OOC Subsea Leak Detection Working Group, Advanced Monitoring Subcommittee

Technical Solutions for Subsea Leak Detection

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Introduction

This report was prepared for the OOC Subsea Leak Detection Working Group – Advanced monitoring subcommittee.

Recent industry leak events have highlighted the difficulty of identifying and arresting subsea leaks in a timely manner. Unlike sales pipelines which operate under single phase conditions and often have comprehensive flow metering instrumentation installed, subsea production pipelines operate under multiphase flow, contain extreme elevation changes, and often are not as well instrumented. Multiphase subsea systems also exhibit complex transient behavior which make it challenging to easily distinguish a real leak from normal multiphase transient events.

The OOC Subsea Leak Detection Advanced Monitoring Subcommittee have reviewed production data from several OOC members to assess the efficacy of different methods of leak detection. These methods are static pressure comparison with hydrostatic, pressure rate of change, and metering balance. This document outlines the current understanding of the technical advantages and disadvantages of three advanced monitoring technologies for subsea leak detection, and provides a recommendation for minimum hardware and data requirements that each method requires.

While each leak detection method is described independently, it is the responsibility of each Operating Company to assess and select the most appropriate method, or combination of methods, that provide sufficient leak detection protection, depending on their leak detection philosophy and capabilities of their respective systems and organization. The leak detection plan and assurance tasks should then be reviewed by the Regulating Authority for approval.

Static Pressure based methods

Under shut-in conditions, a leak will cause the internal pressure to equalize with the external hydrostatic pressure. The time it takes to fully equalize will depend on the size of the leak, the initial internal pressure, the water depth, the geometry (size and length) of the flowline network that is exposed to the leak, and the physical properties of the fluid contained within the flowline.

However, under flowing conditions, the subsea flowline pressure may not fully equalize with the external hydrostatic pressure, due to the influence of higher pressure sources (wells). In Figure 1, a well jumper fails during a “Field A” restart, causing the internal pressure of the affected well jumper (as measured at the nearest tree, and the subsea manifold located 2 miles away, to fall rapidly towards hydrostatic pressure (@2115psia). As the field ramps up to target, the system internal pressure eventually stabilizes to 800psi above hydrostatic pressure at the leak site (well jumper), and 1000psi above hydrostatic at the subsea manifold.

Note that in deepwater subsea systems, the internal flowline pressure can vary substantially, and can be above or below hydrostatic pressure, under normal flowing conditions. Changes in flowrate, boarding pressure, or well mix, will also affect the subsea pressure. Furthermore, a subsea leak may not cause the flowline pressure to equalize at hydrostatic pressure while wells are still flowing. This makes the application of a simple static pressure alarm (i.e. a Manifold PSL or PSH) for subsea leak detection under flowing conditions unfeasible for many subsea systems.

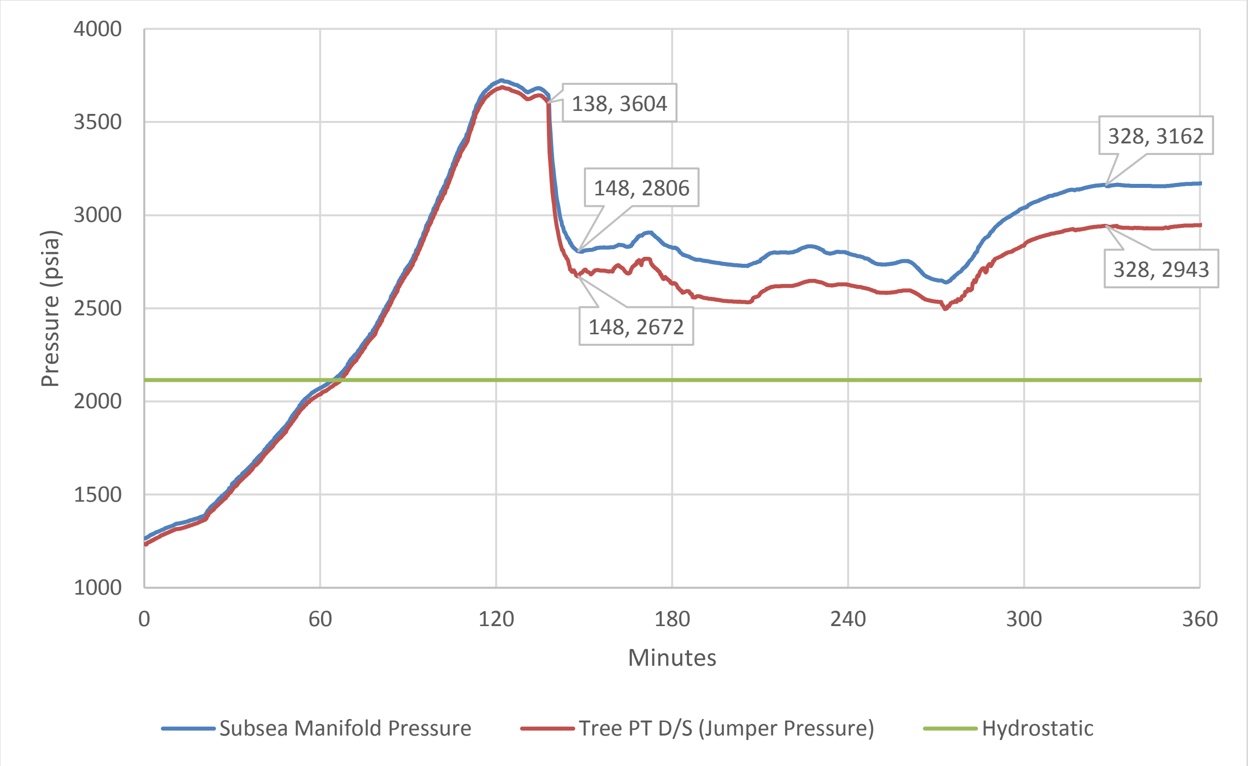

Figure 1 Field A leak – Pressure response following well jumper failure under flowing conditions (Hydrostatic = 2115 psia)

In Figure 2, "Field A" is shut in with the manifold PT still in pressure communication with the leak site, 2 miles away. The subsea internal pressure bleeds down and equalizes with hydrostatic pressure within 18 minutes after flow ceases.

