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Determination of Measurement Uncertainty for the Purpose of Wet Gas Hydrocarbon Allocation

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1 INTRODUCTION

The use of measurement uncertainty in the allocation of oil and gas is gaining interest in the industry. This so-called Uncertainty-Based-Allocation (UBA) utilizes the relative uncertainties of reference meters and allocation meters. The uncertainty of the allocation meters may differ significantly from one another and from the reference meters in both design and performance. The UBA approach attempts to use knowledge of meter uncertainty to equitably assign imbalance in the system. It has found immediate application in assigning the imbalance for wet gas systems in which one or all of the allocation meters is located subsea [1].

While the mathematics used to perform Uncertainty-Based-Allocation is straightforward in its derivation and application, determination of the meter uncertainties that will be input to the calculations can be a formidable task. Not only are the systems that would use the approach often complex, but there are other problems which must be addressed as well. One is the determination of the uncertainty of each wet-gas meter at subsea flowing conditions. Another is the transformation of those uncertainties to the environmental conditions of the reference meter in order that the appropriate equations can be applied. Perhaps the most significant is the detection and allowance for systematic, or bias, errors in different parts of the system. Bias errors are particularly worrisome. After being effectively eliminated by calibration prior to system startup, they may gradually become significant in one or more meters during system operation over time, and be virtually undetectable without removal and test of the offending meter. Their effect is discussed further in Section 5.3.

The effective combination of the Uncertainty-Based Allocation technique with the ability to determine meter and overall system uncertainty is of greatest value to the industry. The process has the potential to deal with difficult allocation situations and to open the door for incremental and marginal production, such as subsea tiebacks. The challenges which must be overcome in this process are not simple, however. Some of the most important will be discussed in what follows.

2 THE ISSUES OF ALLOCATION

The fundamental problem of allocation is illustrated in Figure 1, where meters M_1 , M_2 , ... M_n measure flows Q_1 , Q_2 , ... Q_n. The sum of these readings from individual stream (allocation) flow meters may differ from the reading of M_Z (reference meter), in which case the difference (imbalance) must be resolved in some fashion. Normally the reference meter readings are assumed to be Truth, so the imbalance is allocated back to the streams according to a defined strategy.

Note that each measured quantity Q_i is the sum of a true value $\overline{Q_i}$ and an error ε_i.

2.1 Proportional Allocation

An allocation methodology commonly used in the oilfield is called *proportional allocation* (PA). This strategy simply assigns the imbalance to each stream according to the relative reading of its allocation meter. Thus if two wells contribute to a commingled stream, and meters on these wells read four and six units of flow respectively, then the first well will be allocated 40% and the second 60% of any imbalance - either positive or negative.

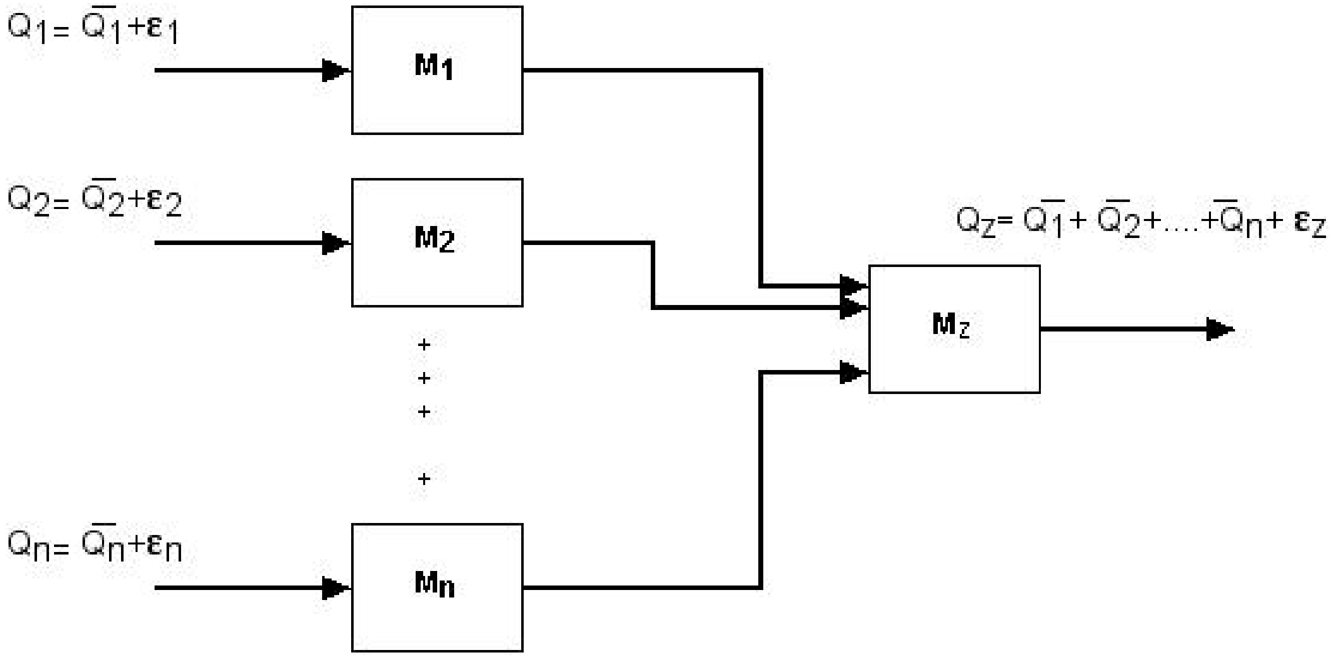

Figure 1. Commingling *n* production streams $\mathbf{Q_i}$ to form stream $\mathbf{Q_z}$.

