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Subsea Hydrocarbon Production Leak Detection Systems Using Process Data

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American Petroleum Institute

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Subsea Hydrocarbon Leak Detection Systems Using Process Data

Introduction

The intent of writing this technical report is to share best practices for selecting, designing, implementing, and maintaining process data-based leak detection capabilities on deepwater subsea multiphase systems. This has been driven by a lack of effective automated leak detection systems and operator training to recognize the occurrence of leaks on subsea production systems. Standards are also outdated and do not contain guidance and requirements for effective subsea leak detection.

1 Scope

This technical report provides considerations and recommendations for selection, design, operation, maintenance, and training related to leak detection on multiphase subsea production gathering systems and gas injection systems. The scope is limited to internally based methods using process sensor data to quickly detect leaks.

It is impractical to define a single threshold for leak that can be readily detected from a change in process conditions (e.g., pressure, temperature flowrate), as this will be system dependent. Factors that influence threshold are:

- Fluid properties and Flow regime
- Total Flow rate
- Operating vs Hydrostatic Pressure
- Reservoir Properties

In general, historical leaks size distribution is bimodal – they are either too small to be identified from process data, or so large that the resulting process changes are readily observable. Leaks detectable by process data under flowing conditions are typically in the order of 100-1000’s of bbl/day, while smaller leaks (cannot be detect from flowing process data) are generally less than 1-2 bbl/d and can only be detected when shut-in or by general observation (slick detection, periodic hardware inspections, 3rd party reporting)

1.1 Leak Detection Considerations

This report does not cover leak detection for umbilical systems, subsea trees, well downhole tubing, water injection systems, export pipelines, and leaks that are not readily identifiable from process data.

It is recognized that no one leak detection method or technology may be applicable to all subsea systems because each system is unique in design and operation. Further, leak detection techniques have a detection threshold below which a hydrocarbon release detection cannot be expected. Detectable limits are difficult to quantify because of the unique characteristics presented by each system. Limits must therefore be determined and validated on a system-by-system and perhaps segment-by-segment basis.

Subsea leak detection system is intended to enhance human judgement when some type of intervention or shutdown of the affected subsea system is warranted.

This report is in keeping with standard industry practice and commonly used technology; it is not intended to exclude other effective subsea leak detection methods.

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2 Normative References

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

BSEE

Safety Alert No. 407 - *Risk-Based Inspections of Subsea Leak Detection Technology Reveals Gaps in System Processes* US Department of Interior, Bureau of Safety and Environmental Enforcement.

OCC (Offshore Operators Committee)

Conditional Rate of Change (C-ROC) Alarm Technical Specifications, OOC Advanced Monitoring Subcommittee, July 2018 (https://www.theooc.org/ssldresources)

Technical Solutions for Subsea Leak Detection, OOC Advanced Monitoring Subcommittee, April 2018. (https://www.theooc.org/ssldresources)

GOM Subsea Leak Detection (SSLDS) Competency Management Process, OOC Advanced Monitoring Subcommittee. Chevron, October 2018 (https://www.theooc.org/ssldresources)

SSLDS Training and Competency Development Plans, Tahiti Subsea Operating Procedures, OOC Advanced Monitoring Subcommittee. Chevron, June 2018 (https://www.theooc.org/ssldresources)

Subsea Leak Detection – LLOG Delta House Project, OOC Advanced Monitoring Subcommittee. (https://www.theooc.org/ssldresources)

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3 Terms, Definitions and Acronyms

For the purposes of this document, the following definitions apply.

3.1 Terms and Definitions

3.1.1
bypass
Override or render ineffective

3.1.2
executive action
Response action by the operator to shut-in or bypass the automated shutdown following a leak alarm

3.1.3
executive shutdown timer
Countdown from the time an alarm is initiated to confirm leak or a system transient (false alarm) at the end of which flowline/flow group and associated wells are shut-in

3.1.4
inhibit
Prevent an action when certain condition(s) are met

3.2 Acronyms and Abbreviations

For the purposes of this document, the following acronyms and abbreviations apply:

APCROC	Automatic Proportional Conditional Rate of Change
CRO	Control Room Operator
C-ROC	Conditional Rate Of Change
GAO	Government Accountability Office
Hi	High
HiHi	High High
LDS	Leak Detection System
Lo	Low
LoLo	Low Low

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MIMO	Meter In Meter Out
MMS	Minerals Management Service
MPFM	Multi-Phase Flowmeter
PSHL	Pressure Safety High Low
PSL	Pressure Safety Low
ROC	Rate Of Change
SDV	Shut-Down Valve
SSLDS	Subsea Leak Detection System

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4 Subsea Production System Leak Detection Requirements

a) Each system shall have an executive Leak Detection Alarm that initiates a Shutdown of the affected flowline(s) within 4 hours of leak detection. The shutdown shall be included in the SAFE chart and noted as a non API14C/API17V device.

b) The leak detection system should be function tested at least annually
   - No actual shutdown is necessary for this purpose. However, if one does occur, the event response and investigation may fulfill the requirement provided the intent is met
   - Use of alarm logs and alarm investigations, including ones that were deemed as false alarms, may be used for assessing the health of the leak detection system.
   - Where no alarms are initiated by the system, alarm setpoints need to be reviewed to ensure setpoints are appropriate for the system.
   - Simulations and other validation methods may be considered with the view that the intent of the leak detection system is met.

c) Process and procedures shall clearly define response actions for evaluating and aborting a leak alarm as well as have means to document operator actions before and after the alarm.

d) Performance of the SSLDS system shall be assessed at least annually, to include review of out of service sensors and health of the control system that supports the SSLDS system.

e) KPI's should be reviewed at least annually to demonstrate the Leak Alarm Set points are optimized to provide the highest practical sensitivity.

f) Operators of Subsea Systems shall have Leak Detection capability and be periodically re-trained and re-assessed as competent per CFR 250.1915 and 250.1503, with a recommended completion at least every 3 years.

g) Repository – To house alarm events, historical data, engineering reviews and actions for maintenance, record keeping, etc.

