Paper 7

Wet Gas Allocation on the Canyon Express Project

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1 INTRODUCTION

In September 2002, production from the three fields that together form the Canyon Express Project - King's Peak, Aconcagua, and Camden Hills - was begun. Drilled in record water depths of 2000 to 2200 meters in the Eastern Gulf of Mexico, each of the nine wells was connected to one of two 12-inch pipelines carrying the commingled wet gas back to the Canyon Station platform for processing, a distance of 91 kilometers away in Main Pass block 261.

Dual-differential wet gas meters were chosen for the task of allocating gas and liquid back to individual wells. Because the gas from all three fields is relatively "dry" (Lockhart-Martinelli parameter < 0.01, GVF > 99%) and because the operating pressures are quite high (~ 250 bar), this was an area of application in which these devices had heretofore not been applied.

The use of these meters on the nine wells making up the Canyon Express Project is reviewed and discussed in detail. Their unusual performance is explained, and the route to an acceptable overall measurement experience is explored, including the manner in which successful allocation was achieved. Finally, several important lessons that were learned during the course of the project are presented.

2 METER EXPERIENCE

The crucial choice of which subsea allocation metering device to use was made around the time of project sanction in the fall of 2000. At that time the primary method for wet gas measurement was use of various differential meters in the manner first suggested by Murdock [1].

SOLARTRON ISA was in the process of introducing their modified dual-differential meter, the DualStream II. Even though production from all Canyon Express fields was expected to be very dry, each partner was keen to know the onset of water from any well. Combined liquid (water, methanol, and condensate) from any single well was not expected to exceed 4 BBL/MMSFD at startup. Since the Dual Stream II had shown the potential to provide such an estimate [2], and appeared to be unique at that time, it was chosen for this job.

It was recognized that Canyon Express would take the meter's technology into measurement territory in which it had not been tested heretofore. Not only was the water depth far greater than the DualStream II - or any other meter - had ever been tested, but pressures of 250 bar at the measurement points would be much higher than had been previously experienced. So careful and thorough measurement testing and calibration at a reference facility was required.

It is difficult to overstate the importance of the subsea allocation meters in the operation of Canyon Express. Raw cash flow through the system is several million dollars each day. Small errors in measurement can thus be financially devastating to the affected partner, and large errors catastrophic.

2.1 METER CALIBRATION

The high-pressure multiphase flow loop at the Southwest Research Institute (SwRI) opened for business in the summer of 2001. As stated earlier, the Canyon Express working pressure of approximately 250 bar was far greater than any application experienced by the meter up to that point in time. Only SwRI was able to achieve this pressure; no other wet gas calibration facility operated at even 50% of this figure. Finally, the fact that SwRI was capable of circulating natural gas, decane, methanol, and water through the meter at varying liquid loads, was also unique. For these reasons, it was the clear choice for calibration of the Dual Stream II meter as planned for Canyon Express.

The test program for the meter was quite exhaustive, and covered not only variations in pressure but also liquid loading and, to some degree, liquid composition. The composite results for the test program are shown in Figures 1 and 2. Plotted against Gas Volume Fraction, the relative uncertainties for gas flow measurement are generally less than 3% for all GVF, and for liquid flow measurement are less than 20% up to 99% GVF. Above 99% GVF, where the Canyon Express meters would operate, the liquid uncertainties bloomed out to as much as 80%. The meter’s performance in this region is not especially surprising. It has often been pointed out [4] that the simple Murdock correction is not sufficient to properly model the flow measurement process for very low Lockhart-Martinelli values. Improvement of the models used for the low-liquid range would certainly improve meter accuracy.

While the calibration results thus obtained might be considered alarming, when viewed in the context of detection of the onset of water production, it was not considered a catastrophe.

2.2 METER PERFORMANCE

The first meters were installed in a jumper configuration on three of the Canyon Express wells during the beginning of September of 2002. First production occurred in mid-September 2002, with all meters installed and all wells having been initially tested by the end of October 2002. Shakeout of early production issues continued through the end of 2002.

During this startup period a great deal of attention was paid to flow rates from the wet gas meters, both for liquid and gas. Although for Canyon Express the gas is by far the more important component, in this early testing, the meter's estimates of liquid drew most attention. Whereas an absolute maximum of 100 - 200 BBL/D of liquids (production plus injected methanol) was expected through each meter, the initial estimates being returned by the meters were far greater, in some cases as much as 2000 BBL/D. Since each separator on Canyon Station is capable of handling 1750 BBL/D and was seeing nowhere near this amount of liquid, it seemed clear that something was wrong in the subsea measurement process.

Initially suspicions were directed toward the sensors, in particular the differential pressure (DP) transmitters. In many cases where everything looked close to normal in terms of gas flow rate agreement between the two differential meters (wedge and Venturi), all six differential pressure sensors on each meter (low and high range, triple redundancy) appeared to be functioning correctly. The differential pressure of each of the six sensors was within about 1% of their average.

There were, however, instances where the redundancy was not sufficient to prevent questionable measurement. The major redundancy problem was the fact that the low range sensors were often saturated. It was not possible to re-scale them remotely. Two of the three fields utilized only dual redundant sensors, thus making it important to set strict limits on the required agreement between a meter's sensors before questioning the data.

There were cases where the calculated flowrates from the two differential devices showed significant differences as the line pressure was changing. Because of the well-known effect of line pressure on differential pressure sensors, this was investigated as a possible cause of the observed problems. A review of the calibration procedure and test reports for the installed differential pressure sensors failed to uncover any obvious errors. Since the original sensor calibration procedure called for testing only at atmospheric and maximum pressures, similar sensors were then tested at intermediate pressures by Advantica Technology. These tests revealed only a very small line pressure effect for these "smart" sensors.

Therefore it was concluded that these potential sources of measurement error in DP were unlikely to cause problems of the magnitude being observed in the Canyon Express meters. Having ruled out sensors as the problem source, only the application of the methodology remained to be considered.

2.3 RESOLUTION OF METER ISSUES

Another of the principal reasons the Dual Stream was selected for Canyon Express was the fallback position its component meters offered in case its primary outputs were somehow not useable. Indeed, of the alternative devices available at the time of selection, wet-gas differential meters (Venturi, orifice, etc.) were the leading candidates.

It is useful to look at the principles used by these meters and to recognize how the Canyon Express application fits. It is well known that differential meters over-read the true gas flow rate when liquids are present. A typical differential over-read curve is shown in Figure 3, with the device over-reading plotted against the well-known Lockhart-Martinelli parameter. The exact shape of the curve depends on the geometry of the meter, the properties of the fluids passing through it, and the pressure in the pipe, but it is linear with respect to L-M, a measure of “wetness”.

The SOLARTRON ISA Dual Stream II incorporates two differential devices in a single meter, each with a different characteristic of the type shown in Figure 3. SOLARTRON ISA have observed that only the difference in the two characteristic over-read curves is required in their analysis. If the slope of the typical characteristic in Figure 3 is **M**, then the slope of the difference characteristic is **ΔM**. An example of this difference characteristic is shown in Figure 4, which is that recorded at SwRI during the calibration tests discussed earlier. As de Leeuw [3] showed with respect to individual differential meters, the slope of the difference curve decreases with pressure. This will be discussed in more detail later.

Nominal Canyon Express operating parameters are:

$$Q_g^v = 50 MMSCFD$$

$$Q_l^v = 100 BBL / DAY \text{ (including methanol)}$$

$$\rho_g = 160 kg / m^3$$

$$\rho_l = 800 kg / m^3$$

These properties result in a nominal range of Lockhart-Martinelli parameters of .006 - .007.

The fundamental tenet of the Dual Stream II meter is that the difference in the amount of over-reading between the two devices it incorporates is indicative of the wetness of the gas, i.e. the Lockhart-Martinelli (L-M) parameter. For gas as dry as that at Canyon Express, the over-reading of the individual meters as well as the over-reading difference should be quite small. From Figure 4 one observes that the relative difference in over-reading of the two meters must be less than .005 (0.5%) for the L-M of .007 calculated above.