While proportional allocation has the advantages of familiarity and simplicity, it is subject to problems. A simple example shown in Figure 2 will illustrate possible pitfalls with use of the PA strategy. From what is revealed in 2 (a), it appears straightforward that the imbalance of 4 MMSCFD should be nearly evenly divided between the two streams. In 2 (b), however, the uncertainty of the measurement M_2 (as revealed by its standard deviation σ_2) is observed to be three times that of the measurement M_1, suggesting that a greater part of the imbalance should be assigned to the M_2 stream than to the M_1 stream. But consideration of 2 (c) raises the question of how inaccuracy of the reference meter should be handled. Finally, 2 (d) points up the fact that what is measured as gas in one set of conditions may be measured as liquid in other conditions. Thus the gas imbalance of 4 MMSCFD may be incorrect, and gas and liquid measurement uncertainties at conditions P_1 - T_1 and P_2 - T_2 may change when brought to reference meter conditions P_z - T_z. Thus, in summary, the simple method of proportional allocation may not accurately calculate nor equitably assign an imbalance as one would wish.

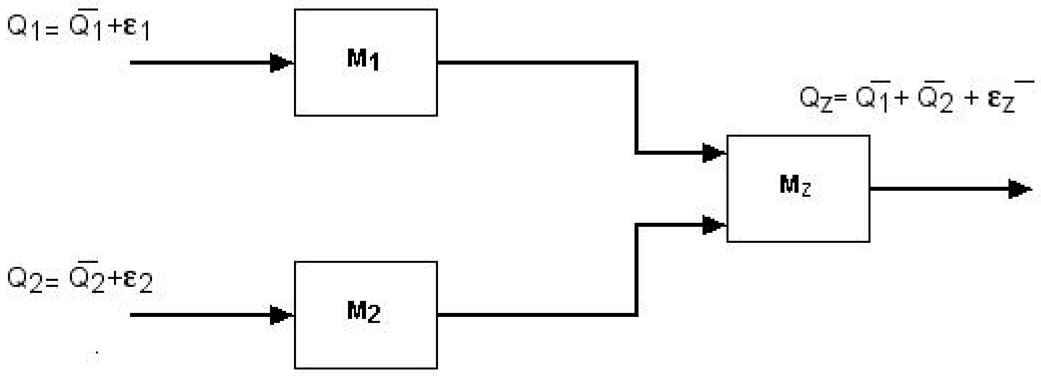

Figure 2. Two Commingled production streams illustrating shortcomings of Proportional Allocation.

(a) Q_1 = 51 MMSCFD, Q_2 = 55 MMSCFD, Q_Z = 102 MMSCFD

(b) $\sigma_1 = .02 \times Q_1$, $\sigma_2 = .06 \times Q_2$

(c) $\sigma_Z = .02 \times Q_Z$

(d) P_1 = 250 bar, T_1 = 140 degC, P_2 = 150 bar, T_2 = 90 degC,
P_Z = 100 bar, T_Z = 65 degC

2.2 Uncertainty-Based Allocation

Some metering systems for recent operational applications in the Deepwater Gulf of Mexico [2] have demonstrated the possibility of significant variations in individual meter uncertainty. This has prompted the U.S. Minerals Management Service to suggest the development of new methodologies for allocation which accounts for these variations. In April 2001, organization of a Technical Advisory Group (TAG) was begun to address this issue through development of a Recommended Practice (RP85), overseen through a Committee of the API [1]. In this instance, with the focus on upstream allocation metering, the effort was a better fit in the Upstream Committee, Subsea Equipment Subcommittee, than in the Committee on Petroleum Measurement, which has traditionally addressed measurement issues.

The principal contribution of this TAG was the development of a methodology that attempts to account for the variation in meter uncertainty. Named *uncertainty-based allocation* (UBA), the technique uses the measurement uncertainties of individual meters as the basis for the imbalance allocation. Specifically, the *allocation factor* α_i – i.e., the fraction of the imbalance allocated to the i^{th} stream - was defined as

$$\alpha_i = \frac{\sigma_i^2}{\sigma_z^2 + \sum_{j=1}^{n} \sigma_j^2} + \frac{Q_i}{\sum_{j=1}^{n} Q_j} \cdot \frac{\sigma_z^2}{\sigma_z^2 + \sum_{j=1}^{n} \sigma_j^2} \qquad (1)$$

where σ_i^2 is the variance of the measurement error on the i^{th} meter, σ_z^2 is the variance of the reference meter error, and Q_i is the flow through the i^{th} meter. The first term can be seen to assign each stream a fraction of the imbalance in proportion to its uncertainty relative to the sum of the uncertainties of all the meters in the system. The second term can be interpreted as the assignment of imbalance due to the uncertainty of the reference meter among the various streams, each according to its throughput.

It can be shown [1] that, if the measurement errors are stochastically independent from one another and have zero mean (i.e., the measurement errors are unbiased), then the result expressed in Equation (1) is nearly optimal in a least-mean-square (LMS) sense with regard to minimization of the errors in assignment of the imbalance.

2.3 Comparison of Proportional and Uncertainty-Based Allocation

It is useful to quantify what differences one might observe in practice between proportional and uncertainty-based allocation methods . Figure 3 shows how differences in uncertainties of the meters used for allocation can be manifest. In this example, Meters 1 and 2 are subject to the same nominal flow rate. If one assumes a constant uncertainty of 3 % for Meter 2, the effect of varying the uncertainty of Meter 1 from 1% to 12 % is shown below. The difference is calculated assuming a "typical" imbalance, which is one standard deviation of the imbalance based on the uncertainties that were used. A reference meter uncertainty of 1% is assumed.

