Field Application of
Accurate, Low-Cost Portable Production Well Testers

Quarterly Technical Progress Report
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by
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DISCLAIMER PAGE:

ABSTRACT:

This project is a continuation of the Stripper Well Consortium project #2775-ORI-DOE-2098 that ended in December 2005 entitled "Design, Construction and Evaluation of an Accurate, Low-Cost Portable Production Tester". That previous project designed, built and tested a multiphase tester that utilized a Gas Liquid Compact Cyclonic (GLCC) separator, to separate out the gas phase, Foxboro coriolis liquid meter, Foxboro shedding vortex gas meter and a RedEye watercut meter. This tester was limited to high liquid rate (100-1500 BPD liquids, and 75 MCFPD gas rate) wells. Later stage testing of the RedEye in this project indicated some watercut errors existed due to the water phase properties that were different than the manufacturer's (Weatherford/ eProduction Solutions) claims. Beam pumped wells were found difficult to meter since half the stroke is below the liquid meter's capabilities and the producing stroke portion is almost double the wells' overall rate. In any event, the tester proved that no or little separation is needed for most Mid-Continent waterflood production wells where the pump is below the perforation interval and the zone is mostly depleted. This can provide great savings in allowing smaller and cheaper portable testers without separation, but is specific to these type meters.

This current project aimed to refine the watercut metering capabilities, test specific fields for designing and installing accurate multiphase meters for Mid-Continent fields and stripper well operators. Several remote data transmission methodologies were evaluated and a cell based system was installed, but later discarded.. Field testing in this project for high watercut (>90% water) wells confirmed the sensitivity of the RedEye2G meter to water properties and its insensitivity to crude oil- just the opposite of what the vendor originally claimed. Weatherford/ eProduction Solutions agreed to upgrade the RedEye capability to include water calibrations and this project was put on hold in April 2006. The insensitivity of the coriolis rate meter to produced gas volumes encountered in Mid-Continent wells was also confirmed.

In late 2006 information on Chevron's microwave based Differential Dielectric Sensor (DDS) technology became available. This new water cut technology is specifically accurate in high water cut applications, as targeted in this project, and newer versions have the potential for very low pricing. However, Chevron's timing in making this technology available is unknown. In May 2007 Weatherford/ eProduction Solutions notified the PI that the RedEye upgrade will be delayed further. With these delays and the lack of a suitable alternative technology, it was felt that the project should be terminated. A new project should be proposed when these new technologies become fully available.

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EXECUTIVE SUMMARY:

This project was a continuation and implementation phase of the Stripper Well Consortium project #2775-ORI-DOE-2098 that ended in December 2005 and was entitled "Design, Construction and Evaluation of an Accurate, Low-Cost Portable Production Tester". That project designed, built and tested a portable multiphase tester that utilized a Gas Liquid Compact Cyclonic (GLCC) separator, to separate out the gas phase, Foxboro coriolis liquid meter, Foxboro shedding vortex gas meter and a RedEye watercut meter. This tester was limited to high liquid rate (100-1500 BPD liquids, and 75 MCFPD gas rate) wells. Later stage testing of the RedEye (version 2G) in this project indicated some measurement errors due to the water phase properties that were different than the manufacturer's (Weatherford/ eProduction Solutions) claims. Weatherford/ eProd Solution agreed to upgrade their RedEye for high watercuts and these improved units were to be announced at the Offshore Technology Conference in May 2007, but were not.

Beam pumped wells were found difficult to meter since half the stroke is below the liquid meter's capabilities and the producing stroke portion is almost double the wells' overall rate. In any event, the tester proved that no or little separation is needed for most Mid-Continent waterflood production wells where the pump is below the perforation interval and the zone is mostly depleted. This provides great savings in next generation testers where this will allow smaller and cheaper portable testers without expensive separation tanks and controls.

This current project aimed to refine the watercut metering capabilities (to include water properties calibration), test data transfer methodologies available, and test specific Mid-Continent fields for designing and installing accurate multiphase meters for stripper well operators. Several remote data transmission methodologies, cell, satellite and radio based systems, were evaluated. A cell based (Verizon) system was installed, but later removed due to lack of current connectivity in actual field locales.

Many oil and gas operators were contacted about using portable testers at the Marginal Well Commission's Fair in Oklahoma City, OK in October 2005 and October 2006. Follow up discussions with five (5) operators covered the proposed field tests and design work for their specific oil fields. In this second testing contract, some of the original wells C574, C576, C578, C5710, C611 were retested with the Portable Well Tester (PWT) using new procedures to shed more light on the new findings of the first contract testing. This work confirmed the sensitivity of the RedEye (version 2G) meter to water properties and its insensitivity to crude oil in high (>90% water) water cut applications-just the opposite of what the vendor originally claimed. Weatherford/ eProduction Solutions agreed to do the research to upgrade the RedEye capability for water calibrations and this project was put on hold in April 2006.

The additional testing also looked again at the sensitivity of the coriolis to gas content. These tests showed minor impact of gas, at the levels we are seeing, on the liquid rate measurement. This confirmed and expanded the original project findings. The additional

testing also confirmed that a gas separator (and related controls and trailer size) is not needed for most Mid-Continent, secondary recovery artificial pumped wells, thereby saving on future testers. The key to utilizing this finding is in the specific coriolis and watercut meter used.

In waiting on Weatherford's upgrade, information on a new watercut technology became available. Chevron developed a microwave based Differential Dielectric Sensor (DDS) in a 9 Gigahertz power level with 9 channel capabilities that is currently available on the market, but very expensive. A lower cost 9 gigahertz/ 3 channel DDS meter version can be developed at a lower cost. In addition, a 3 Gigahertz/ 3 channel DDS meter version has been developed by Chevron and is near ready for field testing that would be significantly cheaper than current industry water cut meters. Chevron is preparing to license this meter technology to industry, but that timing is unknown. With neither of these improved and/or cheaper meters available at this time, this project is terminated to save time and dollars of the Stripper Well Consortium, the Department of Energy and Oak/ Impact. Because of its high potential and need in the industry, it should be re-looked at when these improved meters become available to industry.

We presented a professional technical paper (SPE #10308) at the Society of Petroleum Engineers (SPE) 2006 Fall Annual meeting in San Antonio, Texas. We also made a presentation to the University of Texas' 2006 Multiphase Measurement Users Roundtable (MMUR) in Houston, Texas.

INTRODUCTION:

Secondary Recovery methods, primarily waterflooding, provide approximately 50% of the oil production in Oklahoma. Much of this secondary production is in the northeast and the southern areas of Oklahoma. Secondary and Tertiary Recovery methods also provide a significant amount of production in other states. These type operations typically handle large volumes of water, but small volumes of oil and natural gas. In addition, the Hunton, Bartlesville and Arbuckle formations also produce large amounts of water with smaller amounts of oil and gas under primary production.

Monitoring the watercut in different portions of a field and on a well basis, under primary, waterflood or tertiary recovery methods, is important for efficient and economic operations. As the watercut increases, the profit margin on that well decreases reaching a point where the well is no longer economic and must be shut-in and plugged. Understanding the well's current production and, over time, production history will allow a better understanding of the well or field and what is needed to improve production, profitability and extend their life and reserves.

Accurate testing of such wells is important to determine reserves, the economics of continued operations and to evaluate projects (recompletion, gel polymers, horizontal laterals, other actions) to improve oil and gas production and/or reduce water production, i.e., methods to increase well profitability and reserves. There is no substitute for good accurate data on which to base these decisions and actions. A single incorrect decision to treat (acid stimulate, frac, workover) a given well based on bad data can cost tens of thousands of dollars, which could be used more efficiently on other wells.

Such production well testing is currently done by centralized separation and metering stations (utilizing standard oilfield equipment or expensive electronic testing equipment) or by portable testers (standard oilfield equipment or expensive electronic testing equipment). Centralized systems require extra lines to be installed and maintained over their entire lives. This results in increased cost and risks. Portable systems allow testing at the individual well and do not require additional lines to be installed and maintained. Current low cost portable testers ($10,000) are not accurate enough due to sampling frequency and gas interference. First generation portable electronic test units were about $125,000 (after prototyping and proving). Second generation electronic testing units, such as designed /constructed in the previous 2004-2005 SWC Project, are about $80,000 but are designed to cover the full range of well conditions. That previous project was initiated to achieve next generation testers in the $20,000 price range. A large step in that cost reduction was found in the elimination of the separator, including trailer size and controls.

This current project took the earlier designed and constructed tester into the field for additional testing of wells/fields so that ten (10) field/area specific testers could be designed and constructed at these lower costs. This project included steps of target identification, field testing, specific unit designs and construction, monitoring of units in the field, evaluation of obtained data and reporting of results. The knowledge of industry that these lower cost units are in the field will have a 'snowball' effect on the market- with operators, vendors and manufacturers increasing demand and lowering cost further.

The anticipated results from this work are: driving the cost of well /field specific testers down to the $25,000 price range, getting these highly portable and accurate testers to stripper well operators, driving the market of next generation testers down to the $15,000 price range. However, the most important and lasting result will be more accurate testing results and better decisions made on the stripper wells. This will hopefully result in increased production and more reserves for the nation and consumers.

Original Project Plans-

This project was originally planned to take the earlier designed and constructed tester into the field for the testing of new wells/fields so that ten (10) testers for specific field/area can be designed, constructed and installed in Mid-Continent fields at these lower costs.
This consisted of 10 Tasks- Identify, Testing, Evaluate Tests, Design, Agreements, Construction, Training, Monitor / Obtain Data, Evaluate Results and Reporting. Not all stages were performed continuously nor in the order given- in fact, not all tasks were accomplished (discussed later)-

1. The first stage was to identify geographic areas/ fields with high water cut wells that fit the rate parameters. The goals of this step was to find both primary and secondary/waterflood properties and cover a broad geographic mid-continent area of Oklahoma, Kansas, Texas, Louisiana. Next step was to find and contact operators in these areas to discuss and generate interest in these testers and to obtain approval to test their wells for evaluation. This process included workshops with local groups. Targeting 3 geographic mid-continent areas at 1 month per area.
2. The second stage involved testing these wells to determine the minimum tester equipment needed. This was performed by taking the existing portable tester (built and tested in the previous 2004-2005 SWC Project) to those interested operators/ fields and test their wells. This testing was helpful in determining the level of gas separation and accuracy needed in each field/ area. This service was performed at no cost to the operators.
3. The third stage occurred after the testing stage and evaluated the details of the test results. This involved taking the key detailed (instantaneous and averaged) gas, water and oil data from these field tests to determine the separation level and accuracy needed for the specific wells for these operators.
4. The fourth stage was to design the specific units for each operator/area based on the test results and evaluation. Different gas separation (GLCC, tank with dump, none), gas metering (different types and none), liquid metering(different types) and piping will be considered.
5. The fifth stage was making agreements for payment and sharing field testing results with the operators. This was needed after the design work had set the required equipment and resulting cost for that application.
6. Sixth stage work was to construct the testers based on the design. This work was to be supervised with work done in area contracted shops/ vendors.

