

## **Paper 1.1**

# **Application of Phase Behaviour Models in Production Allocation System**

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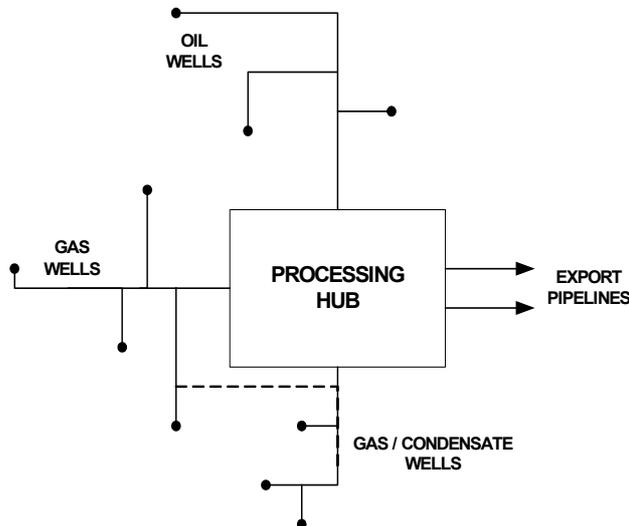
## APPLICATION OF PHASE BEHAVIOR MODELS IN PRODUCTION ALLOCATION SYSTEMS

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### 1 INTRODUCTION

The current and future scenarios for production in the Gulf of Mexico (GoM) are such that application of phase-behavior models within the allocation system is appropriate. Furthermore, the reasons supporting this application are likely to exist in other major production regions throughout the world. The GoM has most recently ventured into ultra deepwater production. Subsequently, development costs (drilling, topsides facilities, and export infrastructures) have risen in some cases to nearly three billion USD. These investment levels are driving a case to tie-back subsea wells from farther distances to new or existing production facilities. The result is a hub like structure with a minimal number of floating production facilities serving many different tiebacks from the surrounding area.



The hub scenario introduces an order of magnitude greater complexity. Specific to measurement and allocation, is that the various tiebacks inevitably contain wells with different owners and different tax rates. This will be referred to as **ownership disparity**. In the past equal ownership and tax rates was more often the case. This equated exposure to only that of the “more accurate” custody transfer measurement. Ownership disparity exposes each owner to the full measurement error over the entire production measurement system. Also note that tax rate differences equates to an ownership difference for the taxing authority.

Fig. 1 – Hub Scenario

The hub scenario makes it more likely that a certain ownership disparity will exist. However, this is only part of the story. With the hub scenario a second disparity is likely to exist, in that fluid types will also likely vary. The more tiebacks that exist, the more likely it is that gas, gas/condensate, and black oil wells will eventually commingle in the same process. This is referred to as **fluid dissimilarity**. Ownership disparity and fluid dissimilarity taken together, compound the measurement error exposure for all parties. The presence of ownership disparity makes relevant the real metrology problem which is phase behavior differences between dissimilar fluids. Once an ownership disparity exists, the full impact of fluid dissimilarity is encountered by the allocation system. A typical measurement error exposure of one or two percent may increase to as high as five to seven percent due to the phase behavior of the dissimilar commingled fluids. A way to reduce the measurement error is to utilize phase-behavior models within the allocation system to better predict the final quantities that determines the associated revenue.

This paper will explain the basic problem of phase changes in production processes and how they affect the allocation system. The typical past methods for dealing with the problem (non-modeled approach) will be critically examined. A phase-behavior model approach will be presented along with optimization techniques needed to effectively apply the solution. Lastly, advantages, disadvantages and possible future improvements will be highlighted. The

realities that have heightened phase-behavior as a measurement issue are here to stay in the GoM and will likely become evident in other major production regions throughout the world.

## 2 PROBLEM

The problem starts with the fact that commingled production streams must be measured prior to commingling in order to perform a proper allocation. However, once commingled, the streams experience a certain production process where the temperature and pressure conditions vary greatly from the original measurement conditions. Within the process the fluids undergo phase changes between gas and liquid phases.