5 Challenges of Leak Detection in Deepwater Subsea Production Systems

5.1 Background

Subsea production systems transport multiphase oil, gas, and water from underwater wells to floating platforms. The subsea systems and flowlines are often located in deep waters and experience significant external hydrostatic pressure. The flowlines operate in multiphase flow regimes which creates uncertainties in pressure and flow. Due to their remote nature, available instrumentation is often limited, and it is impractical to replace or calibrate subsea sensors.

Existing regulations governing leak detection on subsea systems refer to the use of the Pressure Safety Low (PSL) sensor, which is located on the surface facility outboard of the Shutdown Device (SDV), in accordance with API RP 14C. However, it has been long recognized that the PSL sensor is not reliable for subsea leak detection. In 2004, the Minerals Management Service (MMS) initiated a study[1] to investigate the reliability of PSL alarms for offshore flowline leak detection and concluded that in many cases, the PSL alarm setpoints had been set far too low to be useful for leak detection. Additionally, PSL alarms are not reliable for detecting leaks when the hydrostatic head pressure of seawater is high, and for highly compressible flow, conditions which are typical in deep-water multiphase production systems.

[1] Reliability of Pressure Signals in Offshore Pipeline Leak Detection, Dunn-Norman, et. al., 2004

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Two significant oil leaks in the Gulf of Mexico in 2016 and 2017 created impetus and momentum for the industry to find an effective solution to subsea leak detection. The Conditional Rate of Change (C-ROC) method was proposed to address the limitations of the PSL method and has subsequently been adopted by several operators. Subsea multiphase flowmeter technology has also matured, enabling mass balance methods to be used where subsea flowmeters are installed and maintained.

In 2021, the US Government Accountability Office (GAO) issued a report[2] that highlighted the need to improve subsea leak detection capabilities and implement updated regulations to address oversight gaps.

5.2 Distinctions between Subsea Multiphase and Liquid Phase Leak Detection

5.2.1 Fluid Properties and Characterization

Single phase liquids can be mathematically characterized to model the expected hydraulic performance within a particular flowline system. However, subsea gathering systems transport unprocessed well stream fluids which cannot be characterized to the same degree of accuracy. Subsea flowlines typically transport comingled production from multiple wells which makes fluid characterization more challenging. In addition, individual well fluid properties can change over time.

5.2.2 Multiphase Flow Regime Characterization

Multiphase flowlines can also operate in different flow regimes, depending on the relative ratios of gas, oil, and water, flowrates, pressure, temperature, and underlying fluid properties. This complexity creates uncertainty in predicting the pressure and flows, using models and process simulators. Production chemicals such as corrosion inhibitor can also interact with the multiphase flow dynamics in unpredictable ways, creating additional uncertainty.

5.2.3 Changing Flowline Conditions

Subsea systems are subject to flow assurance phenomenon such as organic and inorganic deposition, and emulsions. These factors, if present, can change the hydraulic characteristics of the flowline in ways that are very challenging to accurately quantify.

5.2.4 External Hydrostatic Pressure

The external hydrostatic pressure on a subsea flowline can vary significantly along the flowline route, as the water depth changes. The internal pressure of a subsea flowline can also vary significantly depending on the wells being produced, and the backpressure imposed by the topsides process facilities. As such, normal operating pressures can take on a wide range, and may be higher, lower, or close to the external hydrostatic pressure.

5.2.5 Complex Transient Response

Subsea system pressures may react differently to leaks, as compared to single-phase flowlines. For example, a subsea leak to environment may cause the subsea internal pressure to decrease but cause the topsides arrival

[2] GAO-21-293 Offshore Oil and Gas - Updated Regulations Needed to Improve Pipeline Oversight and Decommissioning, March 2021

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pressure to increase temporarily. This is because the drop in internal pressure causes dissolved gas in the oil phase to flash out of solution and expand in volume, which lowers the effective density of the fluid mixture. The lower mixture density in the vertical riser results in a lower head pressure, which is observed as a higher topsides arrival pressure.

5.2.6 Sensor Availability/Location

Subsea sensors are typically only available in the vicinity of the subsea wells, where subsea electrical distribution hardware is installed. Instrumentation may not be available along the subsea flowline between the subsea drill centers and the topsides facility.

5.2.7 Flow Simulation

Flow simulation of a leak scenario is very challenging, due to assumptions made on its location, size and form. However, they are a useful tool and can aid in selection of SSLDS, subsequent design, and tuning of setpoint parameters.

SSLDS methods are based on a number of variables (pressure, flow rate etc.) and fluid behavior assumptions regarding leaks in specific locations in the production system. The qualitative behavior of these variables is mostly predictable (e.g., equalization with ambient pressure in case of a leak), however there may be some exceptions. Due to a combination of transport and thermodynamics effects, temperature may increase or decrease. Therefore, an optimized SSLDS requires the quantitative assessment of the phenomena to ensure all the variables, their interdependencies and the expected detection threshold are fully understood. The most feasible way to accomplish that task is the computational simulation based on a reliable model for the system to be assessed.

Both transient and steady-state simulations can produce valuable information on how the relevant variables change as a function of the leakage properties, with the transient flow simulation also capable of delivering the rate of change, a critical data depending on the detection strategy. Also, flow simulation may be considered from two perspectives: as a project tool aiming at finding the functional relationship between parameters or as online tool designed to provide instant evaluation of the whole system. In any case the simulation model requirements are roughly the same.