7. The next and seventh stage was to deliver the unit and train the operator's personnel on their new unit. At least one day per unit was to be devoted to this effort, primarily Oak personnel.
8. Once each unit was in operation, questions were to be answered and problems solved. This stage was to provide a help line and perform service calls as needed for a limited period of time (6 months). Monitoring the use and ensuring that test data was forthcoming was part of this stage. Once sufficient testers were in operation in a given area, a Workshop on the use, benefits, cost and operation of such testers was to be performed. We planned 4 workshops to accommodate this task. These workshops were to be conducted in a location convenient for the operators.
9. Ninth stage covered the evaluation of all the data obtained to determine the effectiveness (ease of use, cost effectiveness, accuracy,..) of the process, testers and training. This was to be based on the detail and averaged gas, water and oil rate and quality data. Comments and evaluations from the operators served were to be included.
10. The tenth and last stage was the transfer of these results and information to the industry and specifically to marginal/ stripper well operators. Transfer of this needed technology and capabilities was to be accomplished by-
    - Quarterly reporting in December, March and June
    - Final Report to the Stripper Well Consortium
    - Two technology workshops (one in the northeast (PA, NY, WV or OH) and one in the south & west (OK, TX, KS, NM, LA)) and ,
    - At least one technical paper for the Society of Petroleum Engineers (SPE) at the Production Operations Symposium and/or at the annual Fall Meeting.
    - Perform other workshops as outlined in earlier steps.

The following Tasks and one year Schedule was anticipated:

1. Identify- Identify geographic areas/ fields with high water cut wells that fit the rate parameters. Find both primary and secondary/ waterflood properties and cover a broad geographic mid-continent area of Oklahoma, Kansas, Texas, Louisiana. Identify and contact operators in these areas.
2. Testing- Take existing portable tester (built and tested in previous SWC Project) to interested operators/ fields and test wells to determine the level of gas separation and accuracy needed in each field/ area. This was to be performed at no cost to the operators.
3. Evaluate Test Data- Evaluate key detailed data from these field tests to determine the separation level and accuracy needed for these specific wells for these operators.
4. Design- Design specific units for each operator/area
5. Agreements - Make agreement for payment share and sharing field testing results.
6. Construct Testers- Construct/ fabricate portable tester as designed and deliver.
7. Delivery and Training- Deliver and train operator's personnel on their unit.

8. Monitor and Obtain Data- Monitor operation of units and ensure testing data is obtained for evaluation. Provide help line and perform service calls as needed for a limited period of time. Provide a workshop in a central city when sufficient units are in operation.
9. Evaluate Results – Evaluate the detailed data obtained from all units.
10. Reporting and Technology Transfer– Reporting of the results will be accomplished as :
    i. Quarterly reporting
    ii. Final Report to the Stripper Well Consortium
    iii. Two technology workshops
    iv. At least one technical paper for the Society of Petroleum Engineers (SPE) at the Production Operations Symposium and/or at the annual Fall Meeting, and
    v. Perform other workshops as outlined in earlier steps for the Oklahoma Marginal Well Commission (MWC), Kansas University Tertiary Oil Recovery Program (TORP) and others.

The first result anticipated from this work was in making operators of high water cut stripper wells aware of the availability of highly portable and accurate testers for their production wells. The second result anticipated was in getting these units into the hands of stripper well operators. The third result was in proving the cost ($20,000 to $25,000 range), design and accuracy (1-3%) of such units to expand the marketability- important for operators, vendors of the needed instruments, and other manufacturers. Once this testing methodology is established, more manufacturers will design and target low cost testers for marginal operators. The fourth result anticipated was a reduction in cost of the next (4^{th}) generation of testers into the $10,000 to $15,000 range. However, the most important and lasting result would be in more accurate testing results and better decisions made on these stripper wells. This would hopefully result in lower operating costs, increased production and more reserves.

Only Tasks 1-4 and 9-10 have been accomplished in this project. The project was terminated due to delays in obtaining upgraded watercut meter technology.

EXPERIMENTAL METHOD:

The current project testing and the previous project field tests are summarized in the attached SPE paper and the MMUR presentation and are available as Excel files on the website- www.impact2u.com/projects.

Pictures of the portable tester are shown below in Figures 1 through 6. The data taken in this project is shown below in the attached SPE paper (Appendix F) and summarized in Figures 7 though 9 below . The test procedure is the same as described in the previous project Final Report and in the SPE paper (Appendix F).

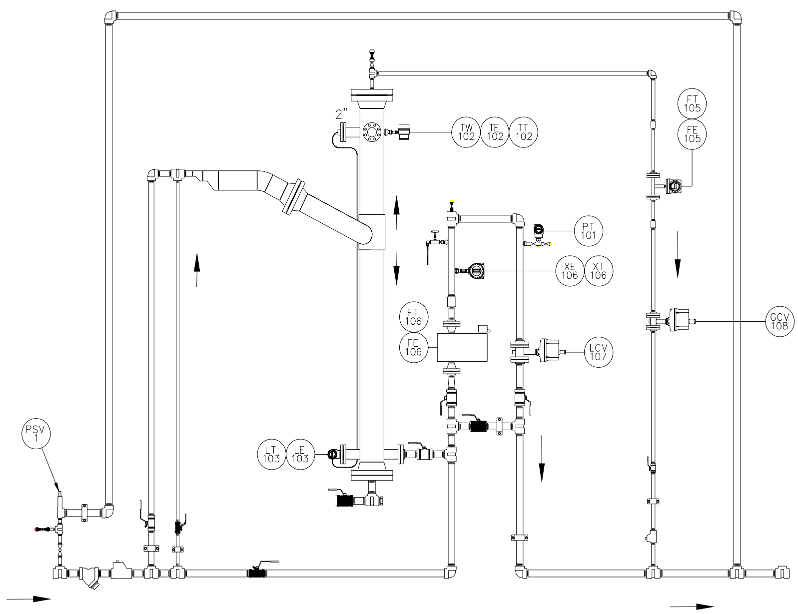


Figure 1 Schematic of Portable Well Tester

Figure 2- Portable Well Tester in Test Mode at well

Figure 3- Portable Well Tester in Travel Mode

Figure 4- Portable Well Tester testing Progressing Cavity Pumped (PCP) Well

Figure 5- Portable Well Tester at Beam pumped well

Figure 6- Portable Well Tester at a production header

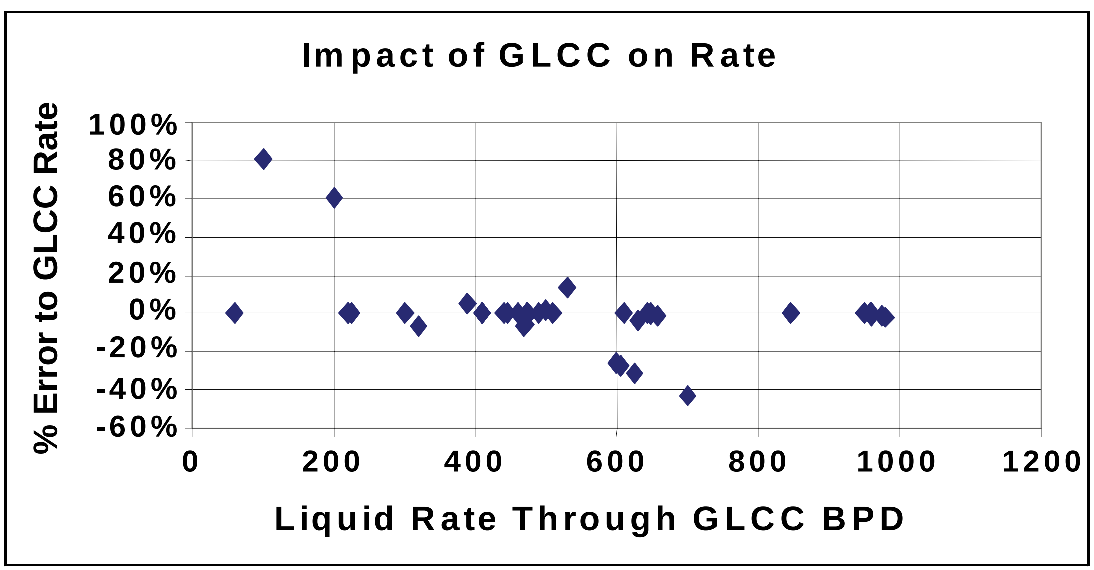


Figure 7 - Impact of GLCC use on Liquid Rate measurement

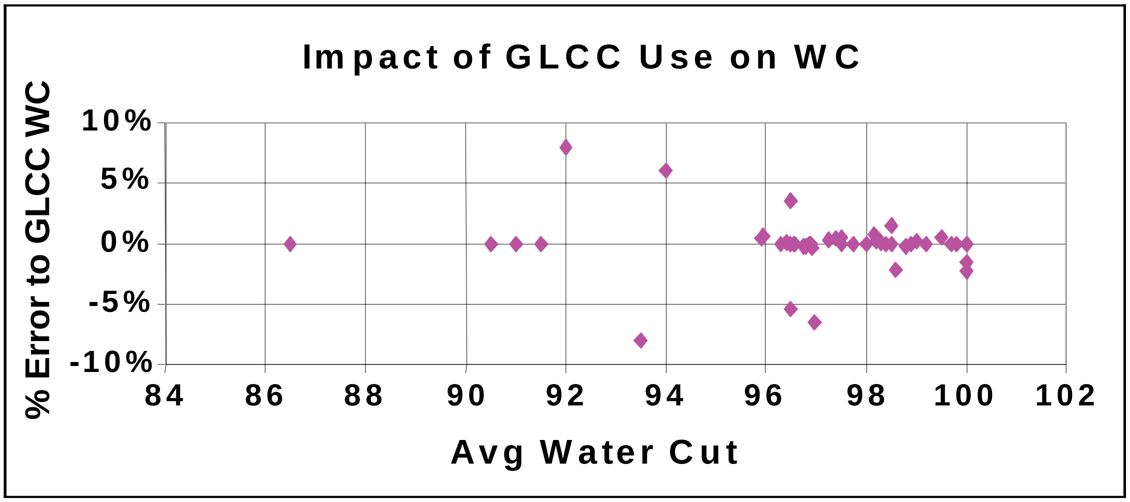
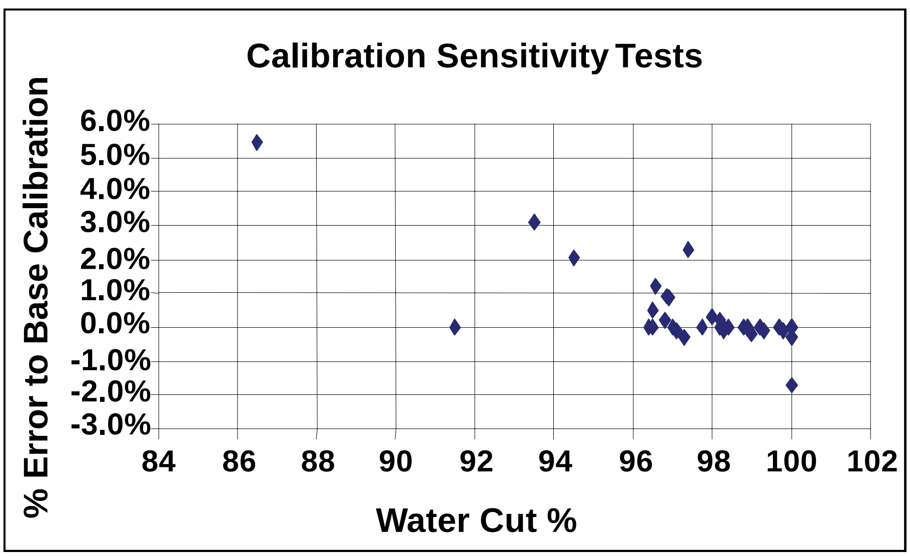


Figure 8 - Impact of GLCC use on Water cut measurements



Perent error in WC due to varing oil calibrations

Figure 9- Oil calibration sensitivity to Watercut Measurement

RESULTS AND DISCUSSION:

In this second testing contract, some of the original wells C574, C576, C578, C5710, C611 were retested with the Portable Well Tester (PWT) using new procedures to shed more light on the new findings of the first contract testing. One finding contradicted the vendor's claim that the RE2G water cut meter was sensitive only to the crude oil and insensitive to water. However, the first contract testing found just the opposite when used in high (> 90%) water-cut conditions. With this finding confirmed in these 2nd round tests, the vendor may consider modifying the meter. It may possibly need "corrected" with a firmware change or adjustment to give more accurate and more reliable readings in these stripper waterflood conditions. On 23 March 2006 the PI visited with eProd/ Weatherford in Houston on these tests and what could be done about getting an upgrade of the RedEye watercut meter for this concern. We gave Weatherford/ eProd all data and suggestions that they requested (see "wish list below"). The fact that the vendor offered to fund (time and money) the research and development for this improvement was significant. The renewed interest of metering vendors in the US marginal/ stripper and high water cut wells market is important for long term metering development and cost.