But this is the crux of the problem. Asking that two differential meters each are accurate to within 0.2 - 0.3% is demanding far too much. It is probably not reasonable to expect that the two devices exposed to production conditions over long periods of time will be accurate to any better than a few percent, either individually or as a difference.

Consider the case shown in Figure 5. The data shown are from one of the Canyon Express wells during three days in November 2002. Shown are the gas flowrates calculated from the wedge and Venturi meters, the difference between the wedge and Venturi flowrates, and the estimated gas and liquid flowrates from the meter’s algorithm.

For this fairly prolific well which produces just under 50 MMSCFD, the two meters read within 1 – 1.5% of one another. For two meters which have been unattended on the sea floor for several months and have had a new producing well "clean up" through them, this difference isn't unreasonable. However it is sufficient to create an estimated liquid rate of about 1 kg/sec, or 680 BBLD, about ten times the true rate. Additionally, it is clear that this estimate of liquid rate from the meter algorithm is correlated directly to the difference between the Venturi and wedge readings. Furthermore, because the estimate of liquid production is too high, the gas rate must be lower to compensate, so the estimated gas flow from the algorithm is always 4-6 MMSCFD too low.

It should be pointed out that the high pressure environment exacerbates the situation by flattening out the over-read curve. Shown in Figure 6 is a lower pressure version of the characteristic curve shown in Figure 4. These data taken at about 80 bar show a ΔM more than twice that of the 250-bar data, a fact that amplifies the effect of errors in individual meters. Based on this and other similar examples, it was concluded that using the Dual Stream II wet gas algorithm would not be appropriate for allocation of gas production for Canyon Express, but that using either wedge or Venturi meters for this purpose should be possible.

3 CANYON EXPRESS ALLOCATION

Once the decision was taken to discard readings from the DualStream II algorithm, and instead to use either the Dual Stream's wedge or Venturi meters as the allocation device for gas (and using GOR for condensate), the performance of these two meters in the individual wells came under much closer scrutiny. Given the exceptional dryness of the gas, with Lockhart-Martinelli parameter less than .01, the over-reading of the Venturi and wedge meters should be quite low. Indeed, the results from SwRI suggest that no more than 1-2% should be observed, and even then all meters should observe such a bias in the same direction, if not by the same precise amount.

While the issues of the SOLARTRON ISA Dual Stream II meter were being wrestled, a more sinister problem was beginning to manifest itself. As of the end of 2002 the official start-up period was at a close, and 'normal' operations were to begin. Unfortunately, the difference between what was being measured on the sea floor and what was seen topside was large, and at times changing in unknown ways.

3.1 TOPSIDE VERSUS SUBSEA COMPARISONS

Figure 7 illustrates the major issue facing Canyon Express as normal steady production began early in 2003. The wedge meters from each of the SOLARTRON ISA Dual Stream meters were chosen over the Venturi meters for the gas allocation, primarily because differential pressure sensor saturation on the Venturis occurred at a lower flow rate. Furthermore, in all cases where there was no sensor saturation it was noted that the wedge and Venturi totals were over-reading the topsides meter totals by virtually the same amount, making the CE partners even more comfortable choosing the wedge. Using the wedge meters, the balance on both flow lines stayed consistently between 5-8% until mid-January of 2003. No one was particularly pleased with this situation, but since it seemed consistent, and since there was no evidence that the over-reading in any one meter was more than any other, the partners accepted the allocations. But in mid-January, the imbalance on both flow lines began to drift to the 15-20% range, indicating inconsistency and fueling the belief that the over-reading was not equal among the meters. Clearly something needed to be done to understand how the process was being corrupted, and to identify a way out of the predicament.

An event that took place in early March uncovered a likely source of the imbalance problem. An ROV retrieved the choke from one of the wells, and revealed what might be called the "smoking gun": the inside of the choke was covered with a thick scale. A camera looking back inside the jumper toward the meter confirmed the existence of scale on the walls of the jumper and meter. Samples of the scale removed are shown in Figure 8. Once it was recognized as a problem on the one well, it was strongly suspected that 3 or 4 of the other wells were also producing scale. Clearly, the scale was impairing not only the choke's proper operation, but also that of the meter located only a few meters downstream.

If the meter on this stream had indeed experienced a reduction in diameter due to a buildup of scale, this change of geometry would have reduced the beta ratio of the meter and caused a corresponding over-reading in its response. The differences between the Venturi and wedge cited were likely an effect of scale in some of the meters, causing the large errors in liquid estimates. The worst result of the scale, though, was the increased error in gas measurement.

Since this had happened on a single meter, could one be sure that all the other meters in the system were not affected? The scale production was quickly stopped by scale inhibitor injection, but the scale that had already formed could not be removed without a multi-million dollar intervention, and even then there were no guarantees that the meter's original geometry could be restored. It was obvious that this was an extremely serious problem, and something had to be done.

3.2 CALIBRATION STRATEGY

With nine meters on the sea floor and the possibility that all might be giving wrong readings, it was of paramount importance to find a way to verify the performance of each device. Given that (1) intervention to replace a meter would be enormously expensive, and (2) gas production was so prolific that any prolonged reduction in rates must be considered only as a last resort, a creative way to verify and, if possible, to calibrate each meter was needed.

It was decided that online calibration of individual subsea allocation meters using the meters on the Canyon Station platform as reference was a viable approach. Making this work would not be straightforward, since there were 80-100 km of pipeline between reference meters and each meter under test. Furthermore, the flow through the meter under test must be commingled with that from several other meters, so the procedure which would be employed could not be that of a classical flow calibration.

The method developed for Canyon Express involved careful calibration of individual meters using difference methods. That is, while flow through all other meters on an individual flow line is held constant (or as nearly so as possible), flow through the meter under test and the reference meter are observed at three or more flow rates ranging from full flow down to shut-in. Changes in the flow of the other meters on the line must be monitored as well, and the (typically small) differences accounted for in the calculations. Any pressure variation must have settled in order to prevent line packing from corrupting the results.

For this analysis it is assumed that the relationship between flow measured at the reference meter and that observed at the meter under test is

$$Q_{ref} = k \cdot Q + b \qquad (1)$$

The three or more measurement points made are used to determine **k** (meter factor) and **b** (meter bias). The measurements made while the well is flowing (not shut in) define **k**, i.e. the amount of change in reference reading caused by a given change in the reading of the meter under test. However the meter bias can only be determined by taking the well to shut-in.

In a normal calibration, the points taken at full and reduced flow would be sufficient to define not only the meter factor, but the meter bias as well. However, in the present case the fact that other wells are flowing into the same line preludes this as a possibility. Without other information, nothing is known about the absolute flow through the meter under test, only its relative flow rate as estimated from the difference in reference readings.

The additional information required comes from reducing the flow through the meter under test down to shut-in, as demonstrated in the following example. In Table 1, the reference readings and those measured by the meter on the Well 305-2 are shown in the first two columns. In this example the first row of data represents full flow from 305-2, the second row approximately 50%, and the third row shows the reference meter reading during shut-in.

Q_{ref}	$Q_{305\text{-}2}$	$Q_{305\text{-}2\ ref}$
239	78	75
199	35	35
164		0

Table 1. Multi-level calibration readings for well 305-2.

Although there is no reference meter in the 305-2 line, if there were it would read zero flow when the well is shut in. Given this fact, and realizing that the differences in Q_{ref} can only be attributed to true flow rate changes in 305-2, one has the data necessary to create a typical calibration curve. Flow through 305-2 is zero during shut-in, is (199-164) = 35 at half flow, and finally is (239-164) = 75 at full flow. With these data, a calibration curve for the allocation meter on well 305-2 is plotted in Figure 9.