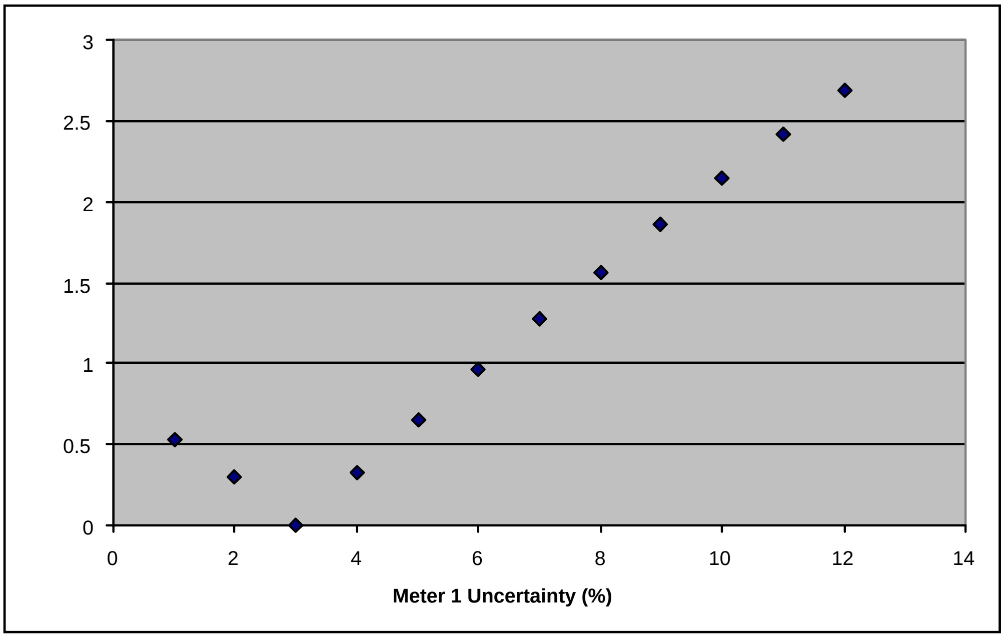

Figure 3. Difference Between PA and UBA in Allocated Quantities as a Function of Relative Allocation Meter Uncertainty.

Note that when the uncertainties are equal - in absolute terms rather than in percentages - the two methods are equivalent. But observe that the difference between the two methods can become almost 3 % of the individual stream flow when the meter uncertainties differ significantly.

It is also interesting to note the differences one can experience between the two allocation methods when the percentage uncertainties are equivalent, but the flow through the meters varies significantly. Figures 4 (a) and (b) illustrate this point. In this example, the reference meter uncertainty is 1%, those of Meters 1 and 2 are 5%. The total flow through the system is 100, divided between the two streams - thus if the flow through Meter 1 is 20, that through Meter 2 is 80.

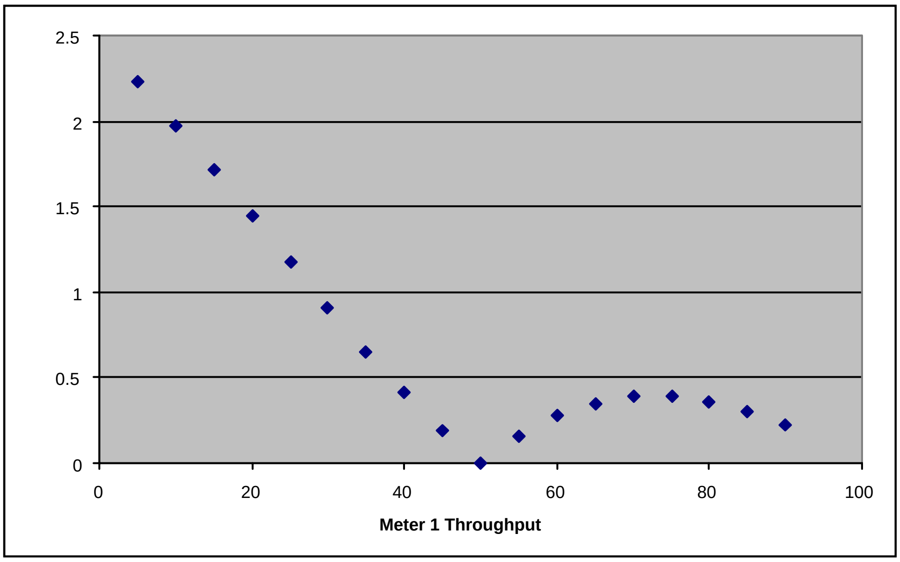

Figure 4 (a). Difference Between PA and UBA in Allocated Quantities on Stream 1.

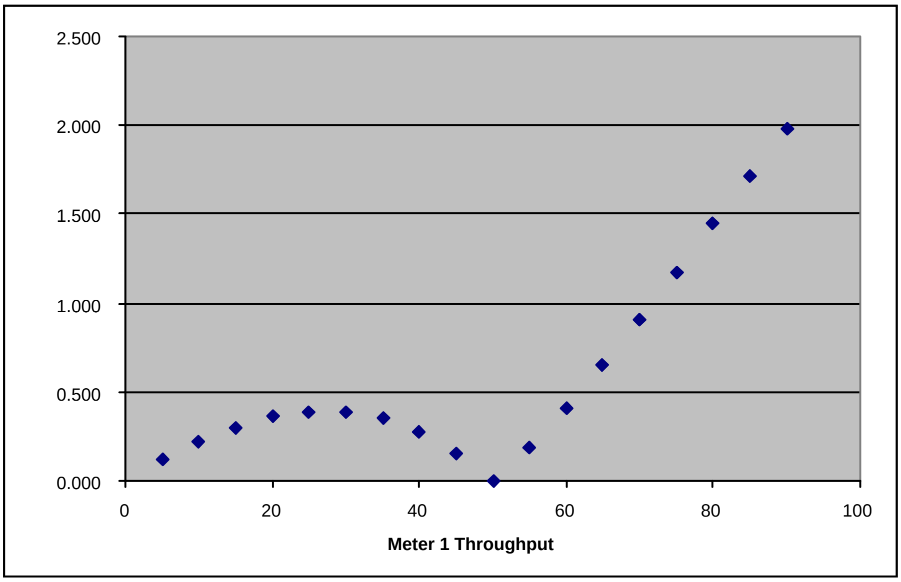

Figure 4 (b). Difference Between PA and UBA in Allocated Quantities on Stream 2.