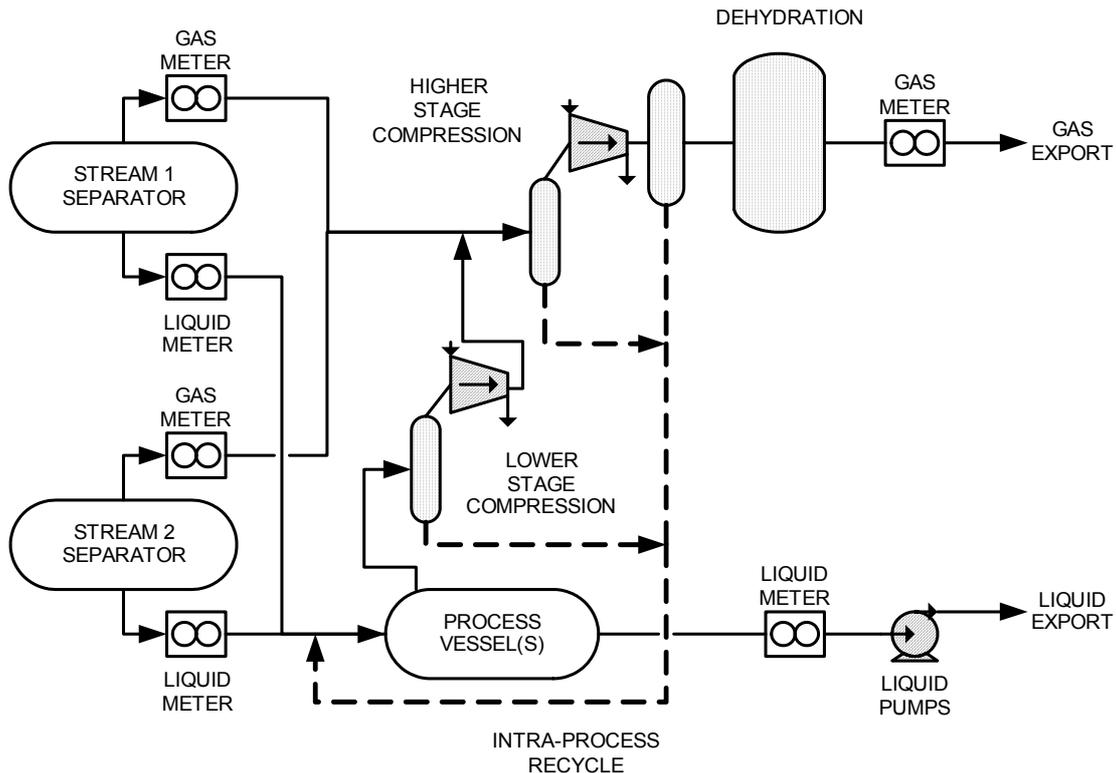


Fig. 2 – Typical Production Process

Therefore, the measured quantities of gas and liquid at the start of the process will not equal the measured quantities of gas and liquid at the end of the process with respect to gas and liquid independently. While the total mass of the gas and liquid combined remains constant, there is an exchange of liquid to gas and gas to liquid during the process. This seems inconsequential given that the total mass is constant. However, since measurement and allocation systems are the basis of revenue assignment between all the affected parties (i.e. working interest owners, taxing authorities, etc.) and the real value of hydrocarbons in the form of gas (natural gas) and liquid (crude oil) are seldom equal, each commingled stream's correct portion of the final gas and liquid streams must be known in order to ensure equity in the fiscal assignments.

A system must be put in place to accurately predict and assign the final quantities of gas and liquid independently to the individual commingled streams. This accounts for gas to liquid and liquid to gas phase changes within the process. Complicating the situation even more is the interaction of individual components within the streams. A stream undergoing the process by itself will experience a certain phase change. That same stream undergoing the process commingled with another stream will experience a different phase change. The two streams (assuming dissimilarity in their respective gas and liquid compositions) will interact and influence the phase change of each other.

## 2.1 The Previous Gulf of Mexico Approach

Typically the problem is approached by a sampling and analysis techniques. The quantity (volume) and quality (composition) of each stream is determined at the beginning of the process independently. This is normally accomplished by independent gas and liquid metering and sampling systems situated at the outlets of separation vessels. The relative pressure and temperature must also be acquired. Once the composition is known from a laboratory analysis, an Equation of State (EoS) is used to predict the phase changes from the measured pressure and temperature conditions to the end-of-process conditions. The appropriate corrections to the liquid and gas quantities are then applied.

In the GoM the above approaches has normally entailed performing flash and shrink calculations on the liquid portion of the stream and assuming the gas portion of the stream remains as gas throughout the process. Shrinkage in these terms is the ratio of the liquid quantity at the beginning of the process to the liquid quantity at the end of the process, and the flash is the quantity of gas that is predicted to evolve from the liquid during the process. The EoS approach can also be used for the gas portion of the process but it is normally not used. The reason for this is that the process includes intra-process recycled streams (see Fig. 2). An intra-process recycled stream is where liquids condensing from the gas (normally collected before and after compression) are diverted back to an upstream liquid process point. These liquids are predominately propane, butane, pentane, and hexane mixtures. In the process these liquids are exposed to a lower pressure and normally would return to the gaseous phase. However, when these liquids mix with longer-chain molecules (black oil) a portion of the liquids remain in liquid phase. As one can see it is difficult to make a simple application of an EoS in this iterative fashion. One must not only predict the gas to liquid phase changes, but also predict the residual gas to liquid quantities. That is to say the quantity of liquid from the gas stream that remains as liquid to the end of the process must be calculated, discounting the liquids that re-gasify before the end of the process. The typical approach in the GoM and possibly other areas has been to ignore this issue. Furthermore, the API standard on allocation measurement [1] only mentions an EoS approach for flash calculations of gas evolving from liquid. The liquids condensing from gas are not mentioned as a quantity measurement issue but only as a quality issue. While the liquid corrections using shrink and flash calculations are roughly appropriate, ignoring any gas to liquid phase change carries a large impact. With the ever increasing hub-based production quantities in the GoM and the realities of fluid dissimilarity, a more rigorous approach is warranted.

## 2.2 Financial Significance

It can be easily seen that the phase changes within the process affect the final answer. And, that due to varying ownership or tax rate for the commingled streams the revenue distribution will also be affected. But the real question concerns the magnitude of the effect. Since no measurement system or technique is perfect, the question becomes how much imperfection is acceptable. Or, more precisely stated, what are the random uncertainties and possible biases associated with the typical approach in the context of the current and expected future fluid compositions? If the errors are small they may be ignored and assumed to be a cost of doing business. However, as this paper will show, the errors in the context of fiscal hydrocarbon measurement are not small. Furthermore, the errors are bias in nature and when applied to the large production quantities on GoM hubs, result in significant financial impact.

In order to demonstrate the significance a comparison is made between the typical approach explained above and a new approach using a phase-behavior model. The model allows the commingled streams to be viewed simultaneously and deciphers the intra-process recycled streams. The comparison is based on a typical GoM deepwater hub accommodating black oil, gas condensate and gas wells. The oil and gas prices are set at US \$30 per barrel and US \$4 per MMBTU, respectively. Please note if the gas price on a barrel of oil equivalent (BOE) basis goes above the oil price the gas to liquid economics depicted below will be reversed.

