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Three Years of Experience of Wet Gas Allocation on Canyon Express

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1 INTRODUCTION

In September 2002, production was begun from the three fields that together form the Canyon Express System- King's Peak, Aconcagua, and Camden Hills. The 9 wells from these fields are connected to a pair of 12-inch flow lines carrying the commingled wet gas a distance of approximately 92 kilometers back to the Canyon Station platform for processing.

At the 21st NSFMW in October 2003, an initial report was given on the status of Wet Gas Allocation for the Canyon Express project [1]. As discussed in that paper, dual-differential, subsea wet gas meters were chosen for the task of allocating gas and liquids back to individual wells. However, since the gas from all three fields was very dry (Lockhart-Martinelli parameter < 0.01) and because the operating pressures were quite high (250 bar), application of the dual-differential function of the meters yielded errors in both liquid and gas flow rates. Furthermore, as these problems were being uncovered, scale was beginning to collect inside some of the meters. Taken together, these problems produced system imbalances as great as 20%.

To address the problems, one of the individual flow metering elements within each wet gas meter was chosen as the allocation meter, operating as a single-phase gas meter. Using a multi-point flow testing methodology, the response of the individual meters was characterized, with the result that a much improved system flowline balance has been maintained since its application. This methodology was approved by the U.S. Mineral Management Service for the Canyon Express field development.

The experiences of operation of the Canyon Express system for the past three years provide useful guidance for future subsea metering installations. This includes the use of line balance monitoring to identify changes to a meter's response due to deposits, early detection and elimination of hydrate formation, and the use of the meters to indicate the onset of water production from a well. Finally, the survival rate for more than one hundred pressure, temperature, and differential pressure transmitters provide a good indication of what one can expect when deploying meters in very deep water for long periods – over three years at this point in time.

2 WET GAS METER

In the initial design of the Canyon Express project, the decision was made to install the subsea flowmeters for allocation in the jumpers. Because of the lead-times of the components, fabrication, and calibration schedules involved, it was necessary to select which type of subsea allocation metering device to use by the fall of 2000. At that time, the primary method for wet gas measurement was the use of various differential meters in the manner first suggested by Murdock [2].

Even though production from all Canyon Express fields was expected to be very dry, it was important to identify the onset of water from any well. At the time, Solartron-ISA was in the process of introducing their dual-differential meter, the Dualstream II for wet gas measurement. Since the Dualstream II had shown the potential to provide such an estimate [3], it was chosen for installation on all of the wells.

It was important to calibrate the wet gas meters in a flow loop prior to installation. The initial Canyon Express working pressure of approximately 250 bar was far greater than any application experienced by the Solartron-ISA meters up to that point in time. Only the high-pressure multiphase flow loop at the Southwest Research Institute (SwRI) was able to achieve this pressure; no other wet gas calibration facility operated at even 50% of this figure. Fortunately, SwRI was capable of circulating natural gas, decane, methanol, and water through the meters at varying liquid loads.

The test program for the meter was quite extensive, and covered not only variations in pressure but also liquid loading and, to some degree, liquid composition. Plotted against Gas Volume Fraction, the relative uncertainties for gas flow measurement were generally less than 3% for all gas volume fractions (GVF), and for liquid flow measurement were less than 20% up to 99% GVF. It has 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. Above 99% GVF, the liquid uncertainties expanded out to as much as 80%. Since the introduction of the Dualstream II and its use in the Canyon Express system, Solartron-ISA has modified its design to extend the range to above 99% GVF.

2.1 INITIAL ISSUES

Initially a maximum of 100 - 200 Bbls/D of liquids (production plus injected methanol) was expected through each meter. However, the amount being reported by the meters was far greater, in some cases as much as 2000 Bbls/D. Since each separator on Canyon Station is capable of handling 1750 Bbls/D and was seeing nowhere near this amount of liquid, it seemed clear that something was wrong in the subsea measurement process.

A comparison of the measurements from the redundant differential pressure (DP) transmitters on each wet gas meter showed agreement within 1%. Therefore, having eliminated the sensors as the problem source, only the application of the methodology remained to be considered.

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 1, with the device over-reading plotted against the well-known Lockhart-Martinelli (L-M) 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 Dualstream II utilizes the characteristic that different differential devices exhibit different curves similar to the one in Figure 1. The meter incorporates two differential devices in a single wet gas meter. The initial problem with the incorrect liquid estimates by the meters was traced to the following:

The typical Canyon Express operating parameters were:

$$Q_g = 50 MMSCFD$$

$$Q_l = 100 Bbls / DAY \text{ (including methanol)}$$

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

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

$$\text{Lockhart-Martinelli : } X = \frac{Q_l}{Q_g}\sqrt{\frac{\rho_g}{\rho_l}}$$

$$\text{Lockhart-Martinelli} \approx .005$$

This extremely small value of L-M was causing the problem in the liquid estimate. Asking that two differential meters each are accurate to within 0.2 - 0.3% is demanding far too much, especially when exposed to production fluids for long periods of time. Since the meter determines the wetness of the gas by calculating the difference in the over-read of the two differential devices, the difference in two values, each with non-negligible uncertainty, can cause significant errors in the resulting computation.