For each meter it can be observed that there is no difference between PA and UBA when the flow through the two meters is the same (equivalent uncertainties). When the flow is different, however, the two methods yield differences as great as 0.5% for the stream with the greater flow, and 2% for the stream with the lesser flow.

3 OVERVIEW OF METHODS FOR UNCERTAINTY DETERMINATION

While the allocation formulation of Equation (1) in the previous section is intuitively appealing, its worth in practice will only be as great as the user's ability to understand and accurately establish meter uncertainties. In this section the question of how one determines uncertainties of meters and meter systems as required by UBA is addressed.

3.1 CONVENTIONAL UNCERTAINTY DETERMINATION: MEASUREMENT OF FLUID FLOW - EVALUATION OF UNCERTAINTY (ISO 5168); ISO GUIDE TO UNCERTAINTY IN MEASUREMENT (GUM)

These two ISO documents [3,4] provide a good framework for the determination of uncertainties in cases where a meter's response can be expressed as a function of all the appropriate influence factors. For meters such as differential devices, where these relationships are straightforward and have been studied for many years, calculation of uncertainties can be accomplished in a relatively easy manner.

Wet gas meters as they exist today are entirely different. Rather than simply characterizing the meter response by its dimensions and a few properties of the fluid, such as density and Reynolds Number, today's wet gas meters defy mathematical characterization of their behavior under the variety of circumstances in which they must operate.

3.2 UNCERTAINTY DETERMINATION BY FLOW LAB TESTING

If a functional relationship between gas and liquid flow rates and the factors which influence them cannot be identified for the myriad of fluid properties under which a meter will be used, then wet gas flow loop testing is necessary in order to determine the meter’s response in the conditions of a specific application. Of particular interest here, in addition to the calibration of flow measurement, is obtaining the measurement uncertainties for use in the UBA process. This requirement puts an additional burden on potential users to calibrate their wet gas meters beyond what is required for users of single-phase devices.

A problem for potential users is that the number of flow calibration facilities for wet gas meters is small. Even after the introduction of several new facilities during the past 24 months, there remain only a handful worldwide, with widely varying capabilities. If a measurement device for wet gas service is to be properly characterized, it must be calibrated in the conditions in which it will be used, else a good explanation must be provided for why this is not necessary.

Examples of the kinds of conditions under which the device might be tested are:

- flow regime
- phase flow velocities
- pressure
- densities
- fluid composition
- temperature
- orientation
- flow conditioning
- meter size

Since a meter may respond in a different way dependent on the conditions under which it is calibrated, it is important for a user to choose a flow calibration facility capable of replicating the conditions which will be encountered in its intended application. An early example of the importance of this requirement involved the pressure dependency on wet gas differential devices demonstrated by de Leeuw [5]. If a wet-gas Venturi is not calibrated at the expected working pressure, its performance will be compromised. To do the meter characterization properly, data must be taken using the proper fluids, orientation, pressures, and so on. Any parameters which are expected to change over the life of the field must be so varied during the meter test.

Finally, if the uncertainty of the meter is to be characterized for both gas and liquid flow rates, multiple samples of the meter response must be acquired at each set of working conditions. The sample distribution function, with characteristics such as mean and standard deviation of the gas and liquid flow rates at a given pressure, fluid composition, gas and liquid flow rate, etc. must be measured to properly characterize the device.

3.3 UNCERTAINTY DETERMINATION BY MONTE CARLO SIMULATION

While the uncertainty of an individual meter or sensor can be calculated or measured as discussed in the preceding paragraphs, when the uncertainties of many devices and points of measurement must be known at a common set of conditions it may be difficult to determine these in a closed-form expression, or even a calculation.

The method known as Monte Carlo Simulation (MCS) can be applied in these kinds of problems to estimate the uncertainties which are the result of very complex systems and/or processes. Recently, MCS has been applied with success to problems in measurement [6,7]. By creating input values to these systems with uncertainties built in according to chosen models, one can conduct a sufficiently large number of computational experiments that output statistics can be determined. This can be especially useful when the conditions in which the various sensors reside are different from one another, and where mass transfer between phases takes place numerous times. While it is conceptually possible to calculate uncertainties in these cases, it may be far more difficult to accomplish than to use MCS for this purpose.

3.4 PERSPECTIVE ON UNCERTAINTY DETERMINATION

Whether the uncertainty of individual meters is determined by analysis or through calibration, it is imperative that the uncertainty of every sensor and meter in the complete allocation metering system be carefully determined. Furthermore, in order to properly apply the UBA methodology, the uncertainty description of the fluid flow through each allocation meter must be transformed to the same conditions as the reference meter to which it is being compared.

Because of the complex and largely undefined behavior of wet gas meters in the presence of various liquid-gas mixes, liquid and gas compositions, salinities, pressures, temperatures, and so on, the need for proper calibration in an appropriate wet gas flow loop is not optional. Uncertainty determination using conventional analytical methods is of little use here. First, the flow meter’s response must be established in an empirical way. Then, in order to address the allocation problem, the measurement uncertainties at each set of conditions must also be determined. This is the procedure which must be followed until such time as meter responses are more easily characterized with respect to all the factors which are of influence.

Meters subject to changing flow conditions such as gas/liquid slugging will have variable measurement uncertainty, possibly with significant non-symmetrical variability. Monte Carlo Simulation deals with the expected or actual variability by integration to find the overall measurement uncertainty characteristics. With this approach it is possible to reflect the true uncertainty of a meter which may be characterized by functional relationships, or empirically from trials, or a combination.

