal sizes at the MWX-2 Well, the following approximate parameters can be used that are applicable to that particular well:

$$r = 39.8 \text{ micro-ohms/meter}$$

$$\rho_o = 38 \text{ ohm-meters}$$

$$\text{ELECTSP} = 19 \ 13/16 \text{ inches} = 0.503 \text{ meters}$$

Equation VIII-K-6

Using these values in Equation VIII-K-5 provides the following:

$$\Delta I = (0.32 \ 10^{-3}) \ I_T$$

Equation VIII-K-7

For I_T equal to about 6 amps 0-peak typically used at the MWX-2 Well, then:

$$\Delta I = 1.9 \text{ milli-amps (0-peak)} \quad \text{Equation VIII-K-8}$$

For the purposes of this particular comparison that is only appropriate for a uniform half-space, it is necessary to choose a point where the resistivity of the adjacent formation is about equal to the average resistivity of the assumed uniform half-space. In addition, Electrode A must be used as assumed for this particular analysis. A candidate point is at the depth of 4,570 feet in Figure 72 where the formation resistivity is about 35 ohm-meters. At that depth of 4,570 feet in Figure 68, the corresponding measured current leakage ΔI is roughly equal to the above calculated value.

Assuming that R_1 , the resistance in ohms between Electrodes C-D, is exactly equal to R_2 , the resistance in ohms between Electrodes D-E, and assuming a unity gain system for simplicity, the net differential voltage ($V_1 - V_2$) in the Measurement State is given by the following:

$$\begin{aligned} V_1 - V_2 &= \Delta I \ R_1 \\ &= 1.26 \ I_T \ R_1 \ (\text{ELECTSP}) \ (r / \rho_o)^{1/2} / 2 \end{aligned}$$

$$\text{Equation VIII-K-9}$$

Equation VIII-K-9 can be used to determine the anticipate size of the differential signal due to the current leakage ΔI which is unaffected by first and second order measurement errors described in Vail (1991c). Assuming R_1 under these circumstances is about equal to 20 micro-ohms, then for $I_T = 6$ amps 0-peak, the anticipated differential signal strength at the inputs to the front-end amplifiers is given by:

$$\begin{aligned} V_1 - V_2 &= 1.9 \text{ milli-amps (0-peak)} \ (20 \text{ micro-ohms}) \\ &= 38 \text{ nano-volts (0-peak)} \end{aligned}$$

$$\text{Equation VIII-K-10}$$

This signal strength is to be compared against the front-end amplifier noise and other relevant noise in the system's detection bandwidth. In practice, there are many other issues to consider.

Equations VIII-K-5 and VIII-K-10 are appropriate for a uniform half-space. The authors chose to derive these equations for simplicity.

The above analysis can be easily generalized for the case of a thick uniform bed having a formation resistivity ρ_f in an otherwise uniform half-space having uniform resistivity ρ_o . All that is necessary to do is to use the correct formation resistivity in Equation 3(b) above that is then given by:

$$\rho_f = K (V_o / \Delta I) \quad \text{Equation VIII-K-11}$$

In this situation, the current leakage into the formation of resistivity ρ_f adjacent to the TCRT in an otherwise uniform half-space having resistivity ρ_o is given by:

$$\Delta I = 0.63 \text{ ELECTSP } I_T (r \rho_o)^{1/2} / \rho_f \quad \text{Equation VIII-K-12}$$

In this situation, the net differential voltage ($V_1 - V_2$) in the Measurement State is given by the following:

$$\begin{aligned} V_1 - V_2 &= \Delta I R_1 \\ &= 0.63 \text{ ELECTSP } I_T R_1 (r \rho_o)^{1/2} / \rho_f \end{aligned} \quad \text{Equation VIII-K-13}$$

As an example, at the depth of about 4,588 feet in Figure 72, the apparent resistivity is approximately equal to 100 ohm-meters. Therefore, using the values of r and ELECTSP from Equation VIII-K-6, 6 amps 0-peak for the value of I_T , and a formation resistivity ρ_f of 100 ohm-meters, Equation VIII-K-12 can be used to calculate the anticipated current leakage that is given as follows:

$$\Delta I = 0.74 \text{ milli-amps 0-peak} \quad \text{Equation VIII-K-14}$$

At that depth of 4,588 feet in Figure 68, the corresponding measured current leakage ΔI is roughly equal to the above calculated value.

Assuming R_1 under these circumstances is about equal to 20 micro-ohms, and for $I_T = 6$ amps 0-peak, Equation VIII-K-13 can then be used to calculate the anticipated differential signal strength at the inputs to the front-end amplifiers that provides the following:

$$\begin{aligned} V_1 - V_2 &= 0.74 \text{ milli-amps (0-peak)} \quad (20 \text{ micro-ohms}) \\ &= 15 \text{ nano-volts (0-peak)} \end{aligned}$$

Equation VIII-K-15

This signal strength is to be compared against the front-end amplifier noise and other relevant noise in the system's detection bandwidth. In practice, there are many other issues to consider. Details concerning such issues have been forwarded to PML's Licensees in various proprietary documents.

