Methods for Optimal Matching of Separation and Metering Facilities for Performance, Cost, and Size: Practical Examples From Duri Area 10 Expansion

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Abstract

New production facilities require accurate metering of produced fluids for optimal reservoir and facilities management. The need for cost and size reduction and the severe effects of high watercut production (>70% watercut) on accuracy are forcing careful evaluation of multiphase metering methods. At this time we are not considering full bore MPMs for reasons of concerns about unacceptable hydrocarbon uncertainty at high watercut. We, instead, are using a process of custom design of multiphase metering systems from commercially available components, selected to optimally perform in accuracy and cost for the production design basis.

We have developed software models of conventional and compact separation, which allow comparison in cost and size for equal performance. Separator performance is defined here in terms of gas carry under (GCU) into the liquid stream and liquid carry over (LCO) into the gas stream. These models demonstrate that separation can rarely be considered to be perfect and that optimal system design must take realistic incomplete separation of gas and liquid into account.

Considerable cost and weight savings are possible (10 X) with compact separation without loss of performance relative to traditional separation methods however overall system performance in both cases must consider the effects of separation performance.

Downstream single-phase gas and liquid metering instrumentation accuracy is severely affected by imperfect separators which deliver mixed phases (gassy liquids and wet gas). These metering errors are dependent on the type of meters used and the customer's production parameters, such as viscosity, rate, GVF and watercut and the separator chosen. Hundreds, even thousands of meter/separator combinations are possible and production fluid properties affect each meter/separator combination differently. Until now no tools were readily available to assist the design team in sorting out the complex issues.

We have developed software and data for design and implementation of partial separation multiphase metering applicable to surface, floating and subsea contexts. These products allow design engineers to input their field conditions and obtain within minutes, performance, cost and size expectations for hundreds of combinations of separation, rate metering and watercut metering for further review.

The Duri Area 10 facilities team has chosen Gas-liquid Cylindrical Cyclone (GLCC©[1]) separation combined with venturi rate metering and Texaco Starcut Microwave watercut metering as the best option

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[1] GLCC© - Gas-Liquid Cylindrical Cyclone - copyright, The University of Tulsa, 1994

for Area 10 expansion. Application of these products has enabled immediate \$3.2mm savings over planned Duri Area 10 development costs.

I. Introduction

Oil production facilities require accurate metering of produced fluids for optimal reservoir and facilities management. One objective of facilities management is to maximize oil production by frequent and accurate well testing. The key parameter discussed here is liquid hydrocarbon rate (Qh) which can be computed from primary measurements of liquid rate (Ql) and watercut (%, WC) , i.e.

$$\mathbf{Qh = Ql * (100-WC) / 100} \qquad (1)$$

The actual metered value of hydrocarbons (Qhmeter) is affected by errors in rate (Qlerr), errors in watercut due to salinity changes (WCs), free gas (WCg) and instrumentation uncertainty (WCu) where:

$$\mathbf{Qhmeter= (Ql + Qlerr) * (100-(WC+WCs+WCg+WCu)) / 100} \qquad (2)$$

The error in hydrocarbon rate, Qherr% can be easily determined as:

$$\mathbf{Qherr\% = 100\%* (Qhmeter - Qh)/Qh} \qquad (3)$$

From examination of equation 2 and 3, we see that errors in both Ql and WC affect Qhmeter. However at high watercut, i.e. > 70%, the major source of hydrocarbon uncertainty shifts from errors in rate measurement to errors in watercut. Furthermore at high watercuts, large bodies of experimental work show that the major source of errors in watercut are primarily due to free gas in the fluid stream and secondarily due to changes in fluid salinity. For example equation 3 results are plotted for various assumed errors in watercut over the entire watercut range in Figure 1. It can be seen that, at 90% watercut, a 5% uncertainty in watercut translates into a 50% uncertainty in hydrocarbon rate. Our accuracy objective is hydrocarbon uncertainty of 10% at 95% watercut and that requirement translates into a required maximum allowable 0.5% uncertainty in watercut.

Modern full flow multiphase meters do not require separation for operation, however many of these meters test at an accuracy 10 times worse than our requirement at high watercut. Our overall system plan therefore is to separate gas and liquid and meter them separately. Given that no separation system is perfect, we want to evaluate the error effects of imperfect separation on novel and on the traditional single-phase instruments used for rate measurement and the watercut measurement system. In general we want to optimize the entire system in the following way:

- Minimize system cost,
- Maximize accuracy, and
- Minimize risk through matching the separation system to the metering instruments chosen.

Another reason for avoiding full bore multiphase meters where possible is their relative lack of dynamic range, i.e. the range over which they maintain their specified performance. Figure 2 indicates the distribution of well production rates presented to the facility indicated in figure 3. Slugging effects further increase this range in rates sometimes by 6 fold. The small circle in figure 2 indicates the dynamic range anticipated with full bore multiphase meters. The large circle indicates the expected enhancement in dynamic range when the metering system is preceded by partial separation of gases and liquids. The solid line indicates the change in a single well's gas and liquid rate performance over its life. It is our belief that in our systems of several hundred wells scattered over many kilometers and operating for many years, no currently available full bore multiphase meter can perform to our requirements.

II. Facility Design Options

The design of the separation and metering facility follows a fairly standard block diagram, figure 3. What is not standard is the identity of the various components. Each operating company has preferences for devices based on history, cost, performance, and reliability. Unfortunately, functional groups within the company value those parameters differently. Management sets budget caps and schedules, Operations prefer reliability over accuracy, whereas Reservoir will prefer accurate data for their management models. Previously installed systems rank high because costs are understood, problems have been resolved. New systems may provide exciting opportunities for cost savings and accuracy but the risk on budget, schedule and performance of new technologies will deter applications.

In the proposed Duri Area-10 production system, engineers were confronted with three general separation options, seven rate meter options, five gas rate meter options, six watercut measurement options, two general separator control options and two general system pressure control options. For each hardware option, additional options are available in terms of the desired performance objective. Since no hardware is perfect, a costly decision must be made as to the desired performance objective of each hardware component. For example should the rate meter component operate perfectly with a turn down of 30:1 with no error, 1 %, 2%, 5% errors?

The performance of each component affects the performance of other components in the system. For example, here, we consider the presence of free gas as the major source of uncertainty in the system. Separator capability in removing gas directly impacts the performance of all other hardware components in complex ways. However attempts to remove all gas from the liquid stream of the separator by residence time control, lead to unacceptably large and expensive vessels. If we cannot remove all of the gas, how much gas should we leave?

Taking all of the possible permutations of hardware and performance objectives we find that as many as 22,000 options present themselves to the design engineer (Figure 4). The end result of this complexity is that the common practice in the field is to simply reproduce the designs of prior projects and reject potentially valuable new technologies due to the overwhelming complexities presented.

III. Decision Process

We have addressed the above questions through a brute force analysis of all permutations of options. Decisions are based on the parameters such as accuracy, cost, size and credibility chosen to characterize each permutation. Graphical methods of reviewing the performance and performance sensitivity are provided in Figures 15 through 24.

We describe here an orderly, computer supported, process of reviewing complex facilities in terms of spatial and temporal distribution of oil well properties, hardware properties, rules of hardware component interconnectivity, fluid properties, customer performance indices and the credibility of the performance model. The process allows entry of users' subjective view of credibility of the component performance data as well as cost and performance criteria to be carried along in the process. The process allows updated hardware performance data to be updated or added as appropriate, thus providing a dynamic process which captures Joint Industry Projects (JIP) data as it becomes available or new components or component designs are introduced by vendors. The process allows full bore multiphase meters to be evaluated in a similar manner, however those data are not presented here.

A. The Cost Of Uncertainty: A Drive to Novel Technologies

Using this review process, we find that the cost of uncertainty can be quantified. This cost of uncertainty can then be used in the decision process of selection of new technology. For example, the cost of testing a novel component such as the GLCC© to establish its true performance may be less than the cost of the conventional alternative. Further, once the credibility of performance is established then the cost of testing is amortized over all future opportunities to use that technology.

As a further example, the cost of not knowing viscosity better than ± 20% at 70 centipoise can be assigned a value of $250,000 (Figure 11); that is, the cost of a conventional separation vessel sized at worst

case vs. best case. That cost can be applied to determining viscosity more precisely, a daunting task, or cost can be applied to proving a new technology, which is relatively insensitive to viscosity.
Figure 5 indicates the process used.

B. Decision Process - Information Collection

Information on all facets of the system was collected. Those sources are public and private and are from JIPs, publications, testing, and from theoretical models. The data come from different databases, in different formats, and with varying credibility. All data must be normalized to a common format compatible with computer processing.

A data-normalizing Wizard was developed which takes as input empirical test data obtained for various sized meters at various test conditions. The Wizard converts the data using a series of normalizations, such as converting to superficial velocity, and interpolation between irregularly spaced data points to create a generalized 3-D surface. Performance of all meters is thus reduced to sets of three-dimensional surfaces of parameter A (rate or watercut), vs. parameter B (gas fraction, salinity, watercut) with error Z. Normalization is carried out using Visual Basic programs which call commercial normalization, interpolation and mapping software well established in the geological industry (Surfer by Golden Software).

Figures 8 and 9 indicate typical Wizard normalized surface plots of watercut meter accuracy for several watercut meters. Plots were generated from data obtained in the National Engineering Laboratory (NEL) High Water JIP. In each case, the X-axis is true watercut, the Y-axis is the interfering parameter such as salinity or free gas percent by volume and the Z-axis is the resulting error % of reading. All meters are reported to have performance indicated by a single uncertainty value, i.e. 5% to 10% of reading, but are demonstrated clearly by the contour plots to be far more complex than any single numerical parameter could reflect (Marrelli, 1998). As with the WaterCut meters, rate meter (PD, Vortex, Venturi, Turbine, coriollis, Orifice Types) performance also reveals itself to be far more complex than any single numerical parameter could reflect (Skea, 1995).

Tools and data bases used or developed for this process

- Optimal Separator Design & Performance Package
  by EnSys-Yocum & Texaco
- Optimal Cyclone Design & Performance Package
  by Tulsa University Separation Technology Projects (TUSTP) JIP & Texaco
- Meter Accuracy Data Bases (continuing) - Texaco affiliated JIPs
  NEL MultiPhase Metering JIP
  NEL WaterCut JIP
  CEESI Wet Gas JIP
  NEL Rate Meter Reports by Skea- Effects of Gas, Oil, Water on Single Phase meters
- Normalization Software and Procedure
  by Digital Consulting and Software Services (DCSS), Surfer by Golden Software & Texaco
- Meter / Separator Combination Design & Performance Package for Accuracy , Size and Cost
  by Texaco, Humble
- Control Valve Stability Analysis & Design
  by Tulsa University Separation Technology Projects (TUSTP) JIP & Texaco
- STARCUT MultiPhase Metering System
  by DCSS & Texaco
- Testing of Separation Type Meters
  Texaco, Humble Flow Facility.

C. Decision Process - Models

Models of system components are critically important in this process. Our separator models vary from strongly theoretical with some empirical basis (Tulsa University Separation Technology Project, Joint Industry Project, GLCC© Model, (Gomez et al., 1999), to strongly empirical with some theoretical basis (EnSys-Yocum, GOSPSIM).

The GOSPSIM model (EnSys Yocum Incorporated, Yocum et al., 1999) is an integrated pressure, temperature, flow simulator from well bore or well head through surface facilities, including two and three phase separators, with extensive field-proven history. The GOSPSIM model has been provided in a Wizard format. Under the Wizard format, a desired separator performance objective such as 3% gas carry under can be specified. Using the entered fluid properties and rates, the GOSPSIM Wizard will converge on the sizing required to meet the specified objective, for example, Figure 12.

The GLCC© model has been also provided in a Wizard format. Under the GLCC© Wizard format, a desired separator performance objective such as 3% gas carry under can be specified. Using the entered fluid properties and rates, the GLCC© Wizard will converge on the sizing required to meet the specified objective (Gomez et al., 1999).

Use of the target performance approach for all input conditions allows the decision process to always compare "apples to apples", i.e., all separation components are properly sized allowing meaningful comparisons for all situations.