That 'wish list' to Weatherford/ eProd in May 2006 for upgrading the RTU and RedEye included:

1. All input and calibration by PDA. Control and Input of unit in the field by wireless only (eg due to weather, rain, dust concerns).
2. Onsite/ RTU readout of set parameters (incase wireless or PDA not available, such as for a relief pumper) showing in sequence or by request.
3. Calibrations for multiple wells 25+ by name (best) or number
4. Adjustment to WC% by input a delta + or - % to set the WC to a known standard. This allows trending from a known WC%.
5. High gas GVF alarm (for no separator cases)
6. Needed output parameters (scrolling or by request on RTU or PDA) - instantaneous oil rate, water rate, gas rate, pressure, mix density, temperature & %WC; same for 1, 4, 12 and 24 hour running averages.

Futher desires for unit were-

7. omitted
8. Detailed data logging (online or stored- stored is best) by (specific to field) bluetooth, SCADA, cell or other wireless means.
9. Onsite calibration RE2G abilities for oil and water (i.e. as for a new well)
10. Ability to store a set number of time registers (all data, for 12 hours) to download later.
11. Program that takes the detail output data (logging or download stored data), allows easy transfer to a PC and processes it into a ready user friendly format to/on a PC.

The additional testing also looked again at the sensitivity of the coriolis to gas content. These tests showed only minor impact of gas, at the levels found, on the liquid rate measurement. This confirmed and expanded the original project findings that no separation is required for most Mid-Continent and perhaps most artificially pumped wells with the specific metering equipment utilized. This is important and will provide significant savings on future testers. These savings come from no separator weight and size, no liquid and gas control valves, no control computer, and smaller trailer or skid.

This trailer based metering package is favorable for field testing, however this specific package is designed for a wide variety of applications and is thus difficult to use. While it can be simplified for future units in specific fields, the current version takes significant time, resources and training to utilize it fully. To minimize that time and training wireless or remote data monitoring systems are desired. In addition, an improved display is needed as the current touch display is not as robust and easy to read as desired. Data transfer technology from the PWT to a computer was desired to minimize time in the field required to obtain significant data for analysis. Satellite systems were studied first, but the cost to implement- purchase, setup (align) at each move and long term contract did not suit this project at this time. New cellular tower based systems were studied next and a Verizon unit was installed on the unit. An antennae was installed to aid in obtaining the signal. The unit was returned when no signal could be obtained in selected areas of Oklahoma. Lastly data transmission from the RTU to a nearby computer via blackberry type transmission was studied. However, Weatherford did not have that capability at that time.

This work was reported in a Society of Petroleum Engineers (SPE) paper (SPE #10308, Appendix A in this report) and presented at the 2006 SPE Annual Meeting in San Antonio, Texas. We also made a presentation to the Texas A&M University Multiphase Measurement Users Roundtable in May 2006, in Houston, Texas. Also, a presentation was made to the University of Kansas' Tertiary Oil Recovery Project (TORP) conference in Wichita Kansas in April 2007 that included discussion of this tester.

In addition, the PIs studied new microwave based water cut metering technology now available that is called Differential Dielectric Sensor (DDS), developed by Chevron. The fact that a major operator like Chevron sees the need and has had continuous development of a new watercut meter based on microwave technology is significant. Versions of the DDS meter are now available in a higher cost, 9 gigahertz and 9 channel version. However, Chevron has stated that they want lower cost and highly accurate water cut measurement. To this end they have developed and are close to field testing a 3 gigahertz and 3 channel lower cost version of the DDS that they want field tested in the near future, as is possible on the Oak/ SWC tester. Unfortunately, Chevron has not gotten to the licensing level of this newer version and it is not yet available to industry.

With the delay in the RedEye upgrade, Chevron DDS meter not yet available and the general lack of similar technology on the immediate horizon, this project was terminated. It should be restudied in the near future when new watercut metering technology becomes available to industry.

CONCLUSIONS:

We confirmed that the Weatherford/ eProduction Solutions' infrared based water-cut meter is insensitive to oil but is sensitive to water at watercuts greater than 90% water. This is contrary to the vendor's original claims. The vendor agreed to make the changes needed in the meter to make it more accurate under high water-cut conditions, but one year later this has not yet happened.

We confirmed that the specific Foxboro coriolis liquid rate meter is not sensitive to the gas volume fractions found in the mature Mid-Continent waterflood fields tested. This means that future testers can use this coriolis meter without separation on many Mid-Continent artificially lifted wells and fields for a very great cost savings. However, it cannot be said to be specifically true for each and every Mid-Continent well.

The trailer based metering package is favorable for a wide range of field testing, however, this makes it difficult to use and requires significant time in the field or training. Also, the display needs to be changed out for a clearer reading touch screen version. Wireless or remote data transfer and monitoring is desired in future units to minimize onsite actions. Future tester versions can have these simplified features for specific field testing.

Information on Chevron's microwave based Differential Dielectric Sensor (DDS) technology indicates a very high accuracy level in high watercut applications and the potential for very low unit costs. This technology should be available to industry in the coming months. Because of the delay in the RedEye upgrade and the upcoming DDS technology, this project is terminated.

The importance of accurate testing of stripper wells is of utmost importance to stripper well operators and to the industry as a whole. Testing the accuracy and proving the use of such equipment/ instruments should continue as technology improves and becomes available.

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Mehdizadeh and Perry, “The Role of Well Testing in Recognizing Deferred Production Revenue”, Journal of Energy Resources Technology, Vol. 126. September 2004

Oglesby, Mehdizadeh and Rodger, “Portable Multiphase Production Tester for High Water-Cut Wells”, SPE 103087, 26 September 2006, San Antonio, Texas

Williamson and Mehdizadeh, “ Alaska Regulatory Guidelines for Qualification of Multiphase Metering Systems for Well Testing” paper presented at the NEL Wet Gas Flow Measurement Seminar, Houston, TX, Sept. 30th, 2004

Note: Release could not be confirmed on Chevron’s DDS research work, SPE papers and University of Tulsa Ph.d. theses and thus they are not incorporated herein

LIST OF ACRONYMS AND ABBREVIATIONS:

BPD- barrels per day
DDS- Differential Dielectric Sensor, patented & trademarked by Chevron
GLCC- gas liquid compact cyclonic separator, patented & TM by Chevron
MCFPD- thousand standard cubic feet per day
MMUR- Multiphase Metering User Roundtable, Texas A&M University
PCP- progressing cavity pump
PI- principal investigator
PSI- pressure unit , pounds force per square inch
PWT- Portable Well Tester
RE2G- RedEye version 2G
SPE- Society of Petroleum Engineers professional society
SWC- Stripper Well Consortium
TORP- Tertiary Oil Recovery Project at the University of Kansas
WC- water cut

APPENDIX:

A. SPE Annual Technical Conference and Exhibition, Technical Paper No. 103087, presented in 26 September 2006, San Antonio, Texas, “Portable Multiphase Production Tester for High Water-Cut Wells”, by Kenneth D. Oglesby, Parviz Mehdizadeh, and G. Joel Rodger.

APPENDIX A

SPE 103087

Portable Multiphase Production Tester for High Water-Cut Wells

Kenneth D. Oglesby PE, Impact Technologies LLC, Parviz Mehdizadeh, PhD, Production Technology Inc, and G. Joel Rodger, PE, eProduction Solutions/Weatherford

This paper was prepared for presentation at the 2006 SPE Annual Technical Conference and Exhibition held in San Antonio, Texas, U.S.A., 24–27 September 2006.

Abstract

Accurate well testing is required for making intelligent decisions on oil and gas production wells. This paper reports on an effort to assess the application of multiphase metering technology to high water-cut (75+% water) and high volume production wells, as found in many North American Mid-Continent brown fields. A portable multiphase oil, water and gas production well tester was designed and field tested for these wells. Key components of the trailer mounted and battery operated tester are: a compact gas-liquid cylindrical cyclonic (GLCC) separator with control valves, GLCC bypass valving, coriolis liquid meter, infrared water-cut meter, vortex shedding gas meter and a data acquisition unit. One key finding is that separation is not needed in many such applications, thereby significantly reducing the size, weight and cost of future testers. This is due to the inherent downhole well separation and annulus venting used in most such well configurations along with specific coriolis/water-cut meter combinations allowing accurate measurements with gas content up to 10 to 20% GVF.

Introduction

Secondary and tertiary recovery methods, primarily starting with waterflooding, provide a significant amount of production in many U.S. Mid-Continent areas and throughout the world. These type operations typically handle large volumes of water, small volumes of oil and natural gas. In addition, many formations also produce large amounts of water with small amounts of oil and gas under primary production (e.g. Hunton, Bartlesville and Arbuckle formations in the North American Mid-Continent region). Accurate testing of these wells is important to determine reserves, the economics of continued operations and to evaluate projects (re-completion, plug backs, gel polymer treatments, drilling horizontal laterals and other well actions) to improve oil and gas production and/or reduce water production– either means to increase well profitability and reserves. There is no substitute for good accurate production data on which to base these decisions and actions.

Production well testing is currently performed by centralized separation/metering stations or by portable testers. Centralized systems require extra equipment to be installed and maintained over the field's entire life. This results in increased cost and environmental risks. Portable well systems allow testing at the individual well or at multiple centralized facilities and do not require additional equipment to be installed and maintained. Low cost portable testers are not accurate enough due to separation limitations, sampling frequency and/or gas interference. Higher cost multiphase testing units are out of the economic reach of most stripper, marginal and brownfield well operators. Also many wells do not have electricity available on site. Thus most brownfield operators must currently accept poor accuracy or high cost fixed sites. Sadly, even most current expensive multiphase metering systems can not accurately measure such small oil volumes in large water flow streams (i.e. a water contamination problem).

Current conventional well testing accuracy for determining the flow rates can range from ±5% to ±50%. In addition, the amount of labor needed to perform well testing, using conventional gravity based test separators or tanks causes the operator to perform well testing infrequently. These two factors combine to produce well rate data uncertainty and inconsistency that results in allocation factors (sum of oil production well tests/oil sales) that vary from 65 to 150% (1).

This project was designed to assess the application of novel multiphase measurement techniques to high water-cut, high volume well testing and was performed under a grant from the Stripper Well Consortium, Penn State University and the U.S. Department of Energy. The major objectives of the project were:

1. Design and construct a prototype of an accurate, affordable portable well testing (PWT) system to overcome the shortcomings of the conventional tank and port-a-check measurement systems.
2. Test the performance and stability of the system and its components.
3. Establish the capability of the different configurations of the system for testing wells.
4. Propose a "next generation" configuration suitable for the next phase (phase 2) of the project on the basis of findings in items 1-3 above.

All work was performed as stated and a final report was issued in January 2006.That report, all data and additional pictures can be obtained at www.impact2u.com/projects.