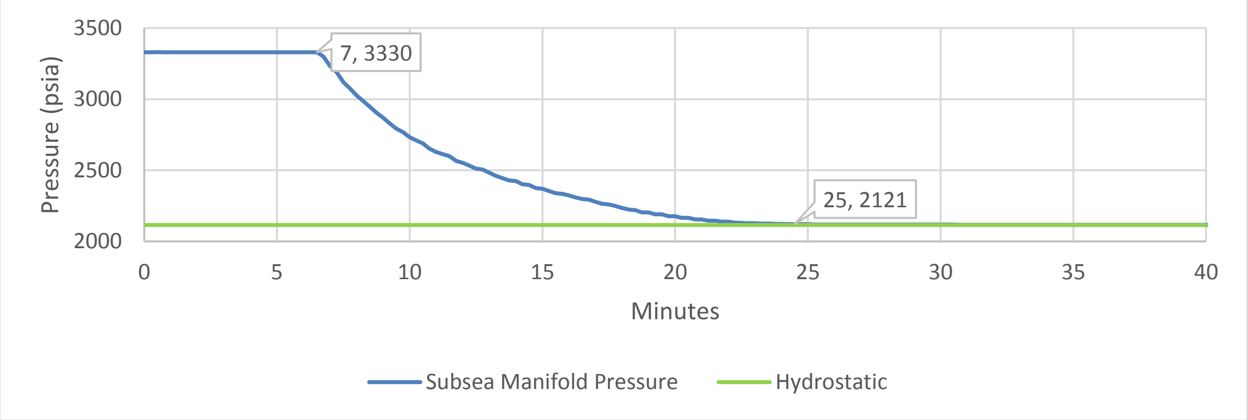

Figure 2 Field A leak – Pressure equalization under shut in conditions (Hydrostatic = 2115 psia)

In Figure 3, a well jumper fails at "Field B" under steady state flow conditions. The tree pressure downstream of the choke is shown alongside the Sled 2 pressure (nearest subsea sled to leak site). The pressure at Sled 3 shows a similar trend, but with an offset, due to Sled 3 being at a different depth.

Initially, the pressure declines at a moderate rate for about 2 minutes, then the rate of pressure decline accelerates. While this may suggest that the leak size increased shortly after initiation, this cannot be conclusively determined, as this process data has been obtained from a historian and has been significantly compressed. This anomaly may be a data compression artifact. Eventually, the system internal pressure stabilizes at slightly above hydrostatic pressure.

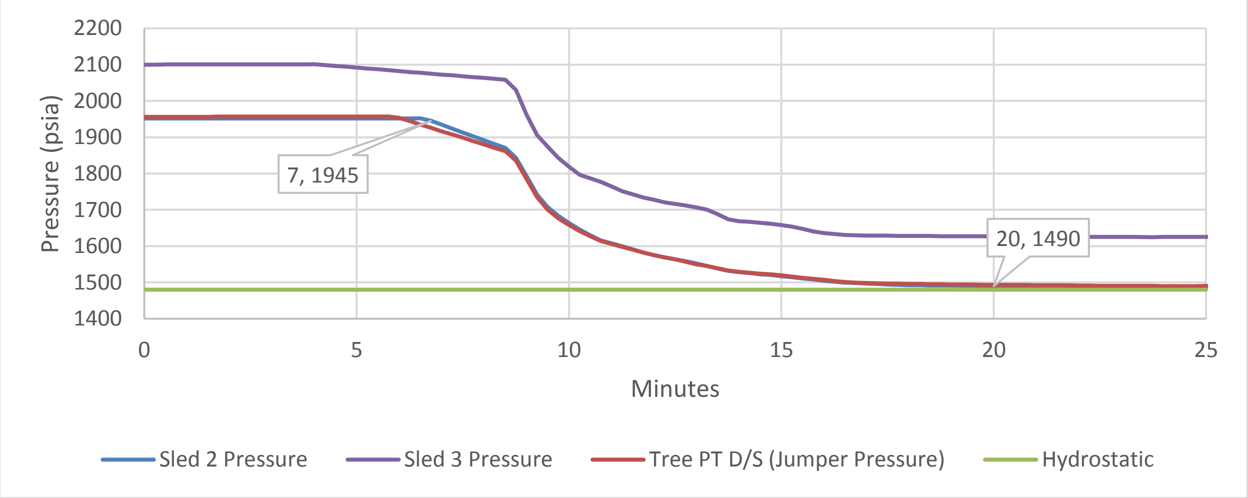

Figure 3 Field A leak – Pressure response following well jumper failure under flowing conditions (Hydrostatic = 1480 psia)

Based on recent operations experience, a large leak during shut-in conditions will result in the flowline pressure equalizing with hydrostatic pressure within 20 minutes, under shut in conditions.

Rate of Change of Pressure methods

The rate of change of internal flowline/jumper pressure is a rapid method of detecting the initiation of a large leak. Immediately after the loss of integrity event, the internal flowline pressure will move rapidly in the direction of the external hydrostatic pressure until a new steady state is established.

The subsea communications system's data sampling rate and the typical stability of the process data (i.e. "fingerprint" of typical operations) will determine the most appropriate ROC setpoints and time averaging window, for a given system. The goal is to select a setpoint that can reliably detect leaks, while minimizing the occurrence of false alarms. Shorter time averaging windows will result in a more sensitive but noisier signal. Using a time averaging window that is too long may over-dampen the ROC response, which will slow down the detection performance or in the worst case, result in missed detection.

ROC works best if the pressure sensor used is located close to the leak. If the subsea architecture consists of long offsets (greater than 2 miles), pressure sensors at each node are recommended to provide more complete leak detection coverage over the subsea system. This is because the ROC signal will be further dampened by increasing distance between the leak site and the pressure sensor.

Flowline ROC

The simplest form of ROC leak detection is to monitor the ROC of the flowline/jumper pressure and set an appropriate alarm threshold that is sensitive enough to detect a leak initiation event, based on the selected time averaging window. However, because some flowline transient operations can also cause rapid flowline pressure changes, false alarms may become a problem unless very high alarm thresholds are used, which will significantly reduce the detection sensitivity of this method.

Figure 4 and Figure 5 show the ROC responses to the leak initiation event at Field A, under 4 different time averaging windows (15s, 30s, 1m, and 2m), at the subsea tree nearest to the leak site and the subsea manifold located 2 miles away, respectively. At both sensor locations, a highly negative ROC is detected immediately following the leak initiation. The sensor closest to the leak (Figure 4) measures the largest peak ROC value of 39083 psi/hour under 15s time averaging, whereas the sensor at the manifold 2 miles away (Figure 5) detects a lower peak ROC value of 25915 psi/hour under the same time averaging. Using longer time averaging windows will result in a smoother signal under steady state, but will yield a lower peak ROC value.

The trade-off between false alarm frequency and detection sensitivity needs to be considered when making ROC setpoint selections. If the desired detection sensitivity results in a high frequency of false alarms, secondary verification is required to efficiently validate these alarms. This secondary verification may be in the form of human assessment, or it may be automated. There needs to be a high degree of confidence that there is no leak, in order to continue to operate after a leak alarm has been received.