Effective simulation requires some conditions to be fulfilled: descriptive model for the pipelines, proper boundary conditions and leakage modeling. The first should include all the relevant equipment for the case, as valves, pumps, chokes, besides the pipeline geometry. Depending on the scenario, some fine details may become relevant, like pipe roughness or solid deposits in pipe walls. The boundary conditions should most likely include the bottom hole inflow relationship since the reservoir flow characteristics directly influence the leakage behavior and associated variables. The thermal coupling between fluids and environment, as well as the thermal inertia of pipe walls and equipment, may also be of great importance if temperature is considered as a variable for the chosen SSLDS.

6 Leak Detection Methods

This report only addresses internally process based leak detection systems that can be readily applied to subsea production systems. Existing sensor measurement data may include internal pressure and temperature at various locations throughout the subsea production system, and multiphase meter flowrates.

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At the simplest level, measured sensor data is compared against a static setpoint, and an alarm is raised if the setpoint is exceeded.

Mass Balance methods work on the principle that the flow entering the flowline must equal the flow exiting the flowline, adjusted for change in flowline inventory. Therefore, the total flowrates entering and exiting the flowline can be calculated and subtracted to monitor for deviations from zero.

More sophisticated leak detection algorithms may utilize multiple sensors and will automatically determine when the subsea system is operating under different operating modes, and dynamically adjust alarm setpoints based on the associated risk profile.

Externally based methods are excluded from this discussion.

6.1 Static Pressure Setpoints

One of the most basic forms of leak detection is monitoring for an abnormal deviation from normal operating pressure range. This is typically implemented by configuring an alarm to trigger if the process variable value exceeds a pre-determined threshold.

Detection speed is very fast, as there is typically no signal conditioning applied. However, for this method to be effective, the leak must cause the internal pressure to move outside the normal operating pressure, such that an effective alarm threshold can be configured.

6.1.1 Pressure Safety Low (PSL) at Top of Riser

A low-pressure alarm set on the boarding pressure of the incoming subsea flowline at the top of the riser is the conventional leak detection method required by regulations (30 CFR 250.852).

However, the conventional Pressure Safety Low (PSL) alarm can be ineffective at detecting subsea leaks which may be located a long distance away from the PSL sensor. It is also often challenging to set a tight setpoint for leak detection, as operating pressures can vary under normal operations, and slugging may also cause large fluctuations in the boarding pressure.

6.1.2 Pressure Safety High/Low (PSHL) at Subsea Flowline Inlet

A low-pressure and/or high-pressure alarm can be configured on the subsea flowline pressure, typically measured at the subsea manifold or sled. If triggered, the operator can be notified, and automated actions can be taken.

However, the subsea operating pressure is highly dependent on the mix of wells being produced, the productivity of the wells, solids deposition along the flowline, and is also affected by topsides operations. Additionally, the internal subsea flowline pressure may not always be above the external hydrostatic pressure, which can be significant at deep-water fields. Therefore, it is challenging to set a fixed pressure alarm setpoint that will be effective across all normal operating conditions.

6.1.3 Hydrostatic Pressure Proximity Alarm

A proximity alarm can be configured to trigger if the subsea flowline pressure is within a certain range of the external hydrostatic pressure. This may be an indicator of potential integrity issues, particularly during shut ins.

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6.2 Rate of Change (ROC)

A Rate of Change (ROC) alarm calculates the change in value over a certain time interval and triggers an alarm if this calculated value exceeds the setpoint thresholds. ROC alarms can be applied to any continuous process variable, such as pressure, temperature, and flowrate.

While ROC alarms have been implemented on downhole pressure gauges to protect against excessive well ramp up rates, they are not typically applied to the subsea pressure gauges due to the high potential for false alarms.

There are many ways to implement a ROC calculation. Some example implementations are given in Annex A

6.3 Meter In, Meter Out (MIMO)

MIMO is a Conservation of Mass method that calculates the measured meter imbalance between incoming (topsides separator or multiphase meter) and outgoing (subsea multiphase meter) flowrates. Conservation of Mass methods work on the principle that whatever enters the flowline must be equal to whatever exits the flowline adjusted for change in inventory of the flowline.

Subsea flowlines transport a mixture of gas, oil and water streams. The pressure and temperature conditions at the subsea end and topsides end of the flowline are also very different. At the subsea end, higher pressures and temperatures cause more gas to be dissolved within the oil phase, resulting in a lower gas fraction. At the topsides end, lower pressures and temperatures cause dissolved gas to flash out of the oil phase and expand, resulting in a higher gas fraction. Therefore, the volume flowrate at two different measured line conditions will not yield a valid comparison. The measured phase streams will have to be converted to mass flowrates to allow for valid comparison.

Alternatively, the oil/liquid streams can be converted to flowrates at standard conditions using the appropriate shrink and flash factors. The standard condition oil/liquid flowrates can then be compared. While this method ignores the gas component of the stream, it can be effective on liquid dominated systems.

If subsea multiphase flowmeters are installed on each well, it is possible to calculate the sum of flowrates or mass lined up to the flowline. Where multiple wells can be lined up to multiple flowlines, each well’s flowline alignment configuration will need to be calculated to ensure that its flowrate is accurately allocated to the appropriate flowline’s meter balance calculation.

The first metering location on the topsides end of the flowline is usually the first stage production separator, where the production fluids are separated into gas and liquid streams. On some separators, the liquid stream may be further separated into oil and water streams.

It can be helpful to condition the flowrate signal by performing a moving average calculation. This can yield a more stable leak indicator, which can allow tighter tolerances to be set. However, using longer time averaging windows will also increase response lag, resulting in slower detection for a given threshold. For example, a 1-hour volume balance set to 500 barrel/day will detect a 500 barrel/day leak in 1 hour, a 1000 barrel/day leak in 30 minutes, a 2000 barrel/day leak in 15 minutes, etc. Using shorter time average windows will yield faster detection, but may be overly sensitive to measurement outliers, resulting in more false alarms.