Multiphase Metering Theory and Available Technologies

The primary information required in the measurement of oil or gas multiphase flow streams is the flow rates of oil, water and gas. The ideal method to obtain this data is to have a multiphase flowmeter that would make direct and independent flow rate measurements of these components. Unfortunately, such a device does not exist as yet. Consequently, much of the extensive development in multiphase metering (1-4) has been directed toward inferential techniques that use the instantaneous velocity and cross sectional fraction of each component to make these measurements. Thus the task of any multiphase meter is to estimate the volume fractions and the individual phase velocity in the flow stream. The developers of the multiphase meters have employed different technologies and modeling of the multiphase flow (2–4) to estimate the volume fraction and phase velocity of the individual components. A number of multiphase meters are commercially available today, as shown in **Table 1**. These systems can be grouped based on their use of full separation (group 1), partial separation (group 2) or no separation (group 3). These systems use a diverse range of equipment from full three-phase conventional separators to in-line multiphase meters that consist of a spool piece with no separation.

The performance data available in the literature (5-17) shows that the level of accuracy for all types of the multiphase meters is affected by two major factors:

- Gas Volume Fraction (GVF)–as the GVF of the flow stream increases, the level of accuracy for the liquid (oil and water) rate determination is adversely affected.
- Water Cut (WC)–as the WC in the flow stream increases, it becomes more difficult for a multiphase metering system to achieve high levels of accuracy for the oil phase, which frequently is the major focus of the measurements.

These effects are to be expected since the gas phase can expand much more than the liquid phase and therefore occupy a larger fraction of the volume. Similarly as the water cut increases the volumetric fraction occupied by oil phase decreases. Both GVF and WC impact the performance of the devices and modeling assumptions that are used in a multiphase metering system. Other factors such as gravity of the oil, salinity of water, flow regimes, etc. also impact the performance of the multiphase meters, but WC and GVF are the major factors.

Selection of MP techniques for a Portable Well Testing System

Based on the preliminary field conditions for the targeted US North American fields, the anticipated WC–GVF map for the wells to be serviced by the PWT is shown in **Fig. 1**.

Previous field experience with this type of operating environment had indicated (2, 9, 10, 13) that the measurement strategy must include separation of gas and liquid in order to obtain accurate water cut. The use of a cylindrical separator using cyclonic liquid forces for separation has been successful in this type of application (10) and was therefore adopted for this project. This approach also offers compactness and light weight, which is important for a portable system.

A number of new water-cut devices are commercially available and have been field tested (17). After reviewing the advantages and limitations of various water-cut meters an infrared sensing meter was chosen to measure the oil and water ratio (18). This technique offers some advantages since it is not affected by salinity, fairly insensitive to low levels of entrained gas, and can measure small amounts of oil (high water cut) accurately. These three features make it uniquely suited for use in high water-cut well testing.

Design of the Portable Well Tester

In designing the PWT, planning the tests, obtaining the data, and evaluating the results, the project aimed to address the following issues:

- Flow rate measurement accuracy and repeatability.
- WC measurement accuracy and repeatability.
- WC accuracy, impact of fluid properties, and water-cut meter calibration on WC measurements.
- Impact of flow rate on rate and WC meter performance.
- Impact of GVF on rate and WC (i.e., through GLCC versus bypassing the GLCC).
- Impact of lift method on rate and WC accuracy.
- Ease of use for PWT operating controls (GLCC, piping, and RTU).
- Estimate the number/percent of mid-continent wells requiring GLCC separation for future use.

The trailer mounted unit was designed to be able to test a wide variety of wells from 15 to 40 API, liquid flow rate range of 100 to 1500 BPD, gas flow rate range of 0 to 75 mcfpd, and 0 to 100% water cut. Gas-liquid separation was thought to be required for this first tester. The test system was designed and built to ANSI 300 specification. Road clearance of 7 ft tall, 8 ft wide, and a 4000 lb weight limit were also required.

As built, the PWT used an 8 in. OD compact Gas-Liquid Cylindrical Cyclone (GLCC™) to separate the liquid and gas. The GLCC is hydraulically lifted upright for testing and lowered to horizontal for traveling. Use of this separation device allowed a much wider range of wells to be tested. Valving to bypass the GLCC was provided to make a number of tests on the same well's flow stream with and without the use of the GLCC to establish the response of the various PWT components. DC electric actuated control valves were used for GLCC level stability with active software. All instruments and components on the unit are 24 volt battery operated with a generator backup. A RTU local controller is used for data acquisition and storage, flow calculation, and system control to operate the unit fully autonomously.

The key component to the low cost portable well testing system is the specialized liquid metering leg. It is comprised of an infrared water-cut meter and a coriolis mass meter (18). This combination has two key advantages–it has the ability to meter oil/water ratios accurately in high water-cut ranges (75+% water) and to measure the total liquid flow volume accurately with the presence of nuisance gas (<10% GVF).

The second component is a traditional mass meter used in a new way. First, a smaller mass meter than traditionally designed for well testing was used because we wanted the liquid (and any entrained gas) to be moving through the meter at a high rate for full mixing and low holdup. Also, the actual mass rate of the fluid is used and not the volumetric output from the meter.

Mass meters make two direct measurements, mass rate and instantaneous density. By dividing the mass rate by the instantaneous density, it outputs a volumetric flow rate. However, when mass meters have gas in the liquid flow stream the density error increases exponentially, resulting in very large volumetric flow rate errors. This is solved by calculating the density of the fluid from the water-cut reading, and approximate oil and water densities. The total error due to not adjusting for mass of the gas (low relative density), changes in water density due to salinity changes (minor variations), and oil density due to GOR changes are fairly insignificant. The result is a metering system that can accurately measure net oil and net water volumes in an application that previously could not be done.

Gas coming off the GLCC was measured with a vortex shedding meter and converted to standard conditions in the RTU. All fluids (gas and liquids) were recombined before leaving the PWT.

Fig. 2 is a schematic of the PWT major component, wiring and piping. It shows that the well's flow stream can be directed into the GLCC for gas liquid separation. The separated liquid is discharged from the lower liquid port of the GLCC into the coriolis mass liquid meter and the water-cut meter to measure the liquid rate and water cut. The gas exits the top of the GLCC and is measured by the vortex meter. Alternatively, the GLCC can be bypassed and the entire well flow stream directed into the liquid leg and through the coriolis and water-cut meter. The two DC electric control valves, designated as LCV109 and GCV109, provide the liquid level control for the GLCC.

Figs. 3 and 4 show the PWT in travel mode and test mode, respectively. Rate verification and instrument calibrations were performed at both the University of Tulsa and Weatherford, Houston test loops. A spare water-cut meter was used to make the oil and water calibrations for the PWT water-cut meter in this project. Later, insitu oil-water calibrations methods will be utilized.

Well test information is obtained from the PWT by several means:

- Instantaneous readings at a given time by visual readings of the RTU screen and equipment transmitters.
- Planned tests over a specific time period providing averaged test results of rates, water cuts, pressure, temperature and other information.
- Modbus logged information obtained by an RS-232 connection from the RTU to a laptop computer for a limited period of time (5 minutes to 6 hours).

For future use of the PWT, a local storage device to record key data and time dependent data will be employed. Short distance wireless system will also aid data acquisition, transfer and analysis.

Field Tests

The PWT project carried out almost 100 well tests in over 35 different oil wells–all in southern Oklahoma. Many wells had multiple tests using different PWT configurations and instrument settings. Specifically, this part of the testing consisted of comparison of results while going through the GLCC and then bypassing the GLCC forcing all well fluids into the metering without any separation. Varying the GLCC controls, testing time length, meter and instrument settings, calibration, and other input variable sensitivities to the rate and water-cut readings. The objective of varying the PWT configurations was to find if “simpler” and cheaper hardware configurations could provide accurate data and reduce the cost of next generation PWTs.

Well tests were conducted to investigate what is normal rate and water-cut behavior of wells under different lift methods. Also specific testing was made to determine the impact of the following parameters on the accuracy of the measurements as discussed earlier. Tests were conducted on wells pumped by electrical submersible pumps (ESPs), beam pump jacks, progressive cavity pumps (PCPs), and on one waterflood injection well (WIW). The range of flow rates tested were from below 100 to above 1500 BPD. All actual water cuts were above 85% water cut. All gas rates on these wells were below 20 mcfpd.

Normal move-in/setup and teardown/move-out times were about 15 minutes each with plumbing changes, or 10 minutes when the well was already properly plumbed. A typical header setup for portable testing at the wellhead for any type lift method is shown in **Fig. 5**. **Fig. 6** shows a typical centralized header where multiple wells come in and are directed to a test point or to the common separator. Pressure drop across the PWT at the highest rates encountered was only 10 psi.

A limitation of the PWT was that no calibration nor real-time detailed modbus data could be obtained in dusty, misting, or rain conditions, because of a required hardwire. Future versions will have full wireless options.

The specified gas meter was oversized for all of the wells tested, thus missing the low end rate conditions that exist. This design rate was an unsuccessful attempt to cover all anticipated gas rates. The actual gas meter was only accurate for 19 to 75 mcfpd, while the actual gas rates from the wells was estimated at less than 1 mcfpd. It is desireable to measure these low gas rates and this sizing issue will be directly addressed in the next generation of testers, where a GLCC is used.

At the high water-cut ranges encountered and targeted in these wells, the water-cut meter was found to be sensitive to different produced waters. This was a new factor and was not known until late in the testing program. Modifications to future water-cut meters are now being designed by the manufacturer for such high water-cut testing.

Significant amounts of low rate data were lost–primarily at the stroke ends in small beam pumped wells. Smaller sized liquid rate meters would help reduce, but not eliminate this error. An empirical formula can be developed to compensate for the below range data for small beam pumped wells.

Analysis of Field Test Data

A plot of PWT flow rate versus operator furnished rate data can be seen in **Fig. 7**. This plot generally shows an average error/difference of less than 10%, with only a few, beam pumped well low rate exceptions. The PWT rate (through the GLCC) averaged 8.4% lower than the operator reported rate. The 622 BPD PWT to 1405 BPD operator rate test was from well C578, a highly variable rate well.

Fig. 8 shows both the PWT’s measured water cut and the operator’s stated water cut compared to instantaneous 500 ml grab samples on that same well. The wells were constantly changing and thus some error is expected, however this error can be reduced with increased sampling volume and/or longer test time. The -48% error test at 97% WC was on a 26 API oil well with strong water properties impacting the result. The remaining tests with over 10% error were from multiple tests on only two wells, UWB14 and US232, where spots on the WC meter lens were later found. The cause of the spots was not found.

Fig. 9 shows the influence of using separation. It is a plot of the % difference in the PWT rate caused by not using the GLCC (i.e., in bypass mode) versus the PWT rate while going through the GLCC (used as the basis). Both bypass and GLCC tests are included in this plot. The % difference calculation is the (rate through the GLCC less rate measured while bypassing the GLCC)/rate through the GLCC 100. This figure shows that inaccuracy only occurs during GLCC bypass on only two wells (six tests)–well C611 (points at 80%, 61%, -42% errors due to unstabilized flow) and well PW6 (error points: 31%, -27%, -26% for unknown reasons, probable gas interference).

Fig. 10 shows the minimal impact of bypassing the GLCC on the PWT WC measurements. The % difference was calculated by using the WC measurement using the GLCC as the basis. This data shows good overall agreement and little impact with only 6 points outside of a 3% (total WC range) range of accuracy. Again, the primary source of this error came from only two wells, C611 (points 6.0%, 3.5%, -8.09%, due to unstabilized flow) and P24 (points -5.5%, -6.6%, due to unknown reasons).

