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PROJECT 13a: PARAMAGNETIC'S THROUGH-CASING RESISTIVITY TOOL

Problem: Imports of crude oil and petroleum products in 1998 averaged 10.3 million barrels per day, the highest level of imports ever. This represents a 220,000 b/d increase over 1997 levels of 10.16 MMb/d. **In 1999 imports averaged 10.55 million barrels per day – a 250,000 b/d increase over 1998 imports.** Imports have continued to constitute over 53 percent of domestic supply of petroleum products. Five years ago, we depended on imports to supply 45 percent of our needs. Crude oil imports have increased to **8.59** MMb/d in **1999**, up from **8.30** MMb/d in **1998**. U.S. petroleum imports (crude & products) in January **1999** were **10.2** MMb/d; imports in the same month last year were **10.18** MMb/d (**U.S. Dept. of Energy, Energy Information Administration (EIA))**. Reducing U.S. dependence on imports remains a critical goal for the nation as a whole.

One way to reduce U.S. dependence in imports is to increase the recovery rate from U.S. reserves. In the continental U.S, there may be more missed oil around existing wells than will be discovered **by** drilling "wildcat" wells. Only about a fourth of the oil and gas in known reservoirs is recovered and some 40% of the nation's reserves are in already-discovered reservoirs. **In the United States alone there are several hundred thousand cased wells that are close to abandonment due to declining production. It is estimated that many of these wells are likely to have hydrocarbons behind the pipes with no record of their presence** But to know where to find that oil, producers must know how the oil moves in the reservoir over time. In many older fields, these behind-pipe zones were originally evaluated using less sophisticated technologies and the presence of productive intervals nay not have been apparent when the original open-hole logs were evaluated.

Electrical resistivity being the key measurement that distinguishes high resistance oil or gas-bearing zones from low resistance water–filled formations, a tool that can measure formation resistivity behind steel cased holes will be invaluable in identifying bypassed or unevaluated hydrocarbons at the well locations. Such a tool will have numerous other applications such as monitoring oil and gas reservoirs during the life cycle of their hydrocarbon production, determination of residual oil saturation for various enhanced oil recovery operations, determination of hydrocarbon saturation information in low porosity formations where PNC and PNS types of nuclear devices fail, obtaining a resistivity log in cases of stuck pipe or collapsing hole, casing inspection and casing color location, etc.

Due to several technical and scientific challenges that most people in the industry thought were impossible to overcome, a tool to measure formation resistivity behind steel casings has not so far been available to the oil and gas industry.

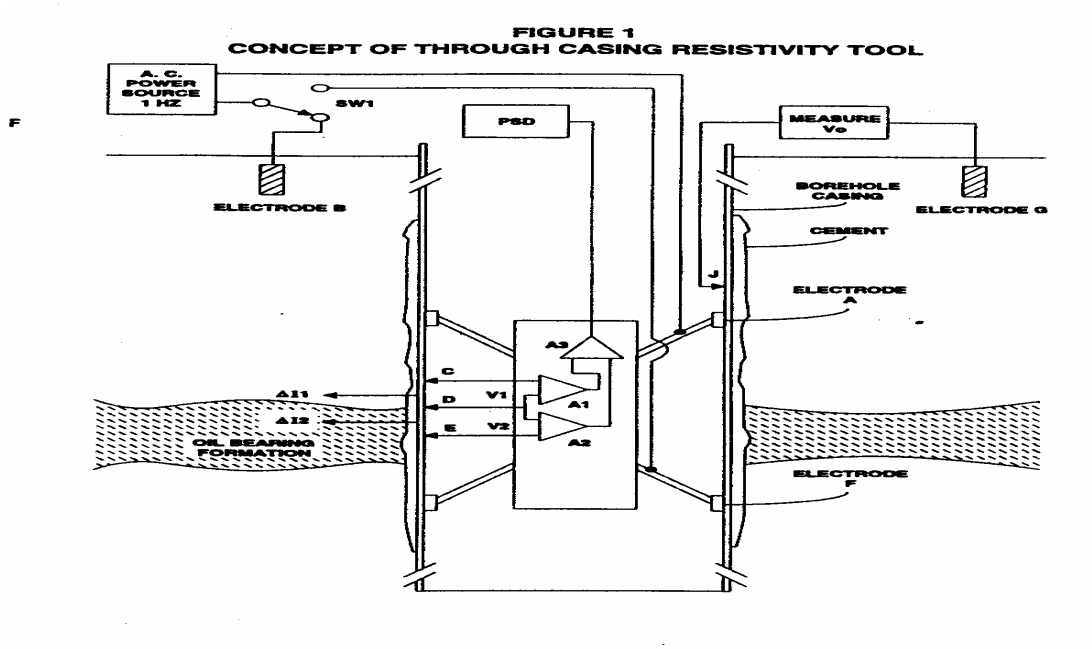
*Updates in “bold”

Project Objective: **In 1984, with a grant from the DOE and under contract with the Gas Research Institute (GRI), Paramagnetic Logging, Inc. (PML), a Seattle engineering firm initiated** research to develop a device for inductive logging through steelcase wellbores. The first step in the research was to prove the feasibility of through case resistivity logging. Subsequent objectives included the design, manufacture and testing of the tool.