Re-arranging the terms in Equation (1),

$$Q = \frac{1}{k} \cdot Q_{ref} - \frac{b}{k} \qquad (2)$$

Here the reference readings are the inferred measurements given in the third column of Table 1. Using these data, the quantities **k** and **b** can be found.

$$k = \frac{Q_{305-2ref2} - Q_{305-2ref1}}{Q_{305-2-2} - Q_{305-2-1}} \qquad (3)$$

$$k = \frac{75-35}{78-35} = .93$$

$$b = Q_{305-2ref1} - k \cdot Q_{305-2-1} \qquad (4)$$

$$b = 35 - .93 \cdot 35 = 2.44$$

Thus the equation used to correct the allocation meter on Well 305-2 is

$$Q_{corr} = .93 \cdot Q_{305-2-1} + 2.44 \qquad (5)$$

Figure 10 shows how it is recommended the procedure be performed. Measurement begins with a quiescent period of at least four hours wherein flow rates and pressures are all nearly constant. During this period, highlighted on the curve labeled “Separator”, the readings from each meter are averaged (integrated) and recorded. Then the flow for the meter under test (348-1) is choked back to a rate which is about 75% of that recorded at full flow, from about 58 to 42 MMSCFD. Although the 348-1 meter reaches a stable value quickly, it is several more hours before the reference meter has achieved stability. Once there, the readings from the four allocation meters and the reference meter are individually averaged for several hours. Then the flow from 348-1 is reduced again, this time to roughly 50% of full flow, and the procedure described above is repeated. Finally, in addition to these three points the necessary shut-in point is taken using the same procedure.

As was pointed out earlier, during the calibration of a meter the changes in flow rates of the other meters on the line must be recorded as well, and the (typically small) differences accounted for in the calculations. Since this accounting assumes the correct application of meter factors and biases for these meters, the total process is iterative. Finally, any pressure variations must have settled in order to prevent line packing from corrupting the results.

Using the data collected in the exercise of Figure 10 results in the calibration curve shown in Figure 11. One of the benefits of having three flowing test points and a shut-in point is that the parameter R^2 can be calculated, providing an indicator of the linearity of the curve, with a value of 1.0 being perfectly linear.

Though the bias in the 348-1 calibration is small, the meter factor in this case is anything but. The fact that the meter consistently measured 15% high was bad enough, but subsequent calibrations of other meters showed them to be over-reading by as much as 20-30%, thus demonstrating why developing such a procedure for Canyon Express was crucial.

3.3 RESULTS OF CALIBRATION IMPLEMENTATION

The Q1 balance results shown in Figure 7 were poor enough that it was hoped that the new methods could be used to fix them. Unfortunately, the new methodology was only developed and ready for use in April. But the desire to improve the balance results for the first quarter was so great that a search for alternative schemes was begun.

What was ultimately employed for the three months in question was a less-than-optimal implementation of the full calibration procedure. For most of the Canyon Express meters there was at least one period during the four months when the meter was shut in for testing of the subsea safety valve. When this occurred, if the other meters on that line were reasonably stable, a two-point calibration could be employed. For some of the meters there was no such data available, so other less direct methods were tried. In spite of these problems, some useful data was available for each meter, although having only two calibration points meant that only a meter factor (no bias) could be found.

When the meter factors thus derived were applied to the production data for the first quarter, the results obtained were those shown in Figure 12. Although the daily balance fluctuated from –4% to +8%, the composite balance was -0.59% on the east line and -0.72% on the west line over the three month period. Large daily fluctuations of this type are normal when flow rates through the meters are varying as much as occurred during this period.

Having dealt with the first quarter when there was no organized program for online meter calibration, attention was then turned to deriving meter factors and biases for each of the meters. Sequentially over a period of three weeks during April and May each of eight meters currently operational on the two flow lines was tested using the four-point method described earlier. Using these meter factors and biases on production data from the months of April and May yielded the results shown in Figure 13. Although the daily balances ranged from –5% to +5%, the balance over the two-month period was better than 1% on each of the two flow lines.

3.4 RESULTS SINCE MAY

Once the methodology for calibrating the allocation meters had been proved, the Canyon Express partners put procedures into place to take action should balances begin to drift beyond specific thresholds for protracted periods. Sure enough, after this practice began in May, alarms were triggered in early July indicating that the balance had wandered beyond acceptable limits.

During the first five months of 2003, when several of the subsea meters were creating the imbalance conditions described earlier, the meters were nearly always reading high. After completing June in a state of good balance, the July problem suggested one or more of the meters was moving in the other direction, i.e., it was under-reading flow based on the April-May calibrations. When the 7-day balance check exceeded -3 %, prescribed steps were undertaken to identify the well(s) and meter(s) responsible and perform the necessary actions.

By the time the problem meter had been identified and re-calibration procedures initiated, the 7-day imbalance was almost -4%. A four-point calibration was performed on the errant meter, which showed its meter factor had changed from 0.74 to 0.89. The meter, which had been over-reading by more than 30%, was now only 12% high. Interestingly, this was the meter on Well 305-3, the one which had shown the large scale deposits when the intervention had been performed in March. What is believed to have happened is that, for whatever reason, some substantial part of the scale broke off the meter, thus increasing its effective diameter and beta ratio and reducing its differential pressure drop.

Once the new meter factor and bias had been applied, the 7-day balance returned to 0.5% and has remained in the range of +/-1% ever since.

4 INSTALLATION AND OPERATIONAL CONSIDERATIONS

In addition to what was learned from a measurement perspective, the Canyon Express project was an excellent teacher in the design, installation, and operation of wet gas meters in extremely deep water. Listed below are several of the Lessons Learned from this demanding exercise.

4.1 SEPARATE METER FROM JUMPER

One of the biggest problems that occurred with the meter involved the installation of the meter and jumper. By incorporating the meter into the jumper from the tree to the flow line, it became necessary to remove the jumper if a meter malfunctioned. In the project phase it was reasoned that, although a jumper recovery is a difficult operation, it could be done if necessary. It was believed that the addition of connectors necessary to make the meter itself removable was a greater risk in the long term, since extra leak paths would be introduced. In actuality, the jumper installation proved much more difficult than expected because the meter and its associated panels and devices made the stability of the jumper during installation a difficult task. Additional rigging was installed on the jumper which made normal jumper installation movements difficult for the ROV (remote operated vehicle), resulting in the ROV becoming tangled in the rigging on more than one occasion. Of the nine jumpers installed, two were bent, one of which so badly that the meter had to be replaced. Because of the difficulty in installation, all field owners became reluctant even to consider a jumper removal for fear of not being able to re-attach it.

Because of this it is recommended that in future subsea wet gas flow meter (WGFM) installations, the design should allow for the meter to be removed without disconnecting the jumper. Though this definitely has its own risks and requires further study, it is believed that for a meter installed subsea, directly in front of a producing well, with no protection from scale, debris, etc., it will eventually be necessary to remove the meter, and this will be easier to do if the meter is not integral to the jumper.

4.2 BETTER HEAT TRANSFER IN METER CAPILLARIES

All WGFM's will have some sort of static sensing line tapped into the flow stream that will be used to sense temperature, static pressure, differential pressure, etc. It is essential to insure that these lines are protected from hydrate plugging. On Canyon Express, methanol was continuously injected so hydrate plugging was not a concern. Even without methanol injection at a well during steady state flow, it was felt that jumper and meter did not need methanol flow because the heat from the produced fluid was sufficient. While this is clearly true for the jumper, Canyon Express demonstrated that this was not necessarily true for the meter.