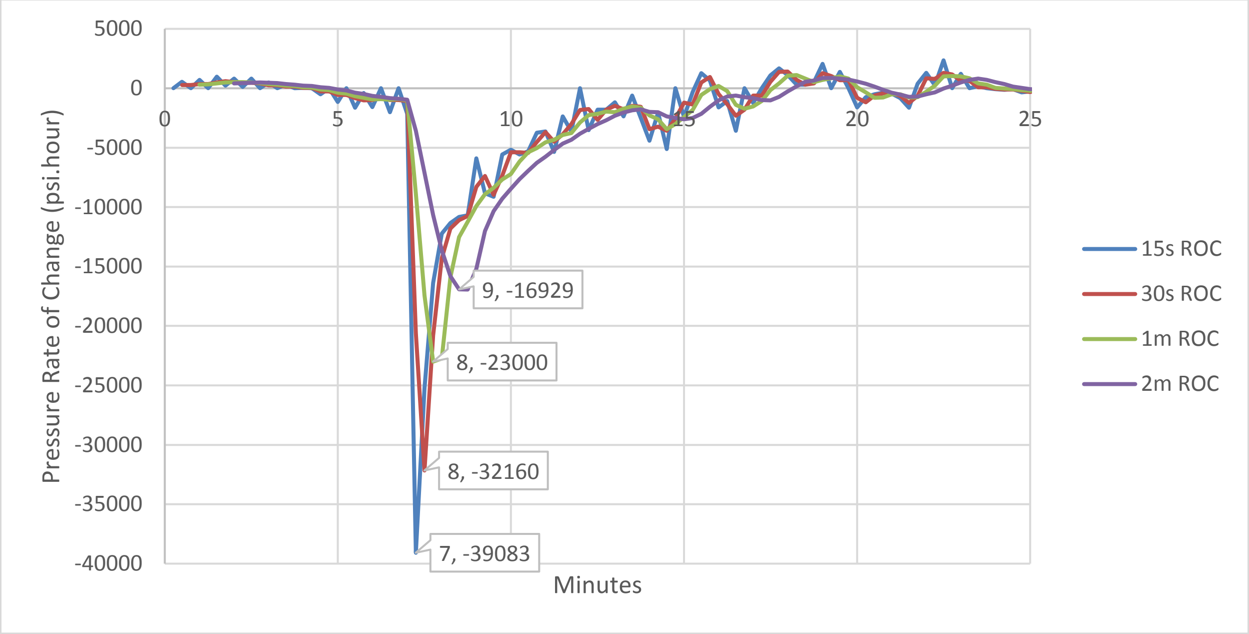

Figure 4 Field A leak initiation - Pressure ROC trend at subsea tree based on 15s pressure data sampling. Pressure sensor is located near the leak location.

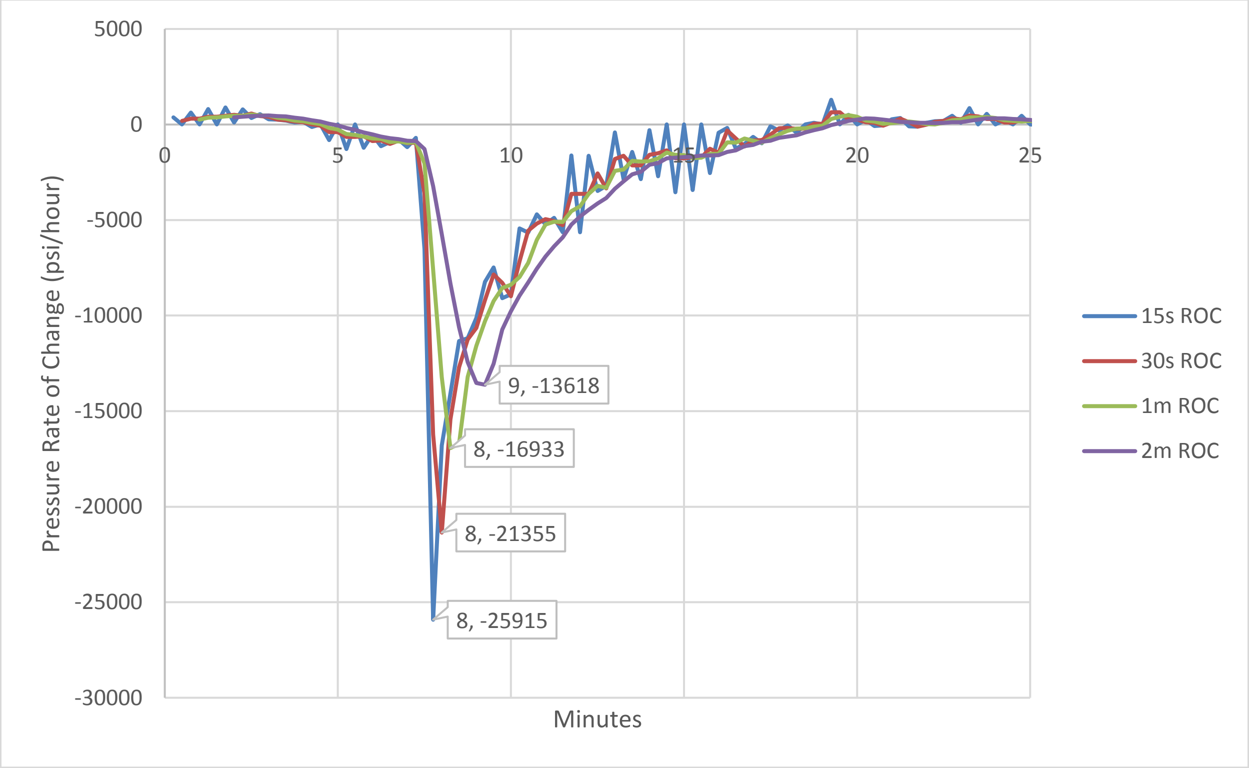

Figure 5 Field A leak initiation - Pressure ROC trend at subsea manifold based on 15s pressure data sampling. Pressure sensor is located 2 miles away from leak location.

Figure 6 and Figure 7 show the ROC responses to the leak initiation event at Field B, under 3 different time averaging windows (30s, 1m, and 2m). The 15s ROC trend has been omitted because the data update frequency of this field is approximately 30s. Both trends show similar responses, with an initial ROC value plateauing at around 2207psi/hour, followed by a peak ROC value of 12149psi/hour. The initial ROC plateau may be the result of compression of the process data by the historian. If this is the case, the peak ROC value should be larger if real-time data from the control system had been available.