4 RESULT OF STATE CHANGE ON UNCERTAINTY - PVT EFFECTS

As has been alluded to previously, it is imperative that the comparisons between allocation and reference meters be performed at a common set of environmental conditions. While it is not required, this normally means that each allocation meter’s flow measurement, and the flow measurement uncertainty, be converted to the reference meter conditions.

Consider the situation shown in Figure 5, where the measurements and uncertainties from a single allocation metering point are to be transformed to reference meter conditions. To understand the dynamics of the measurement process, it simplifies matters to work in terms of molar and mass flow rates. Given that the system is in a steady state, and that the fluid compositions are known at both allocation and reference measurement points, then the measurement of total mass flow rate is sufficient to determine the component flow rates on both a mass and molar basis. Furthermore, since one knows the fluid composition and flow rates at both sets of conditions, a PVT analysis can convert the allocation stream to reference conditions. Thus molar component flows can be converted from gas to liquid and from liquid to gas, based on the specifics of the change in pressure and temperature. In Figure 5, the matrix of conversion fractions β is used for the portions of liquid components which are converted to gas, while α contains conversion factors of the gas components which become liquid in the transformation. In practice these are often called *recovery factors*. Thus, liquid measured at the reference meter is a combination of liquid which was (a) in that state when traversing the allocation meter and (b) converted from gas to liquid between the metering points. Likewise, the gas measured at the reference meter consists of the combination of “native” and converted gas.

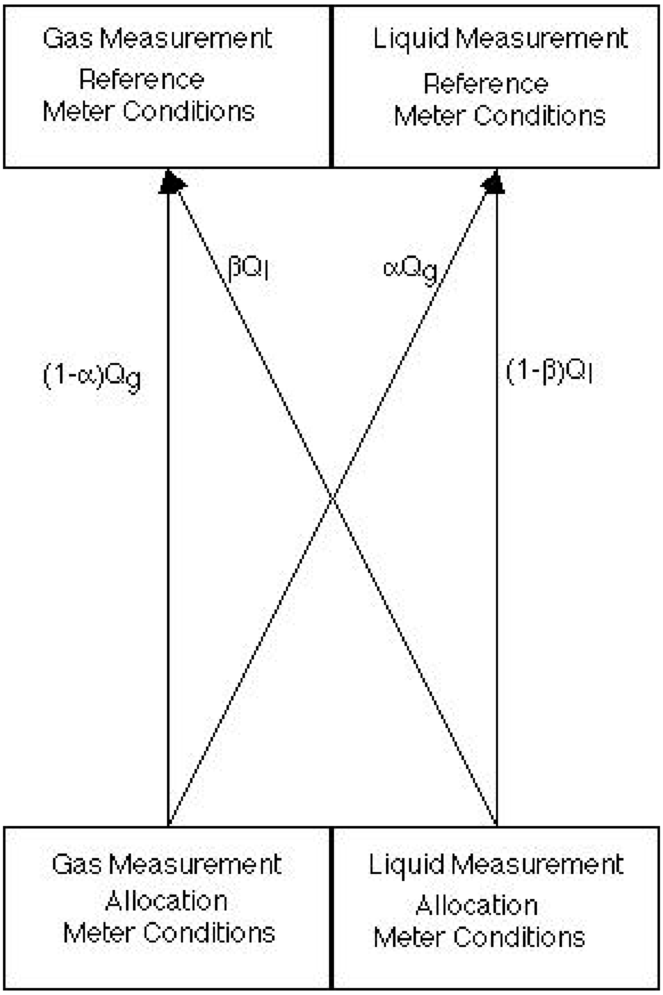

Figure 5. Illustration of mass transfer between phases and its effect on uncertainty.

While the notion of the phase transformation between gas and liquid is certainly not novel, what must be appreciated is the fact that uncertainties in measuring gas and liquid flows at allocation meter conditions will be “cross-reflected” in the uncertainties used in the UBA application. For instance, it may occur that much of the liquid measured at reference meter conditions was in fact in the gaseous state when measured at allocation meter conditions. Hence it should come as no surprise that the liquid measurement errors at reference conditions are reflective of the gas allocation measurement uncertainties, as well as the converse.

One last point which must be made is that the PVT transformation may not be perfect, and that the matrices β and α are error sources of their own. A poor phase transformation model can be as detrimental to the UBA results as measurement errors. In the examples considered here the uncertainties encountered in modeling the phase transformation are also included in the analysis.

5 EXAMPLES OF UNCERTAINTY DETERMINATION

At this point it is useful to consider some examples which illustrate the determination of uncertainty, and the effect of uncertainty on the allocation.

5.1 EFFECT ON UNCERTAINTY OF MASS TRANSFER BETWEEN PHASES

As suggested earlier, it is often the case that the physical conditions under which reference measurements are made is sufficiently different from those of the allocation measurements that partial transfer of components from gas to liquid phase (or the reverse) will take place. This will often have an effect on the measurements themselves, but also on the uncertainties which are used in Uncertainty-Based Allocation.

The data shown in Tables 1-3 are instructive in understanding the manner in which the mass transfer between phases can affect these uncertainties.