Thus Figs. 9 and 10 show that most wells in the mid-continent do not need a GLCC separator with the specific meters used on the PWT. This is because the well's annulus serves as an initial separator of the gas and liquids with the gas vented out the annulus- and normally does a very good job of it! Specifically because they are on artificial lift, with the tubing inlet below the perforations and with no packer or annulus obstructions.

Portable field testing can also be much easier if oil calibration sensitivity is NOT a major concern to WC accuracy. This is because clean crude oil is very difficult to physically obtain from a high water-cut well. **Fig. 11** shows the errors in WC measurements from the water-cut meter due only to online changes in oil calibrations used for the same well stream. The % error plotted uses the wells' actual calibration as the basis. The 'actual calibration' in these cases is the well's own oil and water calibration values or values from the tank battery's mixed oil. Mostly, good agreement is found in this data with only one well P24 (two tests at 5.5% and 3.2%) outside of a 3% accuracy level, and five tests (previous points plus another P24 test at 2.0%, well PW6 at 2.3%, and well C576 at -1.8%) outside of a 1% accuracy level. As this data shows, specific well oil calibrations for this WC meter may not be needed in the future within a given field/region.

As noted earlier, the infrared water-cut meter was reported to be sensitive to oil properties, but insensitive to changes in water properties. However, a 2% WC error was seen in the data between the original tap-water calibration used for most tests and the injected waters found in well PS5-WIW during a test conducted late in the testing session. It was verified again on PW6 and C576 tests. The issue of water sensitivity was discovered too late to make a full evaluation of its impact on WC accuracy in this project. A full study to understand this fact and the causes (turbidity, salinity, scale, etc.) is now underway.

Conclusions

The work conducted in the project has delineated a number of benefits, limitations, and issues that need to be addressed for any future PWTs. These findings were the major outcomes of this project and were:

- Oil phase measurement accuracy of less than 1% is required for stripper wells, due to their relative marginal profitability and small amount of produced oil. Knowing that only 1% change in water cut can make the economic difference in profit or loss for a high volume, high water-cut stripper well, fine tuning the calibrations for each specific well will probably be needed, via adjustments to known values and 'tracking'.
- All meters were found sufficiently rugged and durable for portable testing.
- No separation is needed with the specified meters in this PWT for testing U.S. Mid-Continent wells on artificial lift (i.e., those that have the tubing below the perforations, no annular blockage, and a low fluid level). The well annulus provides sufficient separation. Where applicable, this will vastly reduce the cost of future testers.
- The selected infrared water-cut meter was not as sensitive to oil calibration as

expected and its accuracy was better than the 3% specified by the manufacturer. The unit was found to be durable and rugged for portable use. However, only wells producing in excess of 85% water were tested in this project.

- The water-cut meter was sensitive to water properties at these high water-cut levels and this fact must be investigated further for its impact on accuracy. This fact means that water and not oil calibration, or possibly both calibrations, are needed for high water-cut wells. The vendor is making changes to their meter to apply this finding.
- The coriolis meter was found to be accurate over its full range and durable/rugged for portable testing. However, measuring rates lower than 100 BPD is important for many beam pumped wells (at the ends of each stroke) and smaller meters should be considered.
- The selected vortex shedding gas meter's was oversized for the wells tested in this project and will be reduced for future testing, if a GLCC is used.
- Data acquisition of time dependent values is difficult, time consuming, but is important to understand the well and the test equipment.
- Methods that require opening up electronic boxes in the field for calibrations, data acquisition or data retrieval are impractical. Wireless devices and PDAs are favored.
- In-situ calibration methods are needed for the water-cut meter.

Tables

Metering System Group	Velocity Method	Composition Method
Accuflow–MMS Group 1	Coriolis	Coriolis Dielectric
Haimo MFM 2000 Group 1	Vortex, Cross Correlation	Gas Separation-Densitometer
Phase Dynamics–CCM Group 1	Coriolis, Turbine	Gas Separation Dielectric
eProduction Solutions–REMMS Group 1	Vortex, Coriolis	Gas Separation Infrared
Agar MPFM 400 Group 2	PD, Venturi (liquid) Venturi/Vortex (gas)	Gas/Liquid Split Dielectric
Schlumberger-VenturiX Group 3	Venturi	Densitometer Dual Energy
ROXAR–1900VI Group 3	Venturi and Cross Correlation	Densitometer
Kevaerner–DUET Group 3	Cross Correlation	Densitometer Dual Energy
Jiskoot–MixMeter Group 3	DP, Mixer	Densitometer Dual Energy
Agar MPFM 300 Group 3	PD, Venturi	Dielectric

Table 1 – Commercially available multiphase metering systems by groups.

Figures

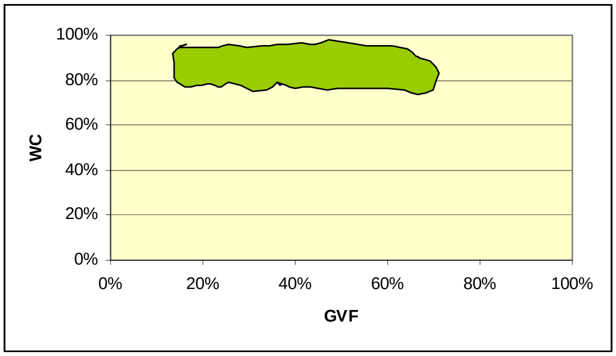

Figure 1 - Anticipated water cut and gas volume fraction map for the wells used in the project.

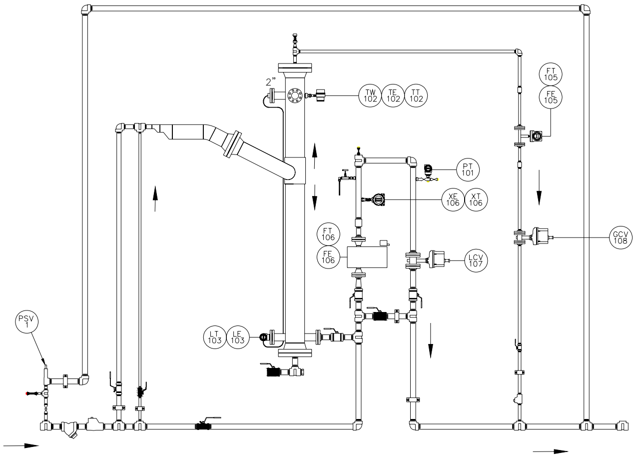

Figure 2 - Schematic of the PWT showing piping, valving, and major components of the system.

Figure 3 - PWT in transport mode.

Figure 4 - PWT in test mode on an ESP well.

Figure 5 - Ideal wellhead test header setup with (from left) wellhead, PWT inflow, isolation and check valves, PWT outflow, and flowline.

Figure 6 - Central header setup with bottom line into main separation and top line for individual well testing.

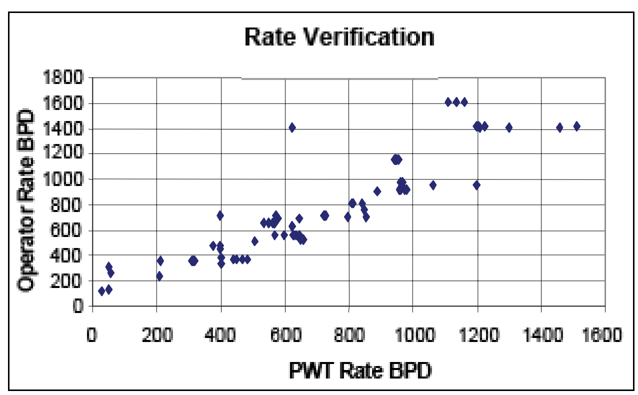

Figure 7 - PWT measured rate versus operator reported rate.

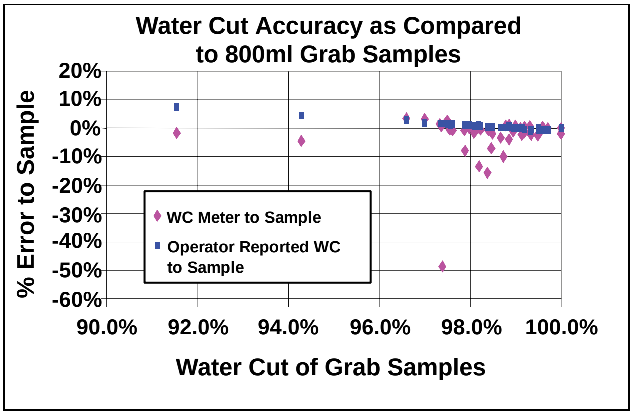

Figure 8 - % error of operator's reported WC and the PWT's measured WC as compared to 500 ml grab samples (basis).

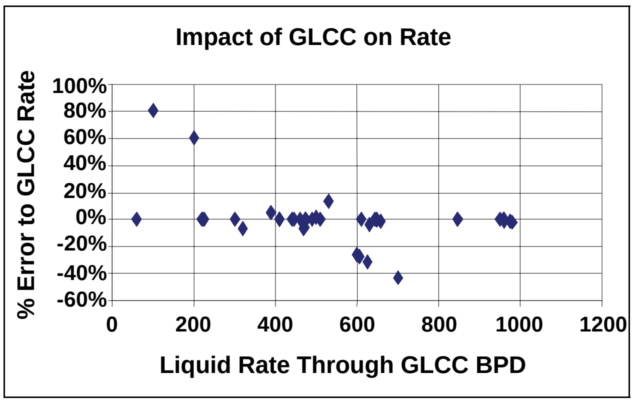

Figure 9 - % error in the average rate measurement due to bypassing the GLCC (rate error= (GLCC rate-bypass rate)/GLCC rate).

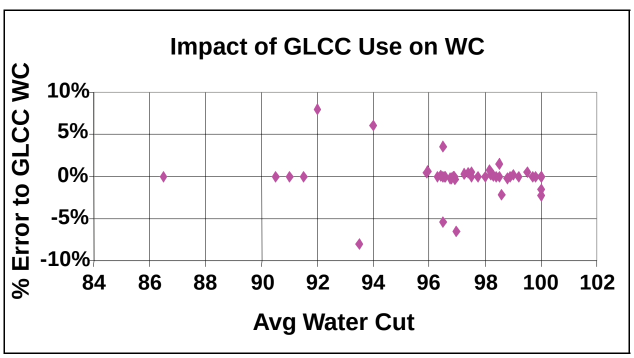

Figure 10 - % error in average WC due to bypassing the GLCC (WC error = (GLCC WC - bypass WC)/GLCC bypass).

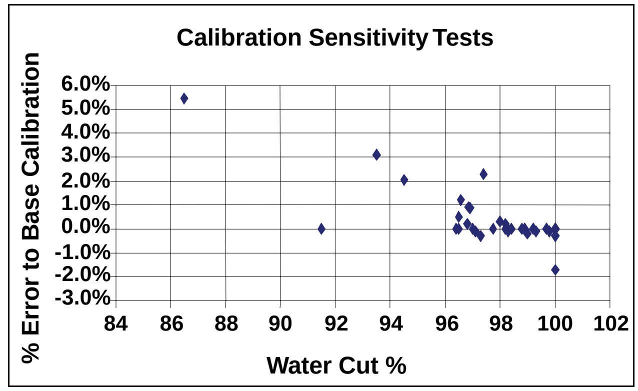

Figure 11 - % difference (error) in WC from using various oil calibrations on a fixed well stream.