An example in reference [1] showed an estimated liquid rate of about 1 kg/sec, or 680 BBLD, about ten times the true rate. Additionally, because the estimate of liquid production is too high, the gas rate calculated by the meter's algorithm was always 4-6 MMSCFD too low.

2.2 MULTI-POINT SUBSEA CALIBRATIONS

The decision was taken to use either the Dualstream II's wedge or Venturi meters as the allocation device for gas, using it as a single-phase meter. It was decided that the best choice would be the wedge meter, because of the fact that the Venturi's DP transmitters had been observed to saturate on the high producing wells. The high range DP's on the wedge meters were able to function correctly up to approximately 100 MMSCFD.

Since the meters were already installed on the sea floor, it was important 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 a reference was a viable approach. This is largely due to the fact that variations in liquid hold-up during the tests were known to be small due to the relative dryness of the gas production. This fact facilitated the test scheme highlighted below. For systems where there is more liquid hold-up and thus more variation in liquid hold-up with varying flow rate, this test scheme may become unmanageable.

The method developed for Canyon Express involved careful calibration of individual meters using a multi-point method. 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 on the platform 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 differences accounted for in the calculations.

Three or more measurement points 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 corresponding to a given change in the reading of the meter under test. The meter bias can only be determined when the well is shut-in.

The relationship between flow measured at the reference meter at the gas outlet of the separator and that observed at the meter under test is

$$Q_{ref} = k_i \cdot Q_i + b_i \tag{1}$$

Changes in the flow from the other wells are accounted for by modifying the above equation as follows:

$$k_i = (\Delta_{ref} - \sum_{j=1}^{j=m} k_{j \neq i} \times \Delta_{j \neq i}) / \Delta_i$$

This equation merely says that in order to account for the change in the flow through the reference meter due to the i^{th} well, the change in the flow of each of the other wells (represented by j, where $j \neq i$) must be subtracted from the total measured change in the reference meter. Since the equation involves **changes** in measured flow, it does not involve meter bias factors.

While this approach will lead to a determination of $\mathbf{k_i}$, the following tasks remain: (a) it requires that the multi-point tests be complete on all wells before we have a solution; i.e., this is an iterative process and the **k**-factors must be known for all the wells on the flowline, and (b) it doesn't address the issue of determining the bias terms $\mathbf{b_i}$ which remain. In order to determine these bias terms, the well under test must be shut in. This is the only point at which the flow condition through the wedge meter is precisely known.

An example of this technique is shown in Figures 2 and 3.

As reported in 2003, this procedure has been utilized periodically to verify and adjust, if necessary, the meter factor and bias for each wedge meter. Once a meter's characteristics have been determined, why would they ever change? Factors that can affect the response of a meter are discussed in the next section.

3 FACTORS AFFECTING METER PERFORMANCE

During these first three years of operation, changes in the calibration parameters of the subsea wet gas meters have been noted. In each case, these changes have been attributed to factors other than a drift in the meters themselves. Changes in the characteristics of the individual wells have certainly been a major influence in the need to constantly monitor and periodically recalibrate the meters.

Experience on the Canyon Express project indicates that it is important to consider the many factors that can cause inaccuracy in subsea flow measurement and consequently in allocation. Our observations are summarized below.

3.1 SCALE BUILDUP

As reported in our 2003 paper [1], one of the first problems to be identified was a drift in the imbalance on both flow lines in the 15-20% range.

When a choke insert was retrieved from one of the wells, it revealed that the inside 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. Since the meter had experienced a reduction in diameter due to a buildup of scale, this change of geometry would have increased the differential pressure across the meter and caused a corresponding over-reading in its response. The differences between the Venturi and wedge flow rate measurements 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.

In order to attempt to stop the scale production within the meters, scale inhibitor was injected, 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.

The solution was to perform a multi-point calibration on all of the subsea meters, as described in section 2.2. With no changes in the meters' characteristics, all k-values should have been equal to 1.0 and all b-values equal to zero. This was not the case. The k-values ranged from 0.74 to 1.04 and the b-values from 0.73 to –2.58.

Utilizing the calibration parameters, the flow line imbalance was maintained within the range of ± 3%. However, after a period of two months, the line imbalance abruptly changed. This was traced to a change in the characteristics of the meter whose k-factor had been measured as 0.74. Redoing the multi-point calibration on that well yielded a new k-factor of 0.89. The supposition is that some of the scale that had built up inside the meter had become dislodged and thus, the internal geometry had been increased.

This experience illustrates the need for constant monitoring of the flowline balance as an indication of changes in a subsea meter's performance.

3.2 DIFFERENTIAL PRESSURE TRANSMITTERS

Since differential flow meters utilize DP transmitters to measure the pressure change across a restriction in the flowline, it is important to insure that the transmitters are functioning properly. Because it is not feasible to retrieve and replace malfunctioning transmitters on the Canyon Express meters, redundant units are utilized. All of the meters contain low range and high range redundant transmitters on both the wedge and the Venturi sections. Some of the meters use triple redundancy and others use double redundancy on both of these ranges.

With redundant transmitters, the question arises as to which unit is correct when there is a difference in readings. Possible criteria for determination are the following:

- If any unit is saturated (maximum output), eliminate it from the calculation.
- If the redundant units are within reasonable agreement, take their average.
- For triple redundancy, if one unit differs from the other two, average the two that are in agreement.