On subsea systems where the subsea multiphase meter is installed at the subsea flowline inlet, MIMO can be applied to monitor the metering balance across the flowline. However, it will not detect subsea leaks that occur upstream of the subsea meter location. In this case, it is advisable to have another SSLDS to provide coverage of the upstream subsea trees and well jumpers.

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Line pack should be taken into consideration when calculating the overall mass balance of the system. For example, if well incoming flow is increased, it may take some time before this increase in flowrate is seen at the separators. Certain subsea systems may be started up by intentionally producing wells for several hours into a closed in or heavily choked flowline, to build up subsea pressure prior to topsides start up. In other times, the boarding choke may be used to temporarily reduce subsea flow to topsides during process upsets, without reducing the subsea well flowrates, thereby packing the subsea flowline. Line pack adjustments can be calculated and added to the balance equation. However, it may be simpler to apply dynamic thresholding.

MPFM's are typically equipped with a low flow cut-off, which causes them not to show any reading until the flowrate reaches some minimum value. This could result in a leak alarm when starting up a well. This can be mitigated through conditional statements to allow for a larger offset until the meter begins to read a value, or by using a calculated flowrate based on the position of the well choke.

6.4 Dynamic Thresholding of Leak Indicators

6.4.1 General

This may be a primary feature of the SSLDS where the SSLDS dynamically adjusts the threshold to provide large volume leak detection during transitions of flow and pressures during the flowline operation, which are typically during startup or shutdown. The dynamic threshold automatically lowers the threshold, typically significantly, when the flowline is operating in steady state.

Dynamic threshold adjustment may be performed automatically by the SSLDS algorithm if a normally operating transient condition is detected. These transient conditions may be detected by monitoring commands issued by the operator, observing changes in valve positions, or changes in certain pressures and flowrate throughout the subsea system.

If done with a good understanding of the system and how a potential leak will affect the system's physical response, dynamic thresholding can dramatically reduce false alarms by increasing the SSLDS tolerance when non-leak transients are occurring, but maintain high sensitivity during steady state conditions, and when leaks do occur. Ultimately this allows the steady state leak indicator thresholds to be configured significantly tighter than would be possible without dynamic thresholding.

It is important to consider that the transients induced by a leak may also trigger dynamic thresholding of the SSLDS which could result in delayed or missed detection.

6.4.2 Conditional Rate of Change (C-ROC)

The Conditional Rate of Change method refers to the application of dynamic thresholding to the subsea flowline pressure ROC, which is the leak indicator.

Three fixed thresholds, or tolerances, are defined for each ROC direction (positive and negative).

a) Steady state tolerance (Hi and Lo setpoint)
b) Moderate transient tolerance (HiHi and LoLo setpoint)
c) Severe transient tolerance, or not applicable (Alarms Inhibited)

Subsea systems can operate above, below, or close to the external hydrostatic pressure. Subsea leaks will cause the internal flowline pressure to trend towards the hydrostatic pressure. ROC alarms away from the direction of hydrostatic pressure may be inhibited. For example, if the subsea flowline is operating below hydrostatic

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pressure, all negative ROC alarms may be inhibited. Similarly, if the subsea flowline is operating above hydrostatic pressure, all positive ROC alarms may be inhibited. If the subsea flowline is operating close to the hydrostatic pressure, no alarm inhibition due to the hydrostatic pressure condition should be applied.

Large and rapid changes in subsea flowline pressure can be induced by changes in well flowrates due to choke or valve position changes. For example, reducing a well flowrate by closing its subsea choke will reduce the associated subsea flowline pressure. This well-induced transient may exceed the desired steady state tolerance of the SSLDS system, resulting in frequent false alarms. However, the SSLDS system can detect that there is an ongoing well-induced transient, for example by monitoring the ROC of the wellhead pressure. It can therefore dynamically adjust the leak indicator threshold proportionally while the well transient is ongoing, and automatically revert to the steady state tolerance once the well transient is over.

Similarly, system startup transients may cause the subsea flowline ROC to exceed the desired steady state tolerance. To avoid bypassing all potential alarms during the entire system startup period, a higher transient condition tolerance is configured. For example, the SSLDS may detect an ongoing unstable flowline pressure condition caused by a system startup, and dynamically adjust the threshold to a higher tolerance until the flowline pressure stabilizes. SSLDS Systems should be designed to be able to account for slugging and still be sensitive enough to detect significant process change that may indicate a leak.

6.4.3 Automatic Proportional Conditional Rate of Change (APCROC)

Automatic Proportional Conditional Rate of Change is a variation of a Rate of Change system which dynamically compares proportionate thresholds to the rate of change of a group of relevant sensors.

To maximize effectiveness of the SSLDS system and its ability to discern the difference between anomalies and “background noise” that is part of normal system operations, the system performs the following:

a) Determination of anticipated system background noise based on current operating conditions within each flow group (riser/flowline or group of risers/flowlines). Operator actions monitored continuously within each flow group while monitoring flow alignment to ensure only relevant actions are considered along with accounting for sensor update rates/polling priority group. For operator driven events which cannot be automatically detected based on available data in the control system, manually initiated events can be created to allow operations to inform the system of the actions they are taking. These events should be based on specific operator actions (examples: Dead Oil Circulation, Well Stimulations, Energized Crude Circulation etc) such that relevant background noise for that specific action can be characterized. Normal response for all present actions in flow group compared to determine maximum anticipated background noise level

b) Determination of overall system state such as identification of wells flowing in a flowline/flow group identifies which wells need to be shut in. Determination of if flowline/flow group is experiencing transient conditions independent of state. Operator actions can cause elevated levels of background noise in shut in system in similar manner to producing systems

c) Determination of relevant sensors for each flowline/flow group – this should be determined dynamically based on current system configuration, flow group state and flow alignment. If sensor quality information is available, it may be used to refine the available sensor group. In the event a sensor is considered unavailable due to bad data quality but experiences an ROC that exceeds normal background noise limits the system should provide notification of this anomaly so operations can perform additional assessment of the ROC

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d) Evaluation of relevant sensors against proportionate thresholds (background noise) for respective flowline/flow groups

To maximize the ability to detect anomalies these thresholds are set proportionally to the operator driven events which are affecting the subsea system at that specific time. These operator-driven events will have a normal response characteristic. The response of the system to these operator actions will determine the baseline which limits the ability to detect anomalies. Any anomaly that elicits a pressure rate of change response less than the threshold, the event will likely be undetectable against the "background noise" of a system operating within its normal operating bounds. To do this, operator actions must be monitored by the system and then the system can apply the most appropriate allowable response limit to the system from a catalogue of limits which have been derived from historic response data and are proportionate to the ongoing events in the system.