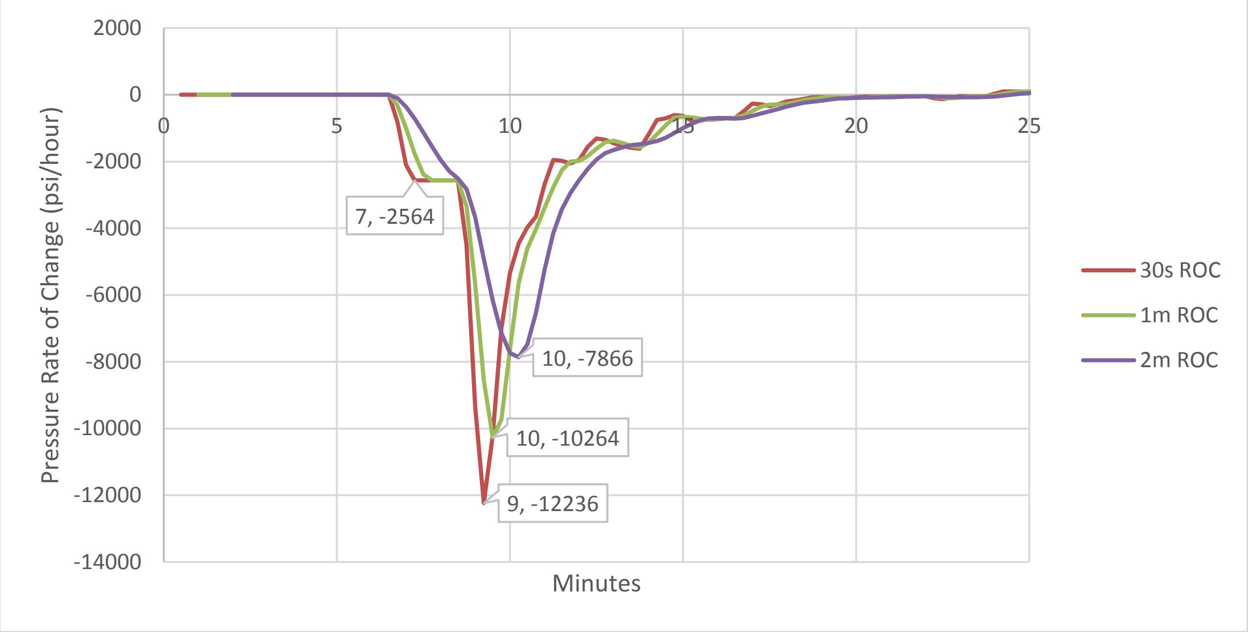

Figure 6 Field B leak initiation - Pressure ROC as measured at Tree D/S PT based on 30s pressure data sampling

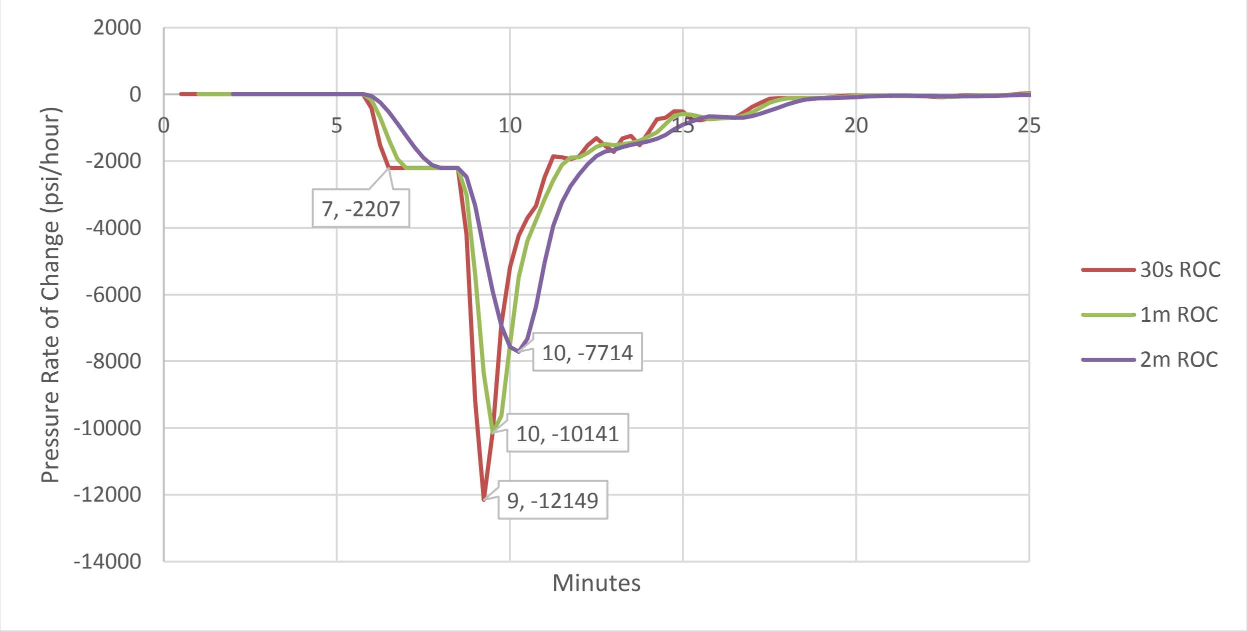

Figure 7 Field B leak initiation - Pressure ROC as measured at Sled based on 30s pressure data sampling

Conditional Rate of Change (C-ROC)

C-ROC is a method of automatically performing secondary verification on Flowline ROC alarms, without human input. The addition of carefully selected logical conditions will dynamically suppress the Flowline ROC alarm when identifiable non-leak transients are occurring, which allows the removal of the majority of false alarms that would occur with a simple Flowline ROC alarm. Transient state detection and the ability to dynamically switch between a lower alarm threshold during steady state conditions, and a higher alarm threshold during unstable conditions, results in better overall leak detection coverage while avoiding an excessive number of false alarms.

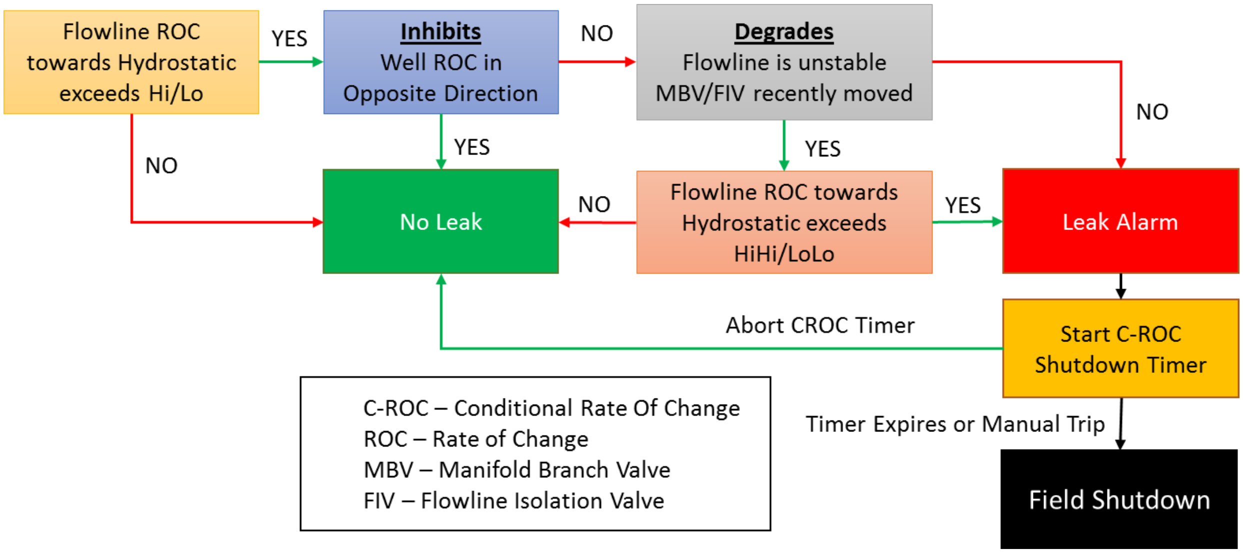

Figure 8 C-ROC flowchart

In Figure 9, the Flowline ROC dropped to a highly negative value which would have caused a false alarm. However, the presence of simultaneous Well(s) ROC in the opposite direction of the Flowline ROC indicate that this Flowline ROC event is due to aligned wells being shut in, and therefore is not a credible leak indication.

This non-leak transient detection and alarm muting occurs automatically in the background and does not require human assessment or intervention. The C-ROC setpoints do not require frequent retuning, once they have been set up correctly. However, each field must be evaluated separately using its characteristic operating data, in order to properly configure the C-ROC setpoints.