The above criteria can be built into the meter's processing algorithms. However, there are cases where an algorithm cannot decide the correct value to use from redundant transmitters. As an example, consider Figure 4. The figure shows the difference between the DP value used in the wedge flowrate calculation and each of the two high-range DP sensors. Points to note:

- The two sensors began to diverge around January 25.
- Between that date and February 14, the algorithm didn't know which DP was correct, so it used the average of the two.
- On February 14 the calculation stopped using the DP1 values and only used DP2.
- Since there was an extra set of redundant transmitters, an ROV was used to switch the connection from bank 1 to the spare bank.
- After the DP1 sensors were changed on March 5, the agreement between the two sensor banks was excellent.

The lesson learned here was that the system cannot always be depended upon to identify malfunctioning components. Deviations between the sensor value used in the flow calculation and the value from the individual sensors must be monitored to insure that there is consistency in the measurements.

Given that the conditions to which the transmitters were subjected during the past three years, the failure rate has been remarkably low. The table shown in Figure 5 summarizes the current condition of the transmitters. This includes not only the DP's, but also the separate pressure and temperature units. None of the transmitters in bank 2 of the flowmeter on well 305-4 have been functioning, because the connector was damaged during installation.

As mentioned earlier, the DP transmitters on the Venturi meters on some of the high producing wells were always saturated, thus rendering them unusable. This was the primary reason for selecting the wedge portion of the wet gas meter as the gas measurement device. During normal operation, care was taken to assure that the DP's on the wedge meters did not saturate. However, a situation occurred during the calibration process when the flow from some of the wells was reduced. This caused a reduction in the line pressure, allowing an increase in flow from the producing wells. An example is shown in Figure 6. There were only two wells flowing during this calibration (305-1 & 305-2). During the period when the high producer (305-2) was flowing at 75% and 50% rate, the line balance was better than 1%. However, at times when 305-2 was at full flow, the imbalance rose to more than 15%.

3.3 HYDRATE FORMATION

During the initial design of the Canyon Express project, the possibility of blockage due to hydrate formation was recognized. For this reason, the system was equipped for continuous methanol injection. Even without methanol injection at a well during steady state flow, it was felt that the jumper and flow meter did not need methanol flow because the heat from the produced fluid was sufficient to inhibit hydrate formation. While this was true for the jumper, Canyon Express demonstrated that this was not necessarily true for the meter.

As shown in Figure 7, the flow meter assembly consists of the metering pipe containing the two differential elements and the assortment of redundant transmitters. A manifold is connected across each differential device and then the capillaries leading to the DP's are connected to it. Unfortunately, there isn't the ability to flush the meter's capillary lines from the surface with methanol.

Hydrate formation in the capillary lines has caused significant problems in the past year because of the need to shut-in the wells for extended periods due to hurricanes in the Gulf of Mexico. After the wells were restarted, there was an initial flow of some liquids from some of them. Coupled with the fact that the jumper and the meter were at ambient water temperature (2 deg C), several of the meters exhibited erratic behavior. Temperatures measured in the flow meters have decreased from their initial values to a range of 5 °C to 33 °C. At the low end of this range, conditions exist for hydrate formation. In fact, the meter on that well (217-2) has been considered as non-functioning and hydrate blockage is a possible cause. The typical location of the flowmeter and jumper is shown in Figure 8.

Consider the example shown in Figure 9. Notice that at the time shown, the wedge meter on well 305-4 was varying wildly, but the separator showed no significant change. Looking at the output of the Venturi portion of the meter on 305-4, a consistent value is seen. This is a possible indication of hydrate blockage in the capillary lines leading to the wedge meter's DP transmitters. The redundant DP's on the wedge were in agreement, indicating that they were all measuring the same (incorrect) pressure.

A similar application of the Dualstream II wet gas meters was in Statoil's Mikkel field [5]. In that case, an insulation material was applied not only to the capillary lines, but also around the flowline. It was reported that this helped inhibit hydrate formation, but the problem at startup was not completely eliminated.

3.4 CHANGE IN LIQUID PRODUCTION

At the beginning of the Canyon Express project, the metering problem related to the gas being too dry. As some of the wells have begun to produce water, the challenge is now to quickly identify the well(s) at fault and account for the over-read in the allocation. Often it is easier to notice the onset of water flow by a daily review of the flowline balance as opposed to an increase in liquid flow at the separator. This is particularly true when the wells are located at a great distance from the platform (92 km in the case of canyon Express). When looking at the separator, the liquid hold-up in the flowline may mask the initial onset of a break through. An example of a gradual change in line balance increase is shown in Figure 10.

Once water production has been identified, it must be accounted for in the allocation calculations. In the case of Canyon Express, the use of the wet gas output by the meter was not possible because of the following:

- The meters on two of the wells had saturated DP transmitters on the Venturi portion of the meters. This eliminated the possibility of a wet gas correction on those wells.
- For the other wells, since the calibration of the wedge portion of the meters have changed since installation, it is reasonable to assume that the Venturi portion has also changed, but not necessarily by the same amount. Thus, the Venturis must also be calibrated using the multi-point technique. The algorithms used to calculate the gas and liquid densities utilize the Venturi flowrates. Therefore, the software must be modified to use corrected Venturi flowrates.
- In theory, is would be possible to calculate a wet gas correction using the Murdock parameters.

$$Q_g = \frac{Q_{giv}}{1 + c_v + M_v X} = \frac{Q_{giw}}{1 + c_w + M_w X}$$

$$Q_g = \frac{Q_{giw} - M_w Q_l \sqrt{\rho_g / \rho_l}}{1 + c_w}$$

where M and c are the Murdock primary and secondary constants and were determined for the Canyon Express meters at SwRI. The difficulty is assigning a precise liquid flowrate through each meter. It is a combination of water, methanol and condensate.