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Table 1 shows the relative theoretical volume of oil and gas for the typical approach, referred to as the “non-modeled approach”, followed by the same calculation using the model. The theoretical quantity is the quantity in terms of energy for the gas and standard volume for the oil, as measured at the start of the process but in terms of the pressure and temperature at the end of the process. Since the model and the non-model approaches begin with the same input quantities and their differences lie in the proportioning of the final quantities, no greater or less mass is generated. Thus, ultimately the net difference is zero. And, if all ownerships remained equal, no party would suffer financially. However as demonstrated above, this is seldom the case.

**Table 1 – Non-Modeled versus Modeled Approach**

Stream Fluid Type		Measured Quantities	Theoretical Quantities	Allocated Quantities	Total Value
Typical Approach (Non-Modeled)					
Stream A Black Oil	Oil (Bbls.)	1,800,000	1,706,966	1,733,314	\$ 51,999,411
	Gas (MMBTU)	737,369	892,454	837,048	3,348,194
Stream B Gas Condensate	Oil (Bbls.)	900,000	733,300	744,619	22,338,561
	Gas (MMBTU)	1,769,360	2,364,437	2,217,647	8,870,587
Stream C Gas	Oil (Bbls.)	120,000	86,095	87,424	2,622,709
	Gas (MMBTU)	2,076,610	2,267,232	2,126,477	8,505,908
Modeled Approach					
Stream A Black Oil	Oil (Bbls.)	1,800,000	1,710,000	1,711,651	51,349,533
	Gas (MMBTU)	737,369	857,130	856,375	3,425,499
Stream B Gas Condensate	Oil (Bbls.)	900,000	760,651	761,385	22,841,561
	Gas (MMBTU)	1,769,360	2,096,955	2,095,108	8,380,433
Stream C Gas	Oil (Bbls.)	120,000	92,231	92,320	2,769,588
	Gas (MMBTU)	2,076,610	2,231,655	2,229,689	8,918,756
Difference Modeled minus Non-Modeled					
Stream A Black Oil	Oil (Bbls.)		3,035	-21,663	(649,879)
	Gas (MMBTU)		-35,324	19,326	77,305
Stream B Gas Condensate	Oil (Bbls.)		27,351	16,767	503,000
	Gas (MMBTU)		-267,481	-122,538	(490,153)
Stream C Gas	Oil (Bbls.)		6,136	4,896	146,879
	Gas (MMBTU)		-35,578	103,212	412,848
Net difference in revenue				Stream A	(572,574)
				Stream B	12,847
				Stream C	559,727
Total Net difference					0

Refer to the Appendix for a listing of the compositions used within this paper for streams A, B, and C.

### 2.3 Sensitivity to the Process

In addition to the problem created by commingling dissimilar fluid types, the configuration of the process itself constitutes another problem. Figure 3 illustrates the process used for calculations in this paper. Based on how the process is configured and where liquids are removed, or where in the process rich and lean gases commingle, a greater variance in the final liquid and gas quantities is encountered. To illustrate this effect a close-up view of one process stream is shown in Figure 4 with the normal separation vessel package. In Figure 5, the above process is changed slightly where one separation vessel is eliminated and the associated gas stream is connected at the discharge of the previous compressor stage.