Project Cost: DOE provided more than $1.1 million in 4 separate projects (DE-FG06-84ER13294, DE-FG19-88BC14243, DE-FG22-90BC14617, DE-FG22-93BC14966). GRI, ARCO, BP and Mobil also supported this project by providing funds (GRI-$4,000,000), equipment or advice.

Technology Change: **Prior to the development of this tool, there was no method available to obtain formation resistivity information behind steel-cased wells. This critical piece of information is needed to compute hydrocarbon saturation from geological formations during the life-cycle of hydrocarbon production of an oil field.**

Several technical and scientific challenges were overcome in the design and development of the TCRT, a schematic representation of which is shown in Figure 1. The basic concept behind through-casing resistivity measurement has to do with the fact that when electrical current is injected into casing through an electrode, it tends to flow upward and downward along the conductive casing, while a certain small amount of the current flowing along the casing leaks into the formation. By determining how much current is leaking into the surrounding formation from the casing, the apparent resistivity of that formation can be evaluated. In this 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 that are in electrical contact with the interior of the casing provide two voltage outputs that are subtracted to provide a differential voltage output, which in turn provides a measurement of the "leakage current", conducted into the formation. A calibration and nulling procedure is used which minimizes the influence in the 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.

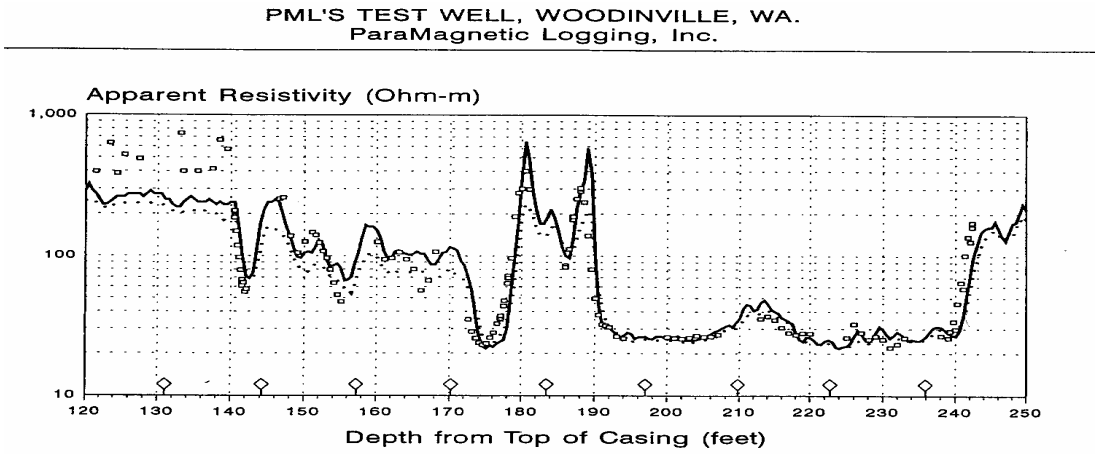


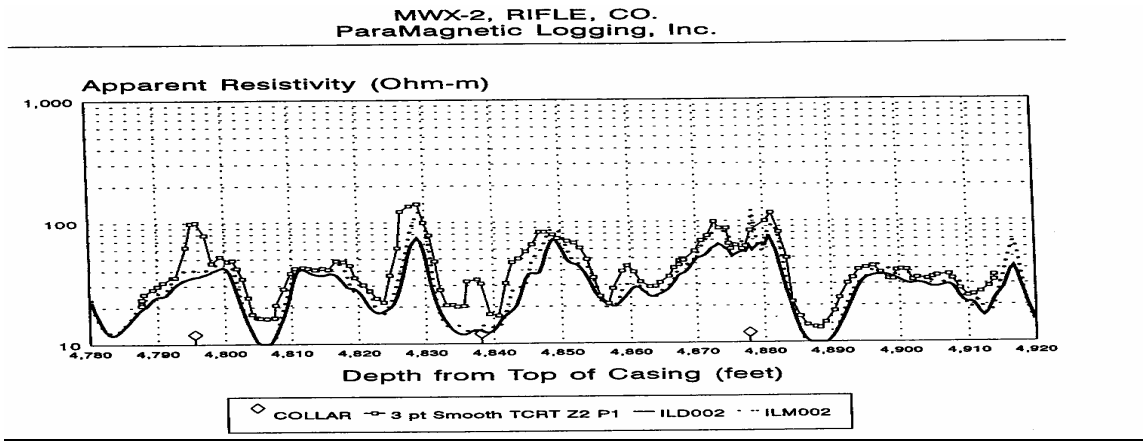
Two technological innovations facilitated the development of the TCRT tool; firstly the development of very low-noise amplifiers to measure extremely low signals in the nanovolt (10^{-9} volt) range from electrodes within the metal casing and secondly, the development of schemes for compensating for or calibrating casing-induced distortions.