If only one of the wells on a flowline is producing water and the rate is constant, it is possible to calculate the over-read due to that well by measuring the flowline imbalance. In order to eliminate the effect of liquid hold-up in the flowline, it may be necessary to make this measurement over a period of several days.

4 CONCLUSIONS

After three years of operation of the Canyon Express Project, considerable experience has been accumulated. Since at the time it held the record for deepwater hydrocarbon production, application of the technologies discussed here were challenging and required considerable flexibility. It is believed that the Canyon Express experiences will benefit future deepwater flow metering projects. The knowledge acquired thus far is summarized as follows:

In spite of the problems encountered, subsea metering for fiscal allocation was a success. Even though the technology needs enhancements to advance further, this is a definite step forward from well testing by difference. Using the multi-point calibration technique has allowed an excellent line balance to be maintained as long as the GVF was >99%. Since subsea commingled flow is essential to the timely progression of new projects, subsea metering is as well.

Differential flowmeters can operate successfully in deepwater applications. After three years of operation in the deepwater environment, only one of the Solartron-ISA meters is currently not functioning. It is possible that this is due to hydrate blockage, since this is the coldest well.

It is important to select the range of the DP transmitters correctly. As shown earlier, the differential meters will fail to perform correctly if the DP's are saturated. Consideration must be given to the maximum flow expected through the meters. As soon as this is exceeded, the well's flow must be reduced.

With regard to the transmitters, there are two goals for future applications: (1) Retrievable transmitters that can be re-calibrated, rescaled or replaced when necessary; (2) Smart transmitters that can be rescaled remotely from the surface.

Hydrate formation in flowmeters is a serious concern. As wells mature and their liquid production increases, the possibility of hydrate formation in the flowmeter increases. This is particularly true for flowmeters with capillary impulse lines. Putting some insulating material around the meter may help, but eliminating the capillary lines would be the best solution.

Consider alternate flowmeter location. To date, the location of choice for subsea wet gas and multiphase meters has been in the jumper. Because of the expense and difficulty of retrievability, alternate locations should be seriously considered for future projects. Some subsea meters that can be installed on the wellhead tree are now being offered.

Continual monitoring of flowline balance is mandatory. As discussed above, the formation of deposits on the inside surfaces of the flowmeters will affect the meter's calibration and therefore, the flowline balance. This is also true when water break through occurs. In order to maintain equitable allocation, re-calibration may be required.

Multi-point flowmeter calibration is a viable means of maintaining flowline balance. This technique has been utilized successfully on Canyon Express for the past three years. Now that some of the wells have shown water production, a variation of this approach will be required, depending upon the number of wells on a flowline that are producing at the same time. However, for wells producing dry gas, this method is vastly preferable to allocation by difference.

5 REFERENCES

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6 ACKNOWLEDGEMENTS

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We also wish to express our appreciation to personnel from Solartron-ISA, Intec Engineering, Kvaerner Oilfield Products and Calsep, Inc. for their continuing support on this program.

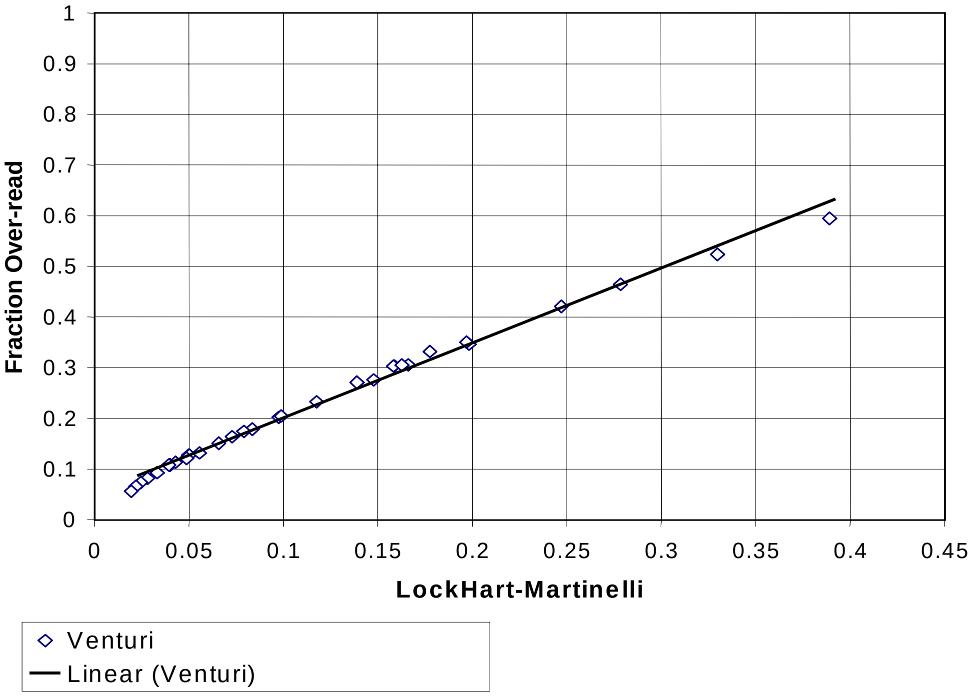


Figure 1. Typical Differential Meter Over-Read as a function of ‘wetness’.