The evaluation of active events at least as frequently as the calculations of rate of change to ensure that the ROC is being compared to the most appropriate limit at that time. Additionally, due to varying data frequency among subsea sensors and different data sources it is possible that events may be detected only after they have caused an ROC. To account for the possibility of a delayed event detection a re-evaluation logic should be considered to compare any potential leak alarm to both the threshold limits at the time of the threshold breach, as well as any revised thresholds the occur following the alarm due to delayed event detection. The re-evaluation period should be based on the maximum anticipated detection delay based on the various data sources and scan frequencies.

6.4.4 C-ROC using other leak indicators

C-ROC can be configured to use other sensors such as temperature sensors, flowmeters, and even topsides sensors. For example, a rapid reduction in fluid temperature could be an indication of upstream seawater ingress on a sub-hydrostatic subsea system. However, other normal operating transients could also result in a similar rapid reduction in fluid temperature, resulting in false alarms. For example, starting up an additional cold well into the existing flow will temporarily reduce the flowline temperature. Dynamic thresholding based on appropriately selected conditions may be applied to provide a reliable leak alarm based on temperature change.

6.4.5 Conditional MIMO (C-MIMO)

During startup and when well flowrates are being changed, there may be a temporary imbalance between the incoming and outgoing flowrates. It may be impractical to accurately calculate the line pack adjustment needed to correct the imbalance. Dynamic thresholding can be applied to automatically increase the imbalance tolerance under these operating conditions. Once steady state conditions are reached, the dynamic threshold automatically reduces the threshold to restore normal sensitivity.

6.5 SSLDS Independence

On subsea fields with two or more flowlines, an independent C-ROC alarm point is typically set up on each flowline header's pressure sensor. The well to flowline alignment is calculated to ensure that only the relevant wells' data are used for conditional filtering of the ROC alarms. Adding unrelated conditional filters will decrease the overall sensitivity of the leak detection system and may inadvertently cause missed detection.

On subsea fields with distributed well clusters connected via a common flowline, the subsea flowline pressure may be monitored at each well cluster location. The flowline ROC signal induced by a leak is strongest near the leak location and dissipates as the signal travels further from the leak location. To maintain optimal SSLDS

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sensitivity, each well cluster should be fitted with an independent SSLDS. Each SSLDS might share similar conditions for dynamic threshold adjustments, but SSLDS should be able to raise a leak alarm if its alarm thresholds are met. This is to avoid the situation where one SSLDS detects a leak, but a second SSLDS located further from the leak location does not detect due to the attenuated leak signal.

6.6 Combination Voting of Multiple Process Sensors

Some systems may only have a single sensor due to legacy design or sensor failures throughout life. For systems with multiple sensors, if it can be demonstrated that two or more leak indicators are always simultaneously present during a subsea leak, it could be advantageous to use a voting system that requires multiple leak indicators to exceed their thresholds simultaneously. This would likely dramatically reduce false alarm rates. However, the timing and persistence of the selected leak indicators needs to be carefully considered.

For example, let us select the flowline ROC and overall meter imbalance as leak detection methods. Both leak detection methods are individually reliable and are expected to be activated during a subsea leak. However, the flowline ROC signal is only activated for the first several minutes of a leak, whereas the meter imbalance signal may only come in after 15 minutes or so. Requiring the simultaneous presence of these reliable leak detection signals may result in missed detection.

As a result, in general, it is recommended that the operator receives each individual leak alarms and uses the condition of other alarms and sensors in their assessment to determine if there is a potential leak and initiate a shut down.

7 Leak Detection Performance

7.1 Performing on demand

Continuous monitoring of the flowline is recommended. If no sensor is available, consider verification of flowline integrity prior to restart.

The subsea leak detection alarm is designed to detect anomalies that may be indicative of a subsea leak to environment. The leak detection alarm should be active and optimized when the system is flowing (i.e. available on demand).

The benefit of the leak detection methods described in this document is that they can be applied retroactively to most subsea systems. However, some of the limitations of using subsea sensors is that they cannot generally be calibrated or replaced. Potential consequences are:

a) Gauge Drift:
   - Can impact alarms based upon absolute measurement such as a PSL using a subsea gauge
   - Minimal impact on alarms based upon rate of change
   - Drift can be assessed by comparison with other gauges when the system is static (shut-in)

b) Gauge Failure:
   - Impacts all types of Alarms
   - Can be mitigated by use of redundant gauges or selection of other gauges in the system

The performance of sensors should be assessed periodically to verify that the leak detection system is still capable of operating as desired with available sensing devices.

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7.2 Mitigating False Alarms due to Operator Actions

Process changes driven by operator action can significantly affect system stability throughout the production cycle. These system responses to operator action can often appear similar to the response that might be seen if a leak occurs, resulting in SSLDS false alarms. When practical to do so, operator actions should be used by the SSLDS. By accounting for these actions and adapting the system to the current production system state false alarms driven by operator action can be reduced.

7.3 Mitigating False Alarms due to Subsea Processing Equipment

Some subsea systems contain subsea processing equipment such as subsea separation, subsea pumps, and gas lift. The operation of these equipment can directly influence the subsea process and could potentially result in additional false alarms. These changes could be initiated by the operator or be controlled by an algorithm. The ways in which subsea processing can cause a false leak alarm for a particular SSLDS should be assessed, and if warranted, should be factored into the dynamic thresholds.