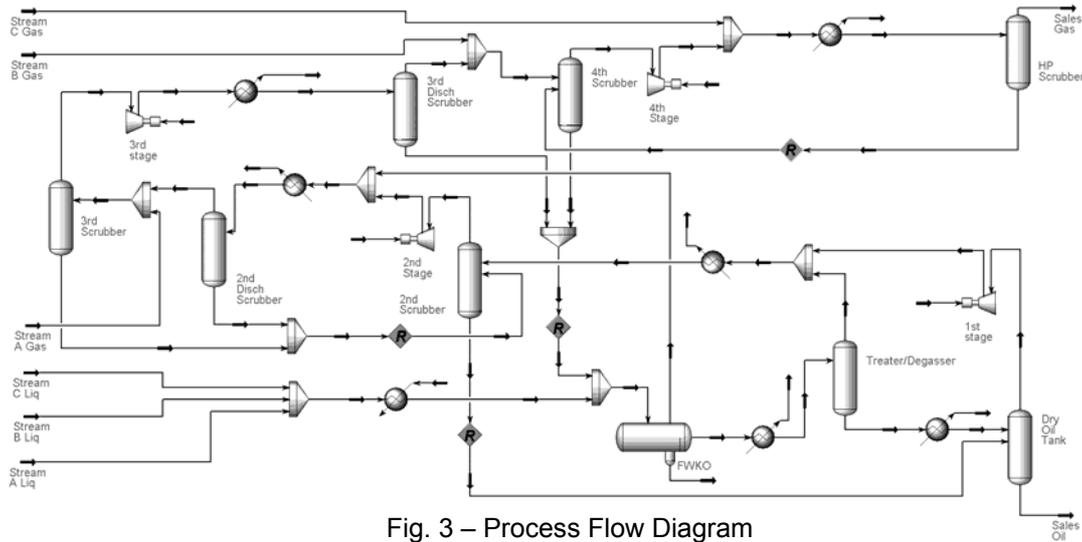


Fig. 3 – Process Flow Diagram

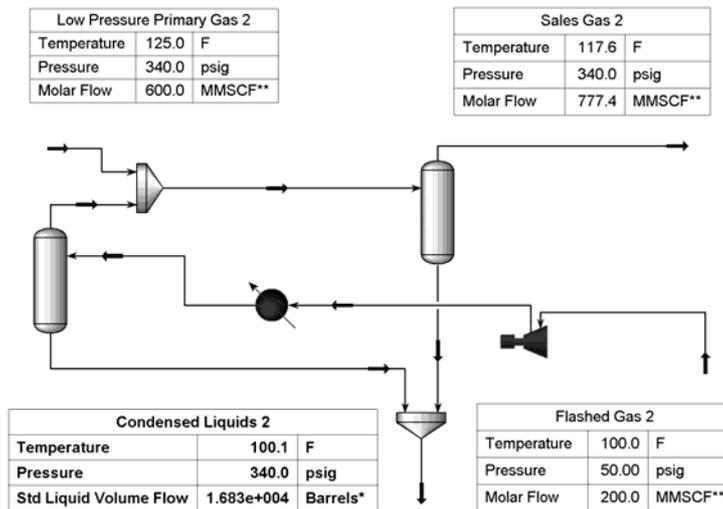


Fig. 4 – Normal Separation Vessel Package (same as Fig. 3)

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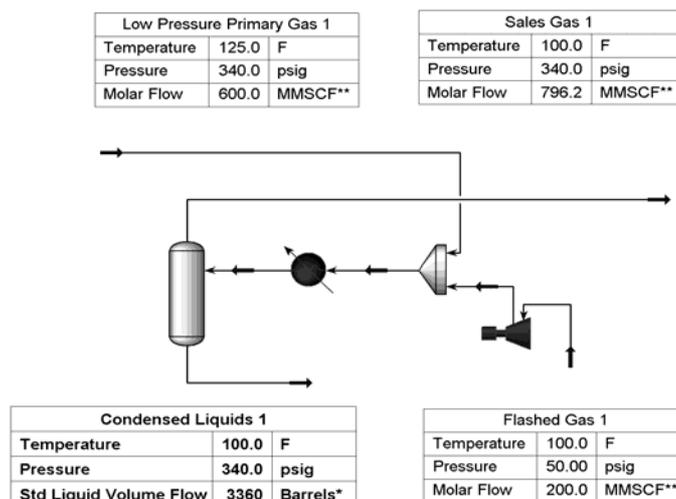


Fig. 5 – Reduced Separation Vessel Package

The process configuration in Figure 5 shows an alternate design normally used for debottlenecking or to reduce weight (capital cost). Note that there is a significant difference in the quantity of condensed liquids. In the Figure 4 design more condensed liquids ultimately exit the process as liquids. Alternatively, in Figure 5, a significant amount of heavier components that would have become liquid, remain in the gas phase and exit the process as gas. Refer to the Condensed Liquids data box in each figure. The Figure 4 design yields 16,830 barrels while the Figure 5 design yields only 3,360 barrels.

The non-modeled approach would treat both these process configurations exactly the same in that the initial fluid pressure and temperature are equal and they have the same process endpoint pressure. However, as can be seen a significant difference exists due to the configuration of the process itself. Simple EoS (i.e. shrink and flash calculations) cannot differentiate process changes beyond a simple pressure and temperature change. The EoS inability to depict the actual process configuration creates an un-resolvable imbalance. On simple systems with low fluid dissimilarity this imbalance may be relatively small, but on complex processes with greatly differing fluid types, this imbalance becomes critical. Additionally, there is a significant financial impact in that gas and oil prices are seldom equivalent compounded by greater ownership disparity.

## 2.4 Dissimilar Fluids

While the inability to depict the process complexity is problematic, dissimilarity in the commingled fluid types presents a greater problem. Since the fluid types can change over time and even within an allocation period, the non-modeled approach can give varied and unrepeatable results. The most direct way to examine this effect is by comparing the shrink factors and flash gas quantities using the non-modeled and modeled approaches. The shrink factor is the ratio of the liquid volume at the end of the process ( $P_2, T_2$ ) over the volume at the beginning of the process ( $P_1, T_1$ ). The volume at  $P_1, T_1$  is the measured volume at the separator and volume at  $P_2, T_2$  is the theoretical volume at the end of the process. For the example streams A, B, and C following are the results of the model and non-modeled approaches.

Table 2 - Shrink Factor Comparison

Stream	Shrink Factor Non-Modeled	Shrink Factor Modeled	Difference
Stream A	0.9483	0.9500	0.0017
Stream B	0.8148	0.8452	0.0304
Stream C	0.7175	0.7686	0.0511

The simple EoS approach assumes more flashing of liquid and thus a lower ultimate liquid volume. Conversely, providing for conservation of mass, the EoS over predicts the flash gas quantity. And, due to an over prediction of heavier components in gaseous phase, the EoS predicts a higher flash gas energy content as shown in Table 3.

**Table 3 – Flash Gas Comparison**

Stream	Flash gas Non-Modeled		Flash gas Modeled		Difference (MMBTU)
	Quantity	Quality (BTU/SCF)	Quantity	Quality (BTU/SCF)	
Stream A	86,113	1,801	80,984	1,479	155,086
Stream B	276,655	2,151	240,902	1,360	595,077
Stream C	76,610	1,594	68,839	1,258	122,154

### 3 SOLUTION

A solution to the problem is to utilize a phase-behavior model to predict the phase changes throughout the process. Generically these are called Process Simulation Models (PSM) and will be referred to as PSM in this paper. The PSM reduces the uncertainty of the shrinkage predictions, is comprehensive enough to resolve the intra-process recycled streams, and accounts for the interaction between the fluid streams when they are processed simultaneously. The PSM still uses a base EoS. Generally, an EoS such as Peng-Robinson or Soave-Redlich-Kwong (SRK) which are cubic equations capable of modeling vapor –liquid equilibrium [2] is used. And, the EoS must still be fit for the particular application in regards to the hydrocarbons and their proximity to critical regions, handling the phase-behavior of polar systems, etc. Different EoS may give rather differing results, especially in terms of the crucial compressibility factor  $Z_c$  resulting in different liquid densities. However, provided the EoS chosen uses the same alpha function and mixing rules, the ability of one EoS to model the process should be comparable to the next [3]. Therefore, the PSM offers a distinct improvement in reducing the biases created by an individual stream application of an EoS. However, even with this improvement, there are various application problems which must be accounted for. In order to properly apply the results in the allocation system an optimization process should be followed. Otherwise certain biases will remain in the allocation that cannot be resolved.