Our rate and watercut meter models are mostly empirical with some theoretical assumptions based on the physics of the device under study. Empirical data are mostly drawn from JIP work done by NEL (Marrelli, 1998).

D. Decision Process – Fluid Properties Characterization

1. Viscosity

The expected chemistry and thermodynamics of produced fluids, their rates, well completion, and physical geometry of approach piping all strongly influence system performance. It is thus very important to determine in advance of design, the expected conditions. Often key data for models are not available. Viscosity, in particular, is a very poorly defined physical parameter. Viscosity is temperature, flow rate, chemistry, time, emulsion-phase and vessel dependent. In the Duri design, team review of all available information regarding oil viscosity still left considerable uncertainty regarding partitioning of emulsions in flow lines, separation vessels, as well as expected emulsion phase, i.e. water or oil continuous, and even temperature. A set of four models were selected to calculate expected emulsion viscosity given base conditions of GOR, oil and water viscosity, stable emulsion ratio to free oil and water and temperature (Figure 6). The typical uncertainty of system viscosity was 50%. Fluid flow rates, pressure and maximum free gas desired in liquid systems were easier to determine (Figure 7) for both the well test systems and the bulk metering systems.

2. Pressure, Volume, Temperature Relationships

Starting with a reservoir fluid compositional analysis, equation-of-state modeling " Soave Redlich Kwong" was applied to establish gas-to-oil ratio, mixture, gas and liquid densities across the range of pressure and temperature for the Duri system. These were used as inputs to both simulators (GOSPSIM and GLCC©).

3. Emulsion Characteristics : Phase

The emulsion characteristics are fundamentally important in all aspects of multiphase and two-phase flow measurement and separation. Immiscible fluids such as Hydrocarbons and Water can be organized in three fundamentally different structures: laminar i.e. a layer of clean oil lies on a layer of clean water, water droplets suspended in oil (Water-in-Oil emulsion) or oil droplets suspended in water (Oil-in-Water emulsion). Combinations of the three types of systems are possible and usually are present in most cases. The prediction of emulsion characteristics is extremely complicated as it depends on parameters, which cannot be easily determined. It is much easier to measure the emulsion state using electronic watercut meters (such as Starcut, Agar, MFI, Phase Dynamics, Fluenta, etc.) which as part of their operation first predict the emulsion state.

Factors determining and controlling emulsion state are:

i. WaterCut
ii. GOR and thus possibly pressure
iii. Temperature
iv. Shear: History of fluid mechanical shear
v. Hysteresis: Fluids once put into a given emulsion state cannot be restored to the previous emulsion state with out considerable additional energy
vi. Presence of emulsifying chemicals such as surfactants which are naturally occurring and changing with time. De-emulsifying chemicals can also be deliberately added for field management reasons.
Emulsions are also stabilized by fine sand particles as are prevalent in Duri production
vii. Flow rate including flow rate of zero.
viii. Duration at zero flow rate, i.e. Settling Time

For the case of Duri fluids, information on emulsion history was obtained through internal Texaco and Caltex reports, which provided data on electronic meters reporting emulsion phase. Work reported by Dowty and Gray (Internal Report: Texaco Report number 97-0220) indicates that for settling times of 0.2 to 2.3 hours the predominant emulsion type in one of the already producing Duri area fields (Area 4) is water-continuous emulsion. Comparable results were reported for other area wells (Internal Report: Caltex Well Test Pilot: Self Monitoring Automatic Remote Test (Balam Station B), Fisher Rosemount Singapore Pte LTD, May 99.

Watercut meters unable to report watercut in water continuous emulsion were considered in this review for example, capacitance meters (meter #6, figure 8). As would be expected, systems using these meters provided among worst error of all systems and are represented in figure 17. All other systems reviewed used watercut meters able to report oil-in-water emulsion status.

E. Decision Process - System Characterization

A mathematical characterization of the selection criteria (Hydrocarbon Accuracy, Cost, Credibility, Size – Table 1) for the overall system is required. In this study we consider only the free gas dependent errors. Watercut and rate errors are obtained from the component surface plots (as in figure 9) for each component from the true rate or watercut and the volumetric fraction of interfering gas phase. Hydrocarbon accuracy is computed as in Equation 3 (Table 1), using the errors obtained from the component surface plots. Cost is simply the sum of component costs. Data source credibility (0 to 1) is summed over all components and is highly subjective but builds into the results the user's subjective biases in a traceable ,repeatable and quantified manner.

Table 1: Using Component Inter- Relational Models	
1	hydrocarbon Accuracy =100% * {{Ql }*{1-[Wcut]}-{Ql + QlErr}*{1-[Wcut +WcutEr]}} /{{Ql }*{1-[Wcut]}}
2	Cost = Sum (Component Cost)
3	Credibility = Sum (Component Data ; Assigned Credibility)
4	Size = Sum (Footprints)
5	Others (?)

F. Decision Process – System Performance

System performance is determined by providing to the system models (separators and meters), expected inlet conditions defined by the customer consisting of fluid rates, GVF, pressure, temperature, viscosity, salinity and uncertainty in those parameters.

1. Hydrocarbon Rate Performance

The system model automatically designs the conventional (GOSPSIM) and compact separators (GLCC©), which will achieve the target performance for that separation component. For example, we have tested the impact on overall system performance, cost and size, of 0%, 1%, 3%, 5% and higher gas carry under as target objectives.

Rate meter errors and watercut meter errors downstream of the separation component are determined from the component properties using the actual fluid rate or watercut and gas fraction flowing in that component. Figures 15, 16, 17 and 18 indicate the calculated hydrocarbon error in four specific separator, rate meter, watercut meter combinations as a function of watercut. In each case, a family of curves is illustrated for gas fractions of 0, 1, 3, 5 and 10%. The rate meter selection for demonstration here did not influence the results very strongly. The greatest effect in every case was due to the watercut meter chosen. All systems show similar results but in very different degrees:

- Case 1 figure 15, indicates performance of a Flat Blade Turbine meter and a watercut meter with high tolerance for gas. Hydrocarbon error rises rapidly to 10% - 12% when watercut exceeds 90%.
- Case 2 figure 16, indicates performance of a Flat Blade Turbine meter and second watercut meter with lower tolerance for gas. Hydrocarbon error rises rapidly to 50% - 150% when watercut exceeds 90%.
- Case 3 figure 17, indicates performance of a Flat Blade Turbine meter and third watercut meter with similar lower tolerance for gas. Hydrocarbon error rises rapidly to 50% - 150% when watercut exceed 90%.
- Case 4 figure 18, indicates performance of a Flat Blade Turbine meter and a fourth watercut meter with very low tolerance for gas. Hydrocarbon error rises rapidly to above 500% when watercut exceeds 90%.

These above cases illustrate the importance of choosing the watercut meter appropriate to the expected service.

2. Separation Performance

Choice of the separation systems was dependent on the availability of software performance models (GOSPSIM and GLCC©) which allowed review of the many design options. Of primary concern in this study was the presence of free gas in the liquid discharge of the separators, (Gas Carry Under Volume %, GCU, or sometimes referred to as Gas Volume Fraction ,GVF, specific to the liquid exit line).

The flow lines to the de-gassing separators were simulated, integral with the separator, using GOSPSIM to provide entry conditions and physical property values for both conventional and compact separator calculations. The GOSPSIM simulator also output slug flow and sand settling velocity predictions. Liquid and gas bubble slug sizes and frequencies as a function of probability were used to provide information to guide control strategies for both the conventional and GLCC© separators.

Sand is reported in the Duri well flow lines at concentrations varying between 2 and 5 weight percent. The grain size is between 0.0083 and 0.0232 sieve inches. A possible Duri process option was to process the sand through the separators. An open question was if the emulsion viscosity would be reduced by the removal of sand particles, either directly by their contribution to viscosity (if any), or by removing the sand particles as a stabilizing agent and thus de-stabilizing the emulsion. Also open to question was the degree (if any) to which a gas foam would form in the well flow lines.

Fine sand particles would be expected to increase the emulsion viscosity and slow down gas disengagement rates. Further fine sand particles acting in turbulent flow would be expected to stabilize the emulsion.

a) Conventional Separator Performance (GOSPSIM)

A total of seventeen GOSPSIM cases were run for vertical de-gasser, horizontal de-gasser and vertical automatic well test (AWT) separators, ("GOSPSIM Cases for establishing Duri Separator Size/Performance And Demonstrating GVF Sensitivity to Design Parameters, " Prepared for Texaco EPTD By EnSys Yocum Incorporated, February 15, 1999).

Within each case set, the effects of:

- varying inlet diverter design
- using perforated plates (horizontal only)
- water addition to reduce viscosity
- emulsion breaking and
- assuming an alternate bubble size distribution (larger bubbles)

were examined. In addition, an AWT performance sensitivity was run to examine the effect of a 10 psi lower separator inlet pressure as could be caused by sand deposition in well flowlines. Results are illustrated (for the horizontal de-gassing separator only) in Figures 10, 11, 12 and 13.

- **As the size of the vessel increases within each set, the Gas Carry Under decreases.** The vertical AWT and de-gasser designs are generally controlled by viscosity, the only exception being the emulsion-broken cases where the gas side capacity controls. The horizontal separator cases with vessel diameters greater than 10 feet are also controlled by the liquid viscosity, the smaller horizontal vessels being controlled by gas side capacity at a Gas Carry Under target of 0.02.

- **Mesh pads or similar devices in the vertical AWT and de-gasser separators were found to be not feasible** because the gas velocities are too low, below 30% of flooding velocity. They are feasible for horizontal vessels of 10 feet diameter and below and have the potential to reduce liquid carryover to 0.1 gal per MMSCF, with vessels without mesh pads anticipated to produce100 gal per MMSCF.

- **The results favored horizontal vessels**, but it is acknowledged that vertical vessels are easier to clean (given the high Duri sand contents) and this finding therefore ties back to sand control measures.

- **Perforated baffles located in horizontal vessels act to reduce vessel size** by coalescing gas bubbles, but again their application links to sand control.

- **Emulsion breaking to create a low viscosity dispersion depends on matching to the proper chemical additive**, if feasible at all, to break the emulsion in the flow lines or a holding vessel.

- **Reducing viscosity by adding more water to the well stream emulsion introduces feasibility questions with regard to water availability and the cost of supply and mixing**.

- **Increasing the sophistication of the inlet diverter appears to offer marginal advantage** in the relatively low GOR environment.

- **Increasing the assumed bubble size distribution from approximately the 20–1000 to the 40–2000 range has a marked influence on vessel size**. Bubble size models as a function of inlet shear force remain to be developed and are expected to provide important design data.

Further uncertainty includes the degree of gas separation and coalescence of gas bubbles in the approach flow lines and in the separator liquid zone.

- **The diameter-versus-GVF plot (figure 12)indicates that separator diameter begins to increase much more rapidly at 0.025 GVF and lower.** Separator cost approximately doubles in going from 0.1 to 0.02 GVF and increases a further 75% going from 0.02 to 0.005 GVF.
- **Clearly a requirement for low GVF performance in viscous flow will drive costs up very strongly.**

b) GLCC Compact Separator Case

A new mechanistic model has been developed (Gomez et. al., 1999a) to predict the aspect ratio (height/diameter) of GLCC© based on its complex multiphase hydrodynamic behavior. This model incorporates an analytical solution for the gas-liquid vortex interface shape, and a unified particle trajectory model for bubbles and droplets, model for inlet flow pattern prediction, operational envelope for liquid carry-over based on analytical approach and semi-empirical model for prediction of gas carry-under into the liquid stream. A simplified GLCC© design methodology, based on this mechanistic model, is developed and specific design criteria are formulated as user guidelines for GLCC© design. A state-of-the-art simulator, based on the above mechanistic model, has been developed in a Visual-Basic platform (Gomez et. al., 1999b). There are two components present in the simulator, namely, design wizard code and performance code. The design wizard is used for performing the preliminary design of the GLCC©, and the performance code enables detailed prediction of the complex hydrodynamic flow behavior in the GLCC©. This user-friendly simulator incorporates the best available technology for the design of GLCC© separators for the industry.