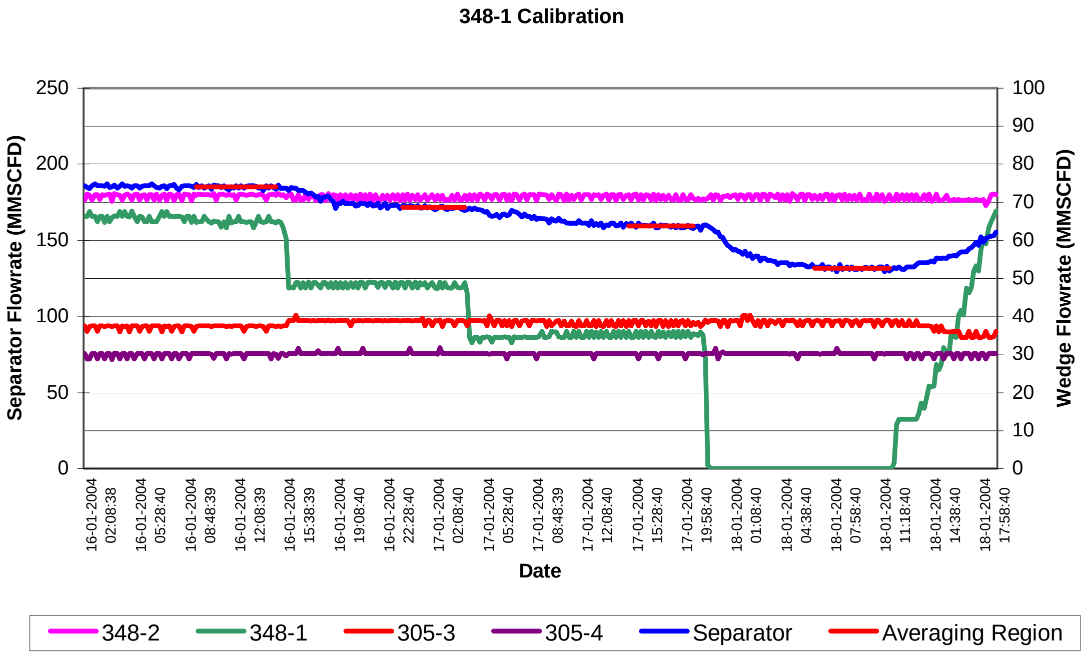


Figure 2. Example of Procedure used for Calibration of Canyon Express Meters

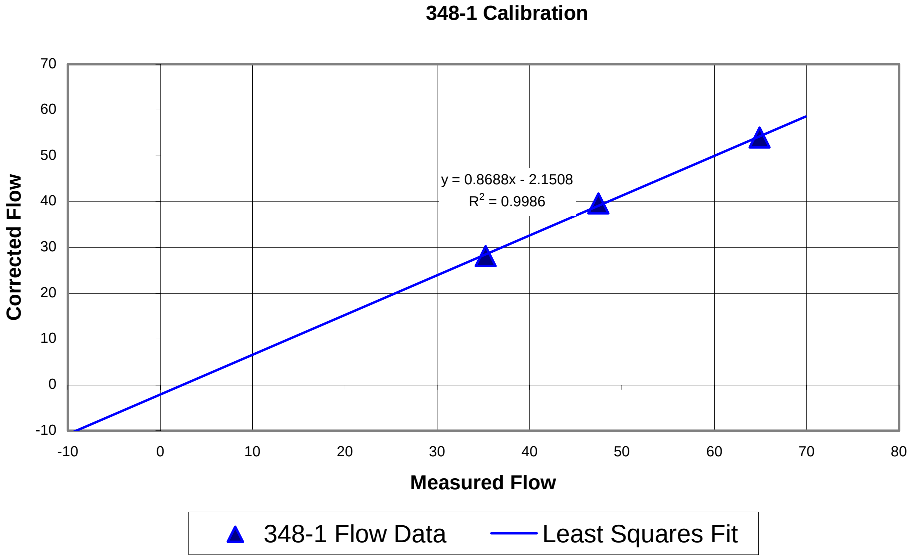


Figure 3. Calibration Curve for Canyon Express Meter

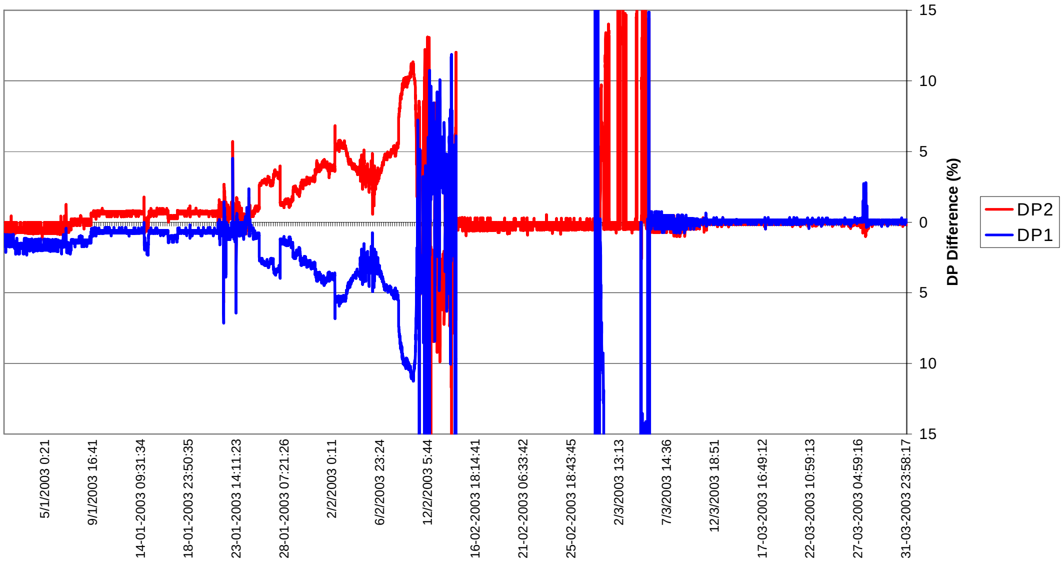
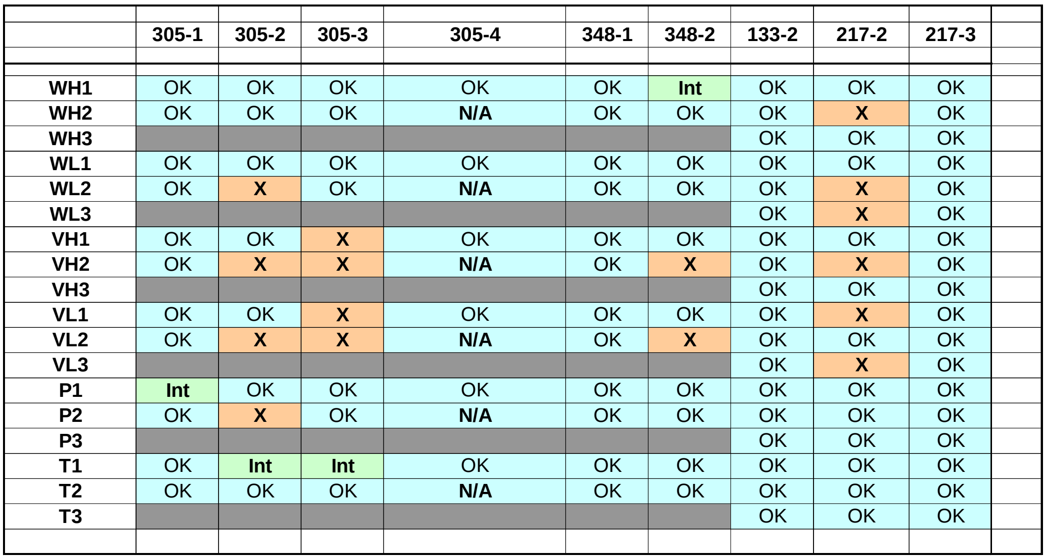


Figure 4. Example of Malfunctioning DP Transmitter



	305-1	305-2	305-3	305-4	348-1	348-2	133-2	217-2	217-3
WH1	OK	OK	OK	OK	OK	**Int**	OK	OK	OK
WH2	OK	OK	OK	**N/A**	OK	OK	OK	**X**	OK
WH3							OK	OK	OK
WL1	OK	OK	OK	OK	OK	OK	OK	OK	OK
WL2	OK	**X**	OK	**N/A**	OK	OK	OK	**X**	OK
WL3							OK	**X**	OK
VH1	OK	OK	**X**	OK	OK	OK	OK	OK	OK
VH2	OK	**X**	**X**	**N/A**	OK	**X**	OK	**X**	OK
VH3							OK	OK	OK
VL1	OK	OK	**X**	OK	OK	OK	OK	**X**	OK
VL2	OK	**X**	**X**	**N/A**	OK	**X**	OK	OK	OK
VL3							OK	**X**	OK
P1	**Int**	OK	OK	OK	OK	OK	OK	OK	OK
P2	OK	**X**	OK	**N/A**	OK	OK	OK	OK	OK
P3							OK	OK	OK
T1	OK	**Int**	**Int**	OK	OK	OK	OK	OK	OK
T2	OK	OK	OK	**N/A**	OK	OK	OK	OK	OK
T3							OK	OK	OK