The result of this effort is a breakthrough technology that measures formation resistivity behind the metal casing of wells making it possible to find oil "through the pipe." The research progressed from proving the concept to testing.

Apparent resistivity measurements using the new tool have been shown to correlate well with open-hole resistivity logs in a total of three cased wells. The depth of investigation of the TCRT appears comparable with deeply focused open-hole logs such as the ILD. A research well in Fort Worth, Texas was logged with a first logging instrument and subsequently much improved second logging instruments were used to log wells in the PML facility in Woodinville, Washington and the MWX-2 well in Rifle, Colorado.

The Woodenville Test Well log and the MWX-2 log from rifle, Colorado shown below both indicate that the TCRT logs taken from within the steel casing, track very well the open-hole induction logs in these wells taken several years earlier.





Technology Transfer Method: Probably the most effective transfer is occurring through the cooperation between the researchers and industry partners. A consortium was formed for the development of this cased hole logging technology. Members include ARCO, BP, Chevron, Conoco, Mobil, Phillips, Shell, and Texaco. Customer mentorship and support during the early phases of the research were essential to obtain the product acceptance that will support the eventual success of a commercial service. This relationship has generated a great deal of interest – so much that companies are offering wells for testing.

Additional transfer was accomplished via papers presented at the International Meetings of the Society of Professional Well Log Analysts in Calgary, June, 1993, and in Paris, June, 1995, and at the Annual Conference of the Society of Petroleum Engineers in Dallas in October, 1995, **Society of exploration Geophysicists (SEG) Annual Meeting, October, 1994 .** *Gas Research Institute Digest* published an article on the development of this technology in the winter of 1989/90. Major articles appeared in **World Oil (1995), Petroleum Engineer International** (1994,1996), **Improved Recovery Week** (1995), **Oil and Gas Journal** (1995), **Energy Perspectives** (1995), **TechLine #3037 (1995**)I **Oil and Gas Journal (1995), American Oil & Gas Reporter** (1995), **Business Week (1995, 1996). It should be noted that after PML had licensed its TCRT patents and**

technology to Western Atlas Logging Services, several very important papers were published by that company in leading technical journals.

Technology Implementation: Implementation will be accomplished via services companies who will work with oil and gas companies. Through their participation, ARCO became the first licensee of the TCRT. The technology has also been licensed to Schlumberger and Western Atlas Logging Services. In December 1997, Western Atlas Inc. announced that it had acquired ParaMagnetic Logging. **Subsequently Baker Hughes acquired Western Atlas and the combined company goes by the name of Baker Atlas**. The PML acquisition positions **Baker** Atlas as the technology leader for identifying oil and gas that may have been bypassed in mature fields when the original wells were drilled.

PML holds **eight** patents on the TCRT tool and the method of measuring formation resistivity through well casing. **The patent numbers and the dates the patents were granted are shown below**:

Patent #	Date Patent Granted
4,796,186	**January 3, 1989**
4,820,989	**April 11, 1989**
4,882,542	**November 21, 1989**
5,043,669	**August 27, 1991**
5,043,668	**August 27, 1991**
5,075,626	**December 24, 1991**
5,187,440	**February 16, 1993**
5,223,794	**June 29, 1993**

The present logging device must be held stationary in the borehole while measurements are taken. This is time-consuming and expensive. After further developments of the tool by Baker Atlas, such as converting the system from analog to digital and redesigning the tool for logging inside 2 $^{1}/_{8}$ inch diameter tubing, the tool is presently undergoing rigorous field testing at several different locations. After successful field testing and market survey, commercialization of the tool is expected to ensue.

End Users: Considering that hundreds of thousands of cased wells exist throughout the world, this valuable technology will allow for more accurate assessment and monitoring of oil and gas properties. The Primary users **of such a tool** will be the 8,000 independents in the U.S. because they drill 85 percent of the nation's wells in 33 states with oil and gas production, produce 65 percent of the natural gas and nearly 40 percent of the oil consumed by Americans. These independent producers have become a major player in developing the resource base in areas onshore, offshore and in the international arena. Armed with advanced technologies, a new generation of independent producers is leading the way in U.S. oil and gas production.

The leading use will be in enhanced oil recovery (EOR) projects such as in ARCO's fields in Alaska, secondary recovery fields in West Texas, and in steam flooding projects in California. The primary providers of this service will be logging companies such as **Baker Atlas** and Schlumberger.