Applications of the GLCC© Simulator are:

- Sizing of GLCC© compact separators based on aspect ratio formulation.
- Detailed performance evaluation of GLCC© separators in terms of operational envelope and equilibrium liquid level.
- Utilization as part of compact separation system analysis for prediction of liquid carry-over and gas carry-under.

The simulator has been used to design over 100 GLCC© units operating in the USA and around the world. Design and performance of GLCC© separators have been conducted for different configurations. Typical applications of GLCC© compact separators are well testing metering system, control of GVF for multiphase meters, pumps and de-sanders, gas scrubbing for flare gas and wet gas metering, external pre-separation upstream of existing conventional separators and for primary surface or subsea separation. The field applications successfully demonstrate that the GLCC© could be configured in a multiphase metering loop utilizing off-the-shelf single-phase flow meters on the gas and the liquid legs where a full separation is required.

One of the critical developments of the GLCC© simulator associated with the current investigation is the development of a correlation for prediction of gas carry-under in the liquid leg (as a function of void fraction) based on detailed experimental data acquired at the Humble flow loop of Texaco. The void fraction in the liquid leg, GVFα is determined as function of the in situ Gas Volume Fraction at GLCC© inlet (*GVFi*), Reynolds Number in the liquid leg (*Rel*) and dimensionless equilibrium level (*Led*) and is given by:

$$GVF\alpha = 46.1\ GVFi^{0.307} * (Rel/1000)^{0.095} * Led^{-3.51} \qquad (4)$$

One implication of equation 4, is that, within limits, GVFα can be set by control of the vortex level in the GLCC©. Control of vortex level thus becomes an important factor in Hydrocarbon accuracy through control of gas to the downstream meters.

Use of GOSPSIM and GLCC© Simulators provide opportunities to compare compact and conventional separation systems. A GLCC© operating at 5% gas carry-under is 99% less in volume than a conventional separator sized for zero GCU. Assuming downstream metering is relatively insensitive to 5% gas, the GLCC© application would significantly reduce costs. Results of the comparison are given in Figure 14.

c) Control of Compact Separation

Control of compact separation greatly extends the performance envelope , allows control of gas carry under and liquid carry over, and implicitly determines the metering system overall limits on hydrocarbon accuracy. .Dynamic simulators have been developed based on Matlab/Simulink® software for evaluation of several different GLCC© integrated control philosophies for the AWT and bulk separation applications. A complete mathematical model has been developed for the links between the liquid control loop and gas control loop (Wang et al., 2000a, b). This model enables a realistic integrated control system simulation.

Based on the operating conditions, several control strategies could be adopted, namely:

- Liquid level control by liquid control valve (LCV).
- Pressure control by gas control valve (GCV).
- Liquid level control by gas control valve (GCV).
- Integrated liquid level control by LCV and GCV.
- Integrated liquid level control by LCV and pressure control by GCV.

Detailed analysis of the GLCC© control system simulators is performed to understand the effectiveness and dynamics of GLCC© liquid level and pressure control. The results indicated that integrated liquid level control is more desirable for severe slugging conditions. The GLCC© control system developed for DURI Area-10 application is very similar to the loop used for the Minas field in Indonesia and is described in Wang et al. (2000a). Figure 26 shows the photograph of a 5-ft GLCC© in the Minas field and the associated Infrared photo of the same system provides insight into the liquid-gas partitioning within the GLCC© during operation.

Preceding analyses indicate that the GLCC© combined with venturi rate metering and Texaco starcut watercut measurement will provide minimum hydrocarbon uncertainty at minimum cost and minimum size under the DURI Area-10 design basis conditions. The image shown in figure 27 is from starcut control screen which integrates the inputs from GLCC© level, venturis and watercut for total system management.

G. Decision Process - Sensitivity of Meter Combination Performance to Well Selection and Well Properties

The overall performance of the system is completely dependent on the selection of wells, i.e., oil, water, and gas rates input into the models. For example, if the customer has predominantly low watercut production (25% watercut), overall system performance as seen in figures 15, 16, 17, 18 at low watercut will be 10 to 100 times better than seen by a customer with predominantly high watercut (80%). For that reason sensitivity of a system is reviewed as a function of watercut and gas carry under performance of the separator used. A desirable system choice is one in which performance changes very little even though watercut and gas composition vary considerably.

Figures 19, 20, 21, 22 present all 60 metering combinations (rate meter and watercut meter) reviewed. The vertical axis is the code name that identifies the meter combination. The horizontal axis is the hydrocarbon accuracy predicted for that meter combination. The meters have been sorted with the best performing meters closest to the origin.

Four cases are reviewed,

- Low watercut medium gas (figure 19)
- High watercut medium gas (figure 20)
- Low watercut low gas (figure 21)
- High watercut low gas (figure 22)

Certain meter combinations always show less than 10% hydrocarbon errors. Some meter combinations show very low hydrocarbon error at 25% watercut low gas but show 1000% or more error at 80% watercut at medium gas.

H. Decision Process – Selection Parameters and Use of Credibility Index to Drive Testing Decisions

Figure 23 summarizes the compilation of selection parameters for each separator/rate meter/watercut meter combination. The graph is illustrative only. We find that cost, accuracy, size of meter combination A is superior. However the credibility index carried forward reflects that there is no supporting data on the GLCC© performance in heavy viscous crudes. Meter combination B costs more, is less accurate and is bigger but the credibility of the supporting data is high. Subtracting the difference in cost between the two options A and B, we find that the cost difference of about $250,000 more than justified testing of GLCC© using heavy crude oils at the Humble Flow Facility.

Testing results provided gas carry under data allowing the incorporation of gas-carry-under correlations into the GLCC© model for high viscosity fluids. Use of those correlations confirmed the model predictions (figure 24) assuming that the level in the GLCC© was controlled properly. Figure 25 shows the schematic of GLCC© liquid level control system using liquid control valve (LCV). The outputs of the simulator for liquid level, liquid flow-rate in and liquid flow-rate out are also shown in Figure 25.

Level control of GLCC© vessels is indicated by our work to be the key aspect underlying hydrocarbon accuracy. As a result considerable effort has been expended to design, test and field qualify control systems for short residence time vessels (references 4,5). In particular meter accuracy during slugging inlet flow has been a special focus topic.

IV. Results & Conclusions

We have illustrated a process, which allows answers to the questions:

- " How will this meter or combination of meters perform in my situation"?
- " Should we use this new technology or the tried and true solutions"?
- " Are testing costs worth the expense"?
- " What is the value to the whole system of upgrading the performance of one component"?
- " What is the impact on the whole system performance if maintenance or calibration is not routinely performed"?
- "What happens to performance as the field ages"?

Our process allows diverse and dynamically changing component performance data to be tested against customer expected production conditions. We use 3rd party test data for all components where possible and models based on the physical basis of the instrumentation or vessels where data are not available or credible. New test results for a given component or brand of a component can be easily incorporated into the secure process database of component properties using password protected access.

The process is deterministic , based on traceable 3rd party test results and does not rely on statistics. The results are startling and decisive.

1. **Designing for Imperfect Separator Performance:** High viscosity fluids result in high cost of conventional separation vessels if designing for zero gas discharge through retention time is required. In our application, by reducing the requirements on gas discharge, very large savings of $3.2 million are realized. It is doubtful that zero gas discharge could be achieved in any case with our viscosity. Incremental costs are incurred because of the requirement for improved gas-insensitive downstream instrumentation. However, those incremental instrument costs are far less than the savings realized from vessel size reduction.
2. **Sensitivity:** Certain combinations of commonly used systems of conventional separators, rate meters and watercut meters are extremely sensitive to production conditions. Qualifying tests done at one set of conditions may not have any relationship to performance at other conditions.
3. **Gross Errors at High WaterCut, Low Gas:** Certain combinations of commonly used systems of conventional separators, rate meters and watercut meters would be expected to produce enormous errors in hydrocarbon rate determination at high watercut and when low percentages of free gas are present.
4. **Integrated Design:** Design of Partial Separation systems can be optimized for cost, accuracy, and sensitivity only if all components are designed together in an integrated fashion.
5. **Level Control:** Level control of the GLCC© has been determined to bean important factor impacting hydrocarbon accuracy for partial separation multiphase meters.
6. **Gas insensitive watercut measurement** such as claimed by STARCUT is extremely important for good hydrocarbon rate accuracy in high watercut production systems.

Finally, the question:
" If the system I have installed is so bad, Why Does it Work So Well"?
must be addressed.

In general our results are taken directly from lab data on individual components and do not include options for adjustments to current conditions by using local references, such as separators. It can be easily demonstrated that if the gross errors we report are not changing with time, then system operators can find settings which will cause the metering system to agree very well with reference for a short time.

Local" tuning" of systems is always performed and is a legitimate process for assessing oil well performance for purposes of maintenance - as long as periodic reference checks are made. The commonly used term "Trending Meter" is used to imply that the meter system is not assumed to be accurate, just relatively stable for a while.

The long-term problem with "Trending Meters" is that they can be very sensitive to operating conditions. Changes in operating pressure of only a few PSI (as can be demonstrated in our models) can send hydrocarbon errors soaring from 1-2% to 50-100% just due to free gas expansion or compression. Calibration of "Trending Meter" under test conditions cannot be extrapolated to higher temperatures, pressures, watercuts, or flow rates.

Our results indicate that significant reduction in Capital Expenditure and long term reduction in Operating Expenditure will result from integrated metering facility design. Costs reductions are due to lower vessel costs and reduced operations problems due to misdiagnosed problem wells or overlooked problem wells.

V. References

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4 Gomez, L.E., Mohan, .S., Shoham, O., Marrelli, J. D., Kouba, G. E., October 1999b. State-of-the-art Simulators for Field Applications of Gas-liquid Cylindrical Cyclone Separators. SPE 56581, Proceedings of 1999 SPE Annual Technical Conference and Exhibition, Houston, Texas, 3–6 October 1999.

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6 Wang, S., Mohan, .S., Shoham, O., Marrelli, J. D., Kouba, G. E., February 2000b. Performance Improvement Of Gas Liquid Cylindrical Cyclone Separators Using Integrated Level And Pressure Control Systems. Proceedings of ETCE 2000: Energy Sources Technology Conference & Exhibition, New Orleans, Louisiana.

7 Yocum, B. T., Dunbar, D. N., Tallett, M. R., May 1999. Advanced Software Technology for Gas, Oil, Water Separation Design. MultiPhase Separator Technologies, Stavanger, Norway, IBC International Conference

VI. Acknowledgements

This work has been supported by CalTex Pacific, Duri, Indonesia (CPI), by Texaco Upstream Technology, Humble Flow Facility, Humble, Texas and by the Tulsa University Separation Technology Projects (TUSTP) JIP. We greatly appreciate the continuing support and encouragement from these organizations and the opportunity to deploy leading edge solutions to the complex problems faced in high watercut steam floods. We greatly appreciate the continued support of Digital Consulting Software Services (Shahzad Asif and Billie Dee Jelin) for the round-the-clock support and service resulting from the12 hour time difference between Houston and Duri.