Component	Liquid Composition	Liquid Mass Flow Rate	Gas Composition	Gas Mass Flow Rate	Condensate Recovery Factors	Recovered Condensate	Flow Rate of Liquid inc Recovered Condensate	Flow Rate of Gas less Recovered Condensate
	mol%	**tonne/day**	**mol%**	**tonne/day**	**%gas**	**tonne/day**	**tonne/day**	**tonne/day**
Carbon Dioxide	2.72%	0.5374	2.48%	46.3056	0.00%	0.0000	0.5374	46.3056
Nitrogen	0.39%	0.0490	0.30%	3.5655	0.00%	0.0000	0.0490	3.5655
Methane	2.49%	0.1793	82.01%	558.1916	2.00%	11.1638	11.3432	547.0278
Ethane	3.56%	0.4806	7.71%	98.3600	3.00%	2.9508	3.4314	95.4092
Propane	5.32%	1.0532	2.85%	53.3193	6.00%	3.1992	4.2524	50.1202
i-Butane	3.77%	0.9838	0.56%	13.8091	8.00%	1.1047	2.0885	12.7044
n-Butane	5.94%	1.5500	1.06%	26.1387	8.00%	2.0911	3.6411	24.0476
i-Pentane	4.41%	1.4285	0.36%	11.0197	10.00%	1.1020	2.5304	9.9177
n-Pentane	7.02%	2.2739	0.40%	12.2441	10.00%	1.2244	3.4983	11.0197
Hexane	9.34%	3.6136	0.09%	3.2905	16.00%	0.5265	4.1401	2.7640
Heptane	11.22%	5.0475	0.11%	4.6764	20.00%	0.9353	5.9828	3.7411
Octane	13.76%	7.0567	0.37%	17.9315	60.00%	10.7589	17.8156	7.1726
Nonane	14.83%	8.5393	0.01%	0.5441	80.00%	0.4353	8.9746	0.1088
Decane	15.19%	9.7032	0.01%	0.6037	90.00%	0.5433	10.2465	0.0604
Hydrogen Sulfide	0.01%	0.0015	0.00%	0.0000	0.00%	0.0000	0.0015	0.0000
Water	0.03%	0.0024	1.68%	12.8405	75.00%	9.6304	9.6328	3.2101
Total	**100.00%**	**42.5000**	**100.00%**	**850.0000**		**36.04**	**78.56**	**813.82**
Allocation Meter Uncertainties:		**20.00%**		**3.00%**		**3.755%**	**10.887%**	**3.019%**
Liquid Component Uncertainty:		**10%**		**No Uncertainty on Recovery Factors**				
Gas Component Uncertainty:		**5%**		**Gas Mass Fraction: 95%**				

Table 1. Illustration of Uncertainty Change Due to Mass Transfer Between Phases. Slightly Wet Gas.

In this example of Table 1, where there is very little liquid present in the gas at the allocation meter, it can be observed that almost half of the liquid at reference conditions which is to be allocated is due to that which was converted from gas. Furthermore, since the recovered liquids were measured in the gaseous state, the uncertainty of the total liquid flow at reference conditions has been reduced due to the superior measurement of gas (3%) versus that of liquid (20%) to 10.9%.

However, the data in Table 2 show another example of a wet gas in which there is more liquid through the allocation meter than in the previous example. In this case the recovered condensate is a smaller percentage of the total liquid to be allocated. Thus its influence on the liquid uncertainty at reference conditions is less, though clearly non-negligible, reducing the liquid uncertainty to 16.2% from 20%.

Component	Liquid Composition	Liquid Mass Flow Rate	Gas Composition	Gas Mass Flow Rate	Condensate Recovery Factors	Recovered Condensate	Flow Rate of Liquid inc Recovered Condensate	Flow Rate of Gas less Recovered Condensate
	mol%	**tonne/day**	**mol%**	**tonne/day**	**%gas**	**tonne/day**	**tonne/day**	**tonne/day**
Carbon Dioxide	2.72%	1.8968	2.48%	46.3056	0.00%	0.0000	1.8968	46.3056
Nitrogen	0.39%	0.1731	0.30%	3.5655	0.00%	0.0000	0.1731	3.5655
Methane	2.49%	0.6330	82.01%	558.1916	2.00%	11.1638	11.7968	547.0278
Ethane	3.56%	1.6962	7.71%	98.3600	3.00%	2.9508	4.6470	95.4092
Propane	5.32%	3.7172	2.85%	53.3193	6.00%	3.1992	6.9164	50.1202
i-Butane	3.77%	3.4721	0.56%	13.8091	8.00%	1.1047	4.5768	12.7044
n-Butane	5.94%	5.4706	1.06%	26.1387	8.00%	2.0911	7.5617	24.0476
i-Pentane	4.41%	5.0417	0.36%	11.0197	10.00%	1.1020	6.1437	9.9177
n-Pentane	7.02%	8.0255	0.40%	12.2441	10.00%	1.2244	9.2499	11.0197
Hexane	9.34%	12.7538	0.09%	3.2905	16.00%	0.5265	13.2803	2.7640
Heptane	11.22%	17.8147	0.11%	4.6764	20.00%	0.9353	18.7500	3.7411
Octane	13.76%	24.9059	0.37%	17.9315	60.00%	10.7589	35.6648	7.1726
Nonane	14.83%	30.1388	0.01%	0.5441	80.00%	0.4353	30.5741	0.1088
Decane	15.19%	34.2466	0.01%	0.6037	90.00%	0.5433	34.7899	0.0604
Hydrogen Sulfide	0.01%	0.0054	0.00%	0.0000	0.00%	0.0000	0.0054	0.0000
Water	0.03%	0.0086	1.68%	12.8405	75.00%	9.6304	9.6389	3.2101
Total	**100.00%**	**150.0000**	**100.00%**	**850.0000**		**36.04**	**186.15**	**813.96**
Allocation Meter Uncertainties:		**20.00%**		**3.00%**		**3.764%**	**16.187%**	**3.022%**
Liquid Component Uncertainty:				**No Uncertainty on Recovery Factors**				
Gas Component Uncertainty:				**Gas Mass Fraction: 85%**				

Table 2. Illustration of Change in Uncertainty Due to Mass Transfer Between Phases. Wet Gas.