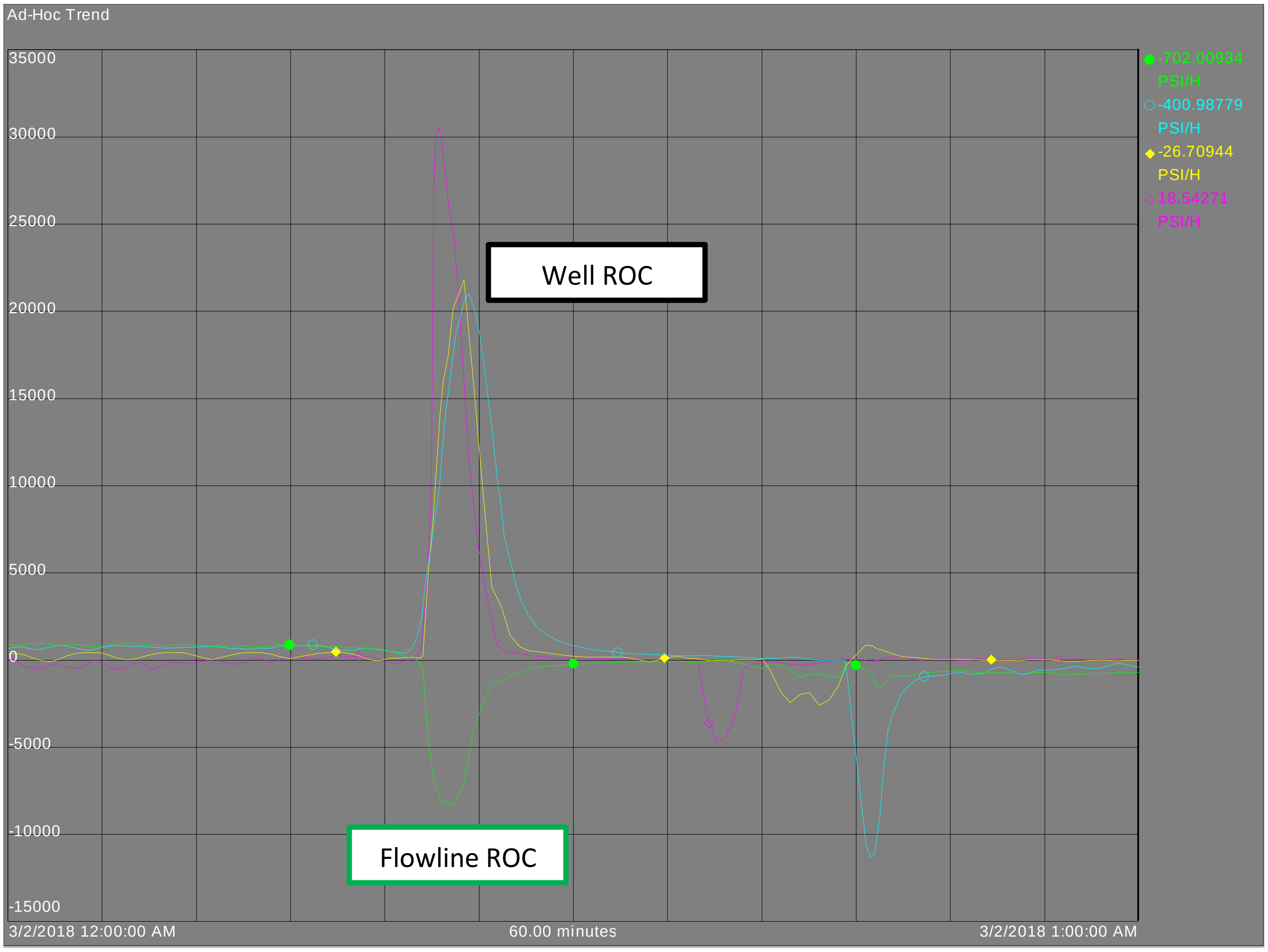

Figure 9 Field C – CROC behavior during non-leak transient operation

Meter In, Meter Out (MIMO)

Calibrating meters and ensuring agreement between subsea and topsides meters during steady state conditions is a requirement of subsea allocation. If all inflows and outflows are accurately metered, performing a continuous balance calculation will give a reliable leak indicator. When the system is at steady state conditions, the outflow rate will equal the inflow rate, giving a very small balance residual. A leak to the external environment may be suspected if the outflow rate is consistently less than the inflow rate.

During startup operations, the inflow can temporarily exceed the outflow, as the flowline inventory is refilled. This effect is larger if the flowline has previously been depressurized. As a result, the metering balance trends can look very much like a leak signature during a startup. To manage potential startup related false alarms, a higher alarm threshold could be temporarily permitted during the initial ramp up phase, after which the system should revert to tighter steady state alarm thresholds.

Other operational changes such as starting and stopping certain chemicals such as defoamer, may affect temporarily affect the flow balance. Subsea operators should be trained and be familiar with how the system normally responds to such operational changes, and be able to recognize the expected response on metering balance trends.

The selected alarm thresholds should be based on the historical performance of the metering balance under both steady state and transient operations.

Figure 10 shows the instantaneous flowrates from Field D during a normal restart. After the initial line packing period, the inflows and outflows converge to the same steady state value. However the separator flowrates still experience significant amounts of fluctuations around the mean value. This could be due to factors such as the type of meter used, flowline slugging, and bad weather causing riser-topsides interactions.

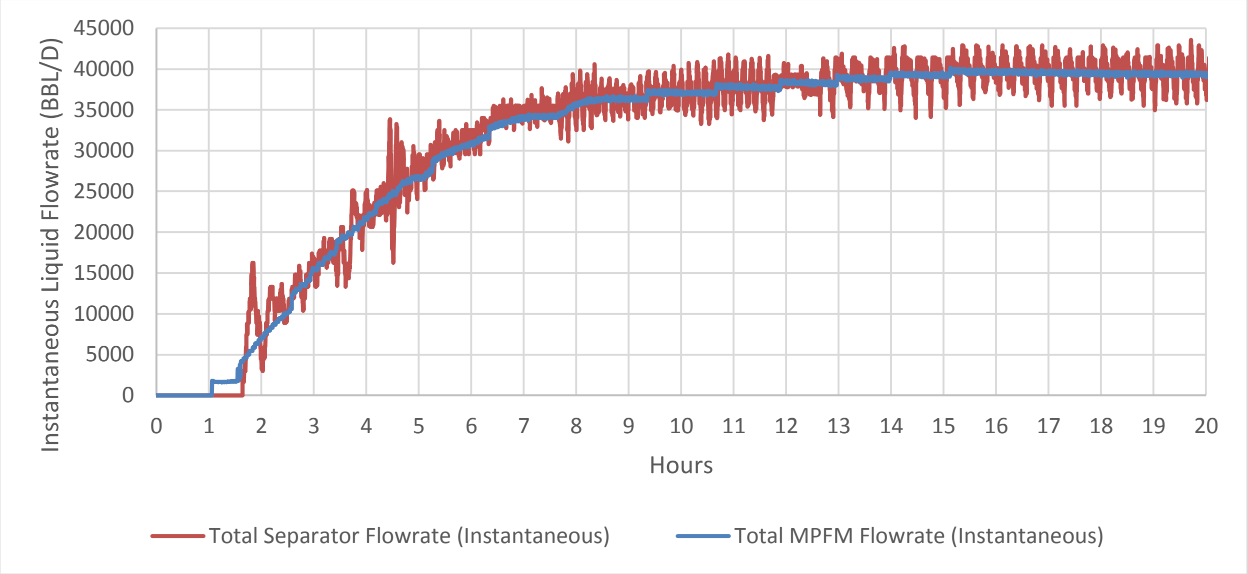

Figure 10 Field D – Normal restart, instantaneous flowrates

Figure 11 shows the 1 hour moving average of the flowrate data from Figure 10. The difference of the subsea and topsides moving averages is also calculated. The metering balance approaches a steady state value of approximately zero.