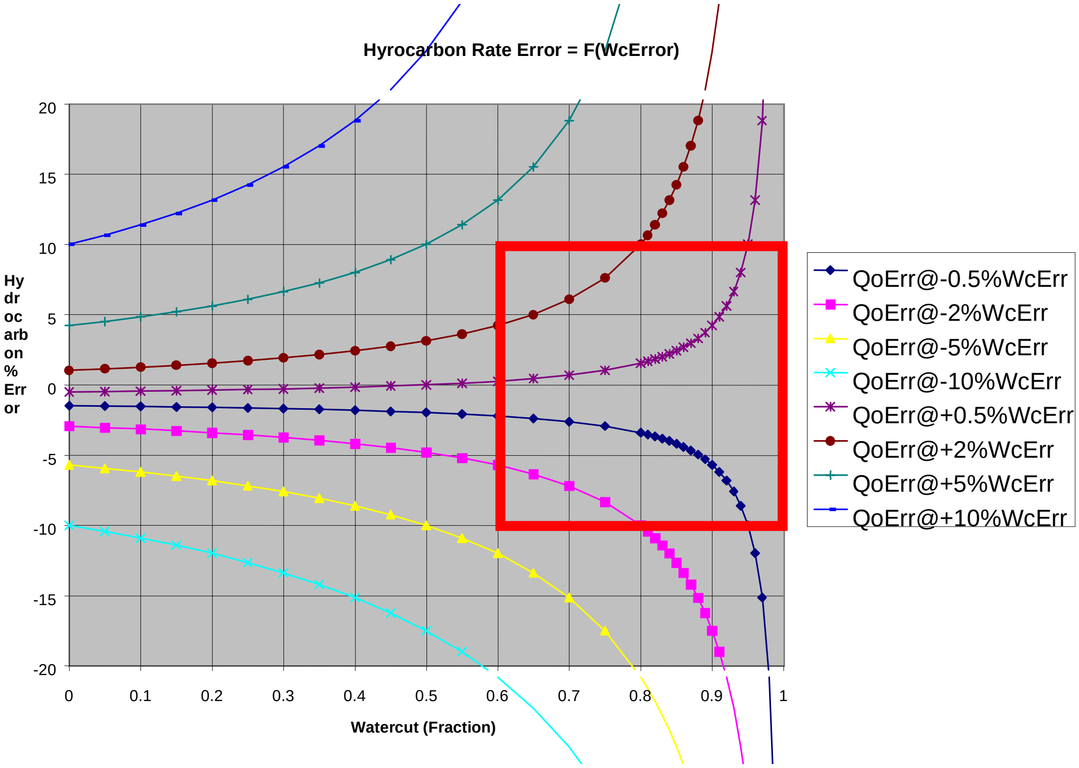


Figure 1: Effects of WaterCut Measurement Error on Hydrocarbon Rate Errors

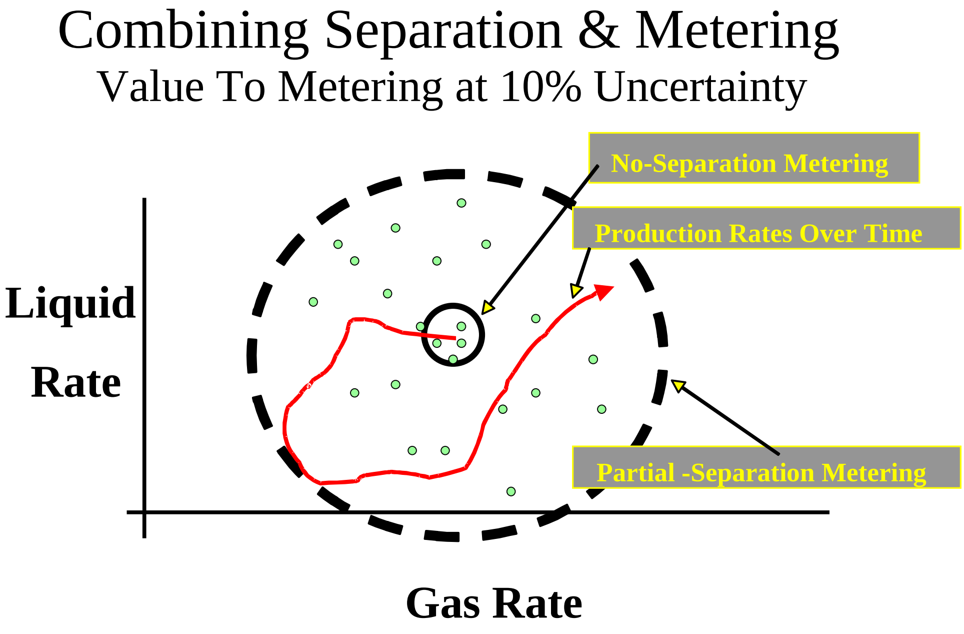
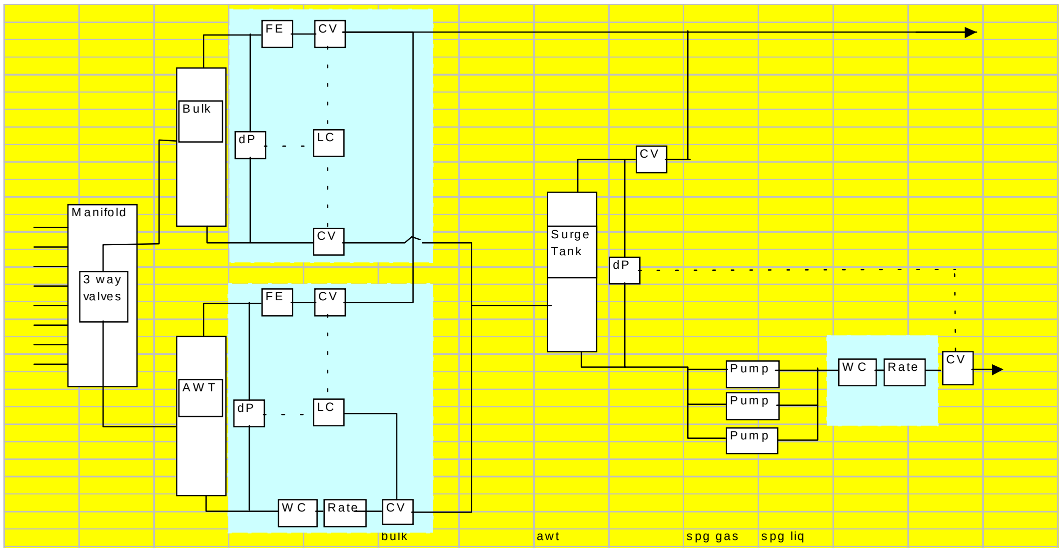

Combining Separation & Metering
Value To Metering at 10% Uncertainty

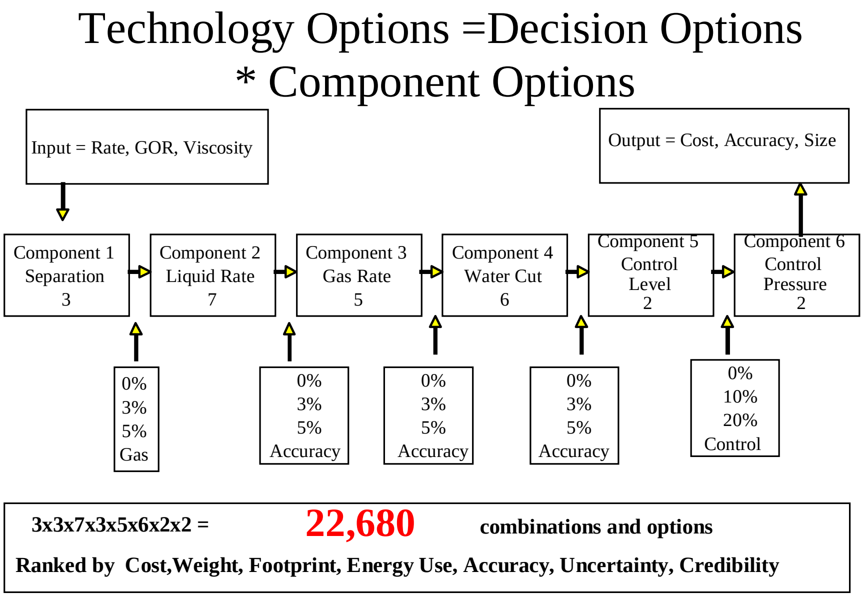
Figure 2 – Value of Partial Separation to MultiPhase Meter Dynamic Range



	AWT	Bulk
Diameter	8 "	36 "
Height	12 ft	33 ft
Inlet line	5 "	24 "
Gas Line	1.3 "	8 "
Liquid Line	2 "	8"

	bulk	awt	spg gas	spg liq
ql	53000	2000		
qg	8,000,000	330	0.78	

Figure 3: Partial Separation Well Test and Bulk Metering Facility - for evaluation



Technology Options =Decision Options * Component Options

Input = Rate, GOR, Viscosity

Output = Cost, Accuracy, Size

Component 1
Separation
3

Component 2
Liquid Rate
7

Component 3
Gas Rate
5

Component 4
Water Cut
6

Component 5
Control
Level
2

Component 6
Control
Pressure
2

0%
3%
5%
Gas

0%
3%
5%
Accuracy

0%
3%
5%
Accuracy

0%
3%
5%
Accuracy

0%
10%
20%
Control

3x3x7x3x5x6x2x2 = 22,680 combinations and options

Ranked by Cost,Weight, Footprint, Energy Use, Accuracy, Uncertainty, Credibility

Figure 4: Block Diagram Representation of the Component Options Considered

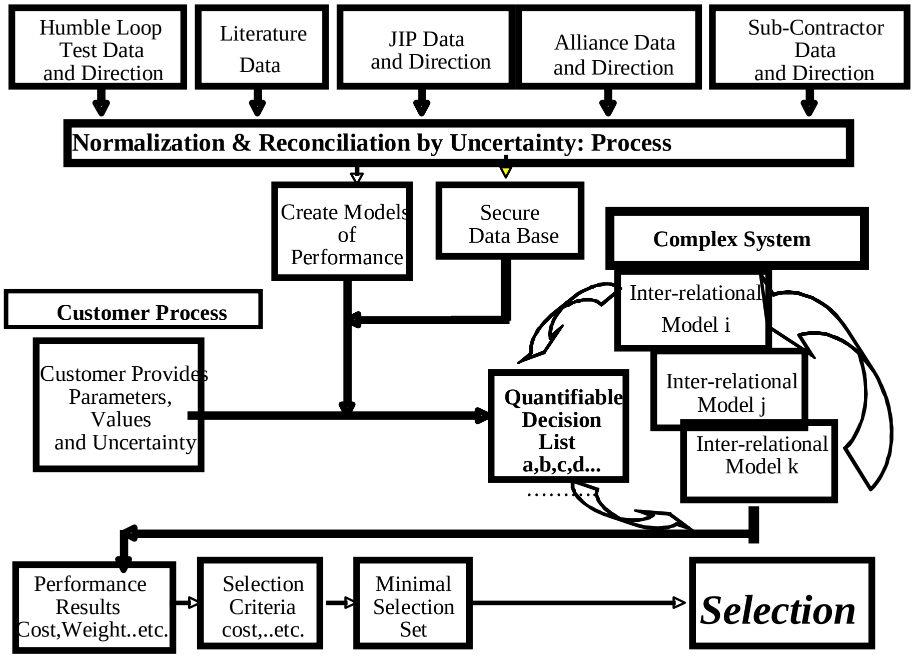
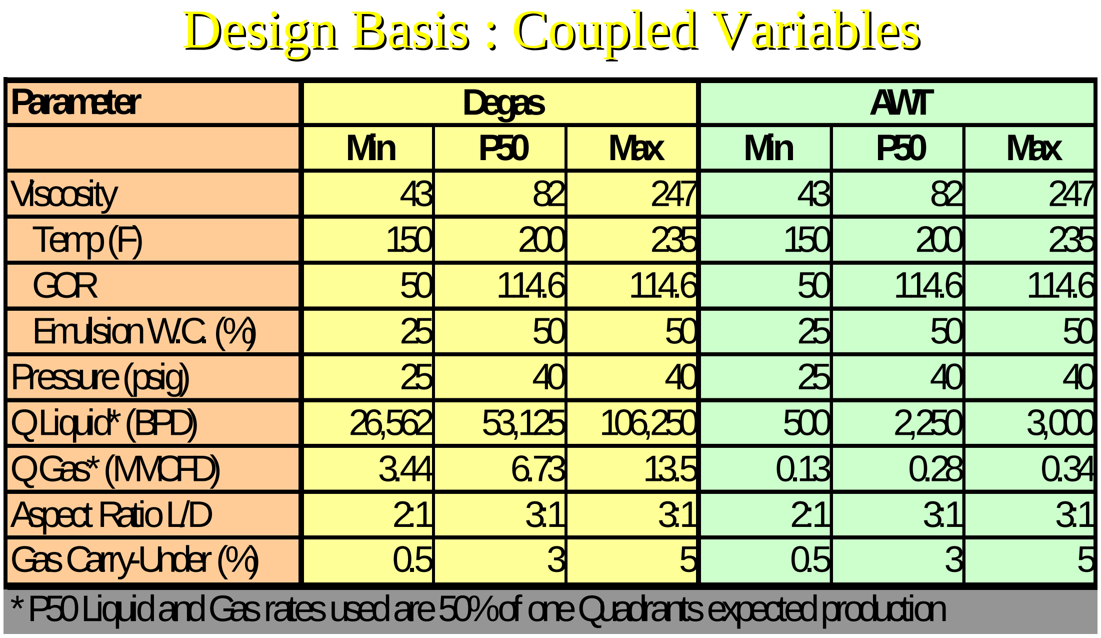