The authors have found such estimations of signal sizes for the practical aspects of instrument design and system debugging to be of great value.

SECTION VIII - L

RETROSPECTIVE ON CALIBRATION CONSTANT K

In 1986, W.B. Vail originally theorized that using the very simple concept for the Calibration Constant K defined by Equation 3 would probably be a good approximation at low frequencies for TCRT data interpretation. It has turned out that way, both experimentally and theoretically. From the theoretical point of view, please refer to much detail in Sections II-A, VIII-A, VIII-B and VIII-C. From the experimental point of view, please refer to Sections II-B, II-C and II-D.

In summary, the use of a Calibration Constant K appears to be a valid approximation at sufficiently low frequencies provided that the formation under investigation is relatively thick and provided it is reasonably homogeneous. Any required corrections for the effects of cement can be performed as set forth in Section VIII-F. Any required corrections for end effects of casing can be performed as set forth in Section VIII-I. Any small corrections required for small departures from "sufficiently low frequencies", and for other relatively small effects, can be performed as set forth in Section VIII-J. Thin bed corrections should be performed in an analogous fashion to those now used to correct open-hole LL3 logs. As shown in the previous section, these simple ideas lead to the ability to algebraically calculate at the wellsite the approximate signal sizes to be observed by any TCRT in any cased well in the future.

It is recognized by the authors that the complete solution of Maxwell's Equations at every different wellsite using the casing characteristics and other unique wellsite specific data would yield more precise data interpretation at any given wellsite than is provided by the approximate use of K. However, the use of K results in an extraordinarily simple approximate means to handle many different types corrections to TCRT logs. The authors have long believed that there is much merit to simple TCRT data interpretation and simple corrections to TCRT logs. Therefore, the authors have diligently pursued simple models to explain the operation of the TCRT.

In this "Retrospective", the author's wish to point out that the analogous use of calibrating factors "k" have been remarkably successful to interpret data from other previous open-hole electric logging tools, and even in other disciplines devoted to the measurement of resistivity.

As a first example, H.G. Doll published the paper entitled "The Laterolog: A New Resistivity Logging Method with Electrodes Using an Automatic Focusing System", Petroleum Transactions of the AIME, Vol. 192, Feb. 17-22, 1951 (Doll, 1951). In that paper, Doll (1951) states:

"The current i is measured by means of a meter located at the surface and connected to both ends of the shunt. The potential ΔV of electrode M is also measured by means of another meter at the surface, and the ratio $\Delta V/i$ gives the value of resistance offered to the current, which is proportional to the resistivity of the formation situated within the current sheet."

Figure 1 of Doll (1951) then shows the following equation:

$$R_a = K \frac{\Delta V}{i}$$

This is the same form as Equation 3 that appears in this Final Report that is appropriate for the TCRT. The authors have simply used the idea that, in many ways, the TCRT operated from inside the casing provides measurements analogous to those obtained with the Laterolog type devices in the open hole. Accordingly, the above equation from Doll (1951) corresponds to Equation 3 of the Final Report.

As a another example, the authors wish to repeat here the following text and Equation 1 from the paper published by Herbert Guyod entitled "Factors Affecting the Responses of Laterolog-Type Logging Systems (LL3 and LL7)", Journal of Petroleum Technology, February, 1964 (Guyod, 1964):

"Let V denote the potential difference between E and the faraway return electrode, and I be the current flowing between these two electrodes. The resistance (R_e) seen by the exploring electrode is V/I , and the corresponding apparent resistivity is

$$R_a = k (R_e)$$

where k is the tool calibration factor."

Accordingly, the above equation from Guyod (1964) corresponds to Equation 3 of the Final Report. The identification of V/I being equal to R_e in Guyod (1964) corresponds to Equation 2 of

the Final Report. Guyod (1964) even calls his k a "calibration factor" that precedes the use by PML of the "Calibration Constant K ". Much of Guyod (1964) derives from the earlier work of Doll (1951) and Guyod (1951).

Similar equations to the above were developed by J.E. Owen and W.J. Greer in their paper entitled "The Guard Electrode Logging System", published in the Petroleum Transactions of the AIME, Vol. 192, page 347-356, Oct. 3-5, 1951 (Owen and Greer, 1951). In particular, see their Equation 1.

Similarly, a factor K_g that is the "geometric factor for the guard electrode array" ⁹ is described by Keller and Frischknecht (1966) - see Equation 46 on page 75. Keller (1949) provided earlier work on this same subject.