Component	Liquid Composition	Liquid Mass Flow Rate	Gas Composition	Gas Flowrate	Condensate Recovery Factors	Recovered Condensate	Flow Rate of Liquid inc Recovered Condensate	Flow Rate of Gas less Recovered Condensate
	mol%	**tonne/day**	**mol%**	**tonne/day**	**%gas**	**tonne/day**	**tonne/day**	**tonne/day**
Carbon Dioxide	2.72%	0.3954	2.48%	46.8462	0.00%	0.0000	0.3954	46.8462
Nitrogen	0.39%	0.0363	0.30%	3.5974	0.00%	0.0000	0.0363	3.5974
Methane	2.49%	0.1352	82.01%	551.0243	2.00%	11.4564	11.5915	539.5679
Ethane	3.56%	0.3494	7.71%	98.7199	3.00%	2.9081	3.2574	95.8118
Propane	5.32%	0.7579	2.85%	54.6300	6.00%	3.2351	3.9930	51.3949
i-Butane	3.77%	0.7561	0.56%	14.0668	8.00%	1.0986	1.8547	12.9683
n-Butane	5.94%	1.1110	1.06%	26.3996	8.00%	1.9714	3.0824	24.4283
i-Pentane	4.41%	1.0388	0.36%	10.5937	10.00%	1.0780	2.1168	9.5157
n-Pentane	7.02%	1.5433	0.40%	11.4936	10.00%	1.2368	2.7802	10.2567
Hexane	9.34%	2.6129	0.09%	3.3340	16.00%	0.5010	3.1139	2.8330
Heptane	11.22%	3.8038	0.11%	4.7164	20.00%	0.9529	4.7567	3.7635
Octane	13.76%	4.8035	0.37%	17.9678	60.00%	12.6586	17.4621	5.3092
Nonane	14.83%	6.3425	0.01%	0.5367	80.00%	0.4861	6.8286	0.0506
Decane	15.19%	7.0167	0.01%	0.6044	90.00%	0.5439	7.5606	0.0604
Hydrogen Sulfide	0.01%	0.0011	0.00%	0.0000	0.00%	0.0000	0.0011	0.0000
Water	0.03%	0.0018	1.68%	12.6962	75.00%	10.8927	10.8945	1.8035
Total	**100.00%**	**42.5000**	**100.00%**	**850.0000**		**36.04**	**78.49**	**813.96**
Allocation Meter Uncertainties:		**20.00%**		**3.00%**		**9.942%**	**11.738%**	**3.007%**
Liquid Component Uncertainty:		**10%**		**Uncertainty on Recovery Factors: 20%**				
Gas Component Uncertainty:		**5%**		**Gas Mass Fraction: 95%**				

Table 3. Illustration of Change in Uncertainty Due to Mass Transfer Between Phases. Wet Gas. Uncertainty of 20% on Recovery Factors.

Finally, the data shown in Table 3 demonstrate the effects of another source of uncertainty, that which reflects imprecision in knowledge of mass transfer between phases. In this example, this uncertainty is modeled as a random error in the recovery factor about the correct value. Comparing these results with those of Table 1, one observes that the uncertainty of the recovered condensate measurement has increased substantially to 9.9%, but that its effect on the total liquid measurement is rather insignificant, increasing the uncertainty to only 11.7% from 10.9%.

5.2 APPLICATION OF UNCERTAINTY-BASED ALLOCATION

Monte Carlo Simulation has been used to mimic the behavior of a two-stream allocation system such as that shown in Figure 2. The results of Proportional and Uncertainty-Based Allocations in this system, in which all meter measurements were free of bias, are shown in Figure 6 below.

