Upstream Deepwater – Surface Engineering – Subsea GOM

Controlled Document

Subsea Leak Detection

Conditional Rate of Change (C-ROC) Alarm Technical Specifications

Project	Subsea Leak Detection
Document Title	Conditional Rate of Change (C-ROC) Alarm Technical Specifications
Document Number	OPS0228
DCAF Control ID Number	NA
Document Revision	001
Document Status	Approved
Discipline/Document Type	Surface Engineering Subsea Specification
Owner/Author	Han Hsien Seah
Issue Date (DD-MM-YYYY)	18-07-2018
Expiry Date (DD-MM-YYYY)	None
ECCN	EAR 99
Security Classification	Unrestricted
Disclosure	None
Revision History shown on next page	

Revision History

REVISION STATUS			APPROVAL		
Rev.	Date	Description	Originator	Reviewer	Approver
001	07-09-2018	Final Draft	Han Hsien Seah	Stephen T. Thompson/ John E. Hayward/ Sohail Izhar	William J. R. Nisbet
• All signed originals will be retained by the P&T Document Control Center and an electronic copy will be stored in SharePoint					

Signatures for this revision

Date	Role	Authority Role	Name	Signature or electronic reference (email)
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Summary

This document provides functional design requirements for the implementation of the Conditional Rate of Change (CROC) algorithm for leak detection in subsea control systems.

Keywords

Conditional Rate of Change; CROC; Leak Detection

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ABBREVIATIONS

Abbreviation	Meaning	Notes
API	American Petroleum Institute	
BSEE	Bureau of Safety and Environmental Enforcement	
CROC	Conditional Rate of Change	
FIV	Flowline Isolation Valve	Isolation valve between a Manifold header or Sled and a flowline jumper
KPI	Key Performance Indicator	
MBV	Manifold Branch Valve	Isolation valve between a well jumper and a manifold header
PI	OSIsoft PI Historian	Shell's enterprise process historian
PIV	Pigging Isolation Valve	Isolation valve between a Manifold header or Sled and a pigging loop
PSDV	Production Shut Down Valve, located downstream of the production choke.	An "Alternate Isolation Valve" per the BSEE definition
PSHL	Pressure Safety High / Low	A BSEE mandated subsea shutdown sequence.
PT	Pressure Transmitter	

PT1	Pressure transmitter located upstream of the subsea tree choke, between the PMV (USV1) and PWV (USV2)	
PT2	Pressure transmitter located upstream of the subsea tree choke, between the PWV (USV2) and the tree choke	
PV	Process Value or Present Value	
ROC	Rate of Change	
SP	Set Point	
Sts	Status	
UPD	Shell Upstream Deepwater	
USV	Underwater Safety Valve as defined by BSEE and API	
XT	Subsea Christmas Tree	

REFERENCES

1. Seah, H. H. "Conditional Rate of Change (C-ROC) Leak Detection Qualification Report" SR.16.12367.

1. SUMMARY

The Conditional Rate of Change (C-ROC) algorithm was developed to provide a robust alarm/alert that allows rapid detection (within minutes) of a large leak in a subsea production system, and leak isolation in a timely manner. Key requirements for robust leak alarms are:

- Operates in the process control domain (part of the control system).
- Easily configurable to a wide range of subsea system architectures.
- Low maintenance: minimal recalibration required (at most every few months) with changes in well rate and well-to-flowline alignment
- High availability: provides leak detection under both transient (start-up and shut-down) and steady state flowing conditions.
- Low false alarm rate (Shell target is less than 1 false alarm per year per subsea system).

C-ROC has been deployed at several Shell GoM subsea systems and has, to date, met the requirements above.

This document provides technical specifications for the implementation of the Conditional Rate of Change (C-ROC) algorithm for leak detection in subsea control systems.

2. THE CONDITIONAL RATE OF CHANGE ALGORITHIM

2.1. Concept

The Conditional Rate of Change (C-ROC) algorithm relies on the PTs installed on the subsea kit to detect pressure transients that are indicative of a significant subsea leak. Figure 1 and Figure 2 show reference layouts of valves and PTs for a subsea tree and manifold.

The algorithm calculates and monitors the Rate of Change (ROC) of the flowline pressure measured by the pressure transmitters (PTs), typically at a subsea sled or manifold header. If this pressure rate-of-change exceeds a certain threshold and is in the direction of hydrostatic pressure, a significant leak may have occurred in the subsea system.