In the early months of operation, Canyon Express experienced plugging in some of its subsea methanol filters, restricting the methanol injection at certain wells. As a boat was being mobilized to replace the filters, some wells continued to flow with barely enough methanol flow. Because it was best to flow the bulk of the methanol in each flowline at the farthest well, the decision was made to shut-in methanol flow at a well closer to the platform, thus diverting methanol to the well farthest from the platform. When this was done, no effect was seen at the chosen well for 12 hours and the meter and jumper both appeared unaffected. However, after 12 hours the flow rate at the well began drifting wildly from peak flow to low flow and back again, as shown in Figure 14. This continued for several hours while the problem was being diagnosed. Further review of the meter configuration led to the conclusion that the meter capillary tubes were in fact far enough away from the flow stream for the ambient water temperature (36 deg F) to counteract the produced fluid temperature (130 deg) and to allow temperatures in the upper ends of the capillaries to reach the hydrate formation range. After 12 hours, enough water vapor had traveled up the capillaries, condensed, and then formed a hydrate plug. The well was temporarily shut in and, once the methanol filters had been repaired, was thoroughly flushed with methanol. Once the well was ramped back up to full flow rate with generous amounts of methanol injected, the plug disappeared. A better look at heat transfer of the produced fluid and ambient seawater to the static sections of the meter should have been undertaken before methanol flow was temporarily stopped. Since it is likely that future projects similar to Canyon Express will experience times where it is desirable to flow a well without methanol injection at that well (while protecting the flow line with upstream well), it is recommended that heat transfer on future subsea meter capillaries is thoroughly reviewed and that heat tracing is considered.

4.3 FLUSHING OF CAPILLARY LINES

There have been several instances in which operations would have been aided if there were the ability for the operator to flush the meter capillary lines from the surface with methanol. The case given earlier of hydrate plugging in the capillary certainly points to the need for flushing the capillaries, but that is not the only example. In the early months of operation, one of the wells started to show a meter drift that was difficult to explain. The well flow rate, pressure, and temperature had been consistent for weeks, but the Venturi and wedge flow rates began creeping up 5-10%.

Investigation showed that the redundant differential pressure (DP) sensors on the meter were no longer tracking each other, and there was an apparent partial blockage of one of the capillary tubes on the wedge meter and two on the Venturi meter . A drift upward was seen on the measured DP on both the wedge and Venturi, which lead to incorrect flow rate calculations .The meter was declared to be malfunctioning, requiring the field owner to fix the meter, which possibly meant replacement. An ROV vessel was mobilized to troubleshoot the problem, and hopefully restore the meter to functionality. Luckily, the meter was fixed by switching out a sensor set on the wedge and Venturi with a spare set on the meter. The meter is functioning properly today, but a $150K intervention had to take place to restore it. The cause of the problem has never been identified, but it is believed that either debris or scale lodged in the capillary tubes were causing a restriction and leading to erroneous DP readings. The ability to flush the capillary tubes with methanol would have been a fairly inexpensive capital expense that would have likely fixed the problem without an intervention. Topside meters need to be cleaned periodically, so it is reasonable that subsea meters in harsher environments next to the well will also need some form of cleaning. The ability to flush the capillaries would give the operator additional options that would likely save future interventions.

5 CONCLUSIONS, THOUGHTS FOR THE FUTURE

The Canyon Express Project was a pioneer experience in many ways, not the least of which was measurement. Since it today holds the World's deepwater hydrocarbon production record, it is obviously the deepest water in which meters to quantify production have ever been deployed. Much knowledge has been gained in the process, some of which is summarized here.

Differential Meters Can Operate Successfully. After over 13 months of near continuous operation, every well has at least one operating meter using one or more DP transmitters. While some sensors have failed, the redundancy that was incorporated in each metering system has permitted the meters to function in an acceptable manner. Furthermore, adoption of the measures suggested in Section 4 above will improve the odds of success here.

Dual-Differential Meters Can Have Problems. As shown earlier, the principles on which the SOLARTRON ISA DualStream meter depend break down under the conditions of (a) high pressure and (b) small Lockhart-Martinelli number (dry gas). There is no reason to believe this meter won't work as intended in those conditions for which it was originally designed and tested.

In the period since the meters were selected for service on Canyon Express, other metering choices have become available for wet gas applications. Some recently introduced devices [5] attempt to detect the presence of very small amounts of water in the flow stream, and to determine the flow rates of oil, gas, and water, rather than just those of gas and liquid. First field applications and tests are in progress.

Well Fluids Alter Meter Characteristics. In the case of Canyon Express the scale which formed on the pipe walls in and around certain of the meters was identified as the source of the severe imbalances observed on both flow lines. Operators must be prepared to recognize and deal with this possibility.

Online Calibration Is Possible. While it is recognized that Canyon Express represents a unique situation, particularly with respect to the minimal amount of liquids present, the methodology developed here should have considerably broader application in the realm of hydrocarbon allocation. It should be tested on a more typical range of allocation problems, such as wet gas or traditional multiphase streams.

One year ago at this meeting, a paper detailing the merits of Uncertainty-Based Allocation (UBA) was presented as a precursor to its being implemented on the Canyon Express project, among others. What has been shown here in no way diminishes the suitability of UBA, but rather addresses the issue of identifying unknown measurement biases before its application. Therefore, use of UBA in the future has been made more likely by the developments presented here.

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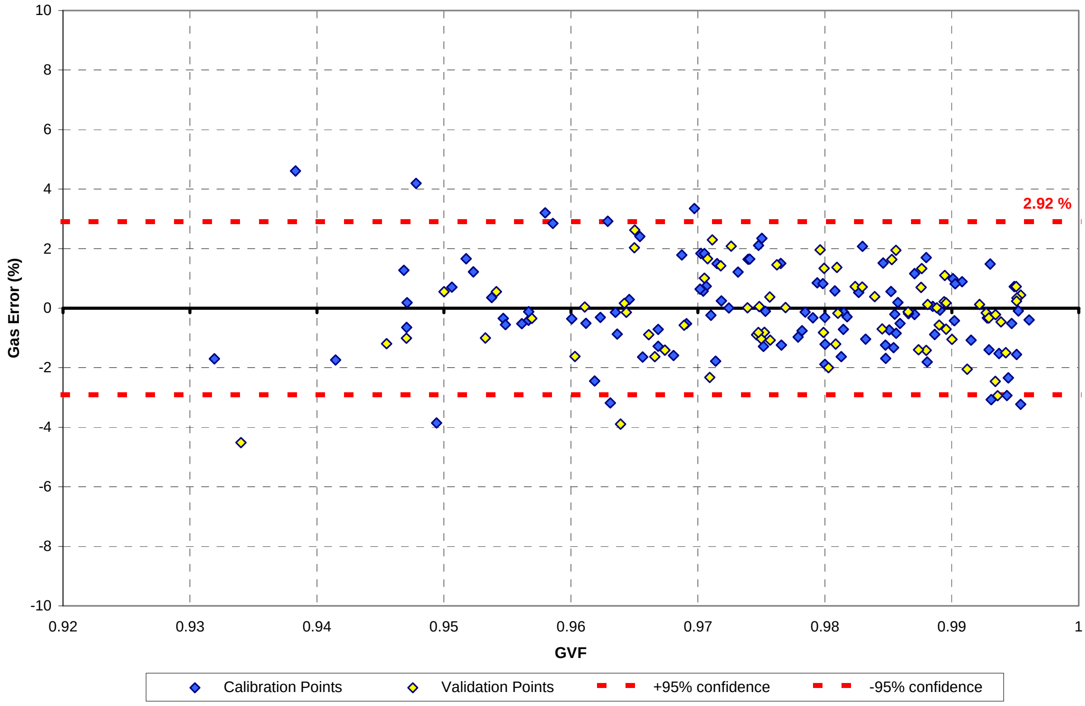

Figure 1. Relative uncertainty in gas flow measurement over all tested pressures at SwRI Test Loop, July-August 2001.