7.4 Subsea Processing Equipment

Subsea processing equipment are typically operated by controlling a subsea system parameter. For example, a subsea pump may be controlled by setting the suction pressure setpoint. The pump will automatically adjust its speed to maintain the suction pressure near its setpoint.

A subsea leak upstream of the pump would normally cause a change in pressure. However, the subsea pump control scheme could potentially compensate for this change by adjusting its speed to maintain the suction pressure. This intervention by the pump control scheme may dampen the pressure response induced by the leak, which may reduce the ability of certain SSLDS to detect the leak.

7.5 Managing SSLDS Sensitivity with Flowline Instability

Certain subsea flowlines will experience flow instability during startup, and in some cases, during steady state. This may be driven by factors such as the flowline bathymetry, fluid properties, flowrates, operating pressures, and production chemical interactions. This in turn will affect the usable SSLDS thresholds that can be set, which determines the SSLDS sensitivity.

For example, on a subsea flowline with severe slugging, the meter imbalance value will always be oscillating due to the fluctuating flowrates entering the topsides separator. This will force the operator to increase the SSLDS steady state thresholds to avoid constantly alarming. Increasing the averaging window will help to reduce the magnitude of the fluctuations but will slow down the leak detection speed accordingly.

7.6 Impact of Leak Offset Distance on Sensitivity

Increasing offset distance from the leak site (negatively) affects the detectability of a leak for ROC methods. Therefore, it is recommended that flowline monitoring sensors are located where practical at multiple locations in the system. This generally means having sensors at each drill center (where monitoring connections are available).

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Mass balance methods are not affected by measurement offset distance to the leak, provided that the leak site is located within the mass balance boundary. However, it may take a longer time to detect the leak if the segment is very long, or if the fluid has a high Gas Oil Ratio and/or operates at lower pressures.

7.7 Selection of Dynamic Thresholding Conditions

Dynamic thresholds, a type of threshold adjustment, may be utilized provided they are well defined and can be rationalized against specific actions occurring within the system such as operator actions or safety system actions.

Dynamic thresholds to accommodate transient conditions need to be optimized in a similar way to steady state thresholds; they need to avoid too many false alarms while not being set so high that they effectively renders the SSLDS incapable of detecting leaks

The leak indicator values under each sensitivity condition should be analyzed to determine the historical range and distribution of values. If a particular dynamic thresholding condition does not reduce the false alarm rate, it should be removed.

Some examples of when it may be appropriate to manually adjust (degrade/bypass) alarm thresholds for short durations are as follows:

- Hot Oiling
- Blockage Remediation
- Pigging
- Operation of ROV operated valves while flowing

7.8 Performance Metrics (Operate Phase)

Key performance metrics relevant to the type of SSLDS, should be implemented and periodically reviewed to demonstrate that Leak Alarm setpoints are optimized to provide the highest practical sensitivity.

Examples are:

a) Number of leak alarms
b) Number of maintenance alarms
c) Distribution of leak indicator values vs. Alarm Thresholds
d) SSLDS Availability
e) SSLDS Communications Uptime with MCS/DCS
f) Sensor Health / Data Quality
g) Duration subsea flowline is producing vs shut in
h) Average Alarm Threshold Value
i) Cumulative duration spent at each Threshold (if using dynamic thresholds)
j) % Time in Bypass or Degrade
k) Leak Alarm Duration
l) Parameter changes
m) Tests conducted
n) Sensor drift alarms
o) Sensor failure alarms

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8 Sensors and Instrumentation

8.1 General

The available and functional sensors and instrumentation on a subsea system will determine the types of subsea leak detection methods that can be applied to it. It is usually not possible to repair or replace subsea sensors.

On new greenfield subsea fields, there is opportunity to design for additional redundancy and/or select additional instrumentation that enable other methods of subsea leak detection.

8.2 Field Instrumentation and Measurement

Since it is often not possible to add or replace instrumentation at subsea systems, this section will focus on how to best utilize commonly available subsea sensors for subsea leak detection.

8.2.1 Managing Subsea Sensor Drift

Over time, subsea sensors may drift and become less accurate. If SSLDS method relies on accurate process value data and is sensitive to drifting sensors, the operator should have a process to detect and quantify sensor drift (e.g. comparison with other sensors) and make appropriate corrections. The drift correction should be made as far upstream as possible, e.g. in the MCS or DCS before the SSLDS. ROC methods are tolerant of sensor drift.

8.3 Subsea Control System

8.3.1 Processor Hardware Selection

If the existing subsea or topsides control system hardware has excess processor capacity, all the required process data tags are readily accessible, and engineering and programmer resources are available to implement the leak detection methods, then expanding the existing control system to include subsea leak detection functionality may be a good option.

Refer to API 17F for best practices regarding processor load or memory use. If adding subsea leak detection software will cause the existing control system to exceed maximum allowable limits (as defined in API 17F), dedicated processor hardware may be utilized to handle the subsea leak detection calculations, and send shutdown signals to the Safety System, if needed. This may be also a better option if data tags need to be collected from multiple control systems.

8.3.2 Data Quality

The SSLDS system may also have built-in data quality checks or a communications watchdog to look out for stale data. Data quality information may be included with the sensor values and may be used by the SSLDS to help recognize and compensate for suspect data.

For example:

a) Communications outage
b) Out of range data

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c) Stale data
d) Out of service flags
e) Sensor arbitration faults

However, if critical sensors become faulty, this may impact the ability of the SSLDS system to detect a leak. The SSLDS system should be able to notify the operator that it is experiencing a faulty sensor. For example, a maintenance notification can be raised.