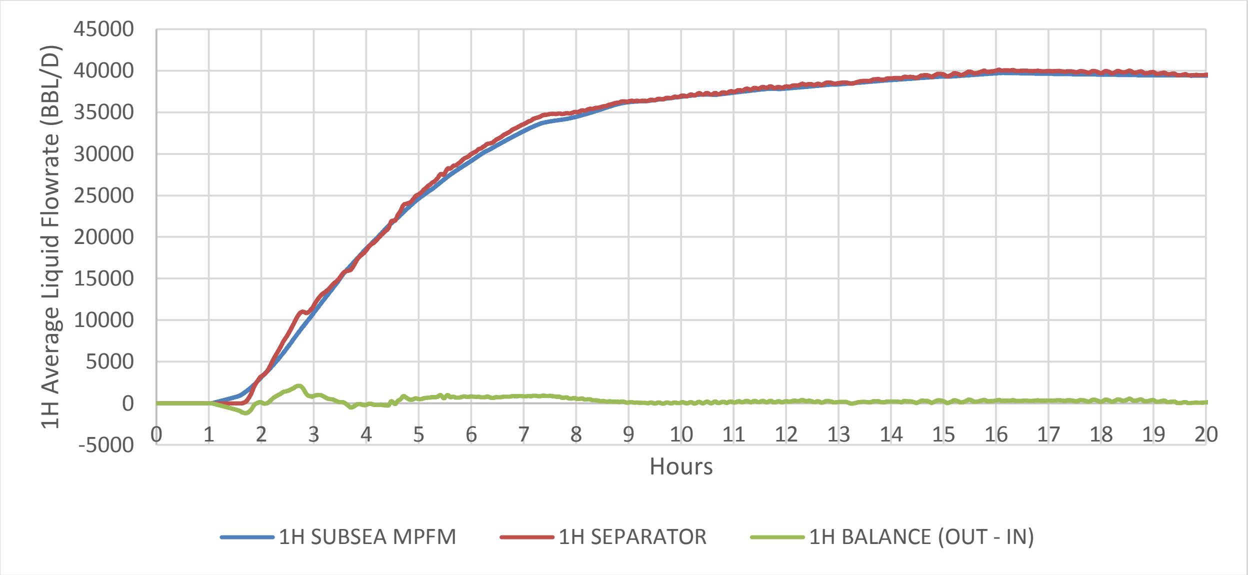

Figure 11 Field D - Normal restart, 1 hour averaged flowrates

A fixed alarm threshold of +/- 3000 BBL/D could be applied to this restart and experience no alarms (Figure 12). This would represent a leak detection sensitivity of 3000/D, or 8% of normal steady state flow.

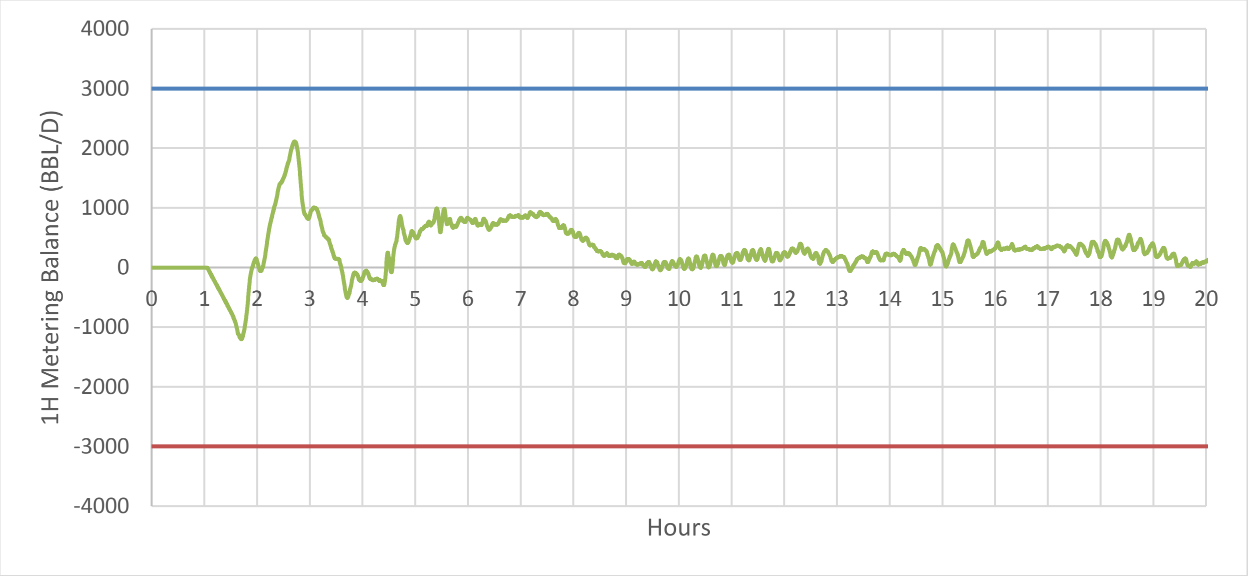

Figure 12 Field D - Normal restart, 1 hour metering balance

The instantaneous meter flowrate trends for the Field A restart is shown in Figure 13. The first 2 hours of well flow are used to pressurize the flowline. This can be seen in the initial pressure trends in Figure 1. However, the separator flowrate trends remain very unstable, and only begins to stabilize after about 5 hours into the restart.