Figure 5: Decision Process Flow Diagram for Meter/Separator Combination Selection

			Average Viscosity of:			Viscosity (cP)		
Temp	GOR	Wcut	Vmin	Vmax	**Vave**	Vmin	Vmax	Vave
150	114.61	0.25				67	167	108
150	114.61	0.50				185	455	314
150	50	0.25				119	167	143
150	50	0.50	174	335	**247**	327	550	424
200	114.6	0.25				29	42	35
200	114.6	0.50				79	134	104
200	50	0.25				42	56	47
200	50	0.50	66	112	**82**	113	217	143
220	114.61	0.25				22	26	24
220	114.61	0.50				60	101	71
220	50	0.25				24	41	32
220	50	0.50	43	82	**56**	65	160	98
228	114.6	0.25				19	24	20
228	114.6	0.50				52	91	61
228	50	0.25				19	37	28
228	50	0.50	36	73	**49**	52	142	85
235	114.61	0.25				16	22	18
235	114.61	0.50				43	83	54
235	50	0.25				16	33	25
235	50	0.50	29	67	**43**	43	129	76

Figure 6- Development of Design Basis. Four Emulsion Viscosity Models are Used to Estimate Fluid Viscosity

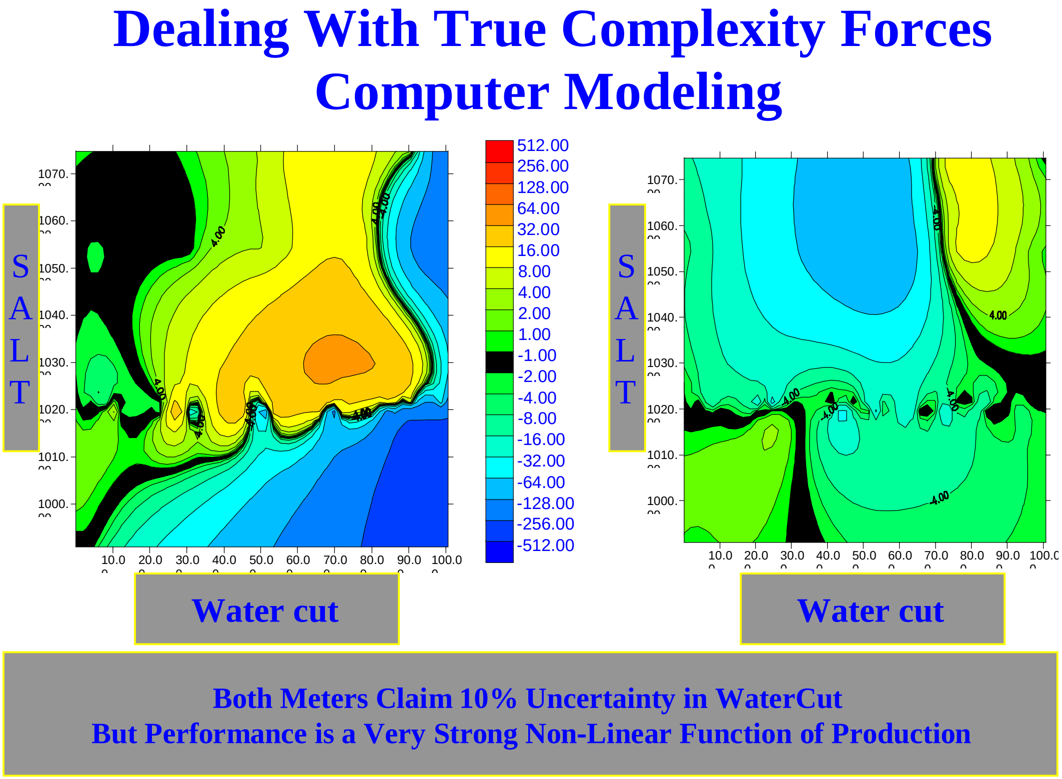


Design Basis : Coupled Variables

Parameter	Degas			AWT		
	Min	P50	Max	Min	P50	Max
Viscosity	43	82	247	43	82	247
Temp (F)	150	200	235	150	200	235
GOR	50	114.6	114.6	50	114.6	114.6
Emulsion W.C. (%)	25	50	50	25	50	50
Pressure (psig)	25	40	40	25	40	40
Q Liquid* (BPD)	26,562	53,125	106,250	500	2,250	3,000
Q Gas* (MMCFD)	3.44	6.73	13.5	0.13	0.28	0.34
Aspect Ratio L/D	2:1	3:1	3:1	2:1	3:1	3:1
Gas Carry-Under (%)	0.5	3	5	0.5	3	5

* P50 Liquid and Gas rates used are 50% of one Quadrants expected production

Figure 7- Design Basis of Well Test and Bulk Metering Systems



Dealing With True Complexity Forces Computer Modeling

Both Meters Claim 10% Uncertainty in WaterCut
But Performance is a Very Strong Non-Linear Function of Production

Figure 8: Example of Surface Plot of Error in WaterCut as a Function of Salinity of the Water Phase and WaterCut

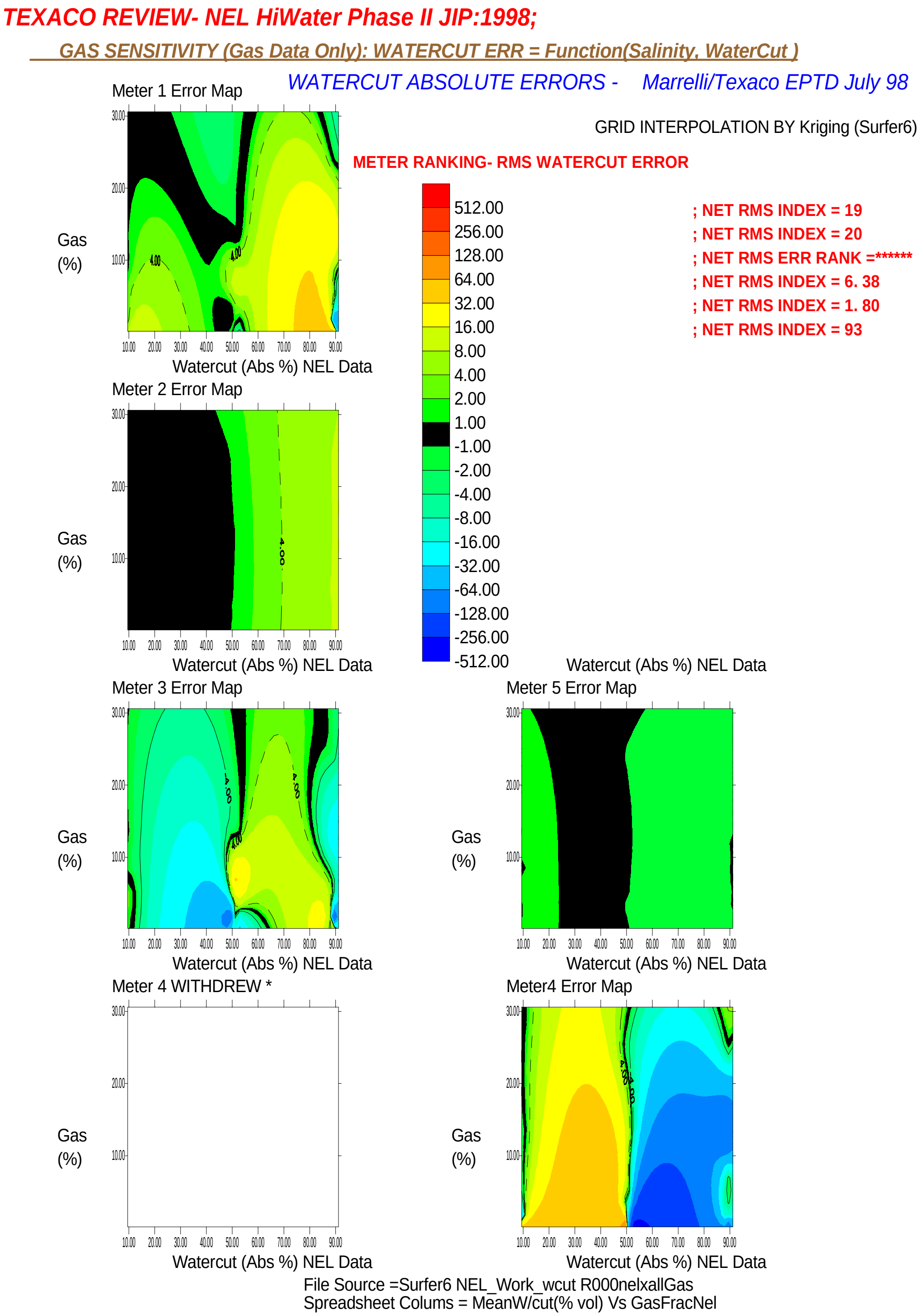


Figure 9: WaterCut meter Performance as a Function of Free Gas % by Volume. Enter the plot using true watercut and gas fraction to find the predicted error in watercut for that device.

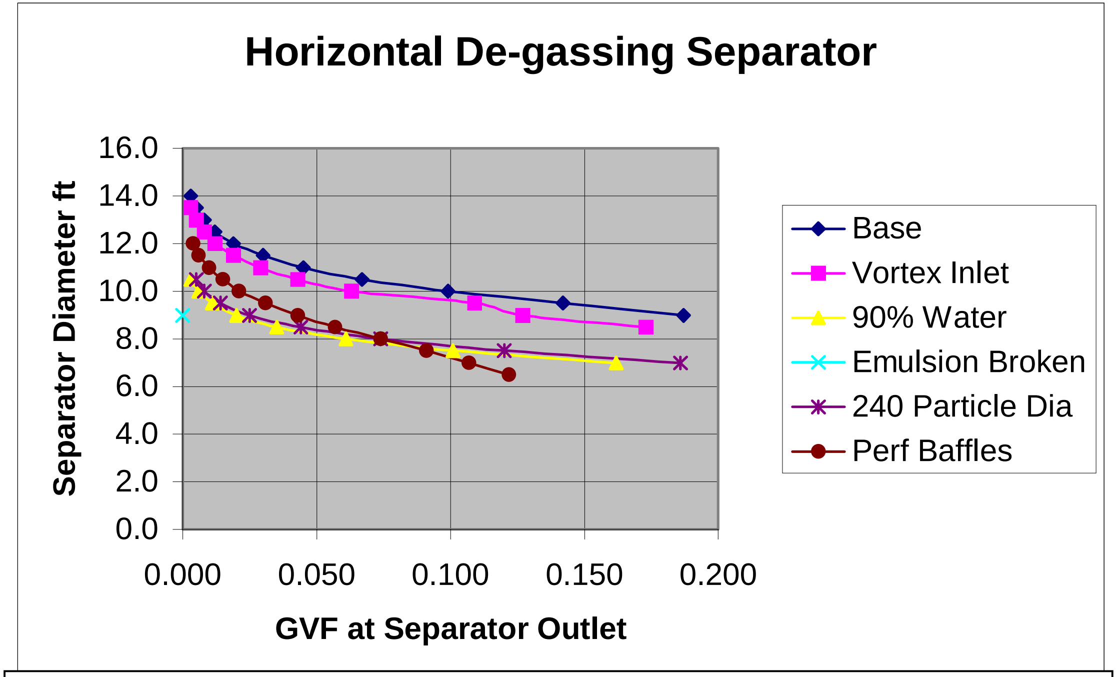


Figure 10: Ensys-Yokum GOSPSIM Software Predicts Gas-Carry-Under As A Function of Conventional Separator Inlet Conditions and Internal Components. This Performance Model is used to Design Conventional Separator Performance Equivalent to the Compact Cyclone.