8.4 Data Presentation

8.4.1 HMI Display

The HMI should serve as a simplified tool to assist the operator in responding to a subsea leak detection alarm. The alarm should trigger the operator to go through his/her flowchart (example below) or evaluation procedure to assess the validity of the alarm

The HMI should contain:

- Alarms which must have visual and audible components
- Timers (for executive action, inhibit, etc) should be readily visible
- SSLDS pages containing all pertinent information
- Trends of relevant operating parameters
- Diagnostic tools to help expedite the evaluation of potential leaks
- System bypasses/degrades/inhibits should be clearly shown on screen
- Ability to read data from multiple sources (subsea, topsides) to improve leak detection reliability
- The current threshold should be displayed to the CRO.

8.4.2 Alarm Display

Alarms should be both audible and visual, and be consistent with MCS or DCS alarms, and should have an appropriate priority. Operator is to be notified when there is a potential leak, and if there are issues that may impact ability of SSLDS to function properly.

Notifications may be subdivided into 2 classes: leak alarms and maintenance notifications.

Leak Alarms: If the SSLDS indicates a potential subsea leak, a leak alarm should be generated, and an executive shutdown timer should be started. In most cases, the operator will make the final determination if no leak exists.

Maintenance Notification: This alarm would occur if critical input data were missing or are determined to be incorrect, such that the SSLDS may be impaired.

8.4.3 Executive Shutdown Timer

Upon detection of a potential leak, an executive shutdown timer shall be started by the SSLDS, which will initiate automatic shutdown of the affected flowline(s) within 4 hours of leak detection, unless the shutdown timer is aborted by the operator, or the system is manually shut in by the operator. This shutdown shall be included in the SAFE chart but noted as a non-API 14C/API 17V device.

The executive shutdown timer should be clearly visible to the operator while it is active. A periodic alarm notification may be used to remind operators of an active pending executive shutdown.

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The operator should be presented with the option to either abort the executive shutdown timer, or to initiate a shutdown of the affected subsea system.

8.5 Integration of SSLDS and Other Control Systems

Standalone SSLDS systems should be closely integrated with the control system. SSLDS alarms and executive timers should be sent back to the Control System to be integrated into the primary controls interface.

8.6 Data Historian

The SSLDS system should be configured to store its processed data to a data historian. Data compression and scan rate settings should be carefully selected to provide sufficient data resolution to recreate an accurate overview of the SSLDS performance from archived data.

If additional procedural sign off are performed, these may be stored in a database for future reference.

Data retention to be in line with company's SEMS requirements.

9 SSLDS System Operations, Maintenance, and Testing

9.1 System Testing

The primary purpose of testing is to assure that the SSLDS logic will function if a leak occurs. Another purpose of testing may be to assure that data failure alarms function as expected. As part of system design, minimum requirements regarding testing protocols, acceptance standards, and frequency should be established.

9.1.1 Initial Tests during Commissioning

As part of initial installation and FAT, the system is tested to ensure that the programming, calculations, and logic functions as intended. All potential scenarios and operator actions for every line/system should be determined ahead of time to develop the testing protocol. While initial testing can be conducted on a simulator, final acceptance checks should be performed on the actual operating system. For testing conducted on a simulator, consideration should be given for using a standard dataset for all systems. If multiple control systems are involved, the communication redundancy and error rates should be verified.

Initial alarm setpoints should be determined as part of commissioning. Initial estimates for these setpoints can be obtained from flow modelling efforts or historical system data. To ensure these setpoints are reasonable, flow modelling, or historical information should include both steady state and non-steady state scenarios that may be experienced during normal operation (e.g., sudden diversion events such as flowline alignments). It may be prudent to allow the system to run for some time (up to 3 months) before enabling the executive timer to ensure the alarm setpoints are set appropriately.

9.1.1.1 Commissioning after significant subsea layout changes

Where existing subsea configuration is modified to add a tie-in, tie-back or step-outs leading to significant change to the SSLDS parameters, it is recommended to re-assess the impacts to setpoints of the SSLDS and verify setpoints are appropriate for the new field conditions. This may include the need to inhibit the executive timer while validating the updated setpoints for up to a period of one month.

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9.1.2 Periodic Testing

SSLDS must be periodically tested to confirm that logic and end devices function as intended.

Function testing of the logic should be conducted at least annually. This testing can be performed either in a test lab or on the actual installed system. While initial tests during commissioning should verify the logic for all flowlines, re-testing may involve only a representative sample of flowlines. The flowlines selected for testing should be rotated annually so that all flowlines are eventually tested. At a minimum, the testing should confirm the following:

a) Shutdown function works as intended when the executive timer expires or if the operator advances the shutdown step manually. The actual shutdown may be inhibited during these tests to prevent the system from shutting down.
b) Alarms and/or the executive action timer are activated under various scenarios. If the logic considers both steady state and transient modes of operation, both should be tested. This activation can be accomplished by changing alarm setpoints, altering end device output, or flow diversion (flowline routing movements). If the logic is tested in a test lab, manual activation can also be triggered in the logic.
c) Actual alarms, activations, and shutdowns experienced can be utilized to meet the testing requirement. However, it should be verified that these incidents give sufficient representation of flowlines and scenarios.

The sensitivity and availability of the end devices used in the SSLDS logic should be verified at least annually. The type of checks performed will vary depending on the type and location of end device. For example, it may not be feasible to calibrate subsea transmitters, so other means of verification must be utilized. Some examples of verification are:

— For rate of change systems, absolute values for individual transmitters are less important. Monitoring for stale values and/or comparing ROC/absolute values with redundant or nearby transmitters could be utilized.
— For volumetric comparison systems, flowmeters are typically calibrated as part of other requirements. Offsets may be utilized to compensate for calibration differences between flowmeters. Also, low flow cut-offs should be verified to ensure system limits are understood.

9.1.3 Test Records

Records detailing the reasons for the tests, the test parameters and methodology, and the test results should be recorded and retained for initial tests and for retests according to the company's SEMS requirements.