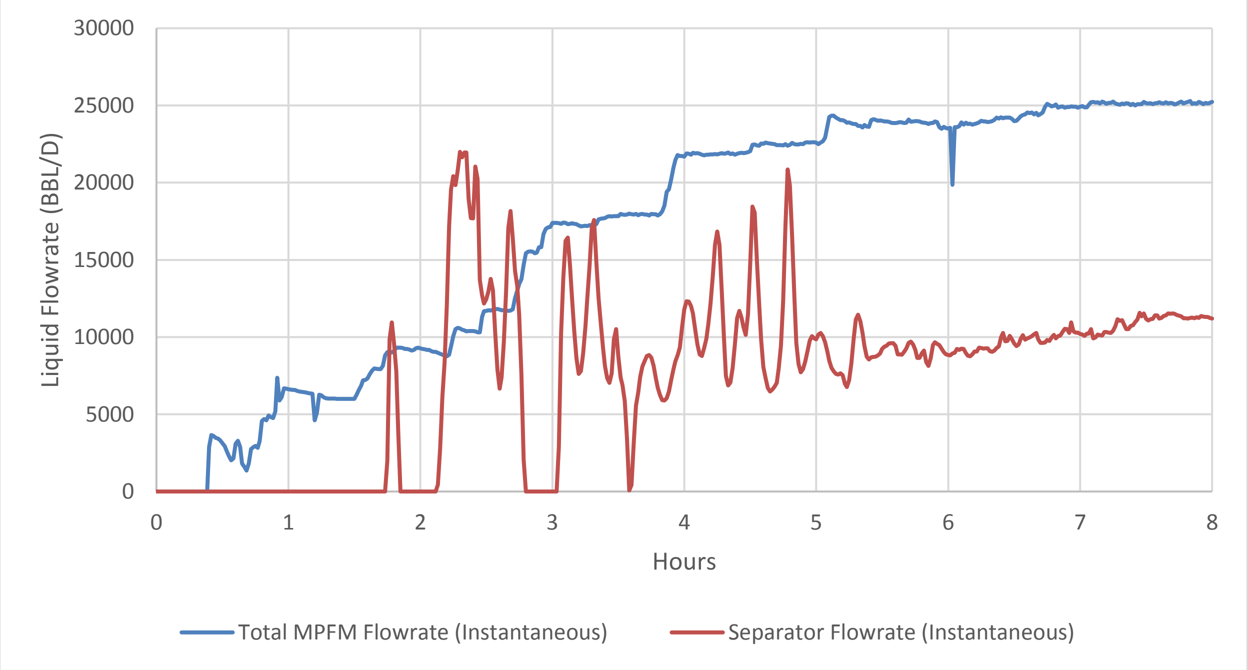

Figure 13 Field A – Instantaneous liquid flowrates during restart

The 1 hour moving average of flowrates and associated balance calculation is shown in Figure 14. Initially the balance calculation goes negative, due to the flowline pressurization. As the topsides starts to receive fluids, the balance calculation returns to zero.

The Flowline ROC method detects a leak event at t=2.7H. After the ROC alarm is received, the separator and the subsea flowrates diverge and the balance goes negative again, due to the loss of flow to the subsea leak.

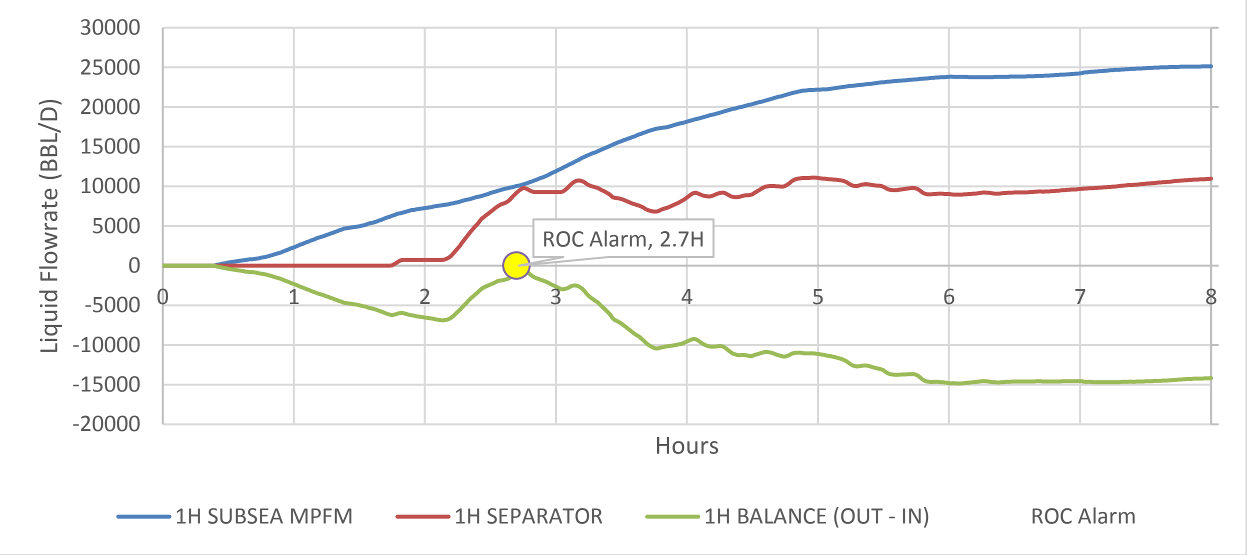

Figure 14 Field A – 1H Metering Balance during restart with ROC Alarm overlay

Figure 15 show the cumulative volume lost after the ROC alarm was received. In this system, the cumulative loss typically does not exceed 500BBL over the course of a restart. This cumulative loss value is exceeded 1.2 hours after the ROC alarm.

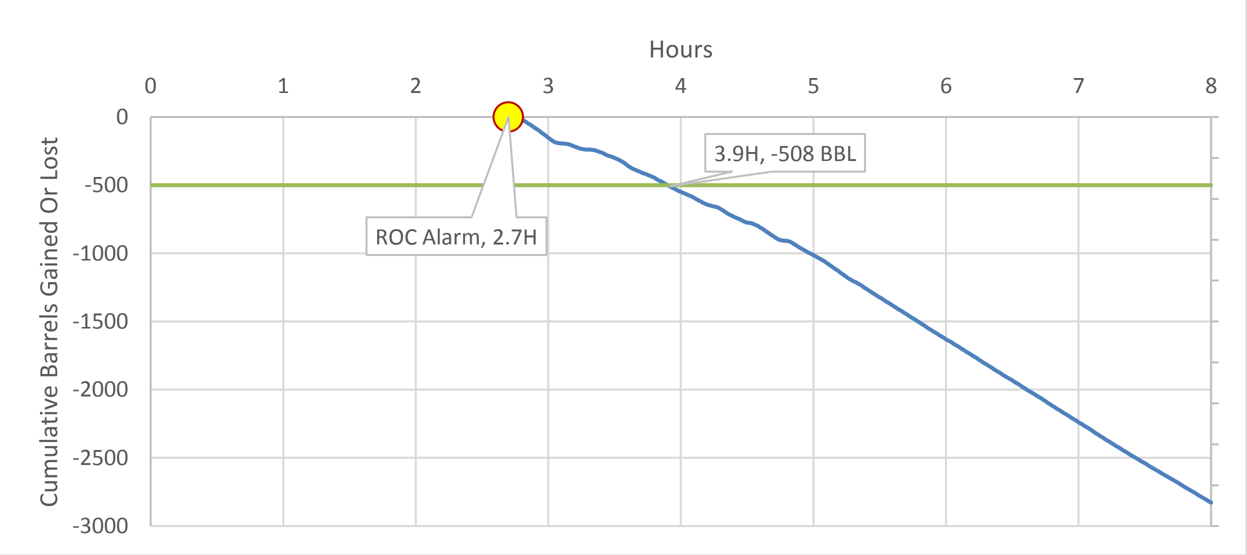

Figure 15 Totalized Barrels following ROC Alarm at 2.7H

Metering balances are useful for detecting smaller leaks and supporting the evaluation of other leak indicators such as ROC/C-ROC. However, they rely on longer time averaging to smooth out random noise and repeating transients in the meter flowrate outputs, and therefore will have slower detection speed.