Conventional Separator Cost Sensitivity to Viscosity Ratio to Base Case: 70cp at 212 f

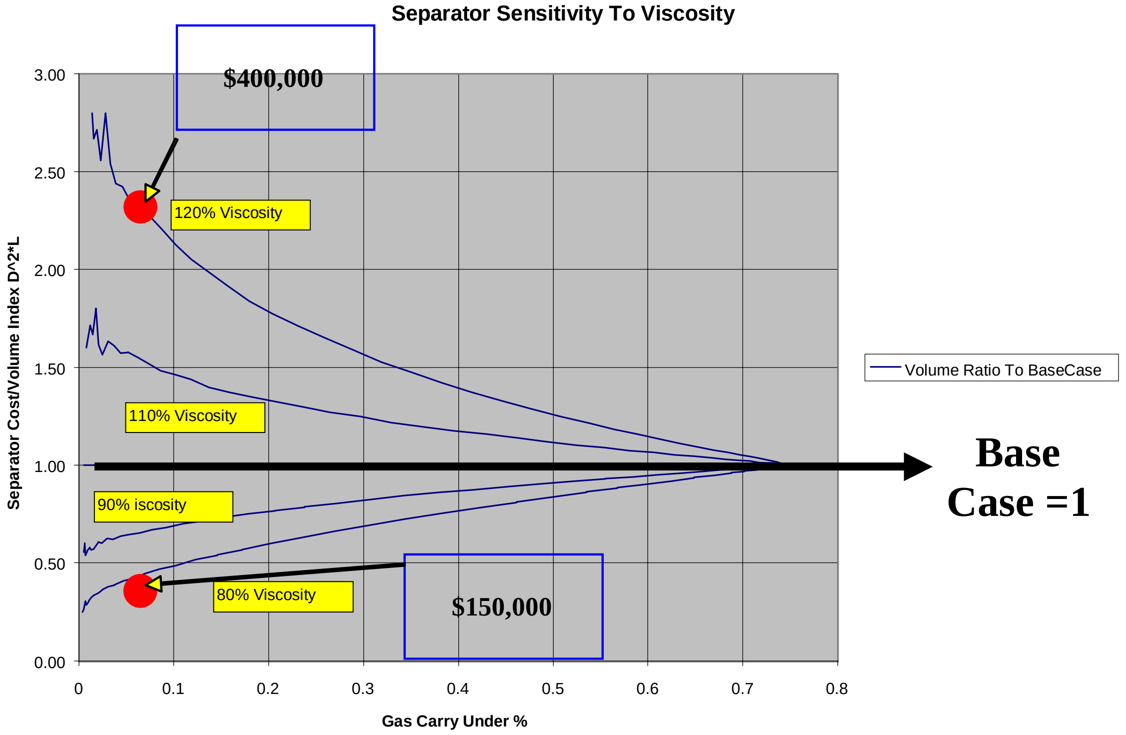


Figure 11: Use Of GOSPSIM Allows Assessment Of the Cost Of Viscosity Uncertainty. Relative to Base Case , Uncertainty in Viscosity of +- 20% leads To A Large Range Of Possible Vessel Costs. Solutions are to Design to Maximum Uncertainty or To Change to Compact Separation Systems Such As GLCC Which are Relatively Insensitive to Viscosity.

Large Size Reduction Occurs If Some Gas Is Allowed To Be Carried Into Liquid Leg

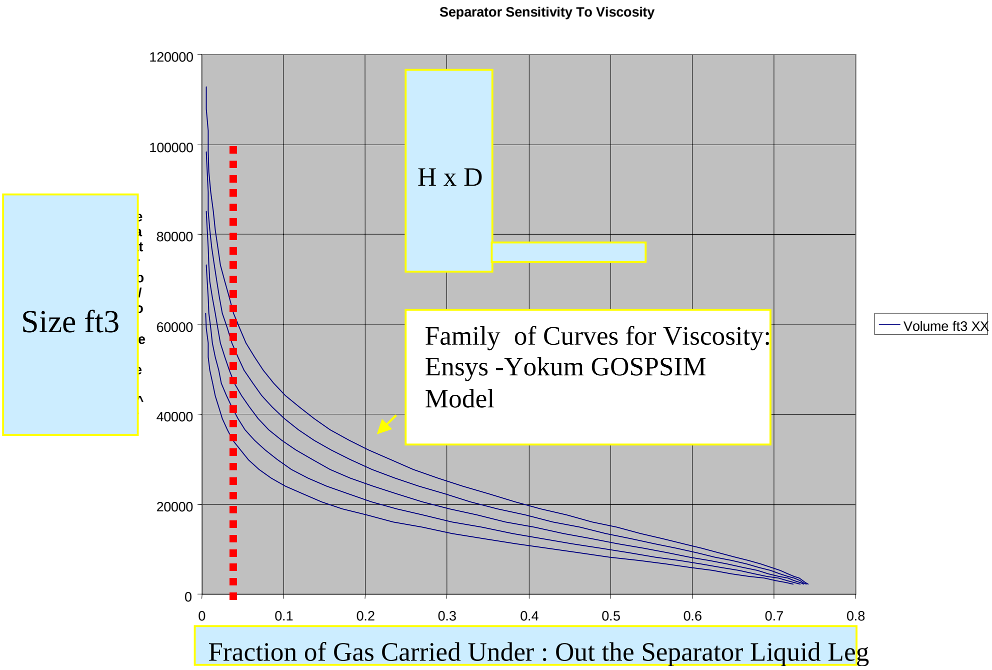


Figure 12: Gas-Carry-Under is a Function of Vessel Size. Allowance of 3% to 5% Gas-Carry-Under in Convention Separator Sizing Causes a Large Reduction in Size. Sizing for More Gas-Carry-Under Does not Provide Significant Incremental Savings In Cost And Places Excessive Requirements on The DownStream Meters.

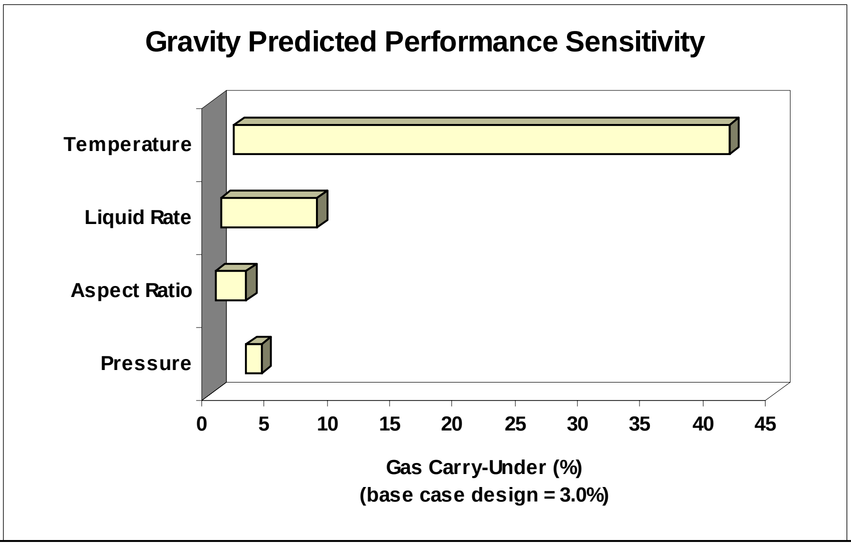
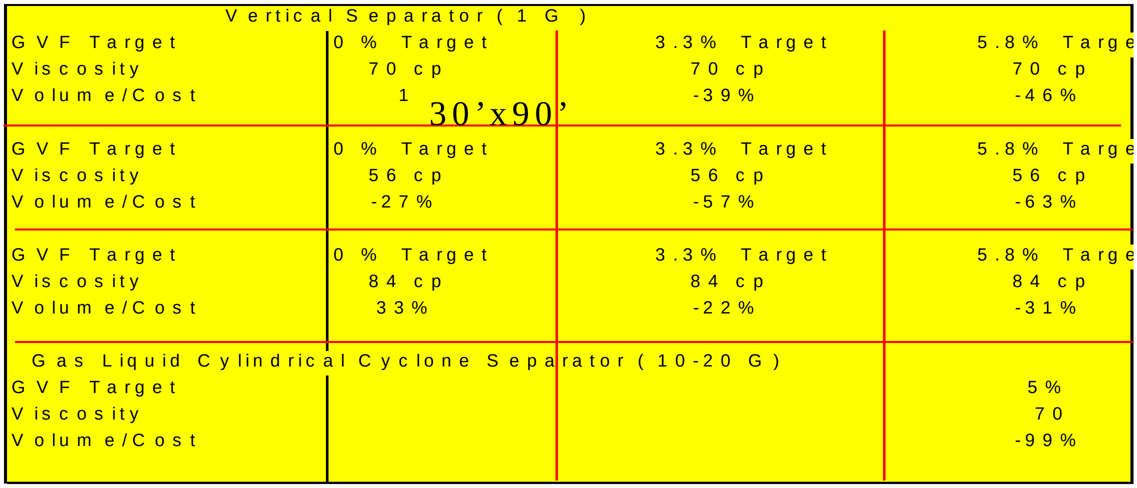


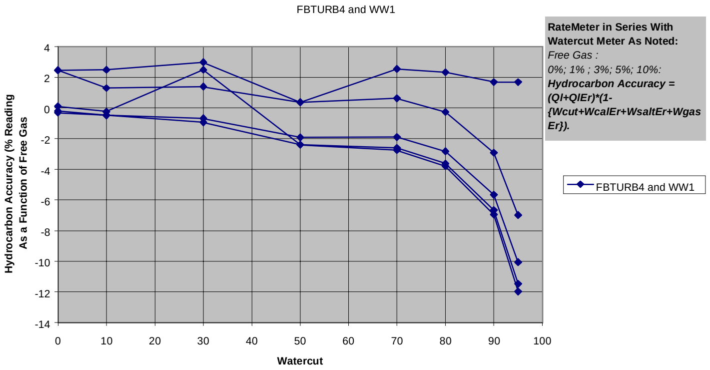
Figure 13: GOSPSIM Modeling Has Identified Temperature As the Parameter Most Important in Gas Carry Under For Conventional Separators. Viscosity, Pressure and Free Gas are Closely Coupled to Temperature For a Given Production System.



Vertical Separator (1 G)			
GVF Target	0 % Target	3.3% Target	5.8% Targe
Viscosity	70 cp	70 cp	70 cp
Volume/Cost	1 30’x90’	-39%	-46%
GVF Target	0 % Target	3.3% Target	5.8% Targe
Viscosity	56 cp	56 cp	56 cp
Volume/Cost	-27%	-57%	-63%
GVF Target	0 % Target	3.3% Target	5.8% Targe
Viscosity	84 cp	84 cp	84 cp
Volume/Cost	33%	-22%	-31%
Gas Liquid Cylindrical Cyclone Separator (10-20 G)			
GVF Target			5%
Viscosity			70
Volume/Cost			-99%

Figure 14: Use of GOSPSIM and GLCC Models Provide Opportunities To Compare Compact and Conventional Separation Systems. A GLCC Operating at 5% Gas-Carry-Under is 99% Less in Volume Than a Conventional Separator Sized for Zero GCU. Assuming downstream Metering is Relatively Insensitive to 5% Gas, Then GLCC Application Would Significantly Reduce Costs.