Impacts: The successful commercialization of this technology produces immense benefit for the industry.

Reserves Additions: As a result of the increasing costs of exploring and drilling for new oil and gas reserves, producers in the U.S. are focusing their efforts on improved recovery techniques to enhance production from existing reservoirs. One such approach is to carefully evaluate fields for infill drilling opportunities or untapped zones hidden behind casing. This technology lowers the risk while improving the recovery rate of previously undetected oil and gas reserves. This new technology could substantially increase the petroleum reserves. **In the United States alone, there are several hundred thousand cased wells that are close to abandonment due to declining production. It is estimated that many of these wells are likely to have hydrocarbons behind the pipe with no record of their presence.** Recent U.S. Geological Survey studies indicate that very little new oil and gas is being added to this country's reserve base as a result of new field discoveries. From 1978 to 1991, 90% of additions to hydrocarbon reserves in the U.S. have come from growth of reserves in existing fields. The DOE reported in a February 1999 publication that past technology has recovered only an estimated one-third of the oil-in-place, leaving two-thirds of the U.S. oil resource base – about 350 billion barrels – still in the ground.

TCRT data can play a crucial role in the identification of bypassed or unevaluated hydrocarbons. When a tool like the TCRT can locate and help produce an additional 2-5% of the oil or gas in a field, 7-17.5 billions of barrels of oil and gas equivalent will be added to our country's reserves.

Daily U.S. oil consumption averaged **18,679,000** million barrels in **1998** and imports amounted to 56% of total consumption (DOE, February 1999). That equates to 10,000,000 imported barrels daily. Every 1% of the 350 billion barrels of oil identified using this technology would result in reserve additions of 3.5 billion barrels of oil which equates to almost one year's supply of imported oil, **and would generate** $7,875,000,000 in royalties and $3,150,000,000 in taxes.

Slowing Abandonment of Fields: Innovations such as this can extend the life of mature fields thus reserves are added with little environmental impact, decommissioning costs are deferred, jobs are preserved, infrastructure is retained, and the window for new technology development is extended.

Cost Savings: In frontier areas, wells could be drilled and casing set before the well is logged, thereby minimizing the risk of loosing the wellbore. This approach would also eliminate the need to drill another well to establish production capabilities. The cost savings are large since drilling costs can vary from less than $100,000 for shallow on-

shore wells to more than $15,000,000 for deep water Gulf wells with the average U.S. cost to drill an oil well (5006') of $351,000 (IPAA, *U.S. Petroleum Statistics*, April, 1999).

At present, this tool must be stationary when operating and takes 6 minutes to log 2 feet. To log a 1000-foot interval would take 50 hours. With further development, continuous logging would reduce this time to a couple of hours, resulting in a cost saving for the rig alone of approximately $10,000 for an average on-shore well to $100,000 for an off-shore well. **It should be mentioned that Baker Atlas, who acquired the patent rights and the technology of this tool has already made some improvements to this tool, such as converting the system from analog to digital and redesigning the tool for logging inside 2 $^{1}/_{8}$ inch diameter tubing.**

Environmental: Lessening the need to drill new wells while continuing to produce is not only a cost savings but also a particularly valuable environmental advantage. Many oil wells are inactive, as they cannot economically produce at prices that prevail in today's market. Such wells may pose potential threats to USDW's, and pressure exists to plug inactive wells before they pollute and/or become orphans. While the future for increased oil prices is **uncertain**, such wells may have value as possible candidates for enhanced oil recovery projects. The Department of Energy has and is currently sponsoring research into cost-effective enhanced oil recovery technology such as this; but such technology will only be viable if wellbores exist where the new technology can be applied.

Many fields produce oil from horizons that are near water aquifers. The potential for oil "behind pipe" to migrate from the reservoir to these aquifers exists. A tool such as this would be useful in identifying potential pollution of aquifers.

Additional Research: **Baker Atlas** states that it is investing multiple tens of millions of dollars to advance this resistivity technology. Baker has scheduled testing of their research tool **at a number of different locations including a number of wells in Conoco's California fields**. Full engineering efforts are on going.

Halliburton (density), and Schlumberger (formation pressure) have each funded major through casing research. Schlumberger has performed 16 field tests in the Middle East on their casing profile tool (CPET).

Taxes and Royalties: Employing a price of $15.00 per barrel, an average royalty payment of 15% of the value of gross production (IOGCC, *A Battle for Survival? The Real Story Behind Low Oil Prices,* April 1999) and an average state gross production tax rate of 6%, every 1% increase in production would result in 3.5 billion barrels of reserves that would in turn result in $11 billion in taxes and royalties. This figure represents a 10,023-fold return on the approximately $1.1 million invested by the Department of Energy.