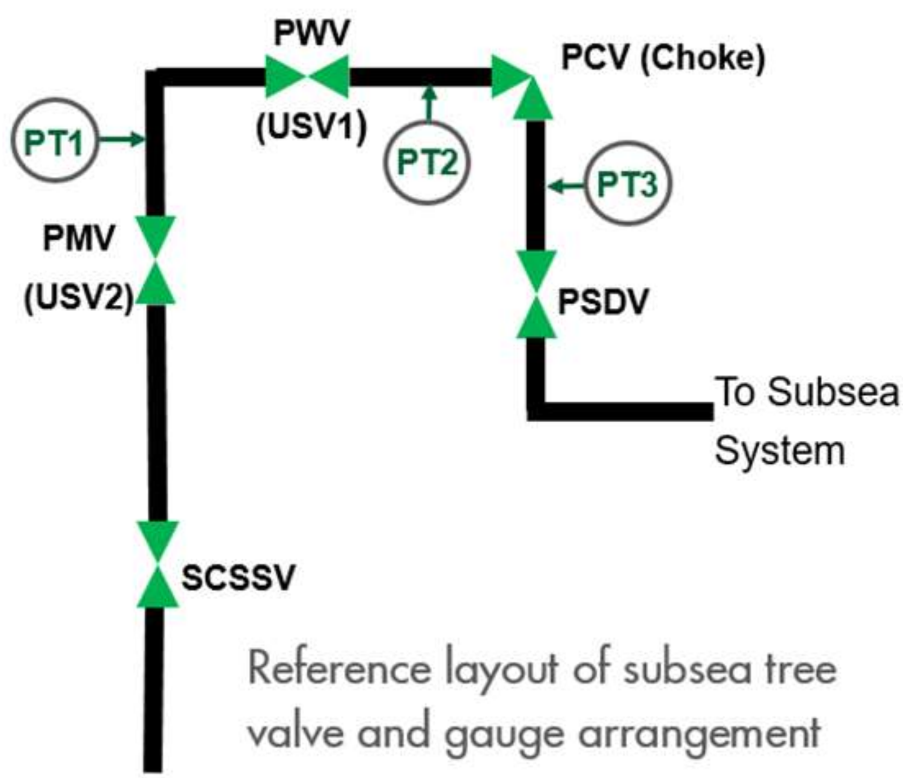

Figure 1: Reference Layout of Subsea Tree Valve and PT Arrangement

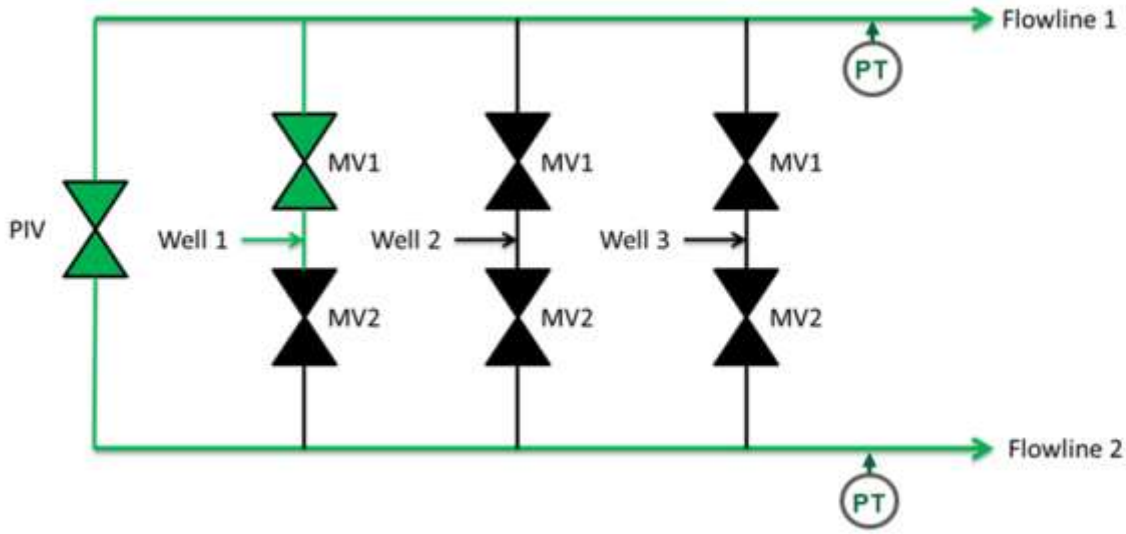

Figure 2: Flowline Alignment for a Dual Flowline Manifold w/ Pigging Loop

However, because certain normal operating scenarios can also produce similar trends in the flowline pressure, conditions are placed on this detection to reduce the occurrence of false alarms. Most importantly, if the upstream of choke PTs on any well (typically PT1 or PT2) aligned to a given flowline show a ROC in the opposite direction (above a threshold) of that flowline's pressure ROC, the system assumes that a normal operational transient is in progress and C-ROC is inhibited from raising alarms while this well condition is active. Such behavior is indicative of rapid flowrate change due to well choke adjustment or tree valve movement. If the flowline does not have any wells flowing into it, the C-ROC alarms for that flowline are also inhibited.

Another set of conditions will be used to 'degrade' the C-ROC alarm behavior by dynamically widening the thresholds at which a Leak Alarm is raised. These degrading conditions include recent manifold/sled valve movements, ongoing transient flowline conditions, and a forced 'Manual Degrade' by the operator. These features will be described in detail below, but they all constitute conditions which may cause false C-ROC Leak Alarms using the HI/LO thresholds. As such, the system will widen the thresholds at which the Leak Alarm is raised, from the HI/LO to the HIHI/LOLO setpoints. When the degrading conditions are no longer present, the system will automatically revert to using the HI/LO setpoints to raise the Leak Alarm.

2.2. Executive Action

The C-ROC algorithm can trigger an executive shutdown action after a delay time (defined by a 'C-ROC Shutdown Pending' timer). This will only occur based on the Leak

Alarm output and the operator will have the ability to abort the shutdown timer if the Leak Alarm is determined to be a false alarm. An existing shutdown sequence, such as the Flowline PSHL (as described in 30 CFR 250.839, Figure 3), may be used as the executive shutdown action.

§250.839 What are the maximum allowable valve closure times and hydraulic bleeding requirements for a direct-hydraulic control system?

(a) If you have a direct-hydraulic control system, you must:

(1) Design the subsea control system to meet the valve closure times listed in this section or your approved DWOP; and

(2) Verify the valve closure times upon installation. The District Manager may require you to verify the closure time of the USV(s) through visual authentication by diver or ROV.