Hydrocarbon Accuracy = (Qliquid+ QlEr)*(1 - { Wcut + WcalEr+WsaltEr+WgasEr})



Hydrocarbon Accuracy = (Qliquid+ QlEr)*(1 - { Wcut + WcalEr+WsaltEr+WgasEr})

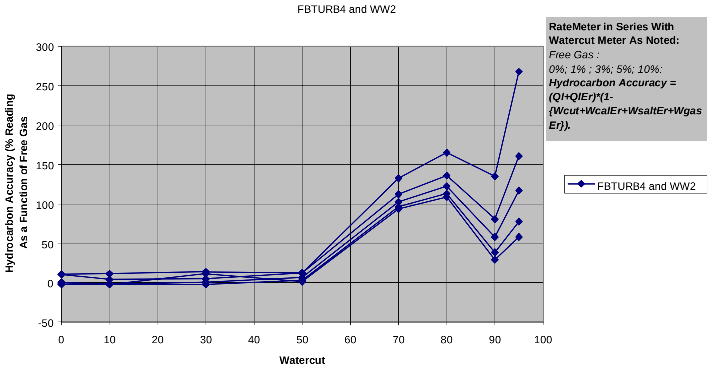
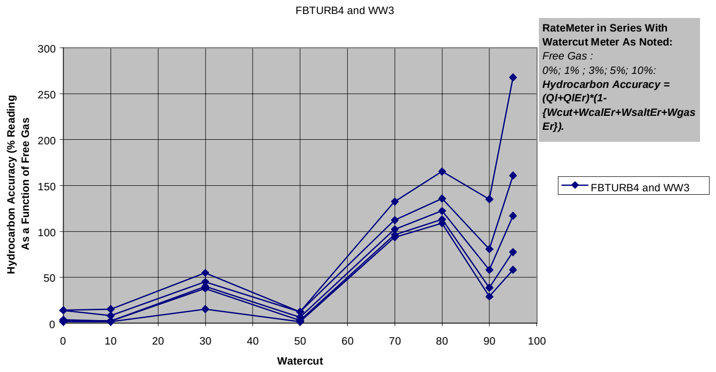


Figure 15, 16: At Low (25%) And High (80-90%) WaterCut, Assuming 0 to 10% Gas-Carry-Under Identical Design Basis Flow Conditions, 35 Combinations of Liquid Rate Meters and WaterCut Meter Types Were Evaluated For Net Hydrocarbon Error. PD, Venturi, coriollis, Vortex, Turbine Rate Meters were Mathematically Combined With Various Capacitance, Low Frequency and High Frequency Microwave, Densitometric and Inductance Based WaterCut Meters. Hydrocarbon Errors Ranged From 2% to 250%.

Hydrocarbon Accuracy = (Qliquid+ QlEr)*(1 - { Wcut + WcalEr+WsaltEr+WgasEr})



Hydrocarbon Accuracy = (Qliquid+ QlEr)*(1 - { Wcut + WcalEr+WsaltEr+WgasEr})

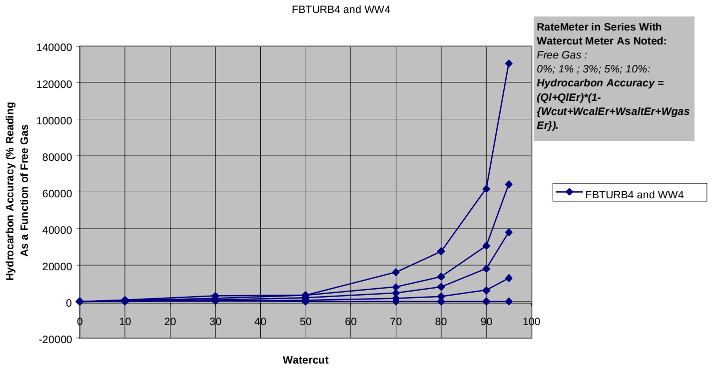
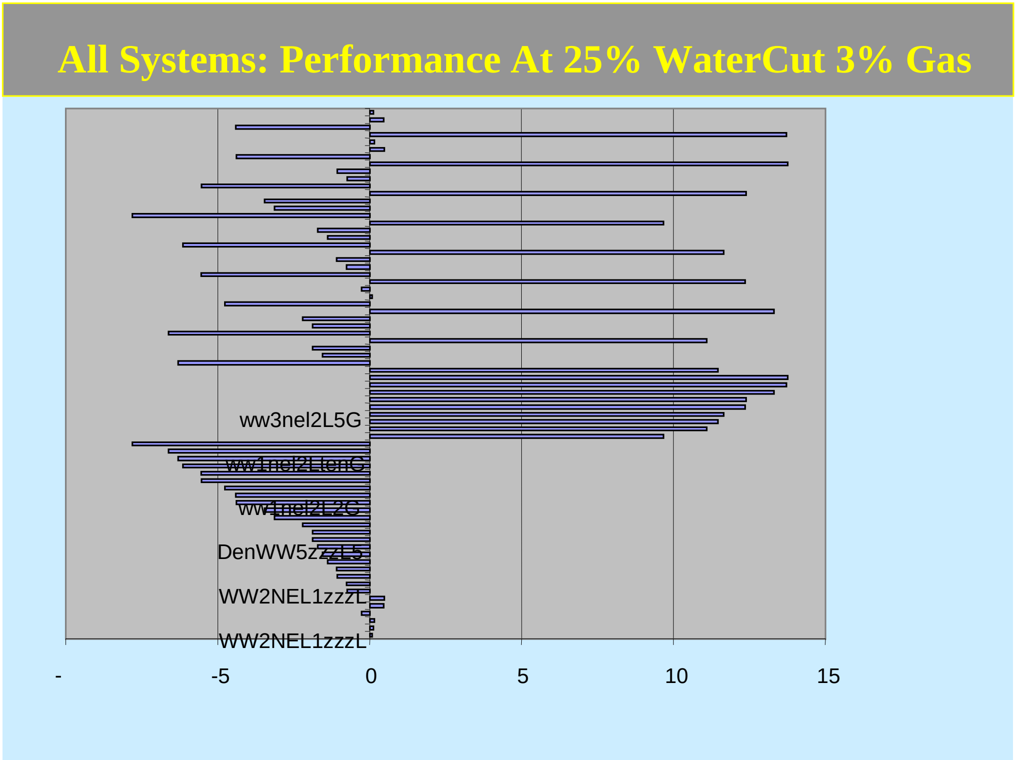


Figure 17, 18: At Low (25%) And High (80-90%) WaterCut, Assuming 0 to 10% Gas-Carry-Under Identical Design Basis Flow Conditions, 35 Combinations of Liquid Rate Meters and WaterCut Meter Types Were Evaluated For Net Hydrocarbon Error. PD, Venturi, coriollis, Vortex, Turbine Rate Meters were Mathematically Combined With Various Capacitance, Low Frequency and High Frequency Microwave, Densitometric and Inductance Based WaterCut Meters. Hydrocarbon Errors Ranged From 2% to 1250%.



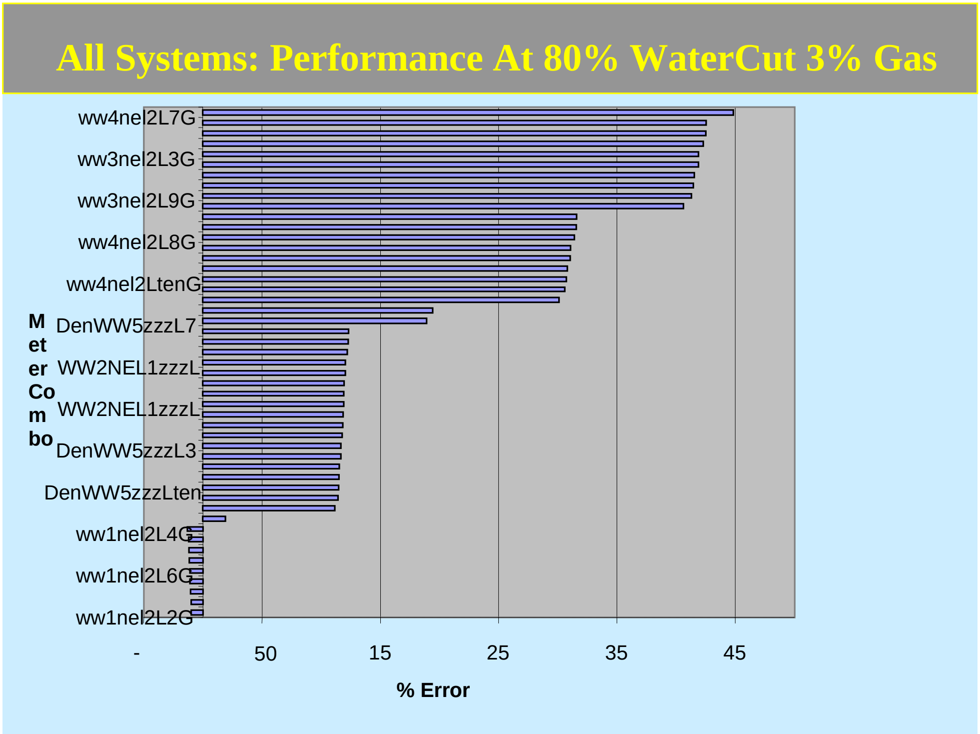
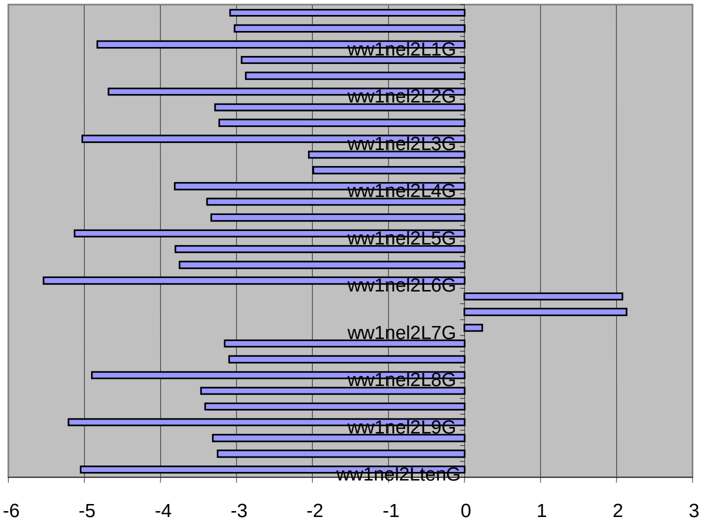


Figure 19,20: Summary of All Meter Combinations Indicates Most Combinations Were Highly Sensitive to WaterCut and Free Gas carried Into the Meter Combinations. All systems Did Well at Low WaterCut and Low % Free Gas. Only 8 Combinations Met the <10% Hydrocarbon Error Requirement When WaterCut Was Above 80% and Free % Gas Was > 3%.

All Systems: Performance at 25% Watercut 0.5% Gas



All Systems: Performance at 90% Watercut 0.5% Gas

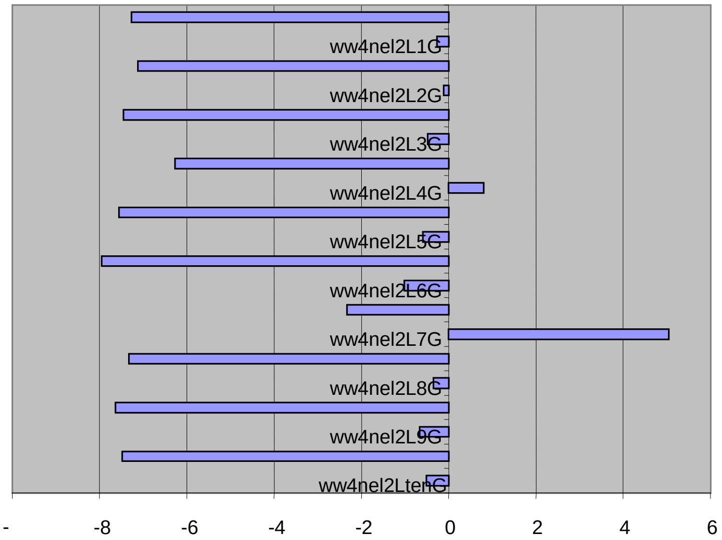


Figure 21,22: Summary of All Meter Combinations Indicates Most Combinations Were Highly Sensitive to WaterCut and Free Gas carried Into the Meter Combinations. All systems Did Well at Low WaterCut and Low % Free Gas. Only 8 Combinations Met the <10% Hydrocarbon Error Requirement.