Metering balance also requires all inflow and outflows to be measured. If a subsea meter fails or becomes unreliable, this will affect the accuracy and reliability of the overall balance, unless the affected well is left shut in until its faulty meter is replaced.

Location of Implementation

The subsea leak detection methods require high reliability real time data. This can be met by implementing these algorithms in the Process Control Domain.

Office domain applications such as PI Historian are not designed for safety critical functions and currently do not have the required level of redundancy and real-time availability.

Hardware Requirements for Detection Methods

Hydrostatic Pressure Monitoring

1. Pressure Transmitters located on the subsea sled/manifold and not normally behind a closed valve
    a. If a dedicated flowline PT is not part of the subsea system design, the requirement for hydrostatic pressure monitoring may still be met by using a subsea tree PT with an open path to the flowline. This may require operations to manually verify the flowline pressure prior to startup.

Flowline Rate of Change

1. Pressure Transmitters located on the subsea sled/manifold
    a. If a dedicated flowline PT is not part of the subsea system design, a subsea tree PT with an open path to the flowline can be used.

Conditional Rate of Change

1. Pressure Transmitters located on the subsea sled/manifold
    a. If a dedicated flowline PT is not part of the subsea system design, a subsea tree PT with an open path to the flowline can be used.
    b. However, additional logic would be required to determine the appropriate well PT that is aligned to a given flowline.
2. Pressure Transmitter located upstream of each subsea well choke

MIMO

1. Subsea meters for each tree
    a. BOEM allocation accuracy testing compliance for multiphase meters
2. Multiphase Meter on subsea flowline topsides or flowmeters on receiving separator outlets
    a. Pressure and temperature readings at topsides metering location for flash and shrink calculations

Calibration/Testing Considerations

Subsea PTs cannot be easily calibrated or replaced, after they are installed. Therefore, the regulatory testing requirements should recognize these accessibility challenges. However, these are some possible methods for obtaining increased confidence in the accuracy of the subsea PTs:

1. **Multiple subsea PT agreement**
   The subsea tree PT downstream of the choke can be compared against the flowline PT. The agreement of multiple PTs adds confidence that the flowline PT is accurate.
2. **Static pressure reference through a chemical umbilical tube**
   A subsea tree PT can be used to measure the pressure of a chemical umbilical tube (such as methanol). The pressure topsides can be measured using a calibrated PT, and the static head of the chemical is added, to determine the reference subsea pressure for testing the subsea PT.

Comparison of Methods

	Operating Mode	Detection Speed	Sensitivity	Hardware Requirements	Desired Shut In Response Time
Hydrostatic Pressure	Shut-In	~20 min	Can detect small leaks (but takes more time to equalize)	Flowline PT	N/A. System is already shut in
ROC	Flowing	< 60 sec	Catastrophic leaks	Flowline PT	Within 1 hour after alarm
C-ROC	Flowing	< 60 sec	Large leaks	Flowline PT Well U/S of Choke PT	Within 1 hour after alarm
MIMO	Flowing	< 1 hour	Can detect smaller leaks (but larger than selected balance threshold)	Subsea meters on every well Topsides meter at flowline or receiving separator	Within 15 minutes after alarm

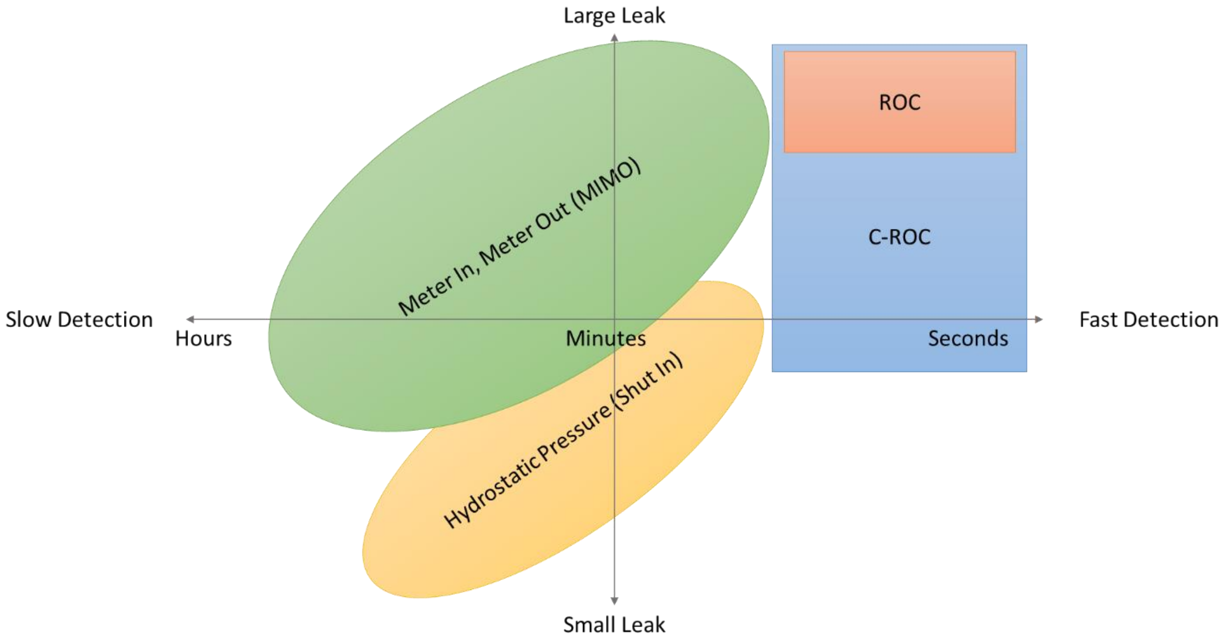

Figure 16 Subsea Leak Detection Methods - Detection Speed and Sensitivity Comparison

Recommendation

For static (shut-in) conditions, integrity verification by comparison of internal pressure against ambient hydrostatic pressure should be done prior to any startup.

For flowing conditions, a ROC-based alarm should be employed for catastrophic leak detection. Historical analysis of 2 recent industry leaks have demonstrated that a ROC of subsea flowline/jumper pressure can rapidly flag the occurrence of a subsea leak initiation, if the appropriate alarm thresholds are applied.

However, simple ROC alarms are prone to false alarms as they are non-specific to leaks. This may require more frequent operator/engineering assessment of alarms.

C-ROC should be considered as it can greatly increase the overall detection sensitivity and reduce the false alarm frequency compared to the simple ROC alarm. The increased alarming reliability will allow operators to reduce the operational burden of assessing frequent false alarms, and consider a time-delayed executive shutdown action to limit the worst-case spill size.

Where the required subsea and topsides metering instrumentation already exist, MIMO should be deployed. MIMO can detect and confirm smaller leaks that may not trigger ROC/C-ROC. MIMO can also confirm if the ROC alarm is valid and compliment the ROC system. However, for many Operators it may require additional metering hardware and calibration to maintain accuracy and reliability.