(b) You must comply with the maximum allowable valve closure times and hydraulic system bleeding requirements listed in the following table or your approved DWOP:

Valve Closure Timing, Direct-Hydraulic Control System

If you have the following. . .	**Your pipeline BSDV must. . .**	**Your USV1 must. . .**	**Your USV2 must. . .**	**Your alternate isolation valve must. . .**	**Your surface-controlled SSSV must. . .**	**Your LP hydraulic system must. . .**	**Your HP hydraulic system must. . .**
(1) Process upset	Close within 45 seconds after sensor activation	[no requirements]			[no requirements]	[no requirements]	[no requirements]
(2) Flowline PSHL	Close within 45 seconds after sensor activation	Close one or more valves within 2 minutes and 45 seconds after sensor activation. Close the designated USV1 within 20 minutes after sensor activation.			Close within 24 hours after sensor activation	Complete bleed of USV1, USV2, and the AIV within 20 minutes after sensor activation	Complete bleed within 24 hours after sensor activation.
(3) ESD/TSE (Platform)	Close within 45 seconds after ESD or sensor activation	Close all valves within 20 minutes after ESD or sensor activation.			Close within 60 minutes after ESD or sensor activation	Complete bleed of USV1, USV2, and the AIV within 20 minutes after ESD or sensor activation	Complete bleed within 60 minutes after ESD or sensor activation.
(4) Subsea ESD (Platform) or BSDV TSE	Close within 45 seconds after ESD or sensor activation	Close one or more valves within 2 minutes and 45 seconds after ESD or sensor activation. Close all tree valves within 10 minutes after ESD or sensor activation.			Close within 10 minutes after ESD or sensor activation	Complete bleed of USV1, USV2, and the AIV within 10 minutes after ESD or sensor activation	Complete bleed within 10 minutes after ESD or sensor activation.
(5) Subsea ESD (MODU or other type of workover vessel), Dropped object	[no requirements]	Initiate closure immediately. If desired, you may allow for closure of the tree valves immediately prior to closure of the surface-controlled SSSV.				Initiate unrestricted bleed immediately	Initiate unrestricted bleed immediately.

Figure 3: Extract from 30 CFR 250.839. Source: https://ecfr.io/Title-30/pt30.2.250#se30.2.250_1839

3. LOGIC REQUIREMENTS

Common functionality has been grouped into 'modules' for understanding and possible code re-use. Refactoring of the algorithm across modules is acceptable, provided that the required overall behavior can be demonstrated.

3.1. Well Module (Figure 4)

One Well Module exists per well and evaluates the ROC of a selected wellhead PT located upstream of the production well choke and outputs discrete signals when the well's ROC value exceeds the HI or LO set point.

Each Well Module has an alignment calculation that takes into consideration only the valves downstream of the well's PSDV (e.g. manifold branch valves, pigging isolation valves), to determine if the well has an open flow path to one or more flowlines.

The well module's HI/LO outputs will only apply to a given flowline if the well is aligned to that flowline. One set of 'HI Active' and 'LO Active' outputs exist for each possible flowline.

The well-to-flowline alignment logic should account for all possible flow path permutations. E.g., if Well 1 is aligned to Flowline 1 via MV1, but the PIV is also open, then Well 1 is also aligned to Flowline 2 via the open PIV (Figure 2).

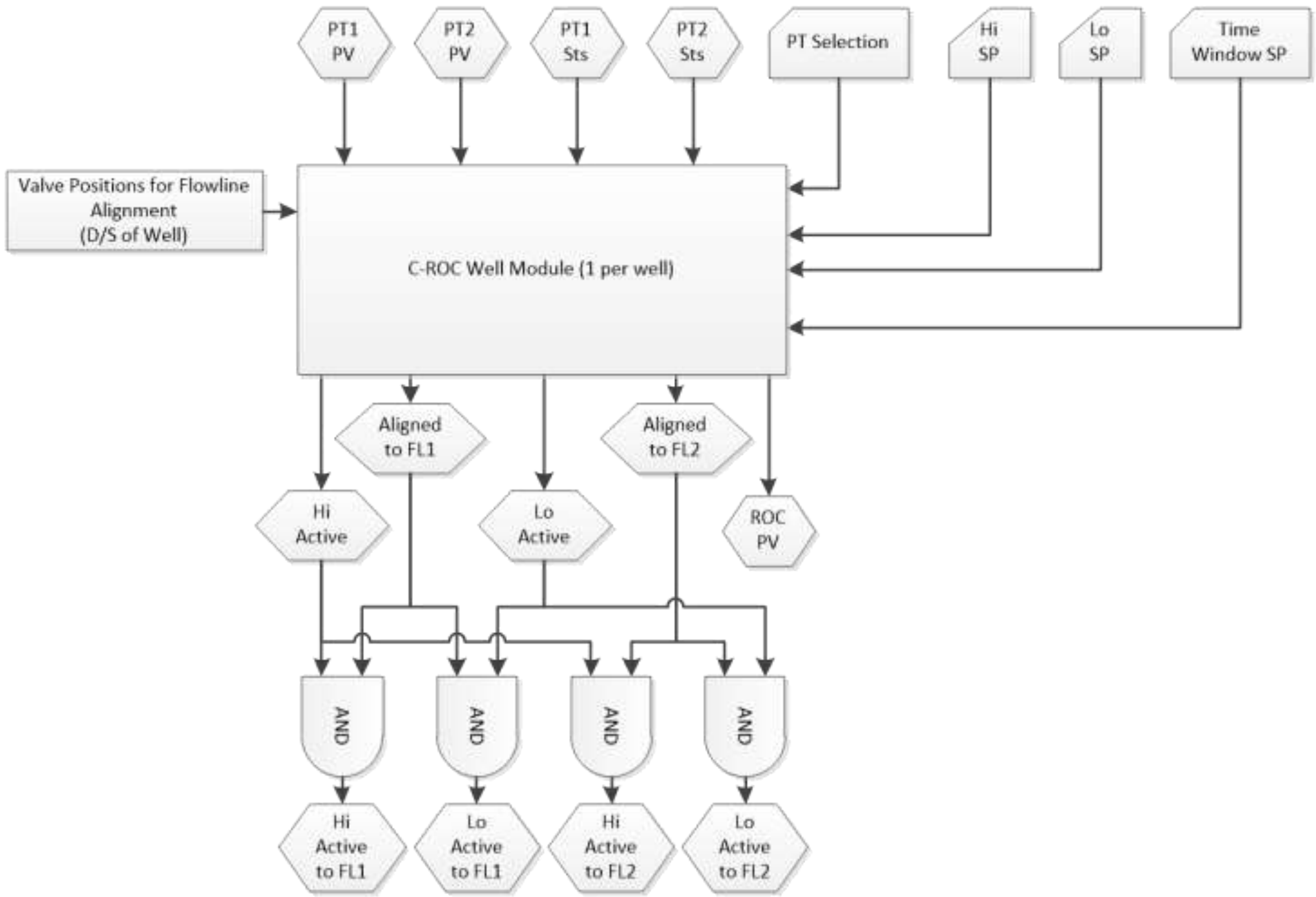

Figure 4: Well Module

Specific details include:

1. PT selection logic:
    a. Selection between PTs upstream of choke (PT1 or PT2)
    b. Use selected PT if status is good.
    c. No outputs if PT status is bad. ROC PV goes to bad status
2. ROC Calculation Method discussed below. The calculation time window interval is configurable, but the time setpoint value shall be common across all wells.
3. If ROC value exceeds the defined allowable range, the ROC value is to be constrained to the range limit and not be allowed to go to 'fault' status.
4. Module produces outputs of:
    a. HI Active (ROC > Hi SP)
    b. LO Active (ROC < Lo SP)
    c. ROC PV – the PV of the ROC calculation.
    d. Aligned Active to FLx – 1 per possible flowline
    e. HI Active to FLx – 1 per possible flowline
    f. LO Active to FLx – 1 per possible flowline

3.2. Flowline Module (Figure 5)

Two Flowline Modules, with different time periods, exist per flowline and evaluates the ROC of a selected flowline PT (if more than 1 PT is available), and determines if the ROC exceeds any of the HIHI, HI, LO, or LOLO set points. The Flowline Module is utilized in both the Leak Detection Logic and Dynamic Suppression Logic of Figure 9.

The Flowline Module will also pass the current flowline pressure to the Hydrostatic Module.

Specific details include:

1. PT selection logic:
    a. Selection between PTs that can be lined up to that flowline (if applicable)
    b. Use selected PT if status is good.
    c. If bad status:
        i. ROC PV and PT PV go to bad status
2. ROC Calculation Method discussed below. The calculation time interval is configurable.

3. If ROC value exceeds the defined allowable range, the ROC value is to be constrained to the range limit and not be allowed to go into fault or bad status.
4. Module produces outputs of:
    a. HI Active (ROC > Hi SP)
    b. LO Active (ROC < Lo SP)
    c. HIHI Active (ROC > HiHi SP)
    d. LOLO Active (ROC < LoLo SP)
    e. ROC PV
    f. Selected PT PV

3.3. Hydrostatic Module (Figure 5)

The Hydrostatic Module compares the flowline pressure against the Hydrostatic Pressure and Deadband tolerance. It will output a HI and/or a LO signal.

1. HI Active if (input PT PV > Hydrostatic – Deadband)
2. LO Active if (input PT PV < Hydrostatic + Deadband)
3. HI Active and LO Active will both be active if the PT PV is within Deadband of Hydrostatic
4. Both Hydrostatic and Deadband setpoints shall be configurable