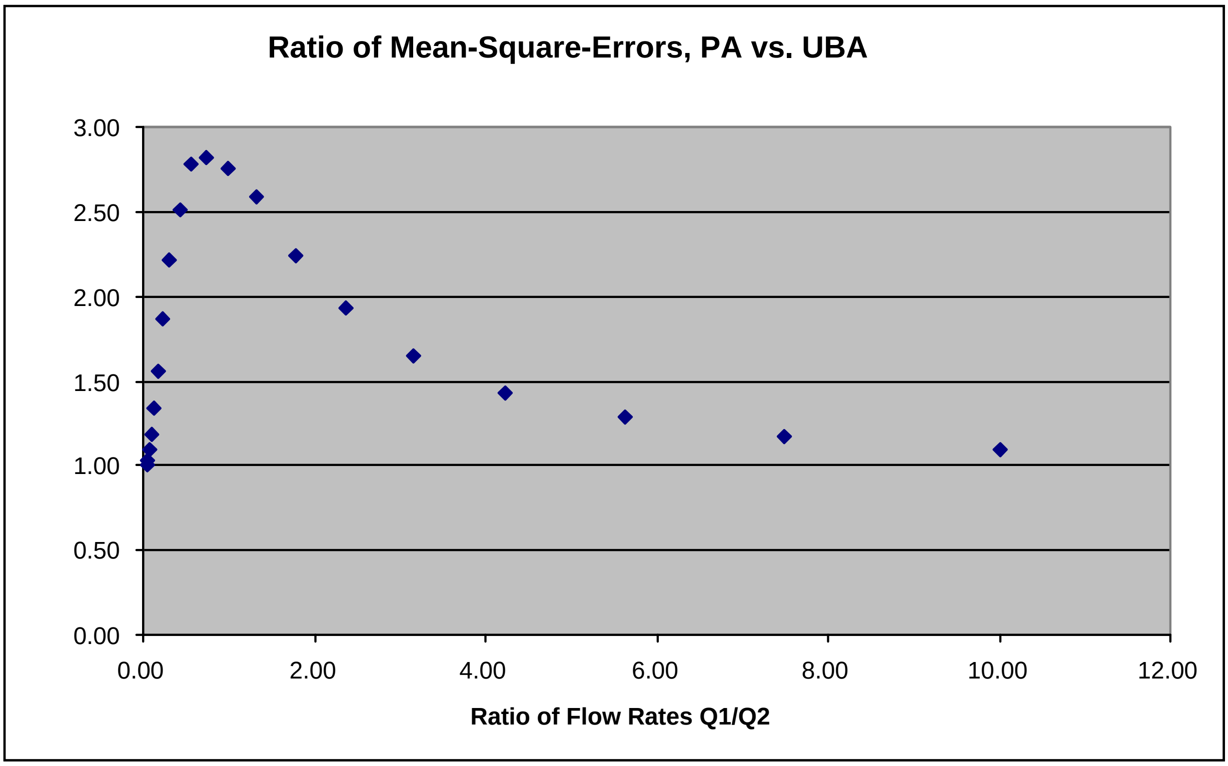

Figure 6. Simulation Results Comparing Proportional and Uncertainty-Based Allocation. Allocation Meter Uncertainties 5% and 1%, Reference Meter Uncertainty 1%.

The important thing to note is that the stochastic quality measure used here, namely the expected value of the mean-square error, is invariably lower when using the UBA method than when PA is applied. In many cases the difference is quite significant.

5.3 EFFECTS OF BIAS ON THE ALLOCATION

It is an important goal that any known bias in the measurement of wet gas will be detected during the meter's calibration and zeroed out. However it is not unlikely that other biases will be introduced during the operation of the meter, and that these may go undetected, possibly for long periods. It is instructive to observe what the consequences of these will be on the allocation of the system imbalance in both PA and UBA schemes.

The flow rate in each stream is assumed to be of the form

$$Q_i = \overline{Q}_i + \varepsilon_i + \delta_i$$

where $\overline{Q_i}$ is the true value of flow through the ith meter, ε_i is a zero-mean random error in the measurement, and δ_i is a fixed bias error in the measurement. The imbalance in the system is defined as the difference between the reference meter and the sum of the readings from the allocation meters, corrected of course for mass transfer effects,

$$\begin{aligned} I &= Q_Z - Q_1 - Q_2 - \ldots - Q_N \\ &= \sum_1^N \overline{Q}_j + \varepsilon_z + \delta_z - \sum_1^N (\overline{Q}_j + \varepsilon_j + \delta_j) \\ &= \varepsilon_z + \delta_z - \sum_1^N (\varepsilon_j + \delta_j) \end{aligned}$$

Since the random errors ε_i have mean values of zero, the expected value of $\boldsymbol{I}$ is

$$E[I] = \delta_z - \sum_1^N \delta_j$$

In other words, the expected value of the imbalance is just the difference between the bias in the reference meter and the sum of the biases in the allocation meters. Its variance is simply

$$E[(I-\bar{I})^2] = \sigma_z^2 + \sum_1^N \sigma_j^2$$

Thus, not surprisingly, the effect of bias errors is simply a hidden, fixed error, $\bar{I}$, which will be allocated back to the streams based on either relative throughput (Proportional Allocation) or relative uncertainty (Uncertainty-Based Allocation).

A logical question to ask is whether meters with large relative uncertainties are more prone than other meters to develop correspondingly large biases, or whether there exists no correlation. The subject warrants further study by those wishing to apply Uncertainty-Based Allocation.

6 CONCLUSIONS

Uncertainty-Based Allocation (UBA) is a promising new method which enables equitable allocation to all parties while using measurements with widely differing uncertainties in the same system. Further it becomes possible to choose or tailor measurement uncertainty to the economics of the development, with an incentive to improve the measurement uncertainty when the economics allow. It will be a key factor to open the door to development of oil and gas resources in harsh environments such as in the Deepwater Gulf of Mexico, in a manner acceptable to the regulatory authorities, in this case the MMS.

While the use of UBA is most attractive, the difficulties in dealing with measurement uncertainties are formidable. Determination of flow measurement uncertainties in the myriad of conditions in which a multiphase meter must operate is difficult. Developing common-condition uncertainty models for the allocation and reference meters is challenging. Perhaps the most daunting problem facing potential users of UBA is how to deal with bias errors in both allocation and reference meters. Monte Carlo Simulations of the sort shown here can be useful in addressing applications of UBA.

Implementation of UBA systems in the Gulf of Mexico is imminent, and should provide valuable experience for other use in other areas. This particularly applies to the North Sea where innovations such as UBA are required to make extraction of small accumulations of oil and gas economic.

Finally, it should be obvious from the results presented that there are far more questions regarding the application of UBA than have been answered. The authors hope that what has been shown here will stimulate interest in the topic on a broader scale.

7 NOTATION

$\boldsymbol{\alpha}$	Gas-Liquid conversion factor
α_i	Allocation Factor for the i^{th} Stream
$\boldsymbol{\beta}$	Liquid-Gas conversion factor
δ_i	Bias Error in Measuring the i^{th} Stream
δ_Z	Bias Reference Measurement Error
ε_i	Random Error in Measuring the i^{th} Stream
ε_Z	Random Reference Measurement Error
I	System Imbalance
$\overline{I}$	Bias in System Imbalance
M_i	Meter on the i^{th} Stream
M_Z	Reference Meter
MCS	Monte Carlo Simulation
P_i , T_i	Pressure and Temperature of the i^{th} Stream
P_Z , T_Z	Reference Meter Pressure and Temperature
PVT	Pressure-Volume-Temperature
PA	Proportional Allocation
Q_i	Flow Measured through the i^{th} Meter
$\overline{Q}_i$	True Value of Flow through the i^{th} Meter
σ_i^2	Error Variance of the i^{th} Meter
σ_z^2	Variance of the Reference Meter Error
UBA	Uncertainty-Based Allocation

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