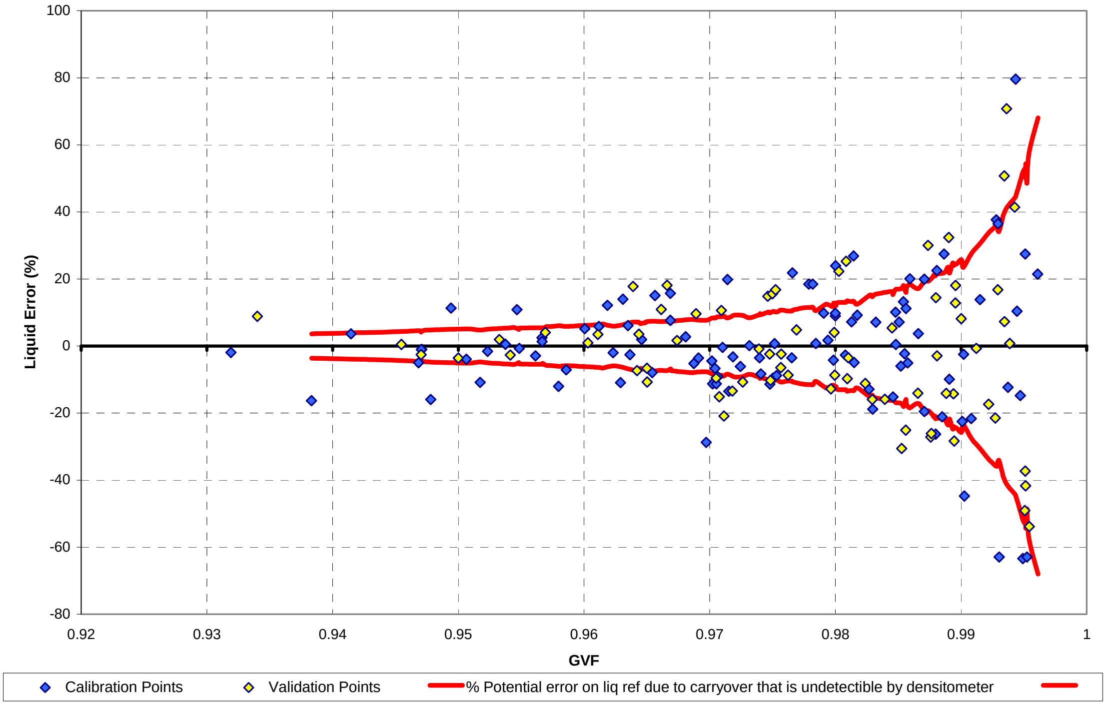

Figure 2. Relative liquid measurement uncertainty over all tested pressures at SwRI Test Loop, July-August 2001.

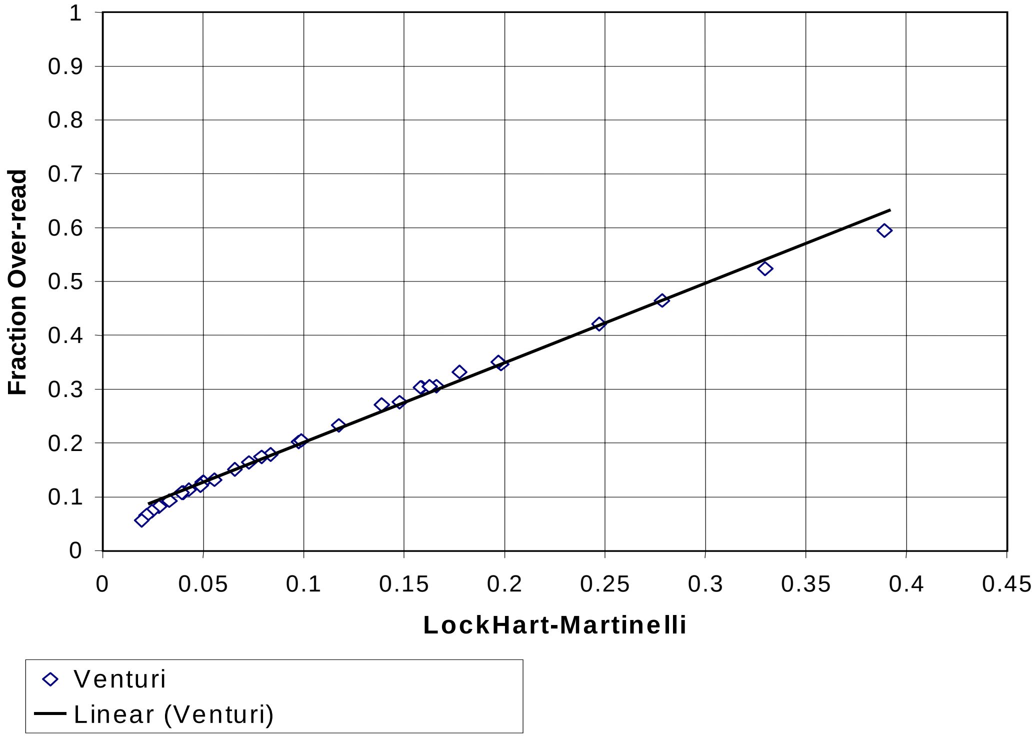

Figure 3. Typical differential meter Over-Read Curve as a function of 'wetness'.

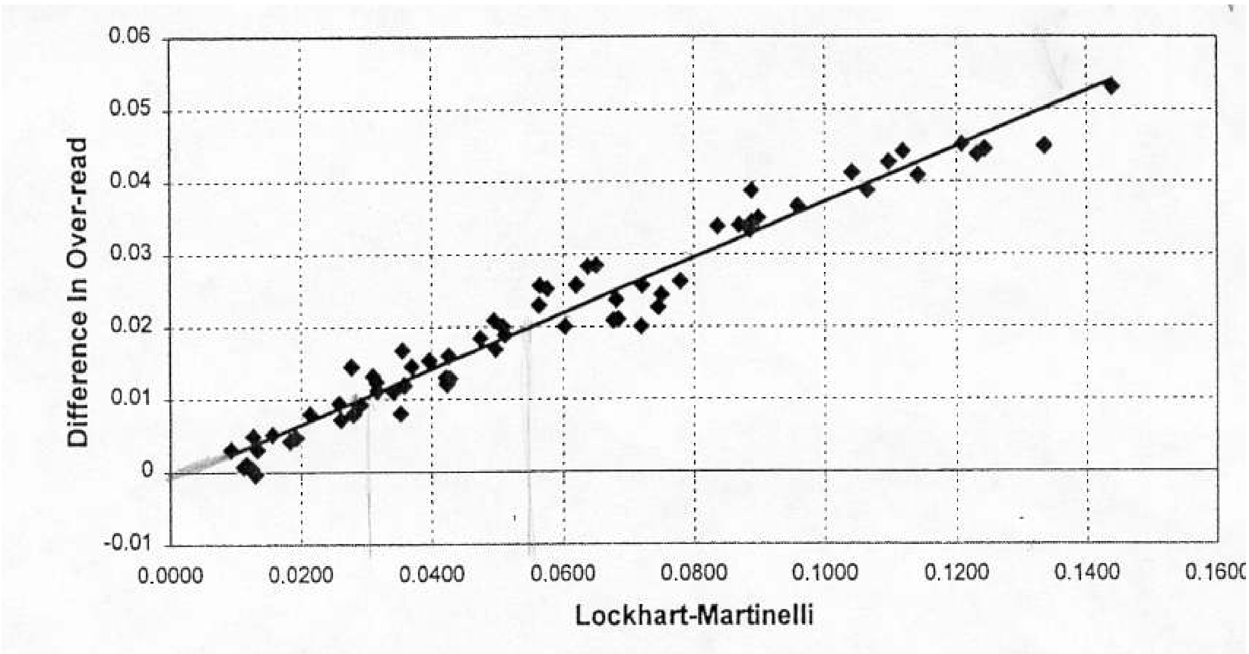

Figure 4. Characteristic Difference in Over-Read Curve for ISA Dual Stream II meter recorded at 200-250 bar, SwRI,