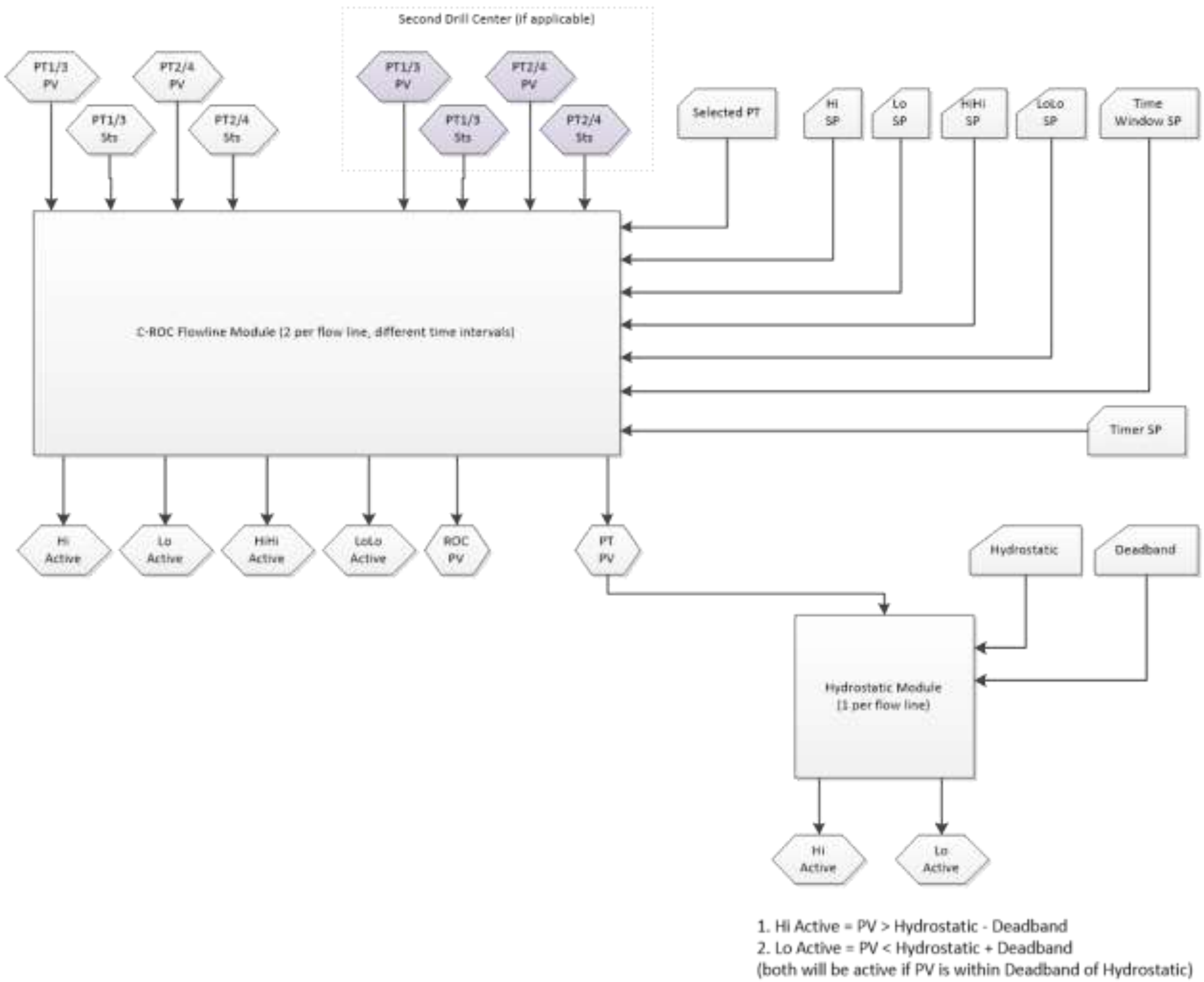

Figure 5: Flowline Module & Hydrostatic Module

3.4. The Rate of Change Calculation

The Rate of Change calculation shall meet the following requirements:

1. The rate of change is the time-derivative of the input pressure values, over a defined time window range
2. The time window range shall be configurable from 0 to 20 minutes
3. The data sampling frequency shall be configurable up to that of the sensor/control system sampling rate
4. All valid, measured data points within the time window range shall be used to calculate the rate of change value.
5. The resulting calculated rate of change values shall be stable in the presence of normal steady-state noise, and be responsive to changes in the underlying sensor value.
6. The Rate of Change calculation should be designed as most appropriate for the sensors and control systems deployed to the field. The calculation should provide the required fidelity and real-time results without an unacceptable burden on the logic solvers deployed in the system.
7. The Rate of Change PV output shall be normalized to the same time units and have engineering units of PSI/H or BAR/H.

Previous implementations have utilized one or more of the following techniques:

3.4.1. Least Squares Linear Regression

$$Slope = \frac{\sum(X * Y) - \left(\frac{\sum X \;*\; \sum Y}{NoSamples}\right)}{\sum X^2 \;-\; \left(\frac{(\sum x)^2}{NoSamples}\right)}$$

Where X = relative time, Y = pressure, and NoSamples = number of data points within the moving time window.

The units of the calculated Slope output will depend on the units of the input time and pressure. The Slope output should be scaled to the required output units.

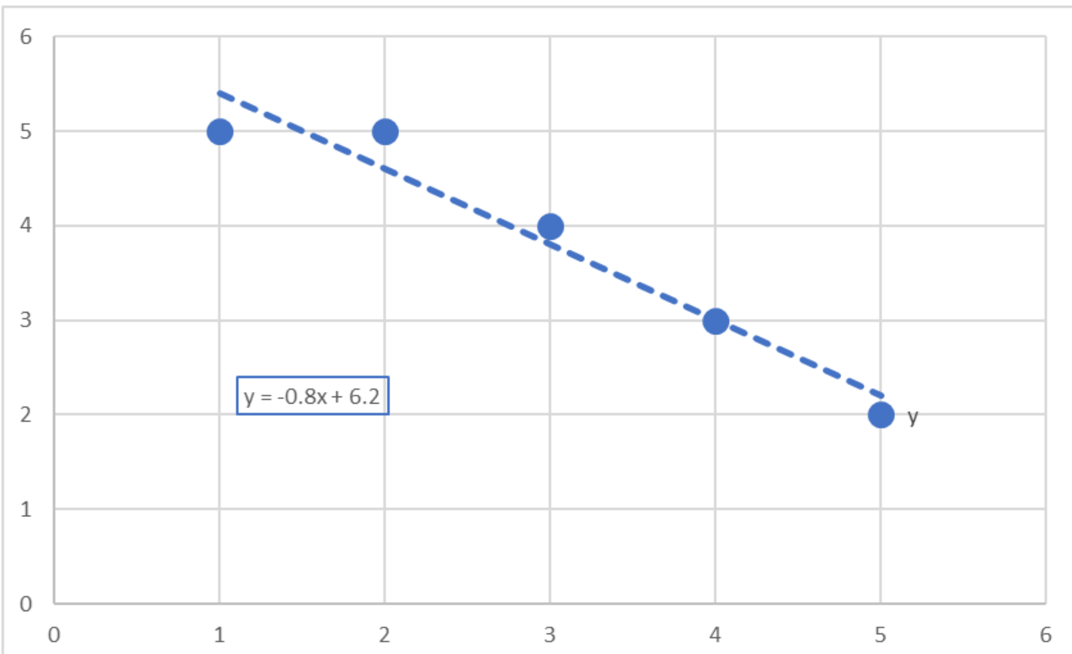

Figure 6 Slope calculated using Least Squares Linear Regression method

3.4.2. Moving Average Offset

Slope = (Current_PV – Average_PV) * (3600 / time_window_in_seconds) * 2

In this method, the slope is approximated by doubling the offset between the current value and the moving average, and dividing the result with the time window of the moving average. The result is then scaled to the required output units.