As an example from entirely different measurement discipline, the measurement of resistivity of samples in a laboratory is considered here. A multiplicative calibration factor is used in typical four-point resistivity measurements as evidenced from the following quote on page 58 of the textbook authored by A. S. Grove of the Intel Corporation entitled "Physics and Technology of Semiconductor Devices" (Grove, 1967):

"The average resistivity of diffused layers is customarily measured by the four-point probe technique illustrated in Figure 3.17. In this technique four probes are placed on the surface of the semiconductor. Current is passed through the two outermost probes and the voltage - the IR drop - due to this current flow is measured between the two middle probes. Thus any problems due to probe-to-semiconductor contact resistances are eliminated. In order to relate the measurements of the voltage drop V and the current I to the average resistivity ρ of the diffused layer we must solve the electrostatic problem which takes into account the spreading of the current from the two outside probes as shown in the top view in Figure 3.17. This has been done and the result for layers whose lateral dimensions are large and whose width x_j is small in comparison to the spacing of the probes is

$$\rho = (\pi / \ln 2) (V / I) (x_j) = (4.532) (V / I) (x_j)."$$

Here, x_j is the thickness of the semiconductor under measurement. Suppose that we defined a factor k that is given as follows:

$$k = (4.532) (x_j)$$

Then, the above equation from Grove (1967) becomes:

$$\rho = k (V / I)$$

Therefore, the apparent resistivity of a semiconductor under four-point resistivity testing is determined with methods analogous to those using the tool calibration factor in Guyod (1964), to those using the constant K in Doll (1951), and to using PML's Calibration Constant K in Equation 3 for interpretation of TCRT measurements.

The authors are further indebted to W. David Kennedy of Mobil Technology Corporation for sending a copy of Moran and Kunz (1962) to the authors during January of 1995. W. David Kennedy pointed out the particular relevance of Equation 17 in that reference. Using that as a starting point, W. David Kennedy showed that apparent resistivity is obtained from induction logging tools by multiplying a suitable calibrating factor k times the ratio of I / V_R - where I is the "current in transmitter coil (ampere)" and V_R is "receiver voltage in phase with transmitter current" - as quoted from page 831 of Moran and Kunz (1962). Here, the units of k are different than that used in Equation 3 of this Final Report.

It is the understanding of the authors that Moran and Kunz (1962) elaborated on the particular approach that was pioneered by Doll (1949). Equation 2 in Doll (1949) defines the "apparatus constant". H.G. Doll coincidentally defined that "apparatus constant" by the capital letter "K". The primary point of this discourse is that, even in the case of induction tools, the use of a single calibrating factor k has proven to be of great use to the industry.

This Section VIII-L has adequately shown that suitable calibrating factors "k's" have been historically used to successfully interpret data from open-hole LL3 type tools, from induction logging tools, and from laboratory four-point resistivity measurements. Accordingly, in this retrospective, and despite the objections of one noted "industry expert" many years ago, it is now evident in hind-sight that the use of PML's Calibration Constant K for the TCRT should work reasonably well under the assumed circumstances.

The authors wish to encourage future theoretical work to rigorously establish when K can be usefully employed, or suitably otherwise corrected as set forth in Section VIII-J of this Final Report.

The authors wish to express their appreciation for the final words on this subject from W. David Kennedy of Mobil Technology Corporation, who is quoted below:

'Tool calibrating factors, or "constants", that are used as multiplicative factors to obtain the resistivity (or conductivity) of conductive media from the ratio of measurements made on the voltages and currents produced by instruments immersed in the media are valid only in very simple (i.e, infinite, homogeneous, and isotropic) media. In heterogeneous media the product of such constant factors with voltage-to-current ratios can at best produce only an approximation of the resistivity in the region close to the tool. That such factors are obtained from the solutions of (simple) boundary value problems does not make the calibrated tool output accurate in heterogenous media. The hope in the logging industry is that the influence of regions remote from the tool can be made negligible by astute tool design and the remaining effects can be accounted for with correction charts; however it is trivially easy to find situations where this hope is dashed due to geological complexity or drilling-induced complications (e.g, the apparent resistivity near the contact of two semi-infinite regions of differing resistivity is not equal to the resistivity of either region). Thus, an empirically determined calibration constant is in no way inferior to the same constant determined by analysis of the boundary value problem corresponding to a tool's principle of operation. In fact, the analytically and empirically determined values should be exactly the same if: (1) the mathematical analysis can accurately account for the tool response and (2) a suitably simple environment can be found or made for the empirical determination. So, whether the first or the second method is used is a matter of convenience; the mathematical physicists will want to calculate responses because they know how (and since they may not know how to design experiments and build tools) whereas the engineers will want an empirical determination because they know how to build tools and design experiments (and since they may not know how to solve the corresponding boundary value problems). It is true that as a general technique the mathematical analysis has a lot to recommend it over empirical characterization of tool responses since it is easier to model infinite media in a numerical experiment than a physical one, and easier to change the parameters of a model; however, from the point of view of the result, either is equally valid.'

SECTION IX

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The authors wish to express their appreciation to the following individuals who supported this work prior to October of 1994, which is the time period relevant for this Final Report.

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