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PROOF OF CONCEPT OF MOVING THRU CASING RESISITIVITY APPARATUS

Final Report for the Project Period
October 1, 1989 to January 31, 1993

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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 (herein), 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
Title: "Fabrication and Downhole Testing of Moving Through Casing Resistivity Apparatus"
Status: All experimental work completed, Final Report in preparation, all reports except Final Report have been completed, and close-out pending receipt of Final Report.

In terms of the above definitions, this is the Final Report to DOE resulting from the work performed during the Third DOE Grant.

The TCRT was invented during the First DOE Grant while doing work on another unrelated topic - the Paramagnetic Logging Effect (PLE). The basic invention of the TCRT was made at a time when DOE was funding the work by PML. A total of 8 patents have already issued to W. Banning Vail, Ph.D. in the U.S. related to the TCRT, one more will issue shortly, and a number of others are still pending. One patent in this field was acquired from another firm. See Table 1 entitled "ParaMagnetic Logging, Inc. - Through Casing Resistivity Tool® Patents". PML has elected to retain the rights to those patents from DOE. See Table 2 entitled "Summary of Election of Patent Rights by DOE Contract Number".

Rights to five U.S. patents related to the TCRT were elected from the First DOE Grant. After that grant was closed-out, and PML was requested by DOE to do so, rights to three more U.S. patents related to the TCRT were elected from the Second DOE Grant. In addition, yet another U.S. patent will issue shortly that was also elected from this Second DOE Grant.

The Second, Third, and Fourth DOE Grants were co-funded with Gas Research Institute (GRI) of Chicago, Illinois under the auspices of GRI Contract No. 5088-212-1664. The Final Report to GRI (Vail and Momii, 1996) summarizes in one document the decade-long effort to prove the feasibility of the TCRT. The Final Report to GRI is 328 pages long that includes 169 figures. The Final Report to GRI particularly summarizes the important results from the blind tests at the MWX-2 Well and a summary of most of the important theory necessary to make the TCRT work in practice that are also the subjects of the forthcoming Final Report to DOE for the Fourth DOE Grant.

It should be noted that the basic and fundamental invention of the TCRT was made during the First DOE Grant during which time no co-funding had been received from GRI. In fact, the basic invention of the TCRT is referred to as "Background Know-How" and "Background Patent Rights" in GRI Contract No. 5088-212-1664. Therefore, considerable credit must be afforded to DOE for funding the earliest work on the TCRT.

PML has entered into a patent cross-licensing agreement with Atlantic Richfield Corporation involving the TCRT. 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. For the purposes of this Final Report, Western Atlas Logging Services and Schlumberger Technology Corporation are PML's service company licensees and shall hereinafter be referenced together as "PML's Licensees" for simplicity.

Most of the experimental work for this Final Report was completed by the end of 1991. For example, please refer to the reports addressed to Mr. Harvey Haines of GRI respectively dated: 9/11/91; 10/17/91; and 11/20/91. Copies of those reports were forwarded to DOE. In any event, absolutely all of the data and all theory presented in this Final Report to DOE was in the possession of PML and known to PML no later than the date of September 30, 1994.

It should also be noted that Through Casing Resistivity Tool® (TCRT®) are Registered Trademarks of ParaMagnetic Logging, Inc.; and Measurement-While-Drilling-Bit-Stopped™ (MWDS™), and ParaMagnetic Logging™ (PML™) are Trademarks of ParaMagnetic Logging, Inc.

ACKNOWLEDGEMENTS

The authors wish to express their appreciation to the following individuals who supported this work prior to 1992, which is the time period relevant for this Final Report.