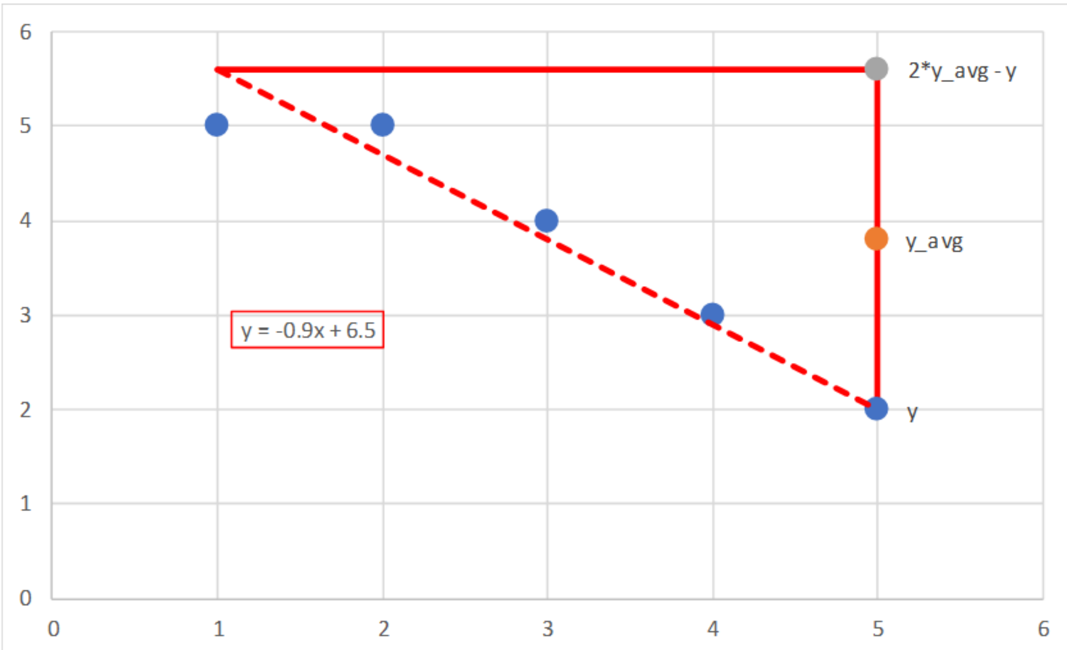

Figure 7 Slope calculated using Moving Average Offset method

Figure 8 shows a comparison between the outputs of the Least Squares Linear Regression method and the Moving Average Offset method, using the same underlying pressure dataset. For typical real world data trends, the two methods produce similar results.

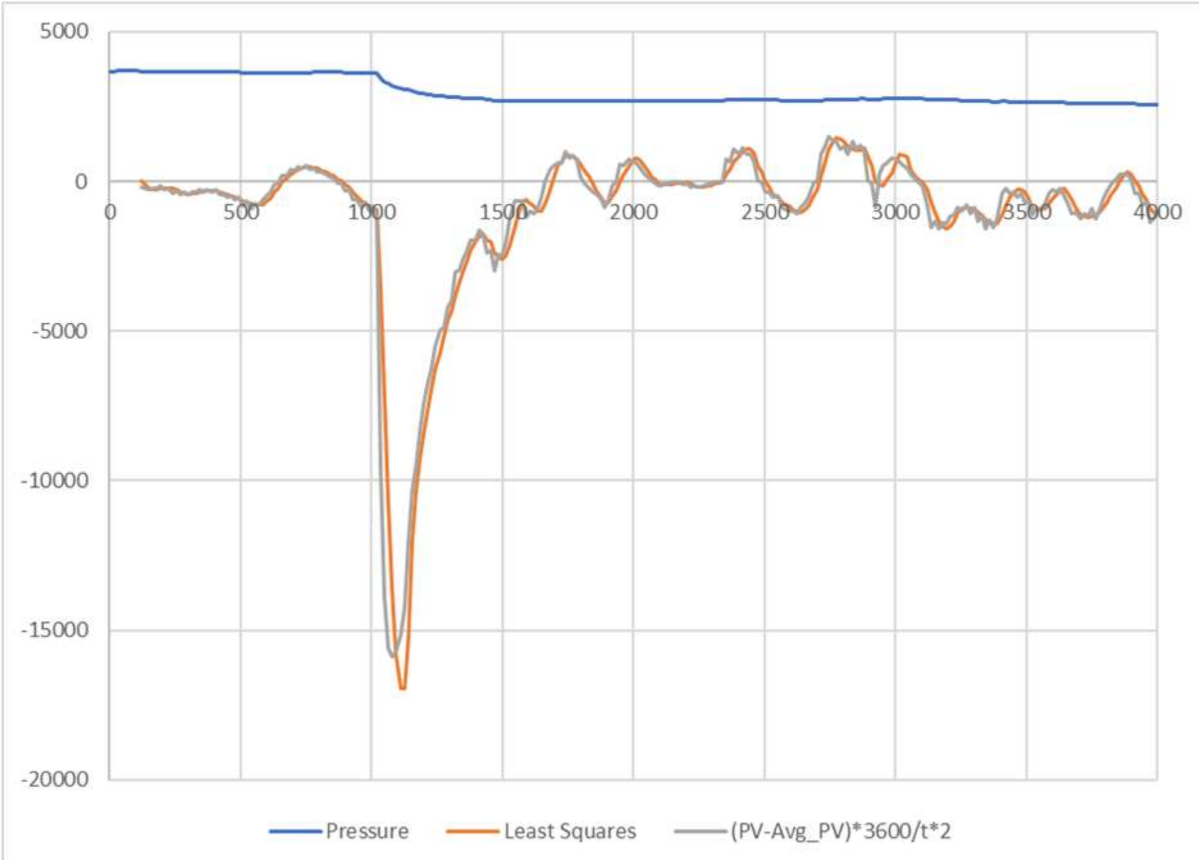

Figure 8: Comparison between Least Squares Method & Moving Average Offset Method.

3.5. Overall Logic Requirements

The C-ROC algorithm cycle shall run at a configurable frequency up to that of the data update rate from the subsea system.