Int = intermittent

Note: Bank 2 connector is broken

meter is not working

Figure 5. Summary of Current Status of Transmitters on Canyon Express Flowmeters

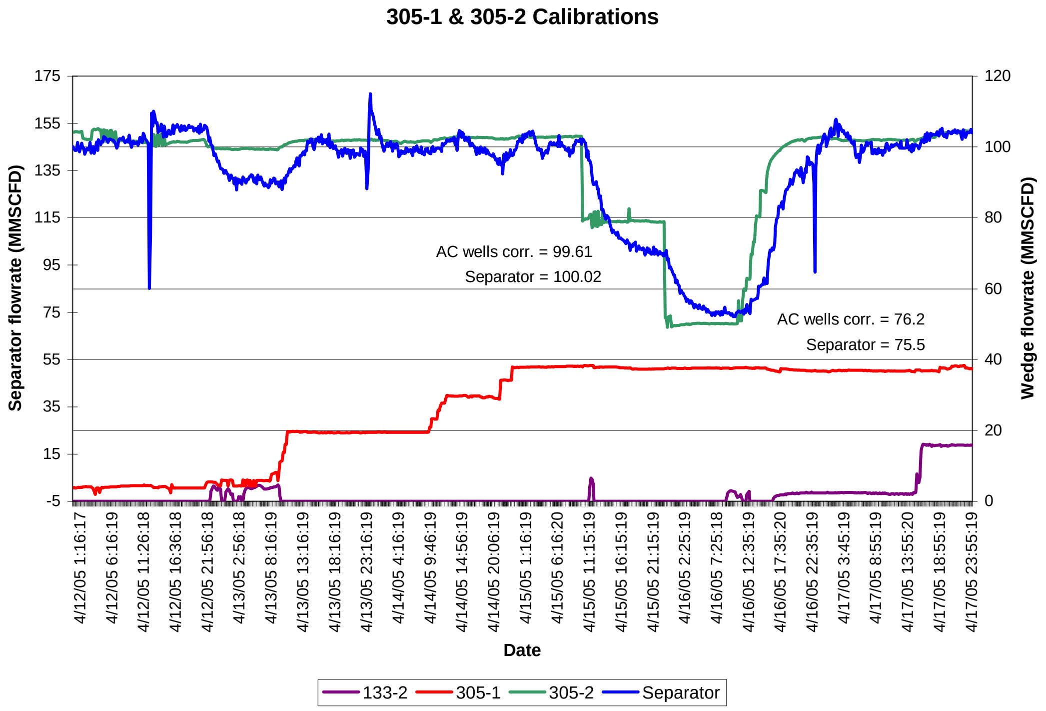


Figure 6. Example of the Effect of Saturated Wedge DP Transmitters

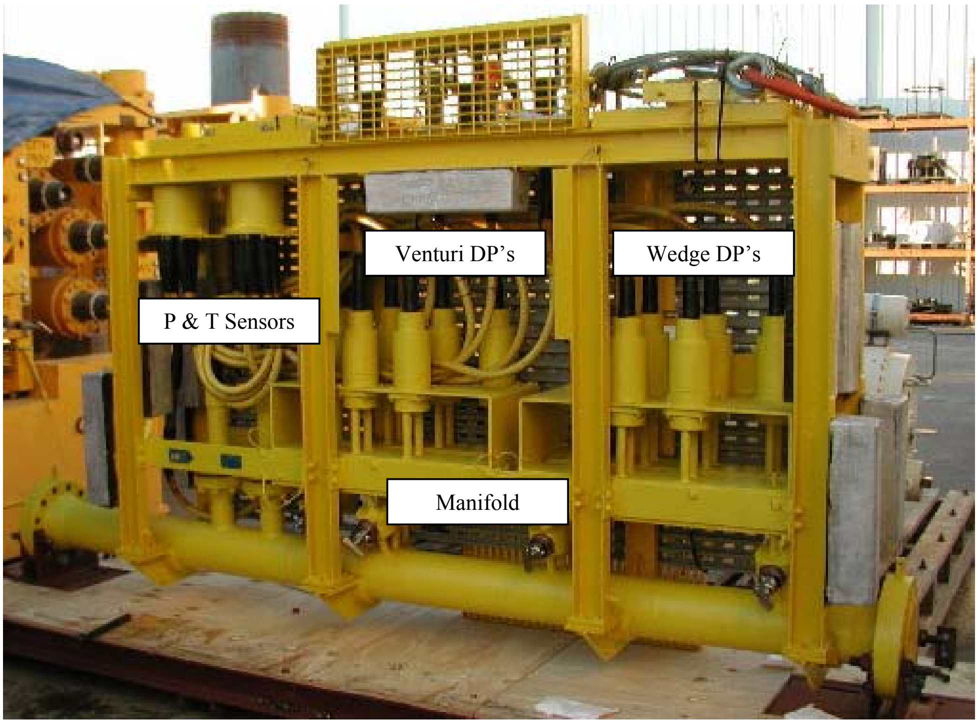