#### 3.1 Application of the PSM

Whenever a PSM is used in an allocation system, there exists a particular problem. The PSM can only give the correct answer when all inputs are considered simultaneously. However, the theoretical quantity for each input (or commingled stream) is needed on an individual basis in order to perform the allocation. Therefore a particular method of application must be employed to divide the more precise quantity considering all the commingled streams simultaneously into individual quantities relative to each commingled stream.

Three distinctive approaches are used in combination to resolve the problem. First, all the inputs are taken simultaneously to develop the best estimation of the theoretical quantity (note that normally two theoretical quantities are determined namely one for gas and one for liquid). These quantities represent the best estimation of the amount gas and liquid available at the end of the process based on the input quantities, their respective compositional make-up, and the various pressure and temperature changes relative to the process. This calculation is referred to as the “combined calculation” where all inputs are taken in combination. It is the results of the combined run that eventually are used on a stream-by-stream basis to perform the allocation. Let  $q$  stand for the quantity determined by the combined calculation.

Second, a theoretical quantity for each input ( $i$ ) must be determined. The best approach is the “by difference” method. For every input stream a calculation is performed using all the inputs except the one input in question. Let  $q_{xi}$  stand for the quantity determined excluding the  $i^{th}$  input. Then:

$$q_i'' = q - q_{xi} \quad (1)$$

This calculation ( $q$  double prime) is called a “by-difference” quantity. The by-difference quantity is normally very close to the proper or optimal quantity for an individual stream. However, when all the by-difference quantities are summed, the summation does not equal the results of the combined calculation. A differential ( $\delta q$ ) exists as follows:

$$\delta q = q - \sum_1^n q_i'' \quad (2)$$

The differential represents a small, but noticeable, difference in the PSM calculations due to the interaction of the different fluid types. The dissimilarity of the fluid properties causes a change in the result each time the PSM calculation is performed. Removing one stream from the combination constitutes a change in the overall “combined” fluid properties. The only exception to this rule is the rare case where the fluid properties from each combined stream are identical. This is never really the case, but often is nearly so. In fact, if the stream compositions are nearly all the same (e.g. all black oil, or all gas condensate, etc.) the need to perform a by-difference calculation or even a combined calculation would not be necessary. However, in today’s complex hub arrangement, one can expect a significant dissimilarity in fluid types to exist.

### 3.2 Determination of the Differential

The differential between the combined calculation and the by-difference calculation must be incorporated back into the allocation system. This is accomplished by determining the projected theoretical quantity when an input stream is considered by itself (i.e. no commingling). Let  $q'$  represent the “individual” calculation. Based on the individual calculation ( $q'$ ) in comparison to the by-difference calculations ( $q''$ ) an assignment of the differential is made so that the sum of the quantities assigned to each input will balance to the total quantity ( $q$ ) determined in the combined calculation. The process of assigning the differential is referred to as an “optimization” since it optimizes the assigned quantities to fit the combined calculation, which ultimately is the correct answer.

There is more than one approach to this “optimization” process. A simple approach is to assign the differential proportionally based on the by-difference calculation. While this method distributes the differential, it is not the most optimized. Since some of the input streams changed more than others when considered simultaneously in the combined calculation, it is unfair to assume they all changed proportionately to their respective original measured qualities.

Another way to distribute the differential is based on their respective change between their by-difference calculation ( $q''$ ) and their individual calculation ( $q'$ ). The following formula represents this relationship:

$$\delta q_i = \left( \frac{q'_i - q''_i}{\sum_1^n (q'_i - q''_i)} \right) \times \left( q - \sum_1^n q_i'' \right) \quad (3)$$

### 3.3 Divergence of Differentials

While this method appears to be more consistent than a simple proportional distribution it has a fatal flaw. Since some of the changes are positive and some are negative the distribution may diverge and result in larger and larger positive and negative numbers that when combined equate to the differential, but in very erroneous ways. Ultimately this method

produces an unlimited number of solutions each diverging from a single “optimal” solution. Table 4 shown below, provides two cases to illustrate the divergence of the differentials.

Case one is a typical case. The sum of the differentials ( $\delta_i$ ) as always equals the difference between the combine quantity ( $q$ ) and the sum of the “by-difference” quantities ( $q_i''$ ) as per Equation (2). The divergence is evident in that the sum of the absolute values of the differential is greater than difference between the combine quantity ( $q$ ) and the sum of the “by-difference” quantities ( $q_i''$ ). For case one the divergence is only about 6%.

In the extreme case (Case 2), however, the divergence is over 45 % of the original difference value. It is illogical to expect the magnitude of the differentials as a whole (sum) to be much greater than the original difference. Each assigned differential is supposedly only a portion of that difference. Therefore, in a perfect world the magnitude of the differentials (i.e. their absolute values) will equate to the original difference. The fact that some input streams change in a positive direction while others change in a negative direction keeps this from being the case. But this difference in mathematical sign, positive or negative, is also a prime consideration in the solution.