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SPE 103087
Portable Multiphase Production Tester for High Water-Cut Wells

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2006 SPE ATCE
San Antonio, Texas, U.S.A.
24–27 September 2006

Need for Accurate Production Well Testing

- Intelligent decisions
- Primary, Secondary and Tertiary
- Large water - small oil & gas volumes
- Current Testing methods

Project Scope

- High water-cut (75+% water) & high volume (200-1500 bpd) wells
- Major objectives
  - Assess multiphase metering technology
  - Design & construct a portable well tester
  - Test component performance & durability
  - Evaluate different configurations
  - Evaluate “next generation” configurations

Project Scope- continued

- Flow rate & WC measurement
  - accuracy
  - repeatability
  - impact of fluid properties, calibration, flow rate, GVF & lift method
- PWT operating controls- ease of use
- Actual need of separation

Available Multiphase Metering Technologies

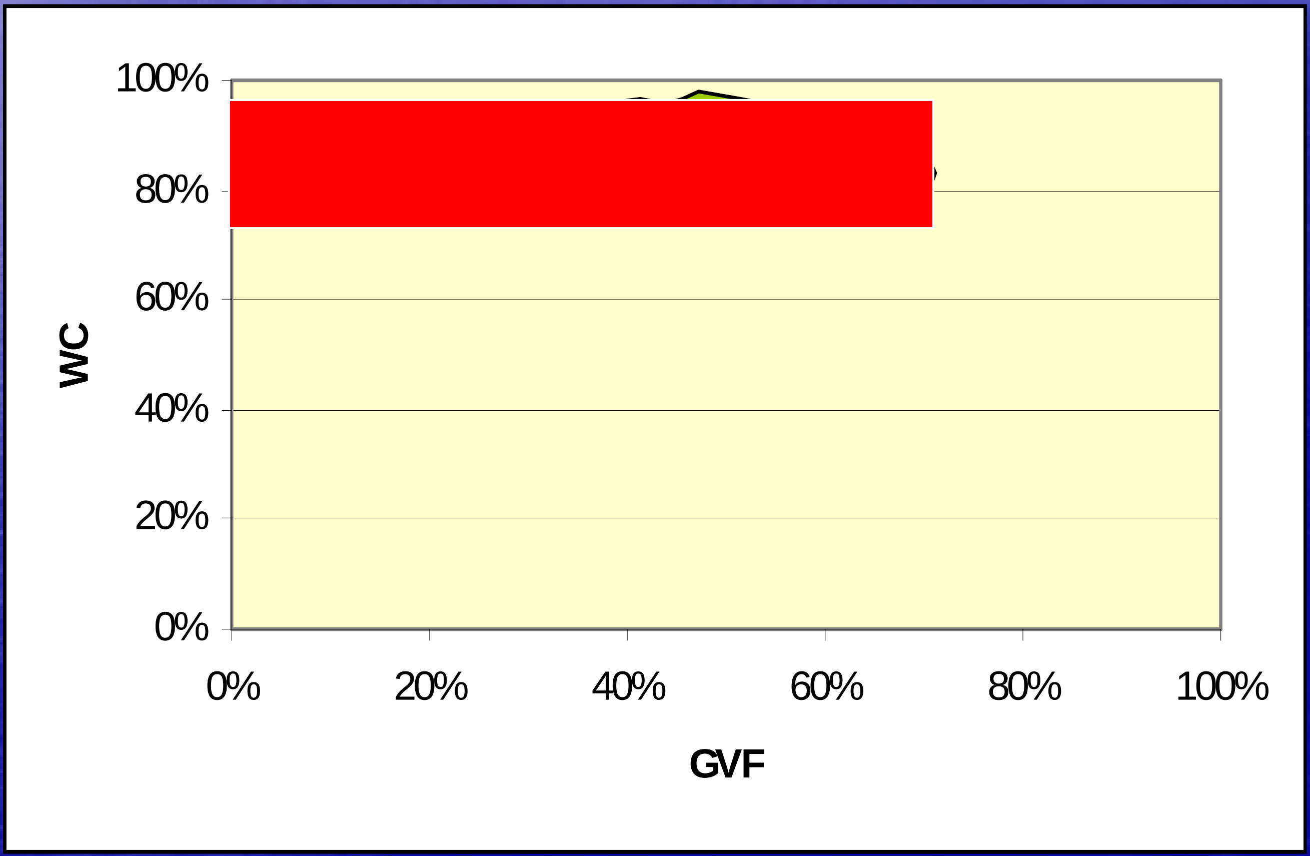
- Meter performance affected by
  - Gas Volume Fraction (GVF)
  - Water Cut (WC)
  - Minor oil gravity, water salinity, flow regime

- Multiphase systems by separation use
  - full separation (group 1)
  - partial separation (group 2)
  - no separation (group 3)

Commercially Available Systems

Metering System Group	Velocity Method	Composition Method
Group 1		
Accuflow–MMS	Coriolis	Coriolis Dielectric
Haimo MFM 2000	Vortex, Cross Correlation	Gas Separation-Densitometer
Phase Dynamics–CCM	Coriolis, Turbine	Gas Separation Dielectric
eProduction Solutions–REMMS	Vortex, Coriolis	Gas Separation Infrared
Group2		
Agar MPFM 400	PD, Venturi (liquid) Venturi/Vortex (gas)	Gas/Liquid Split Dielectric
Group 3		
Schlumberger-VenturiX	Venturi	Densitometer Dual Energy
ROXAR–1900VI	Venturi and Cross Correlation	Densitometer
Kevaerner–DUET	Cross Correlation	Densitometer Dual Energy
Jiskoot–MixMeter	DP, Mixer	Densitometer Dual Energy
Agar MPFM 300	PD, Venturi	Dielectric

Anticipated Mid-Continent Conditions



PWT Requirements

- Portable, Trailer mounted
- Max 7 ft tall, 8 ft wide, 4000#
- ANSI 300
- 15 to 40 API oil
- 100 to 1500 BPD liquid rate
- Max 75 mcfpd gas rate
- 0 to 100% water cut

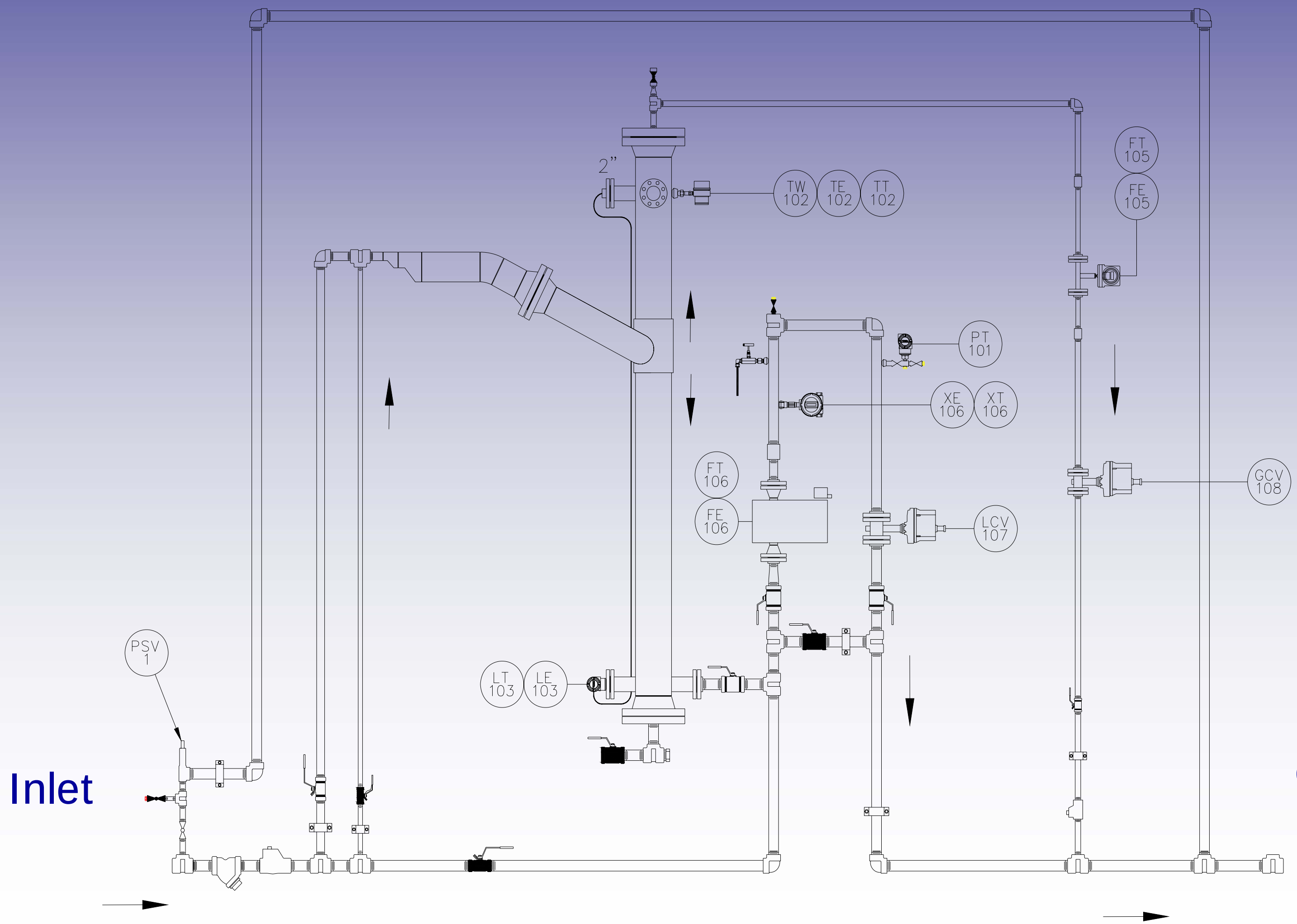
PWT Specifications

- 24 Volt Battery system
- 8” OD Compact GLCC separator
  - DC control valves , hydraulic lifted
- GLCC bypass valving
- Coriolis liquid meter
- Infrared water-cut meter
- Vortex shedding gas meter and
- Data acquisition unit