Figure 7. Dualstream II Assembly for the Canyon Express Project

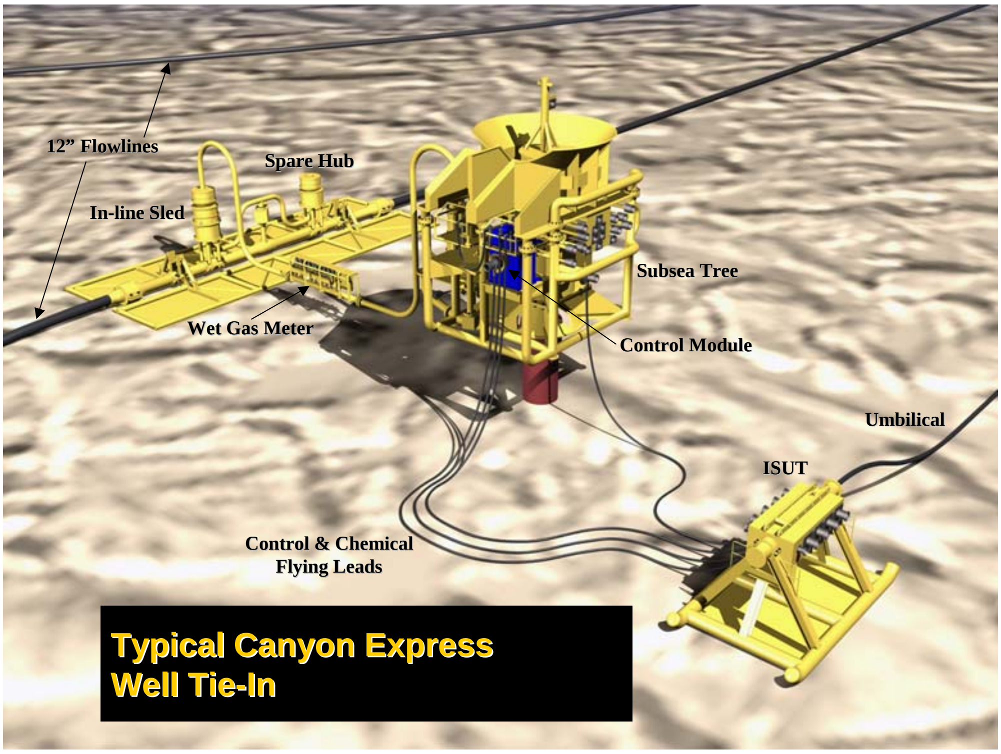


Figure 8. Installation of Metering Skid in Jumper on Canyon Express Well

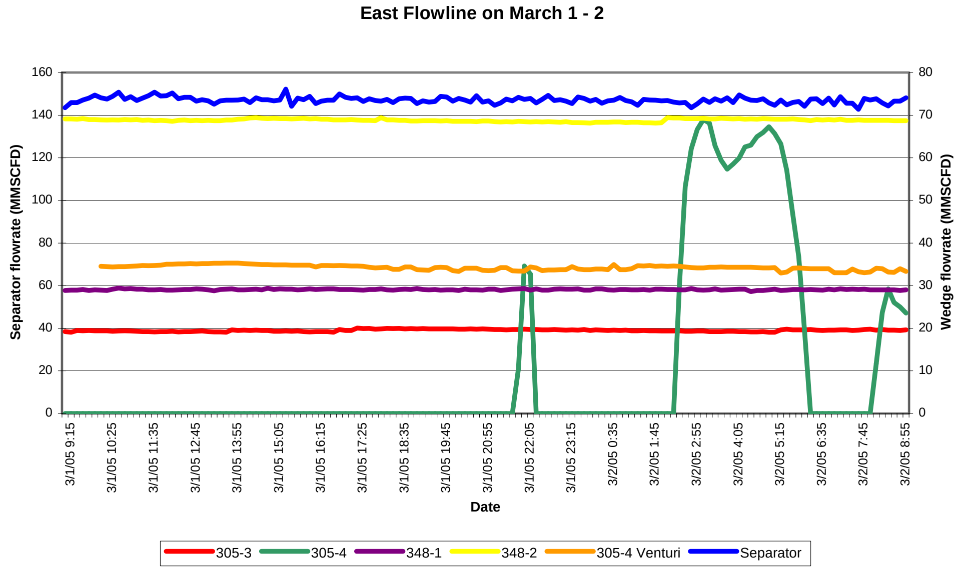


Figure. 9. Example of Hydrate Blockage in the Wedge Capillary Lines

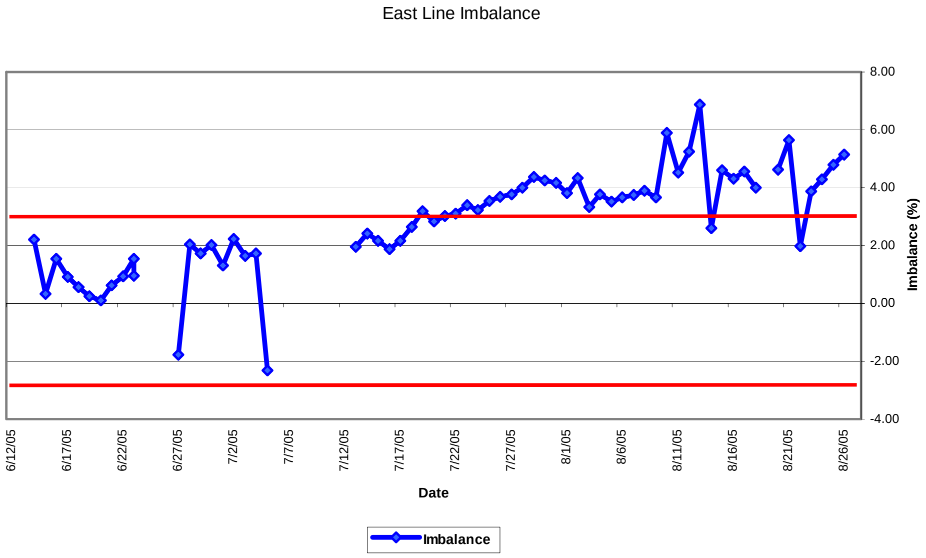


Figure 10. Change in Flowline Imbalance