Particular appreciation should be extended to Robert E. Lemmon of DOE, an early and continuing supporter of the TCRT; to Harvey Haines of the Gas Research Institute (GRI); to Robert W. Siegfried, II for his assistance while at ARCO and more recently at GRI; to John F. Gould, Jr. and to W. David Kennedy of Mobil; and to James D. Klein of ARCO for his pioneering research on the resistivity of cement. We wish to further express our appreciation to William G. Crossland and Harold "Bud" Fauska as employees of PML, and to Walter Cubberly and John Stoltz as consultants to PML, for their outstanding collaborative work on the mechanical portions of the instruments; to John Tatum of the Randolph Company for a perfect zero-defect, on-time production run of the parts; to Bobby and Helen Gotcher of Gotcher Cable Service for manufacturing the hoist and for expert wireline advice; to Ryszard Gajewski and Duane L. Barney of the Office of Basic Energy Sciences of the United States Department of Energy (DOE) for their courage to be the very first to support this technology during the earliest possible conceptual phase *prior* to any successful demonstration of this technology; to Edith C. Allison, Fred W. Burtch, James W. Chism, E.B. Nuckols, Herb Tiedemann, and Thomas C. Wesson of the Bartlesville Project Office of the DOE for their steadfast support of this technology *prior* to any successful demonstration of this technology; to John Aslakson, Steven D. Ban, Charles F. Brandenburg, Myron Gottlieb, Greg W. Handke, Scott Hathaway, Robert W. Meyer, and Bruce C. Smith of GRI and the member companies of GRI who have steadfastly supported this work during the difficult years required to solve the relevant technical problems *prior* to any successful demonstration of this technology; to Laura K. Blacker, Curtis Blount, Sherman Bradley, Jerry L. Brady, Eddie Howell, Gary D. Myers, Dave McNaughton, and Joe Smith for their help at ARCO; to Mark Alberty, Juma Attid and Roberto C.A. Peveraro for their interest at BP; to John Fitch at Mobil for his very early encouragement of this work; to David C. Herrick, Gus L. Hoehn, Robert E. Maute, Bill Mills, and Jose Olmos for their help at Mobil; to Al Jageler, Tony Nekut, Jay Patchett, and Ralph Wiley for their interest at AMOCO; to Bruce Nelson, James J. Smolen, and Steve Waite for their technical assistance; to Marvin Gearhart whose critical help over a several month duration many years ago allowed this technology to proceed; to Bob Chicko of III Oaks Software, to Arthur F. Kuckes of Vector Magnetics, to Howard C. Merchant of MerEnco, to Paul B. Schwinberg of the University of Washington, and to Richard Woodhouse of Petroleum and Earth Science Consulting for their consulting expertise provided to PML on various important matters; to John T. Dewan of Dewan & Timko, to E.R. Hunt of ResTech, to Stephen Park of the University of California at Riverside, and to Liang C. Shen of the Well Logging Laboratory of the University of Houston for their separate positive technical reviews of PML's research work on the TCRT provided to GRI on different occasions; and to Sheldon Breiner, Reta Leeson, and Marilyn Vail for their long-term administrative support and personal encouragement of this work as PML employees; and to the families of PML employees who put up with many hardships during this long and difficult development effort.

We wish to particularly express our gratitude to Mr. Bobby Gotcher for his help, generosity, friendship and unparalleled practical knowledge, and to Dr. Duane L. Barney who championed this work at a time when he alone, besides the authors, believed in the technology - they are now, and shall continue to be missed.

To paraphrase a quote attributed to Edward Schon of M.I.T., those above have demonstrated "*courage of heroic quality*" to overcome "*the indifference and resistance that major technological change provokes.*"

ABSTRACT

ParaMagnetic Logging, Inc. (PML) demonstrated for the first time during 1990 in a Test Well located in Fort Worth, Texas that formation resistivity could be measured, in-principle, from within cased wells with the Through Casing Resistivity Tool (TCRT) designed and built by PML. Early results from this first instrument provided the impetus to investigate measurements methods to increase data acquisition rates and mechanical designs to improve vertical resolution which were implemented in the second experimental version of the TCRT.

PML investigated the design requirements for a tool that could continuously move upward within a cased well. It was found that although such measurements can be done, various interfering signals, including those identified as due to the Triboelectric Effect, would mask the weak borehole casing signals if standard wirelines and components from the industry are utilized which limit the amount of electrical current delivered to the well. Extensive laboratory measurements were performed with the Moving Test Jig to investigate the properties of the Triboelectric Effect. Successful methods of measurement were devised to achieve acceptable performance objectives and to overcome problems with the Triboelectric Effect. One such method is called the Slider Method of Measurement.

EXECUTIVE SUMMARY

Overall Objective. To investigate whether the resistivity of geological formations can be measured from within cased wells with a moving TCRT.

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 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.

INTRODUCTION

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 PML's First TCRT in the Research Well at Gearhart Industries, Inc. in Fort Worth, TX. 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 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 Final Report is to briefly review the experiments involving the Triboelectric Effect and the development of new measurement techniques to overcome related effects.

As a result of the experiments reported here, signal processing techniques and methods of measurement were developed that are capable of providing acceptable data acquisition rates suitable for commercial logging with the TCRT. Those techniques and methods were used during later well tests under the auspices of another follow-on grant from DOE, that is DOE Grant No. DE-FG22-93BC14966, the Fourth DOE Grant. Under that Fourth DOE Grant, 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. Successful 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". Those "blind test" results definitely proved to the oil and gas industries that the TCRT works. However, these well test results are provided in the Final Report on DOE Grant No. DE-FG22-93BC14966, the Fourth DOE Grant.

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", that also has an average logging speed of 2 feet per minute, and 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 the section that is entitled 'Anticipated Performance Specifications of the Prudhoe Bay Through Casing Resistivity Tool ("PBTCRT"), November 12, 1992'.

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 the previous section. Please refer to Figure 1 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 previously defined "Acceptable Performance Specifications".