New Technology Selection Process – Use of the Credibility Index to Drive Testing Needs

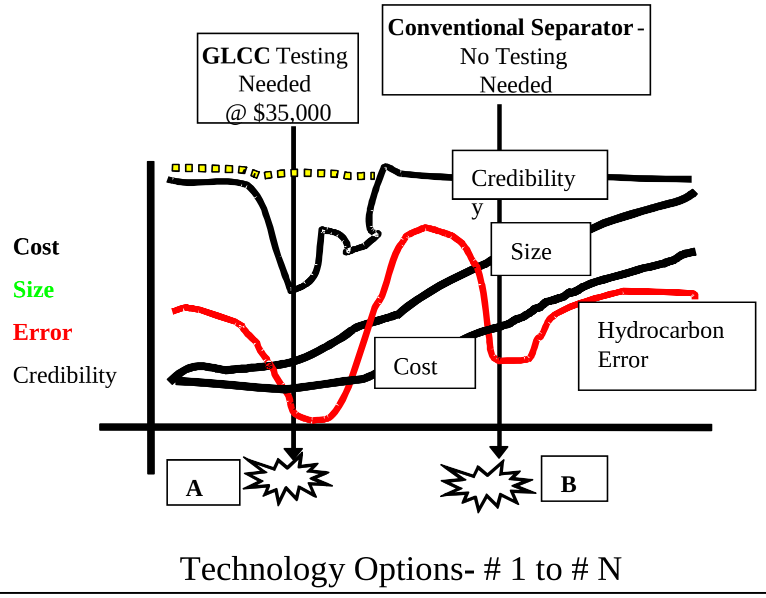


Figure 23: Performance Results of Analysis of Separator / Rate Meter /WaterCut Meter Combination for the High WaterCut Case. Two Cases, A and B, Stand Out. Case A is optimum But Indicates Low Credibility of GLCC Supporting Data, Thus Justifying The Cost of Flow Testing of GLCC Component To Confirm Gas Carry-Under Result.

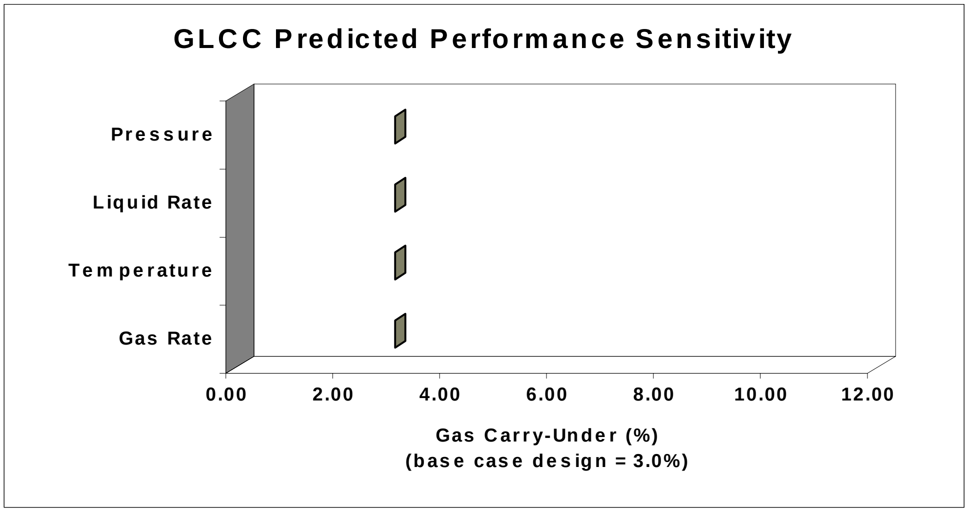


Figure 24: Model Predictions were Supplemented By Empirical Testing At The Texaco Humble Flow Facility Using Viscous Captain Field Crude Oil. Liquid-Carry-Over and Gas-Carry-Under Were Determined as A Function of Viscosity, Flow Rates, GVF and WaterCut. Performance of GLCC Using Control Valves Indicated That If Vessel Level is Controlled Properly Then Gas-Carry-Under is Largely Independent of Fluid Properties Over the Operational Range.

Short Residence Time Separators: Control Valve Simulation with PID Controller

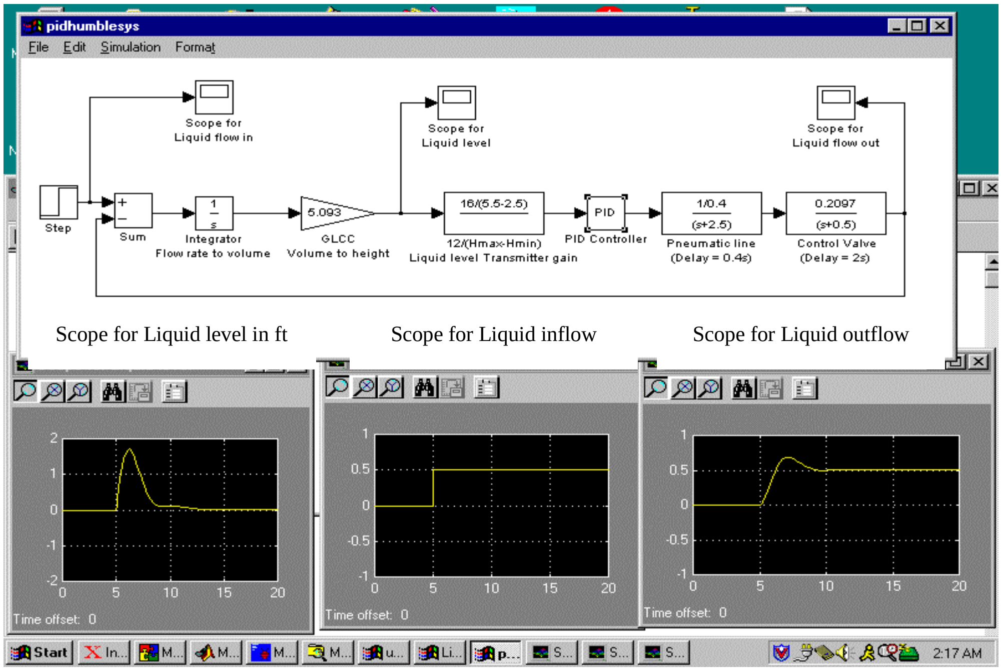


Figure25: Control Systems For Short Residence Time GLCC Separators Have Been Implemented To Improve GLCC Performance. Simulation As Above Demonstrates That Control Is Possible. Field , Univ. Of Tulsa TUSTP Lab and Humble Flow Lab Testing Verify That Good Level Control Greatly Improves GLCC Performance (Reference 4).

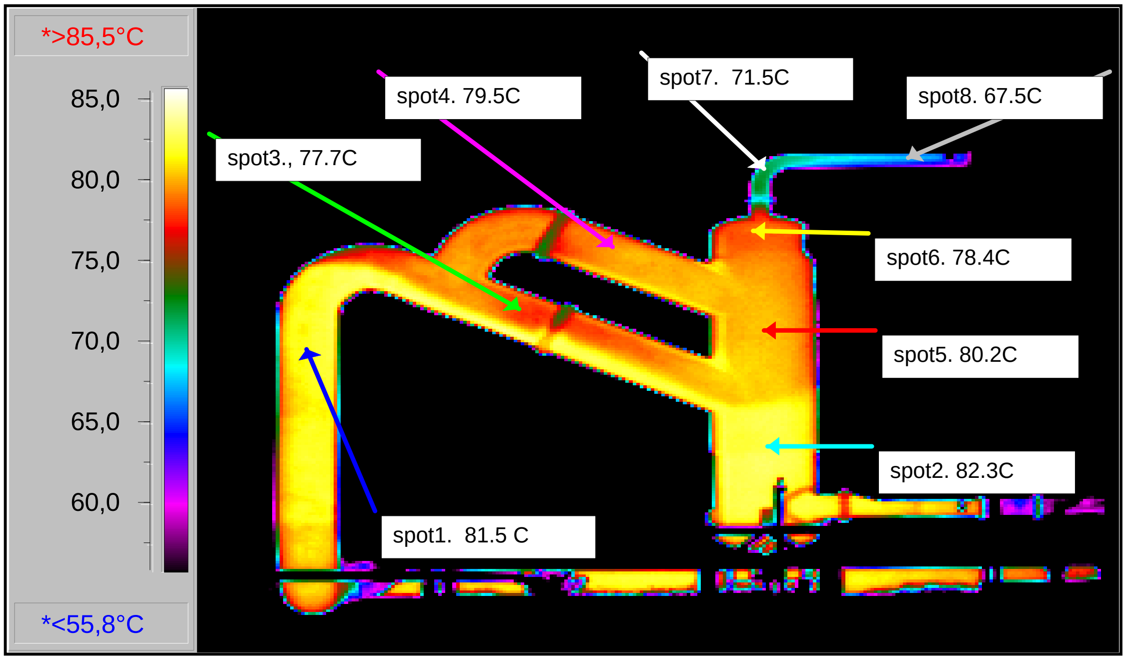
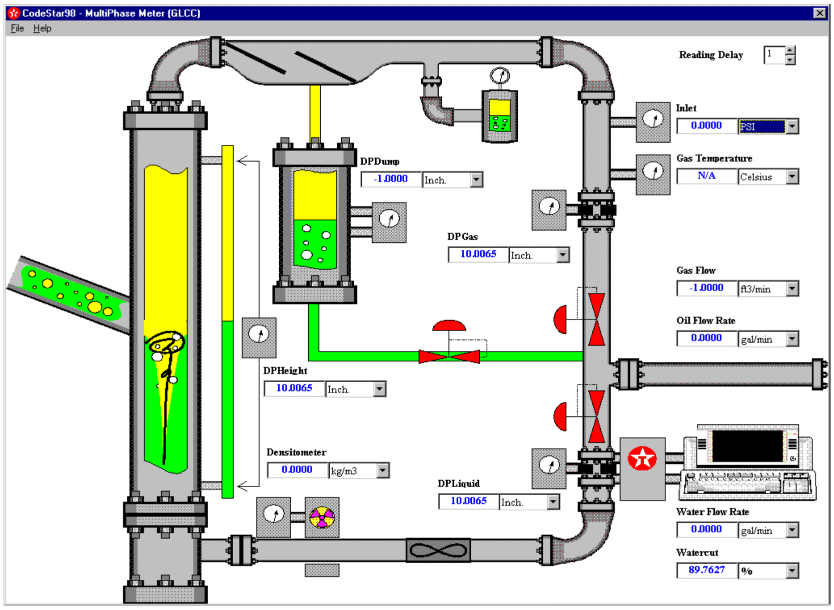


Figure 26: Kevin Solomon Of CPI Duri Indonesia, Provides a Perspective on the 180,000 BLPD, 80,000,000 scfd 5 foot Diameter GLCC in Minas, Indonesia. Infrared Photo Of the Same System Provides Insight Into The Liquid Gas Partitioning Within The GLCC© During Operation. Surfaces In Contact With Liquid Are Hotter Than Those In Contact With Gas. Credits To Paulus Siboro of CPI Minas For Infrared Photos.

LOSF AWT Solution - GLCC , Vortex Shedding, Starcut:

LOSF Bulk Solution -GLCC, Orifice, Automatic Sampling of WaterCut



Reading Delay: 1
DPDump: -1.0000 Inch.
DPGas: 10.0065 Inch.
DPHeight: 10.0065 Inch.
Densitometer: 0.0000 kg/m3
DPLiquid: 10.0065 Inch.
Inlet: 0.0000 PSI
Gas Temperature: N/A Celsius
Gas Flow: -1.0000 ft3/min
Oil Flow Rate: 0.0000 gal/min
Water Flow Rate: 0.0000 gal/min
Watercut: 89.7627 %

Figure 27: Preceding Analyses Indicate that the GLCC Combined With Venturi Rate Metering and Texaco STARCUT Watercut Measurement Will Provide Minimum Hydrocarbon Uncertainty at Minimum Cost and Minimum Size Under The Duri Area 10 Design Basis Conditions. The Image Shown Is From STARCUT Control Screen Which Integrates The Inputs From GLCC Level, Venturis and Watercut For Total System Management.