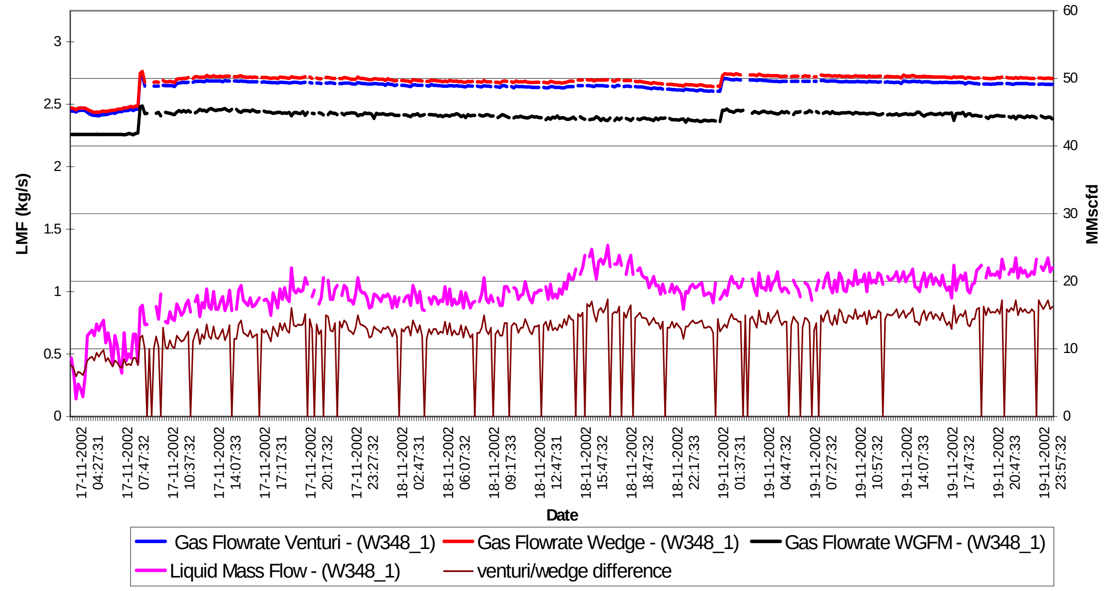

Figure 5. Example of Dual Stream II operation on a Canyon Express well.

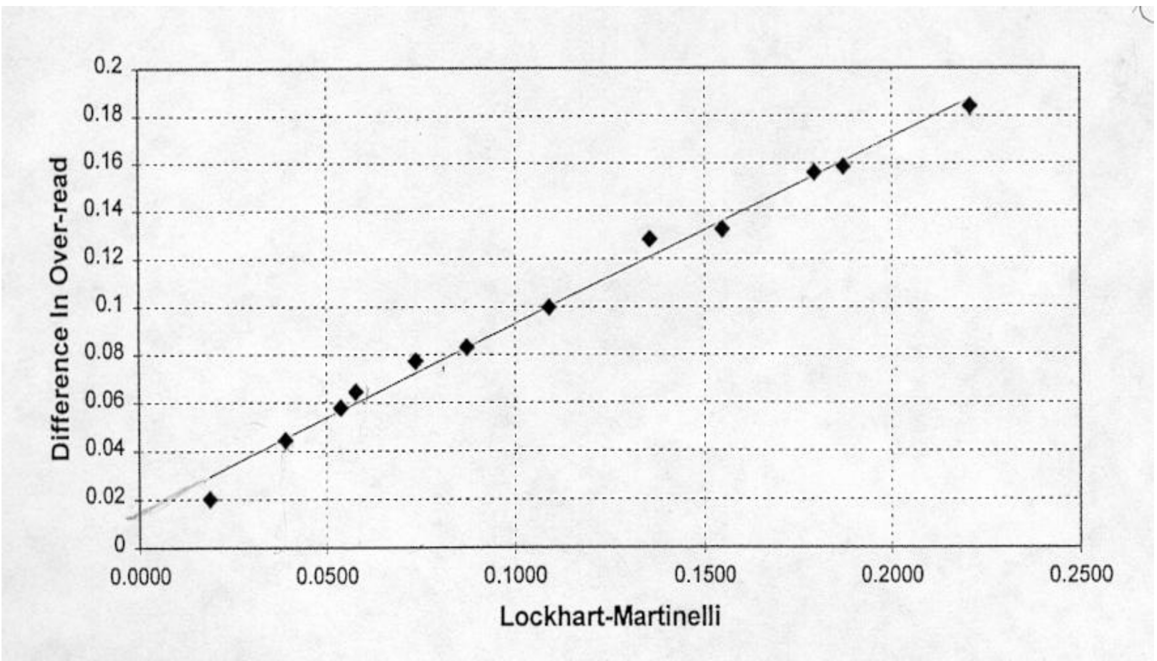

Figure 6. Characteristic Difference in Over-Read Curve for ISA Dual Stream II meter recorded at 80 bar at SwRI.

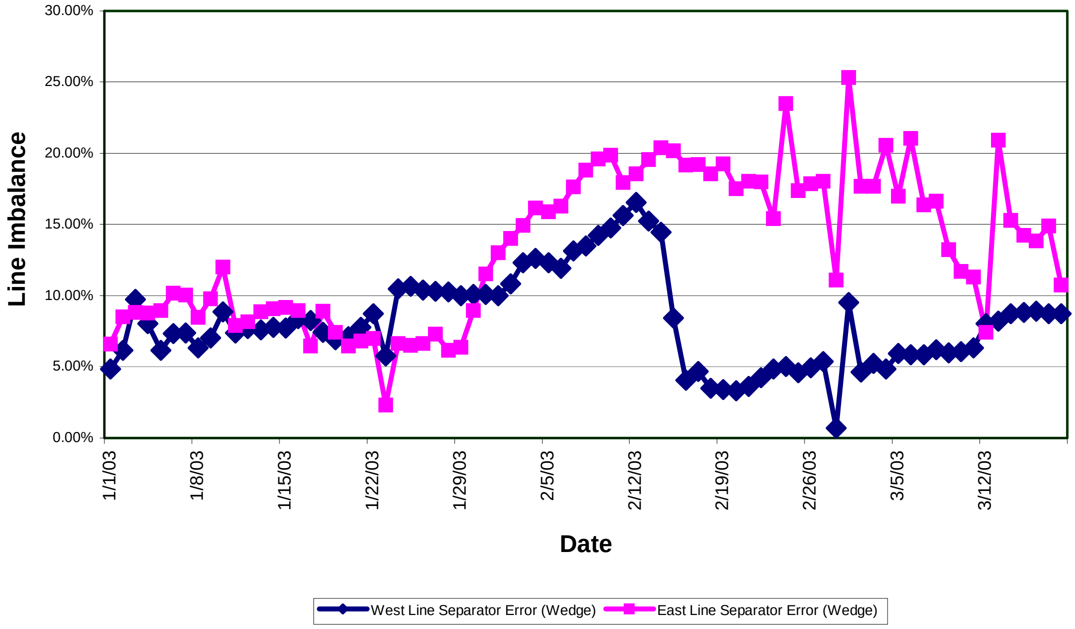

Figure 7. Imbalance in daily totals for Canyon Express east and west flow lines during Q1 of 2003.