The Test Pipe in Figure 1 is a rusty piece of casing that is 20 feet long with a 7 inch O.D. and 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. Front-end amplifiers are mounted on the Moving Test Jig allowing measurement of the required voltage signals.

In Figure 1, 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 1 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 2 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 2 shows Runs 1 and 2 which were done at slightly different logging speeds.

Figure 2 shows that at one foot per minute, we can measure about 11 milliamps leaking from the casing. 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 2 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 3. 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 3. The cause of that noise is the Triboelectric Effect.

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.

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 4. In Figure 4, one probe is in electrical contact with the metal, is held stationary, and is called the "Reference Electrode". In Figure 4, 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 4 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 4, 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 4.

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 causes 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.

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 Figure 1.

Figure 5 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 6 shows a repeat run obtained on a different day.

Figure 7 shows the same measurement as in Figures 5 and 6, 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 7 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 8 is similar to Figures 5 and 6, 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 9 is similar to Figure 8, 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 10 is similar to Figures 5 and 6 except here, proper account is taken for the thickness variations of the casing. In Figure 10, 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 milliamperes/inch near the center of the "bump" in Figure 10. 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 1 (0.333 milliamperes/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 of the Final Report to GRI (Vail and Momii, 1996).

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. Various slider mechanisms have been described in pertinent patent applications.

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.

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

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 1 from electrodes separated by 18 inches located on inside and outside of the Test Pipe. Please refer to Figure 11 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, TX.

The difference between the measurements performed inside and outside of the casing in Figure 11 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.

**ANTICIPATED PERFORMANCE SPECIFICATIONS OF THE
PRUDHOE BAY THROUGH CASING RESISTIVITY TOOL ("PBTCRT")
NOVEMBER 12, 1992**

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: About 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 PBTCRT 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

FIGURES

**FIGURE 1
TEST PIPE
WITH MOVING TEST JIG
EXPERIMENTAL SETUP**

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

Figure 2
Printed Out 7/4/94
Data Collected: 7/23/91

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

Figure 3, Jerk & Hold with 10 mAOP on Test Pipe
Printed Out 7/4/94
Data Collected: 11/7/91, Run #1

MATERIAL	SIGN	MAGNITUDE
STEEL	-	200 mV
COPPER	+	20 mV
ALUMINUM	+	100 mV
BRONZE	+	150 mV

WITH THE SAME FORCE, F , AND SAME VELOCITY, V .

FIGURE 4
DEMONSTRATION OF THE
TRIBOELECTRIC EFFECT

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

Figure 5
 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 6
 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 7
 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 8
1 Hz, 3 pts, TC=1s
Data Collected: 2/6/92 Run #2

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

Figure 9
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 10
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 11
Printed Out 7/4/94

TABLES

Table 1:

ParaMagnetic Logging, Inc.

THROUGH CASING RESISTIVITY TOOL® PATENTS

Issued and in Allowance

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
28	5,570,024	10/29/96	06/28/93	08/083,615	C.I.P. PML Patent No. 22
29	In Allowance		03/17/94	08/214,648	C.I.P. PML Patent No. 28

Table 2:

Summary of Election of Patent Rights
by DOE Contract Number

PML Pat. No.	U.S. Patent Number	Patent Name	DOE Contract No.	DOE "S" No.
5	4,820,989	"Methods and Apparatus for Measurement of the Resistivity Geological Formations From Within Cased Boreholes"	DE-FG06-84ER13294	S-66,323
7	4,880,542	"Methods and Apparatus for Measurement of Electronic Properties of Geological Formations Through Borehole Casing"	DE-FG06-84ER13294	S-66,907
10	5,043,669	"Methods and Apparatus for Measurement of the Resistivity of Geological Formations From Within Cased Wells in Presence of Acoustic and Magnetic Energy Sources"	DE-FG06-84ER13294	S-69,887
14	5,075,626	"Electronic Measurement Apparatus Movable In A Cased Borehole and Compensating for Casing Resistance Differences"	DE-FG19-88BC14243	S-71,163
16	5,043,668	"Methods and Apparatus for Measurement of Electronic Properties of Geological Formations Through Borehole Casing"	DE-FG06-84ER13294	S-69,886
21	5,187,440	"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"	DE-FG06-84ER13294	S-74,088
22	5,223,794	"Methods of Operation of Apparatus Measuring Formation Resistivity From Within A Cased Well Having One Measurement and Two Compensation Steps"	DE-FG19-88BC14243	S-75,438
28	5,570,024	"Determining Resistivity of a Formation Adjacent to a Borehole Having Casing Using Multiple Electrodes and With Resistances Being Defined Between Electrodes"	DE-FG19-88BC14243	S-81,888
29	In Allowance	"Formation Resistivity Measurements From Within a Cased Well Used to Quantitatively Determine the Amount of Oil and Gas Present"	DE-FG19-88BC14243	S-85,144

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