PWT Specification- continued
Specialized Liquid Metering Leg

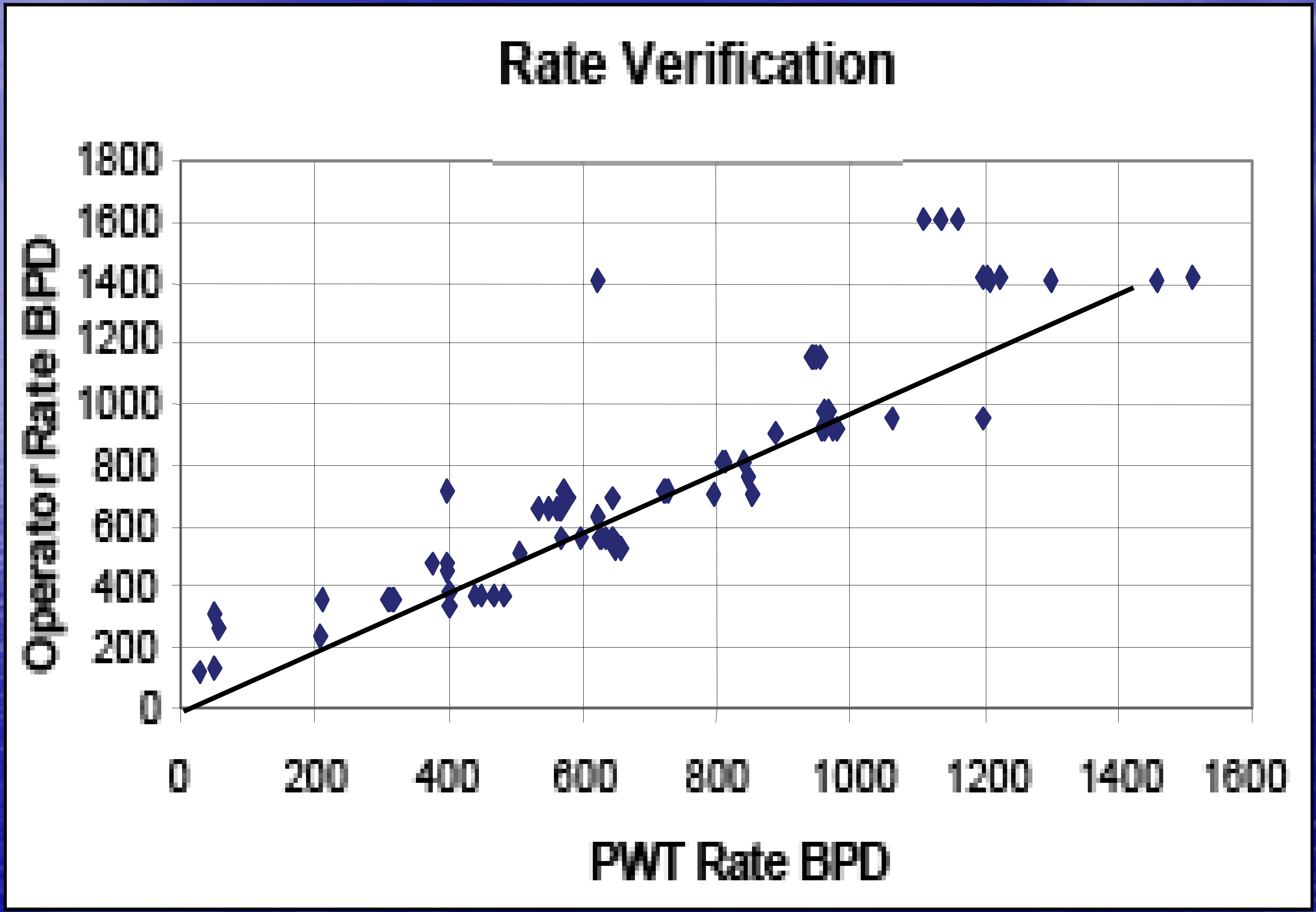
- Infrared WC meter & coriolis mass meter
- Smaller mass meter to keep liquid and entrained gas fully mixed
- Mass rate used - not volumetric output
- Accurate WC in high WC ranges (75+% water)
- Accurate liquid flow rates with nuisance gas (<10% GVF).