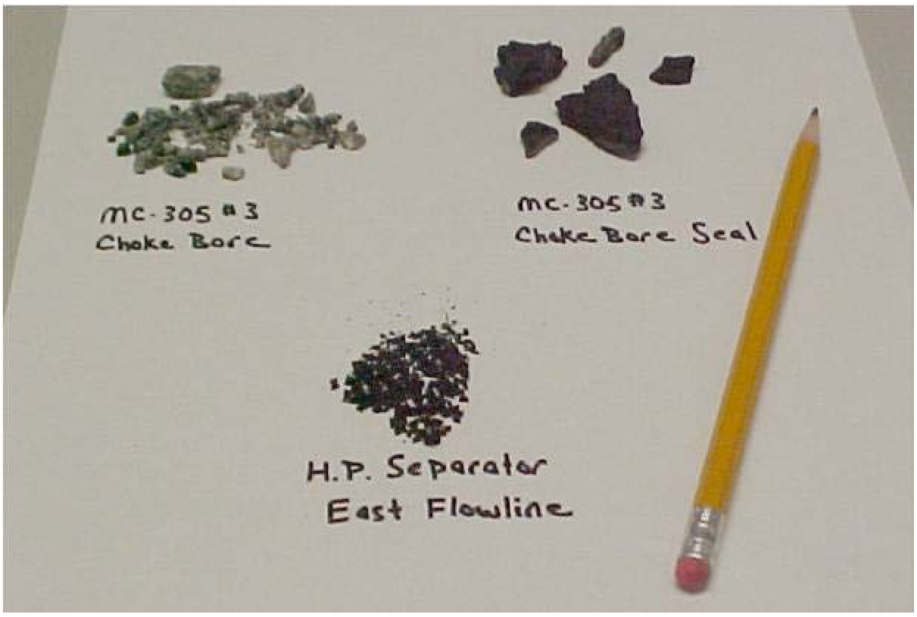

Figure 8. Scale found inside flow line of Well 305-3 after intervention.

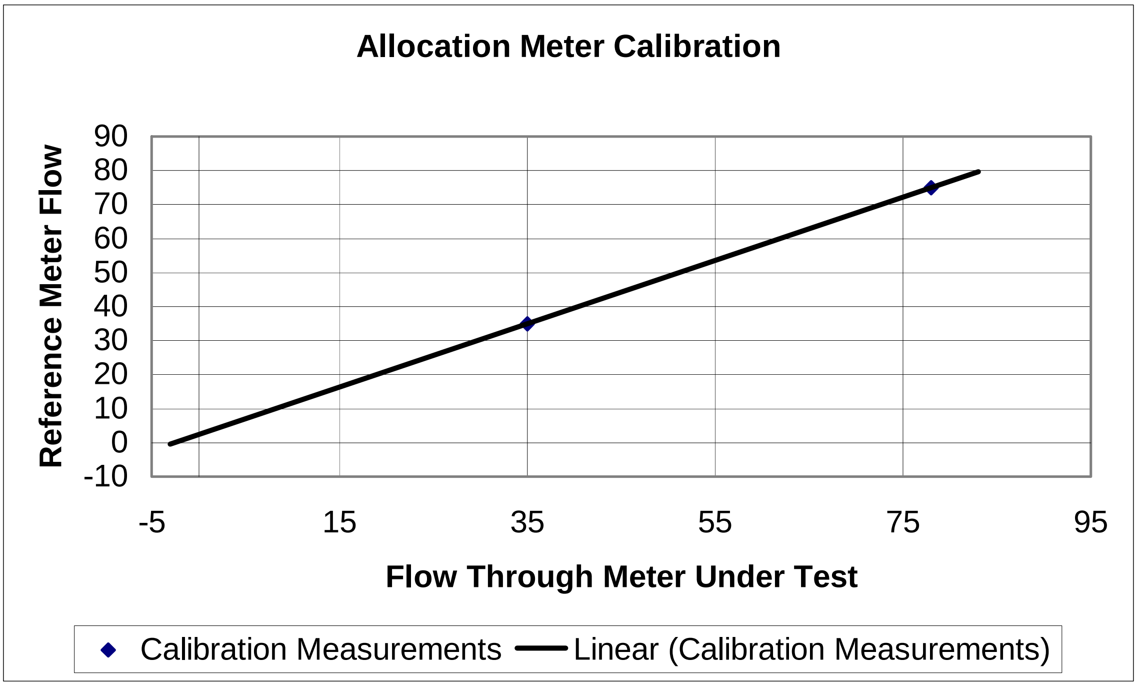

Figure 9. Calibration results obtained from data shown in Table 1.

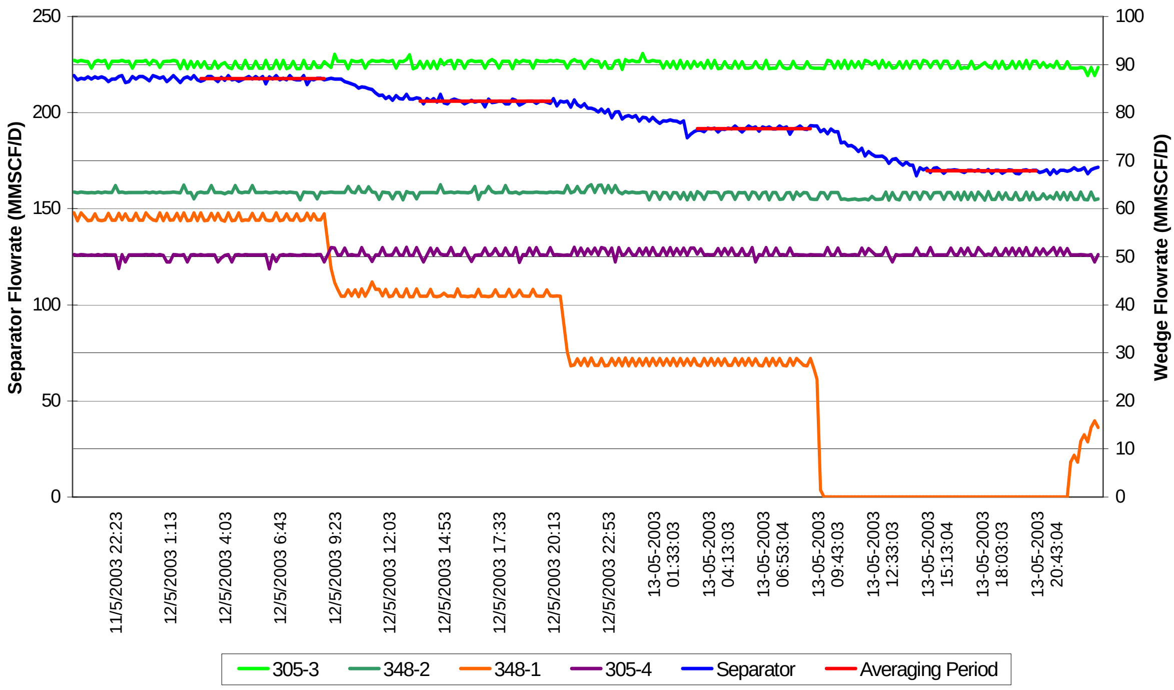

Figure 10. Illustration of procedure used for online calibration of Canyon Express allocation flow meters.

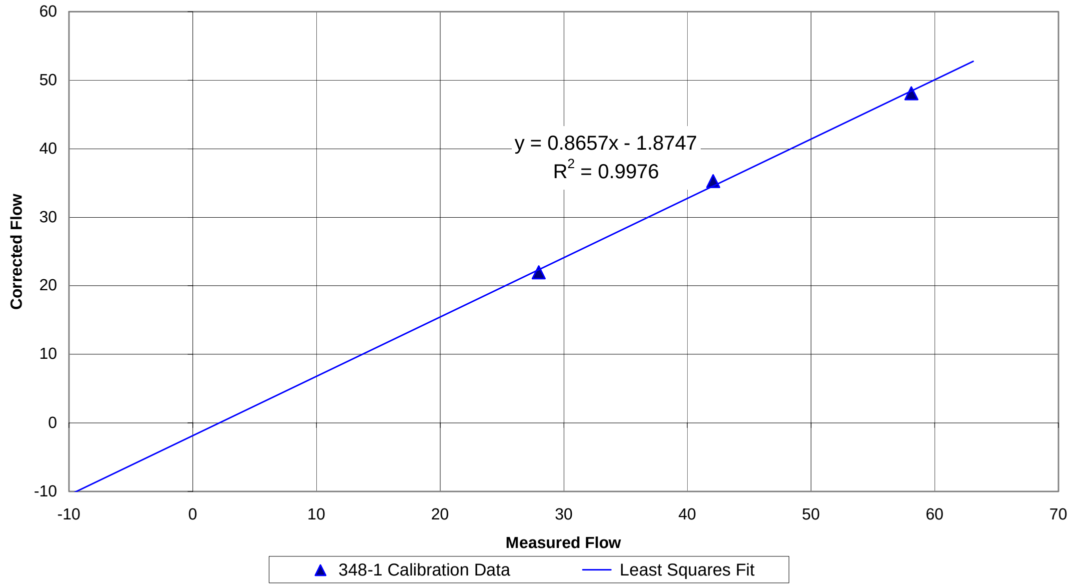

Figure 11. Calibration curve for data shown in Figure 10.