**Table 4 – Divergence of Assigned Differentials**  
(all quantity values in barrels)

Input $q_i$	By-Difference $q_i''$	Individual $q_i'$	Difference $q_i' - q_i''$	Differential $\delta q_i$
<b>CASE1 - Typical</b> (same as streams used in Table 1)				
Stream A	1,710,000.19	1,712,668.35	2,668.15	1,264.55
Stream B	760,651.02	763,357.10	2,706.08	1,282.53
Stream C	92,230.54	92,076.96	-153.58	-72.79
Sum	2,562,881.76	2,568,102.41	5,220.65	2,474.29
Combined ( $q$ )	2,565,356.05	Sum of absolute values		2,619.86
Difference $q - \sum q_i''$	2,474.29	Divergence $\frac{\sum ( \delta q_i  - \delta q_i)}{\sum \delta q_i}$		0.059
<b>CASE 2 – Extreme</b> (uses only liquid streams from Table 2)				
Stream A	1,708,027.46	1,719,914.73	11,887.27	950.76
Stream B	751,729.17	752,818.25	1,089.08	87.11
Stream C	91,485.71	89,086.16	-2,399.55	-191.92
Sum	2,551,242.34	2,561,819.14	10,576.80	845.95
Combined ( $q$ )	2,552,088.29	Sum of absolute values		1,229.79
Difference $q - \sum q_i''$	845.95	Divergence $\frac{\sum ( \delta q_i  - \delta q_i)}{\sum \delta q_i}$		0.454

### 3.4 Optimization of Differential

The differential created is distinctively either positive or negative. While, incorporated into the differential is any offsetting positive and negative changes, it is fair to assume that the resulting positive or negative differential was created more by those streams changing in the same (positive or negative) direction as the differential. Keep in mind that the differential represents a net positive or negative change. This is similar to distributing the system imbalance within a measurement system utilizing Uncertainty Based Allocation (UBA) [4]. However, unlike UBA where all inputs are assume to have additively created the imbalance, in this case a means to determine if an input contributed positively or negatively is possible.

Therefore, a more optimal approach is to divide this net negative or positive differential ( $\delta q$ ) among only the input stream demonstrating a like positive or negative change between the individual calculation ( $q'$ ) and the by-difference calculation ( $q''$ ). These particular inputs are designated as “participating” (part) and the other input streams as non-participating (non-part). The participating and non-participating differentials are defined such that:

$$\sum_1^n \delta q_{i,part} \equiv \delta q \quad (4)$$

and;

$$\delta q_{i,non-part} \equiv 0 \quad (5)$$

When considering only the participating input streams and considering the relative change between the individual and by-difference calculations, the following equation emerges as the assigned differential:

$$\delta q_{i,part} = \left[ \frac{q'_i - q''_i}{\sum_{1,part}^{n,part} (q'_i - q''_i)} \times (\delta q) \right] \quad (6)$$

Using the same scenario as above Table 5 shows the results of optimizing the differential according to equation (6).

**Table 5 – Optimized Differentials**  
(all quantity values in barrels)

Input	By-Difference $q''$	Individual $q'$	Difference $[q'' - q']$	Part.	Differential $\delta q_i$
Stream A	1,708,027	1,719,915	11,887	✓	775
Stream B	751,729	752,818	1,089	✓	71
Stream C	91,486	89,086	-2,400	☒	0
Summation	2,551,242	2,561,819	10,577		846
Combined ( $q$ )	2,552,088				
Difference $q - \sum q''_i$	846				

### 3.5 Mass versus Volume

A fair question at this point is why a mass based systems is not used. The mass of the streams whether in the form of gas or liquid at the beginning of the process will equal the mass of the combined stream at the end. This is true. Therefore, if the compositions of the streams are known at the beginning of the process, and likewise known at the end of the process, then simple mass balance of each component seems to resolve the problem. However, two realities must be dealt with. First, the rudimentary measurement of the inflow and outflow is based on volume. In the GoM the typical gas meter is an orifice meter and the flow equation can be easily converted to yield mass terms. The liquid meters, however, are typically turbine meters where a mass registration would require integration of the flowing liquid density. Therefore, the conversion to mass, at least on the liquid metering systems, represents another direct multiplier in the uncertainty, i.e. flowing density. However, this is not the main reason for using the volume based system.

The main reason mass is not used is that one export stream is inherently based on volume terms. The crude oil business in the US commercially operates on a volume basis. Since ultimately the purpose of the allocation system is to distribute the revenue, eventually a conversion to a volume basis is needed. It is possible to maintain a mass component based system and make the conversion to standard volume (barrels at standard temperature and pressure) at the end of the theoretical quantity calculation. To suggest this approach is a fair debate point, since it may simplify the process. It would be a very strong debate point if the base measurement of the liquid were in the form of mass such as with a direct mass measurement like Coriolis meters.

Overall, however, approaching the problem from a mass perspective will not diminish the need to use a PSM in the allocation process. The differential between the combined and the by-difference calculations will still exist and will need to be distributed among the inflow streams. While the total mass in will always equal the total mass out, the division of the mass outflow between gas and liquid phase will change. That is, some mass will change (predicted via the PSM) from gas to liquid or visa versa, when the streams are viewed individually as compared to when viewed in combination. Considering these issues, however, the mass question is still a valid point and should be studied for future implementation in the US metrology community.