PWT Schematic

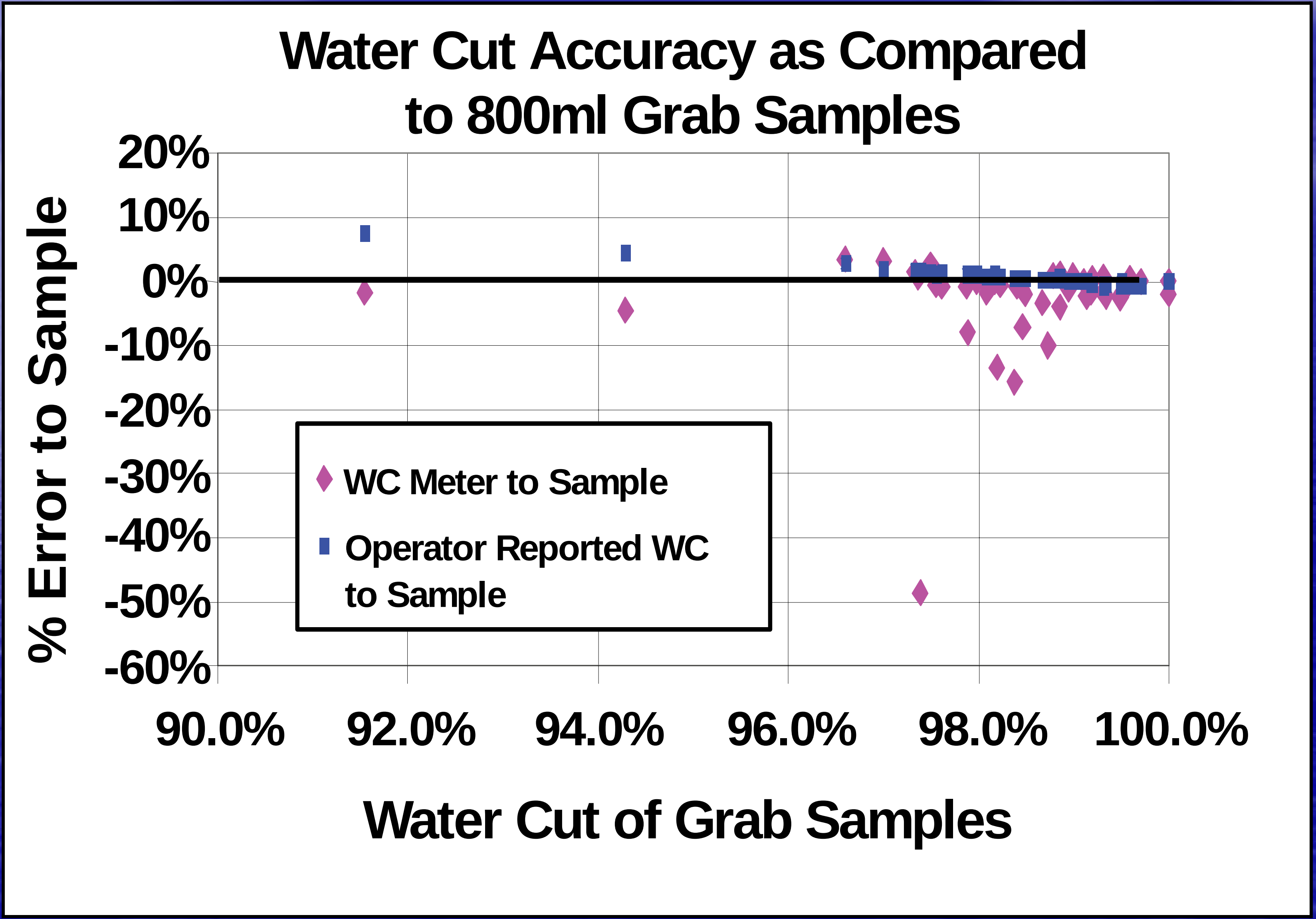


PWT in Travel Mode

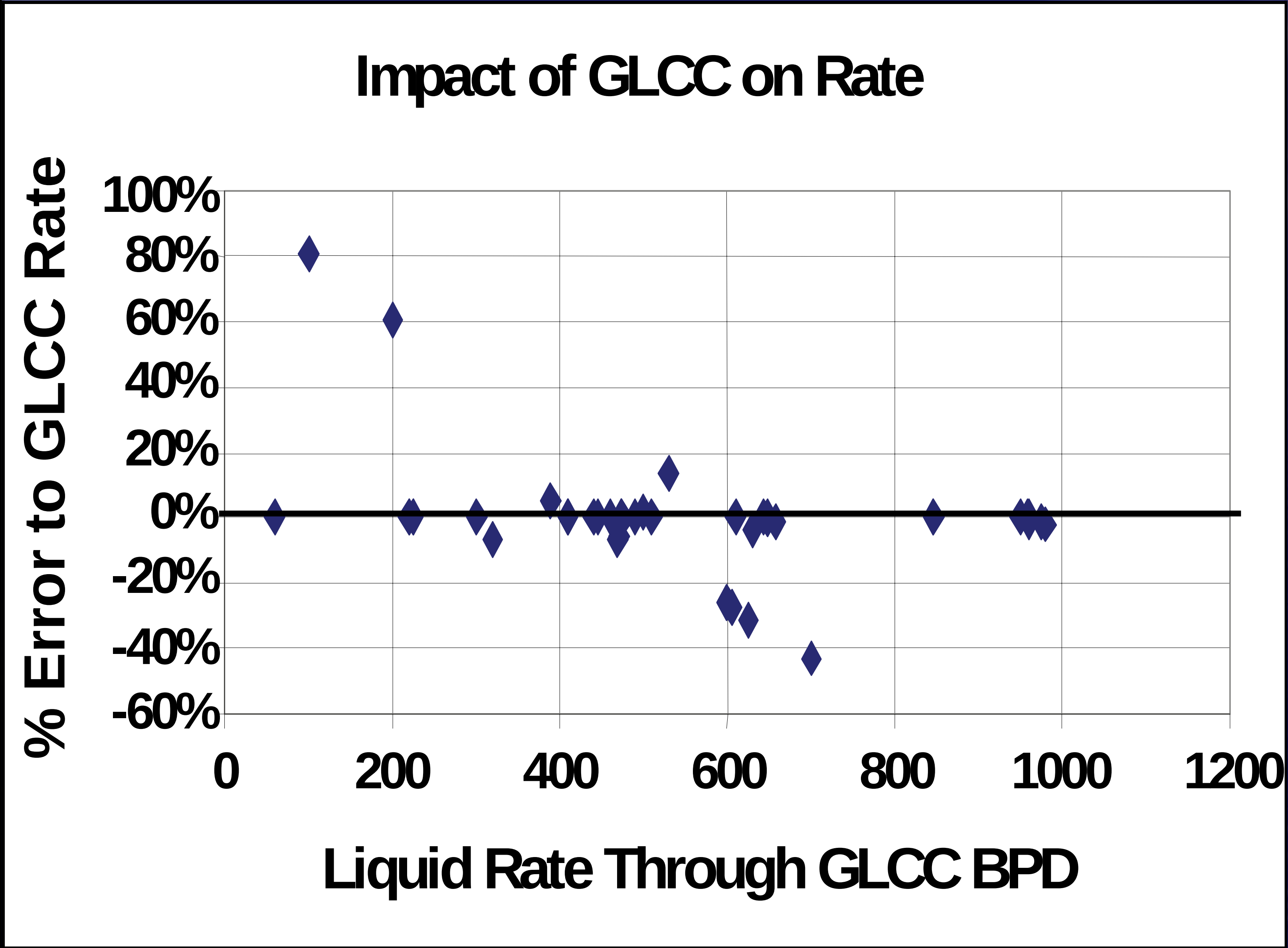
PWT in Test Mode



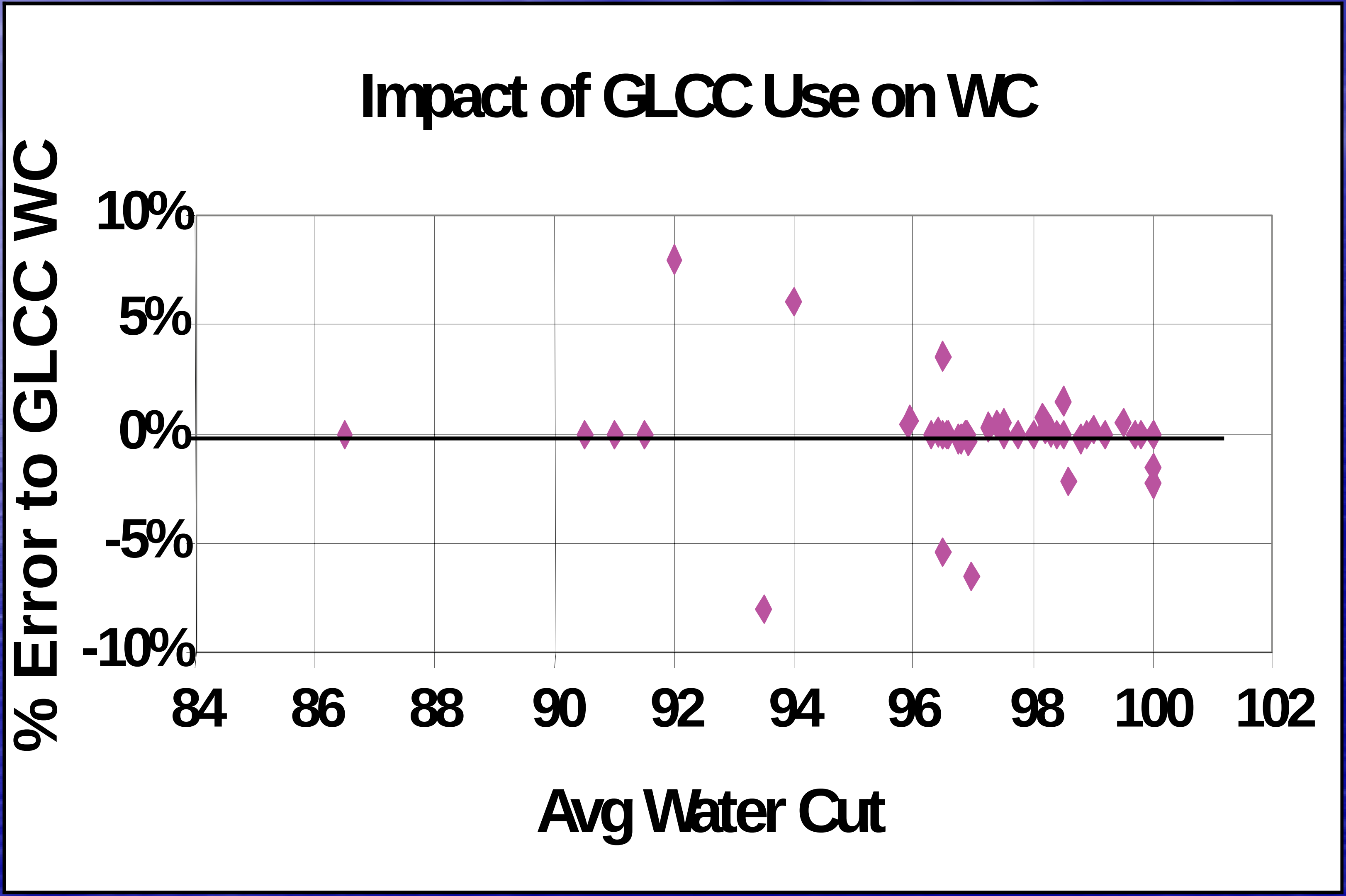
Rate Verification
Operator Rate BPD
1800
1600
1400
1200
1000
800
600
400
200
0
0
200
400
600
800
1000
1200
1400
1600
PWT Rate BPD



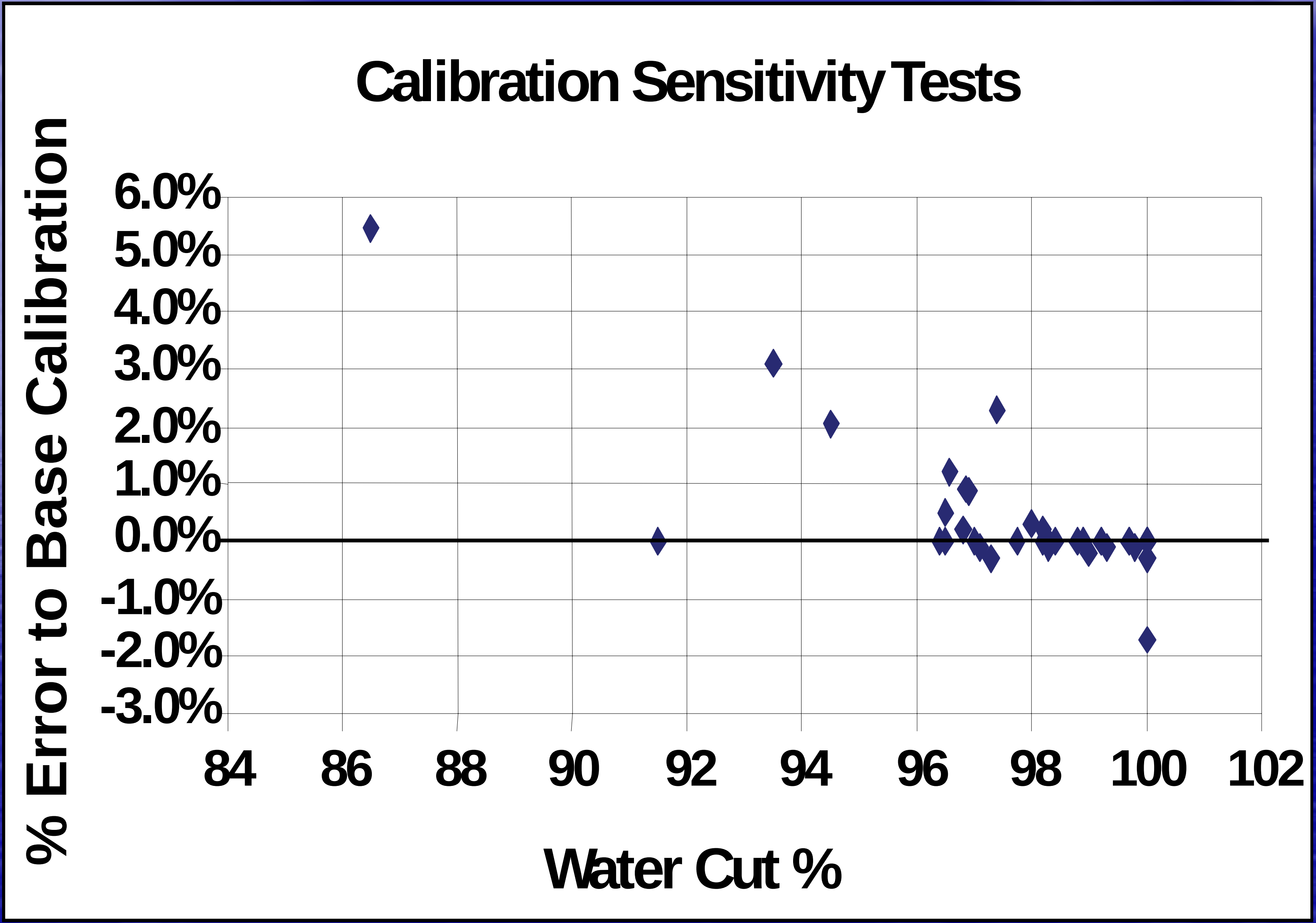
Water Cut Accuracy as Compared to 800ml Grab Samples
20%
10%
0%
-10%
-20%
-30%
-40%
-50%
-60%
% Error to Sample
90.0%
92.0%
94.0%
96.0%
98.0%
100.0%
Water Cut of Grab Samples
WC Meter to Sample
Operator Reported WC to Sample



Impact of GLCC on Rate
% Error to GLCC Rate
100%
80%
60%
40%
20%
0%
-20%
-40%
-60%
0
200
400
600
800
1000
1200
Liquid Rate Through GLCC BPD



Impact of GLCC Use on WC
% Error to GLCC WC
10%
5%
0%
-5%
-10%
84
86
88
90
92
94
96
98
100
102
Avg Water Cut



Calibration Sensitivity Tests
% Error to Base Calibration
6.0%
5.0%
4.0%
3.0%
2.0%
1.0%
0.0%
-1.0%
-2.0%
-3.0%
84
86
88
90
92
94
96
98
100
102
Water Cut %

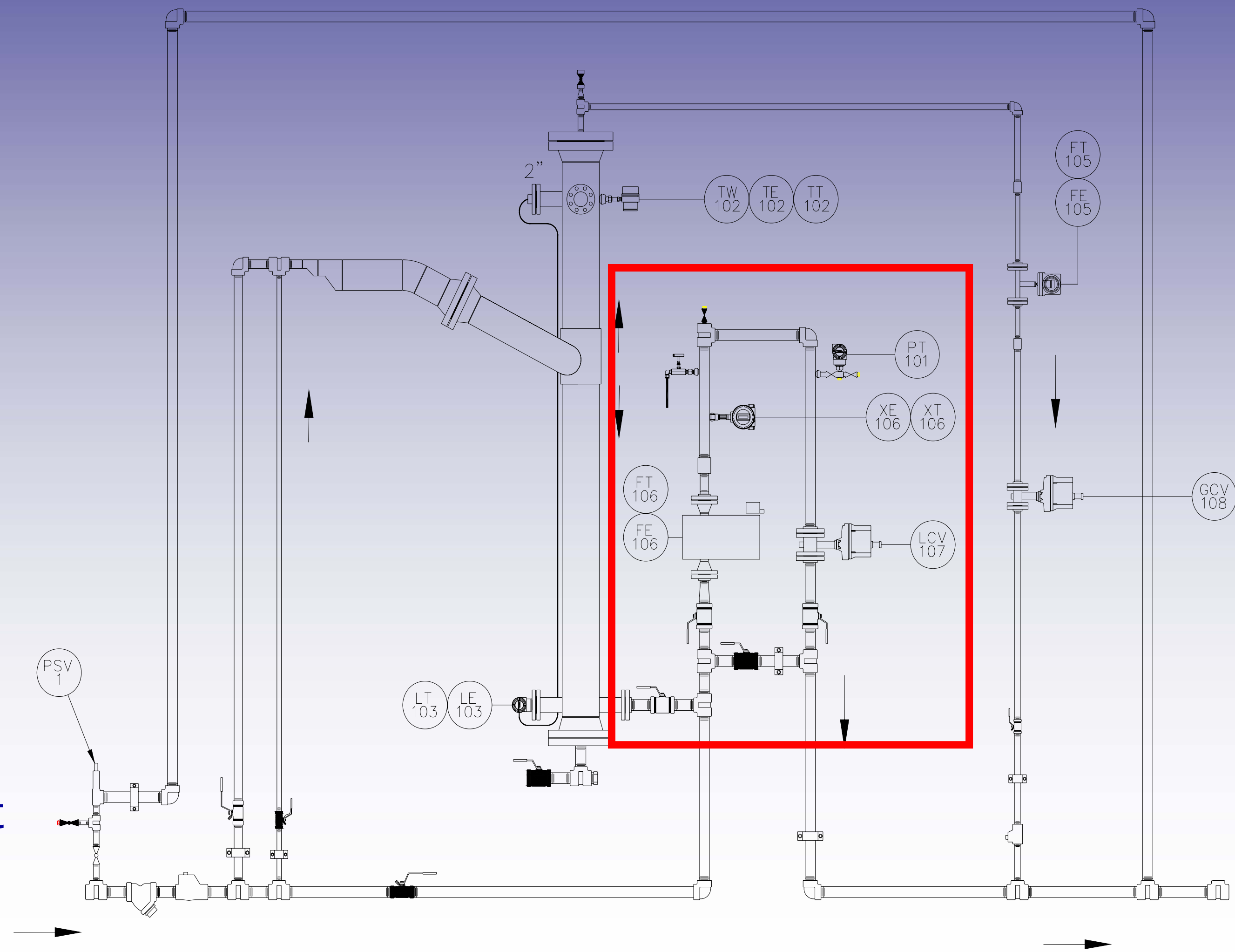
Conclusions

- Oil measurement accuracy < 1% required for high volume stripper wells
- All meters sufficiently rugged and durable
- No separation needed with the given meter combination for the wells tested
- The infrared WC meter <u>not</u> sensitive to oil calibration at high WCs
- The infrared WC meter <u>was</u> sensitive to water properties at high WCs
- The coriolis meter was found to be accurate over its full range

Conclusions- continued

- Rate measurement for beam pumped wells problematic at both ends of the stroke
- The selected vortex shedding gas meter was oversized - resized if GLCC used
- Data acquisition of time dependent values is difficult, time consuming & important
- Wireless devices and PDAs are favored for closed box data retrieval
- In-situ calibration methods needed for the WC meter.

Next Generation PWT Schematic



Inlet

Outlet

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