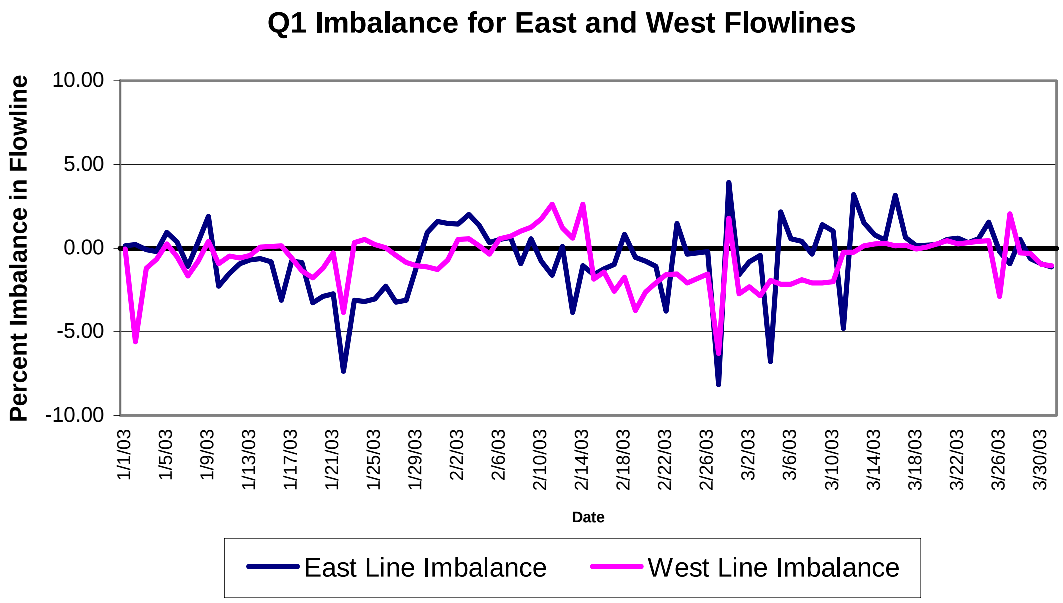

Figure 12. Daily balance results for Canyon Express for the first quarter of 2003.

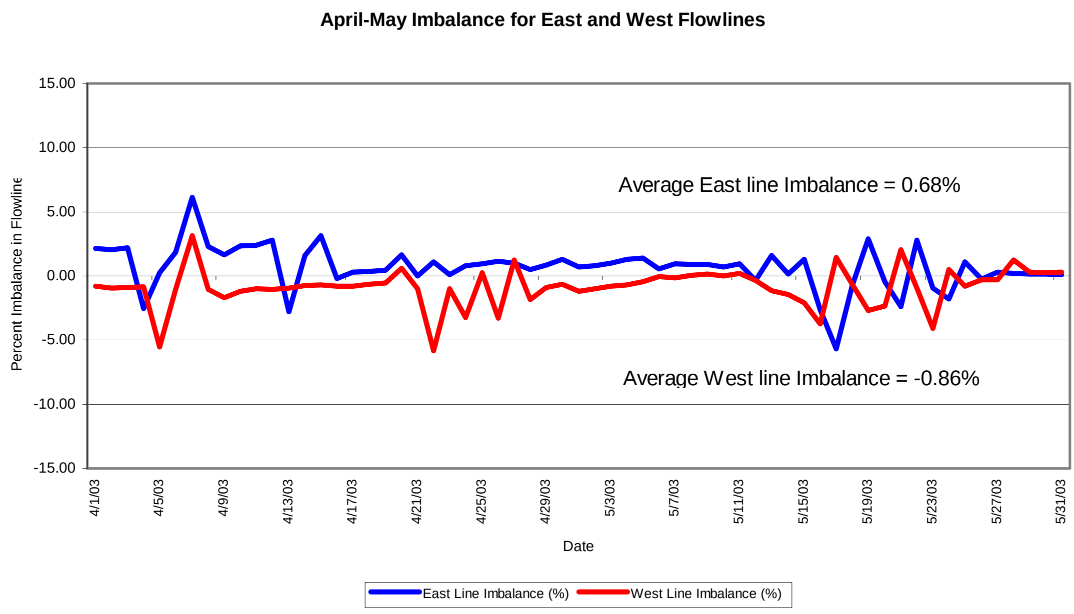

Figure 13. Daily imbalance in east and west flow lines during April-May 2003.

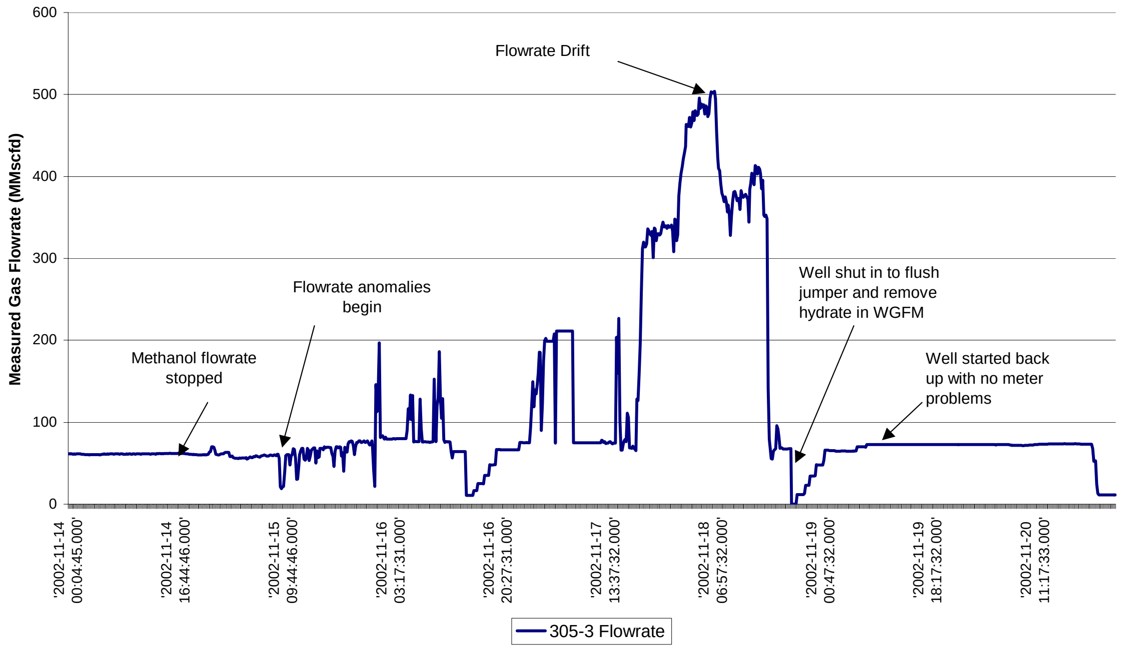

Figure 14. Example of meter performance indicating hydrate plugging of sensor capillary tubes