## 4 ADVANTAGE, DISADVANTAGES AND FUTURE IMPROVEMENTS

### 4.1 ADVANTAGES

**Equity Assurance:** Overall the primary advantage is equity assurance in the assigned theoretical quantities. This improvement has long-reaching effects. The model approach reduces the measurement loss risk created by second generation tiebacks. Whenever a deepwater hub is installed, there exist a certain number of original tiebacks. The fluid types of the original tie-backs are often the same and thus dissimilar fluid type discrepancies are less of a problem. However, when new tiebacks seek to join an existing hub structure, a dichotomy is created. The new tieback may contain a different set of owners and a different fluid type. Often the second generation tiebacks are gas wells since gas can travel a longer distance. The arrival of a second generation tieback with a dissimilar fluid type will increase the measurement risk, either for itself or the original tiebacks, or possible for both depending on the scenario. The use of a PSM minimizes these effects. This greatly helps in the commercial viability of new production that needs to occupy the ullage created over time on the existing deepwater hubs.

**Balance Performance:** As highlighted in section 2.4 above, the PSM improves the system balance when viewed as a liquid and gas balance independently. Since the gas and liquid measurement systems within the process operate somewhat independently, monitoring their respective material balance independently is an advantage over a simple mass balance for the entire gas-liquid combined systems. The overall measurement system is better controlled and mis-measurements are more easily detected.

**Fuel Allocation:** A large secondary advantage offered by a PSM is the capability of predicting energy requirements for compression and pumping equipment. Normally the most detailed portion of the allocation systems is the fuel assignment. Since each stream requires a different amount of fuel for processing, the fuel assignment must be very detailed in order to allocate the consumed gas properly. Calculating a proper fuel allocation is very tedious. The PSM however, when calculating a stream on an individual basis, can predict the energy required for compression (the major fuel consumption need). This becomes a theoretical fuel and is called the "primary fuel". The fuel for smaller equipment, crew quarters, light, etc. is called the residual fuel and is taken as the difference between the total measured fuel gas and the sum of the theoretical fuel calculated by the PSM. The residual fuel is normally small compared to the primary fuel and is allocated on a general produced volume basis. This simplifies the fuel assignment a great deal.

**Sampling:** The main advantage here is a general reduction in sampling and a simplification of the analytical process. Previously, non-modeled approaches required a determination of the shrinkage and flash factors. This is extremely difficult and costly to do precisely. The best approach has always been to perform a full PVT (pressure-volume-temperature) analysis which can range up to US \$3,000 per test. Short-cuts have also been developed to avoid a full PVT analysis but this normally involves an EoS and detailed compositional analysis. These “short-cut” tests have traditionally been hampered by high random uncertainty, resulting in degradation in the confidence level in their results. The short-cut test cost about US \$1,000 per test. By utilizing a modeled approach, only the composition of the liquid and gas is needed to be known. As a comparison to past practice, the simple composition tests are more easily performed which results in better repeatability and reproducibility and thus instill higher confidence. Composition tests generally cost less the more complex tests.

Furthermore, use of the model can validate samples. Whenever a liquid or gas sample composition is determined, the model is used along with the pressure and temperature of the associated separation vessel to check the sample. If the model indicates that a liquid sample does not exist fully as a liquid, or visa versa for a gas sample, the samples are disqualified. Normally this indicates that some free gas or free liquids were inadvertently introduced to the sample. Overall, however, the greatest sampling advantage found by using phase-behavior modeling, is that the laboratory analysis is simplified. The laboratories can concentrate on what they do best; compositional analysis. Shrinkage and flash analysis which are by far the highest variables in the measurement system are greatly reduced through the proper application of a PSM.

## 4.2 DISADVANTAGES

**Engineering Oversight:** The greatest disadvantage to using a PSM within the allocation process is the depth of engineering oversight needed. Previously, in the GoM measurement data was passed to hydrocarbon accounting personnel for processing. That was generally the end of the story. The use of PSM creates an additional step in the allocation process. The process pressure and temperature, and fluid compositional data must be validated prior to executing the PSM logic. Additionally, abnormal operations must be viewed critically against the PSM. The individuals needed to perform this work are either process engineers or under the direction of process engineers.

**Intra-Process Points:** There is also a greater dependence on pressure and temperature data from within the process (i.e. not just at the metering points). Often pressure and temperature data not associated with metering systems is less scrutinized. Therefore, errors may be made by faulty instruments that, being not critical to day-to-day operations, may be overlooked.

**Individual Routines:** To the author’s knowledge no known vendor markets allocation software systems where a PSM model is integral to the routine. However, even if this were available, it would likely not be attractive, since it would make future revision to the PSM software very difficult. And due to the individualistic nature of the PSM, it makes it almost impossible to duplicate or standardize an allocation routine. However, it is the opinion of the authors that duplicating allocation routines between various operations is dangerous and should be avoided. Most operations are different enough to warrant individually developed allocation routines.

## 4.3 FUTURE IMPROVEMENTS

**Standardization:** One primary future improvement is the standardization of PSM selection and application. Which EoS is chosen, and how the PSM is formulated should follow a set of general principles. Generally little is known or standardized in this area. Furthermore, it is known that each EoS may yield different results, especially in predicting the behavior of long-chain molecules [5].

**Auditability/Security:** Another area for improvement is auditability. While normally the pressure and temperature data is well documented, and the PSM itself is documented, during times of the abnormal operation some critical decisions must be made. Integrating a system to provide an audit trail and thus security on necessary process data changes, will improve the accounting aspects of using a PSM.