9.2 Life of Field Maintenance

9.2.1 Management of Change

The company shall define what changes to the SSLDS will fall under their Management of Change process. Issues to consider include, but are not limited to, changes to the following:

a) SSLDS design
b) Significant process conditions
c) SSLDS technical requirements
d) Testing and assessment methods

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e) Control logic
f) Procedures
g) Setpoints
h) Maintenance reviews

9.2.2 Alarm Setpoint Validation

Alarm setpoints shall be reviewed at least annually to ensure they can maintain effective leak detection. If the SSLDS contains both steady state and bypass/degrade setpoints, both should be reviewed. More frequent reviews may be needed if there are sustained changes to the system (well performance, flowline alignment, etc), or if KPI's related to false alarms, time in bypass/degrade, or time in inhibit cannot be met.

9.2.3 Obsolescence

Obsolescence Management should be defined, addressing critical sensors, external interfaced equipment, and other SSLDS components.

9.2.4 Maintenance Records

Maintenance records should be retained per the company's SEMS program requirements.

9.3 Documentation

The following documentation is recommended as part of development and delivery phase:

a) Technical/Functional Design Specifications and As-Builts, which describes the following:
   - SSLDS method(s) used
   - Sensor tags used by the SSLDS
   - Calculations performed
   - Conditions and states that may change the sensitivity of the SSLDS
b) Onshore factory acceptance test records
c) Installation and commissioning records

Development of a Leak Detection Program Management Document (following API 1175 or similar) is recommended once the SSLDS is operational. This document should follow the outline recommended in API 1175 (or similar).

10 Training and Capability

10.1 General

Personnel who operate subsea system (e.g. Control Room Operators), support subsea leak detection alarm reviews (e.g. production engineer), or are involved in decisions to abort alarms (e.g. UWA, ops managers) should receive training and periodic reassessment to demonstrate competency in leak detection.

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Personnel who supervise Control Room Operators (e.g. Operations Supervisors, Offshore Installation Manager should receive training and periodic reassessment to demonstrate competency in leak alarm response requirements.

In general, it is recommended that reassessment takes place at least every 3 years. Training material should also be updated with company and industry learnings and provided periodically to the personnel noted above.

Records should be maintained for all offshore and offshore personnel who have been assessed and received the training.

Recommend that CRO must have completed SSLDS training before operating independently.

10.2 Subsea Leak Detection Training Curriculum for CRO's

10.2.1 Course Objectives

Provide training for developing Control Room Operator (CRO) competency and verification to ensure CRO's have the skills and knowledge to manage and execute the proper SSLDS response.

10.2.2 General Overview

The learning objective in training should include a review of significant leaks in the industry and their associated causes, identification of large vs small leaks in production systems, as well as understanding of the barrier components.

The learning objectives are as follows:

a) Understand different types of leak detection alarms and their limitations
b) Identify Anomalies and diagnostics
   — Review diagnostic steps to validate or invalidate an alarm
c) Identify Monitoring Techniques and Best Practices
d) Identify Response Actions Required
   — Review time requirements for specific actions
e) Demonstrate how to use Tools (Exercise, checklists, decision matrix/trees, etc.)
f) Review proper notification requirements (What/Who/When)

10.2.3 Operator Training Simulator (OTS) scenario IF part of company strategy

The learning objective is to test the CRO's understanding and response to potential leak scenarios Including a Leak while shut-in, under transient operations, and confirmation of leak/non-leak after shut-in.

10.2.4 Subsea Leak Detection Training Curriculum for Offshore Supervisors

The learning objective is to understand historical leaks in the industry, awareness of companies as well as regulatory environmental release policy, and required actions following a suspected leak or leak alarm. Training should include:

a) Recognize the significance of CRO training (Think Leak First)
b) Learning from incidents: review of significant leaks in the industry and associated causes

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c) Response Actions Required to Leak Alarms
   — Review time requirements for specific actions
d) Understand proper notification requirements (What/Who/When)

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Annex A
(Informative)

Rate of Change Calculation Methods

A.1 Two-points subtraction method

The historical process value from a fixed interval in the past (e.g. 5 minutes ago) is subtracted from the current process value, to determine the change in value over this time period. This method does not account for additional data points that may have been captured within the time interval, which may result in a higher amount of noise.

A.2 Linear regression method

All sensor datapoints within a given time interval are used to fit a line using least squares (or similar) method. The slope of the line represents the Rate of Change of the variable over the time interval. Since more data points are used to calculate the ROC, it is more robust to outliers. However, it does introduce a small amount of lag time.

Care should be taken to ensure that memory arrays and variable types are sized appropriately to handle the expected number and size of intermediate variables, to prevent arithmetic overflow. This method may be computationally intensive.

A.3 Moving Average Offset method

All sensor datapoints within a given time interval are averaged. This average value is then subtracted from the current value. The resulting calculated value is then scaled with the appropriate factors, to arrive at the Rate of Change value.

This method is much less computationally intensive than the linear regression method, but still considers all the data points within a given time interval, making it more robust to outliers than the two-points subtraction method.

A.4 CROC Dynamic Threshold Time Delays

In certain cases, it may be helpful to delay turning off the dynamic threshold adjustments, if the conditions that trigger the threshold adjustment do not persist long enough to adequately cover the timescale of the flowline transient. For example, certain wells may have reservoir dynamics that result in the wellhead pressure stabilizing very quickly after shutting in the well. However, the flowline may take significantly longer to reach its new operating pressure. Once the wellhead pressure stabilizes, the dynamic threshold adjustment will revert to the steady state thresholds. If the flowline ROC is still higher than the steady state thresholds when this happens, the LDSSSLDS will raise an alarm. To prevent this type of false alarm, a short time delay can be implemented to extend the dynamic threshold adjustment until the flowline transient caused by the well shut-in is complete.

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