There shall be a Class B Inhibit timer that starts when the first well is opened into an inactive flowline. While this Class B Inhibit timer is counting, any C-ROC alarms and actions will be inhibited. Subsequent wells that are opened into an already active flowline will not restart this timer.

When an associated MBV/FIV/PIV is actuated, the Degraded State for all associated flowlines shall be activated and remain latched for a configurable time period. (Recommended: 5 minutes).

There shall be an operator activated ‘Manual Degrade’ which will force the Degrade state to be active for a configurable time period (Recommended: 1 hour). After the time period is completed, the ‘Manual Degrade’ shall be automatically cleared. The Manual Degrade may be manually removed within the time period.

There shall be a configurable on-delay timer to activate the Degrade status, after the ‘Long Time Flowline Module’ output turns on. This delay is implemented to ensure that a sudden flowline pressure loss that simultaneously activates both the Short Time and Long Time ROC outputs will still result in a Leak Alarm being be raised if no other Veto signals are present.

There shall be a configurable off-delay timer to deactivate the Degrade status after the ‘Long Time Flowline Module’ output turns off. This delay is intended to keep the Degrade status enabled during conditions such as slugging, where both positive and negative slopes occur periodically, and it is possible that the long term slope is calculated as close to zero, despite being in an active transient condition.

While the Leak Alarm is active, the Leak Alarm shall be re-flashed to the operator periodically (Recommended: 10 minutes) until the timer expires, to remind the operator that the C-ROC Shutdown Pending timer is still counting down and an operator action is still expected.

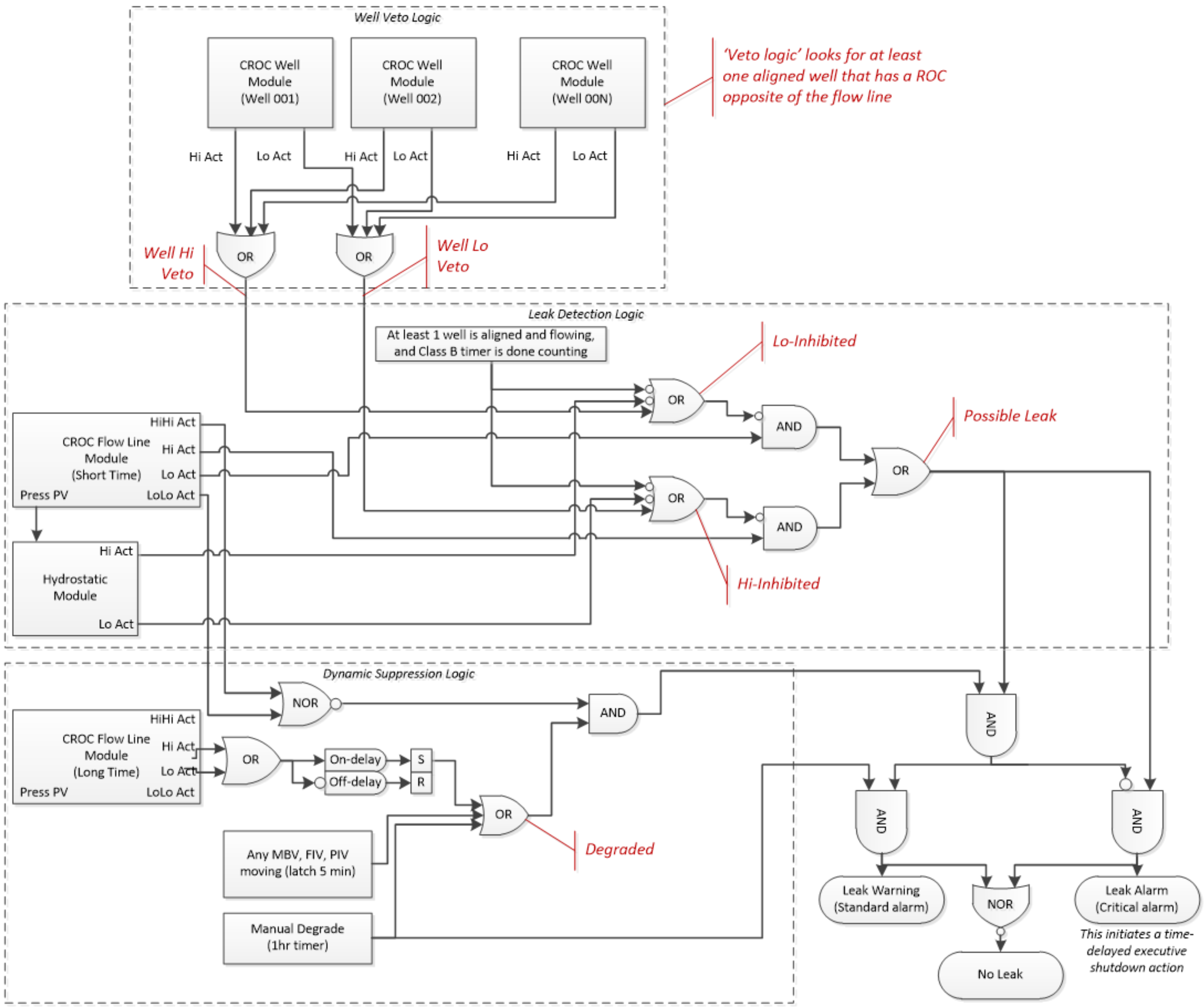

Figure 9: Overall C-ROC Logic

The following C-ROC variables shall be made available to the Data Historian for tracking performance of the algorithm:

One set per well

1. Well HI setpoint
2. Well LO setpoint
3. Well PT Selection
4. Well ROC Value
5. Well HI Active
6. Well LO Active

One set per Flowline

7. Flowline "Wells Aligned" configuration
8. Flowline "Wells Aligned-and-Flowing" configuration
9. Flowline HIHI setpoint
10. Flowline HI setpoint
11. Flowline LO setpoint
12. Flowline LOLO setpoint
13. Flowline Short Term Time setpoint
14. Flowline Long Term Time setpoint
15. Flowline Short Term ROC value
16. Flowline Long Term ROC value
17. Flowline Cumulative Daily Calculation cycles executed
18. Flowline Hydrostatic setpoint
19. Flowline Hydrostatic Deadband setpoint
20. Flowline Class B Inhibit timer setpoint
21. Flowline Short Term HIHI Active
22. Flowline Short Term HI Active
23. Flowline Short Term LO Active
24. Flowline Short Term LOLO Active
25. Flowline Degraded State (see below)
26. Flowline Long Term HI/LO Active
27. Flowline Manual Degrade Forced Status
28. Flowline Hydrostatic HI Active
29. Flowline Hydrostatic LO Active
30. Flowline Hi-Inhibited State (see below)
31. Flowline Lo-Inhibited State (see below)

32. Flowline Leak Alarm Active
33. Flowline Leak Warning Active

<u>One set per Field/Drill-Center</u>

34. Field/Drill-Center C-ROC SD Timer Setpoint
35. Field/Drill-Center C-ROC SD Timer Remaining

3.6. C-ROC Outputs

3.6.1. Degraded State Output

There shall be an output that indicates when the C-ROC calculation for a given flowline is in a 'Degraded' state. This shall be indicated when:

- the Long Term Flowline Module HI/LO output is active (the Degraded State shall remain latched until the off-delay timer completes)
- the Manual Degrade is forced by the operator
- an associated MBV/FIV/PIV has been actuated within a configurable time period (Recommended: 5 minutes)

3.6.2. Inhibited State Outputs

There shall be two outputs per flowline that indicate when the C-ROC calculation for the given flowline is in an 'Inhibited State'. These are the Hi-Inhibited and the Lo-Inhibited, which inhibit any leak alarms due to positive ROC and negative ROC, respectively.

- If no wells are aligned and flowing to that flowline, both the Lo-Inhibited and Hi-Inhibited states are active.
- While the Class B Inhibit timer is still running, both Lo-Inhibited and Hi-Inhibited states will remain active.
- Any aligned well with a 'LO Active' will activate the Hi-Inhibited state for that flowline
- Any aligned well with a 'HI Active' will activate the Lo-Inhibited state for that flowline
- Hydrostatic Module HI output being 'off' will activate the Lo-Inhibited state
- Hydrostatic Module LO output being 'off' will activate the Hi-Inhibited state

3.6.3. *Leak Alarm Output*

The Leak Alarm Output from the C-ROC algorithm results when the following conditions are satisfied:

- Above hydrostatic steady state
    - Hydrostatic module outputs a LO Active
    - Short Term Flowline Module outputs a LO Active
    - Degraded State is not active
    - Lo-Inhibited State is not active
- Above hydrostatic transient state
    - Hydrostatic module outputs a LO Active
    - Short Term Flowline Module outputs a LOLO Active
    - Degraded State is active
    - Lo-Inhibited State is not active
- Sub hydrostatic steady state
    - Hydrostatic module outputs a HI Active
    - Short Term Flowline Module outputs a HI Active
    - Degraded State is not active
    - Hi-Inhibited State is not active
- Sub hydrostatic transient state
    - Hydrostatic module outputs a HI Active
    - Short Term Flowline Module outputs a HIHI Active
    - Degraded State is active
    - Hi-Inhibited State is not active

The Leak Alarm output corresponds to a high-confidence detection of a leak event and shall initiate a 'Shutdown Pending' timer, followed by an executive shutdown action as described below.

When a Leak Alarm is raised, the Leak Alarm shall remain latched on until the Abort command is received, the Trip command is received, or the C-ROC SD timer expires. The operator cannot reset the Leak Alarm while it is latched. An active Leak Alarm shall suppress a subsequent Leak Warning from being raised.

The alarm priority of the Leak Alarm Output shall be determined by an alarm management process.

3.6.4. Leak Warning Output

The Leak Warning Output results when the Manual Degrade state is forced by the operator and the following conditions are met:

- Above hydrostatic
    - Hydrostatic module outputs a LO Active
    - Short Term Flowline Module outputs a LO Active
    - Degrade State is active (due to manual force by operator)
    - Lo-Inhibit State is not active
- Sub hydrostatic
    - Hydrostatic module outputs a HI Active
    - Short Term Flowline Module outputs a HI Active
    - Degrade State is active (due to manual force by operator)
    - Hi-Inhibit State is not active

The Leak Warning Output shall NOT be generated when Leak Alarm Output is already active and the C-ROC Shutdown Pending timer is running (see 'Executive Action' section below).

3.7. Executive Action

As previously stated, the Leak Alarm Output will initiate an executive action after the Shutdown Pending timer has expired. The timer functionality is as follows:

1. This timer shall be configurable with a sufficiently high user access level and is not resettable with the global timer reset button.
2. While the timer is active, the Leak Warning Output shall be suppressed.
3. The timer shall NOT reset or stop when the Flowline ROC PV returns to normal range. The 'C-ROC Shutdown Pending' status shall latch.
4. The timer can be aborted by the operator via a button.
5. The timer can be advanced to expiration via a button such that the shutdown action occurs immediately upon pressing the button.
6. There is only one C-ROC shutdown timer per field/drill center.
7. If the timer is aborted and the conditions for a Leak Alarm are still present, the Leak Alarm will be generated again, and the timer shall be restarted.
8. If the timer is aborted and the conditions for a Leak Alarm are no longer present, the timer is reset and alarm states are cleared.

Upon expiration of the timer, the PSHL sequence shall be initiated for all wells and manifolds at the drill center for which the C-ROC algorithm triggered. For the case where multiple drill centers are daisy-chained, all related drill centers will execute the shutdown sequence.