## 5 CONCLUSION

Based on the direction of large oil and gas operations, disparity of ownership together with dissimilarity of fluids is a continuing reality. The consequences when applied to oil and gas valuation make the use of phase-behavior models in production allocation systems advantageous. The advantages outweigh the disadvantages by an overwhelming amount. Continued use of non-modeled systems introduce biases that over the life of a production facility will likely disadvantage one party over another well beyond the capital cost required to establish and operate the PSM. Improvements within the PSM application, especially improvements in the EoS applications and reproducibility between competing equations, should be a primary goal of the metrology community within the oil and gas industry. In the author's opinion, the industry should move quickly to recognize the practice and standardize the selection and application of the PSM. In the future the PSM should be considered as a basic component of most measurement and allocation systems.

## 6 NOTATION

$q$	stands for a quantity predicted by the PSM considering all input stream simultaneously
$q_{xi}$	stands for a quantity predicted by the PSM considering all input stream simultaneously except the $i^{\text{th}}$ stream
$q_i''$	stands for the "by-difference" quantity predicted by the PSM (see equation 1)
$\delta q$	stands for the total differential between the PSM predicted quantity considering all stream simultaneously and the sum of the "by-difference"
$\delta q_i$	stands for the portion of the differential assignable to the $i^{\text{th}}$ stream
$\delta q_{i,part}$	stands for the portion of the differential assignable to the $i^{\text{th}}$ ( <i>participating</i> ) stream, where a like change between individual and by-difference calculations either positive or negative as compared to the differential either positive or negative, constitutes participation
$\delta q_{i,non-part}$	stands for the portion of the differential assignable to the $i^{\text{th}}$ ( <i>non-participating</i> ) stream, which is always equal to zero.

## 7 REFERENCES

- [1] API Manual of Petroleum Measurement Standards, Chapter 20, Section One, "Allocation Measurement", First Edition, September 1993
- [2] Suppes, G.J., year unknown. "Selecting Thermodynamic Models for Process Simulation of Organic VEL and LLE Systems", Department of Chemical Engineering, The University of Missouri-Columbia. Available via online search at the following source: <http://students.aische.org/pdfs/thermodynamics.pdf>
- [3] Twu, C.H., Sim, W. D., Tassone, V., "Getting a Handle on Advanced Cubic Equations of State", Chemical Engineering Process (CEP) Magazine, Vol. 98, (November, 2002): 58-65.
- [4] Webb, R., Letton, W., Basil, M., "Determination of Measurement Uncertainty for the Purpose of Wet Gas Hydrocarbon Allocation", North Sea Flow Measurement Workshop, September, 22-25, 2002.
- [5] Ghosh, A., Chapman, W.G., French, R. N., "Gas Solubility in Hydrocarbons – a SAFT-based Approach", Fluid Phase Equilibrium, Vol. 209 (2003): 229-243.

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**APPENDIX**

Following is the gas and liquid composition of the three streams (A, B, and C) used as an example within this paper.

**Table 6 – Stream Compositions**

	Gas			Liquid		
	A	B	C	A	B	C
Methane	0.8906	0.8954	0.9647	0.0642	0.2129	0.4346
Ethane	0.0194	0.0435	0.0109	0.0152	0.0299	0.0190
Propane	0.0384	0.0303	0.0112	0.0285	0.0368	0.0360
i-Butane	0.0050	0.0069	0.0021	0.0108	0.0233	0.0248
n-Butane	0.0188	0.0093	0.0060	0.0312	0.0376	0.0293
i-Pentane	0.0161	0.0038	0.0019	0.0171	0.0280	0.0303
n-Pentane	0.0083	0.0042	0.0024	0.0220	0.0370	0.0287
n-Hexane	0.0016	0.0041	0.0003	0.0248	0.0704	0.0373
n-Heptane	0.0004	0.0019	0.0002	0.0311	0.1372	0.0843
n-Octane	0.0004	0.0003	0.0001	0.0496	0.1628	0.0575
n-Nonane	0.0004	0.0002	0.0000	0.0313	0.0699	0.0327
n-Decane	0.0007	0.0002	0.0001	0.0319	0.0579	0.0362
n-C11	0.0000	0.0000	0.0000	0.0383	0.0345	0.0292
n-C12	0.0000	0.0000	0.0000	0.0392	0.0187	0.0218
n-C13	0.0000	0.0000	0.0000	0.0441	0.0130	0.0194
n-C14	0.0000	0.0000	0.0000	0.0456	0.0073	0.0153
n-C15	0.0000	0.0000	0.0000	0.0444	0.0050	0.0133
n-C16	0.0000	0.0000	0.0000	0.0369	0.0026	0.0094
n-C17	0.0000	0.0000	0.0000	0.0366	0.0019	0.0083
n-C18	0.0000	0.0000	0.0000	0.0317	0.0012	0.0069
n-C19	0.0000	0.0000	0.0000	0.0311	0.0008	0.0056
n-C20	0.0000	0.0000	0.0000	0.0264	0.0005	0.0043
n-C21	0.0000	0.0000	0.0000	0.0233	0.0003	0.0035
n-C22	0.0000	0.0000	0.0000	0.0200	0.0002	0.0027
n-C23	0.0000	0.0000	0.0000	0.0191	0.0002	0.0025
n-C24	0.0000	0.0000	0.0000	0.0163	0.0002	0.0020
n-C25	0.0000	0.0000	0.0000	0.0169	0.0016	0.0015
n-C26	0.0000	0.0000	0.0000	0.0143	0.0016	0.0014
n-C27	0.0000	0.0000	0.0000	0.0138	0.0012	0.0001
n-C28	0.0000	0.0000	0.0000	0.0115	0.0010	0.0009
n-C29	0.0000	0.0000	0.0000	0.0110	0.0012	0.0009
n-C30	0.0000	0.0000	0.0000	0.1218	0.0032	0.0001
	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000