Practical Alarms and Metrics for BAHX

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ABSTRACT

Alarms provide real-time feedback that operating conditions are likely causing damage to a brazed aluminum heat exchanger (BAHX). Metrics are performance measurements that are reviewed on a periodic basis to quantify the operation of a BAHX. They are both useful tools to improve operator training and extend the life of a BAHX. This paper lays out strategies and recommended criteria to formulate practical alarms and metrics from BAHX operating guidelines found in various sources.

Introduction

Brazed Aluminum Heat Exchangers (BAHX) play a critical role in many industrial processes. If a BAHX must be removed from service because it has developed a leak, it can take a processing train or sometimes an entire plant offline, costing millions of dollars in lost revenue. As such, owners have a high interest in maintaining operational reliability of their units, and in getting the most service life out of their equipment.

This paper discusses two strategies for using DCS data to monitor and improve BAHX operation. The first strategy is to implement alarms to warn operators when immediate action should be taken to prevent damage to a BAHX. The second strategy is to implement metrics that are reviewed regularly for long-term operational improvements. Several groups have attempted to develop metrics that predict the likelihood that a unit will leak based on its operating history, but none have been successful. Even so, metrics can prove to be a useful tool for improving operator training. Alarms and metrics should be used together to minimize operational risks associated with leaking BAHXs.

Background

In Chart’s experience, most BAHX that are involuntarily retired from service are due to leaks, and most leaks are caused by thermal fatigue. Chart and ALPEMA have offered guidelines to instruct operators on how to best operate BAHX to avoid thermal stress and thermal fatigue damage. These guidelines are known to be conservative, and are developed to result in negligible fatigue damage, theoretically offering billions of cycles of fatigue life.

If operators could simply operate the BAHX within the thermal guidelines, would all BAHX effectively last forever? Certainly not, as BAHX can be damaged by means other than thermal fatigue, such as through particulate plugging, erosion, corrosion, fouling, and ice expansion.

Practical considerations may also prevent operating strictly within the thermal guidelines. Plant operation can be affected by upstream conditions such as changing flowrates, compositions, or maintenance that is out of the operators’ control. Also, the economics of running profitably may affect the operation, such as when and how mole sieve bed regeneration is handled, or how frequently operating conditions are changed, such as switching from ethane rejection to ethane recovery in gas plants, or when the plant must be operated in turndown conditions. Lastly, plant design may contribute its own difficulties against ideal operation. Operators may not have all the instrumentation or control valves that would allow them to fully know and control the BAHX.

There is a need for real-time alarms that will alert operators to conditions that are likely to be causing fatigue damage. They must be relevant and actionable without becoming nuisance alarms that are routinely ignored. There is also a need for metrics to assess the quality or severity of a unit’s operation. These metrics would be periodically reviewed to determine where operations and operator training can be improved. There is a chance that sometime in the future these metrics could be used to predict the likelihood of a unit developing a leak. This would make them extremely useful to the industry for classifying which BAHX are likely to need replacement or more frequent inspection in anticipation of leaks appearing. Development of this capability has been attempted by several groups, but no reliable success has been found.

Strategy 1: Alarms

The alarms are intended to inform operators when there is a high likelihood that fatigue damage is occurring to a unit or that stress is exceeding the design envelope. The intention is that every alarm should be a call for immediate action to stop the alarming condition. After the alarm is controlled, it should be reviewed based on the following criteria:

1. If the alarm was appropriate
2. If the alarm was preventable
3. If the response to the alarm was appropriate

By performing the above actions after each alarm, the alarm settings can be tuned so that nuisance alarms are diminished and operator training is improved.

Basis

The alarms presented here are based on the operational guidelines for BAHX. The two primary sources of guidelines are:

1. "Chart Installation, Operation, and Maintenance Manual for Chart Brazed Aluminum Heat Exchangers (BAHX) and Core-in-Kettle® Assemblies," 2024 edition (Chart IOM)
2. "The Standards of the Brazed Aluminium Plate-Fin Heat Exchanger Manufacturers' Association," 4th edition, 2024 (ALPEMA)

Table 1: Chart and ALPEMA guidelines

	Chart IOM - 2024	**ALPEMA 4th edition - 2024**
Transition	Limit stream temperature rates of change to 108 ΔF/hr (60 ΔC/hr) [Section III. C. 3.]	Limit stream temperature rates of change to 60 ΔC/hr (108 ΔF/hr) [Section 4.10.1]
	Limit stream temperature rates of change to 9 ΔF/min (5 ΔC/min) [Section III. C. 3.]	Limit stream temperature rates of change to 5 ΔC/min (9 ΔF/min) [Section 4.10.1]
	When introducing new stream, limit the temperature difference relative to local metal to 50 ΔF (28 ΔC) [Section III. C. 3.]	When introducing new stream, limit the temperature difference relative to local metal to 30 ΔC (54 ΔF) [Section 4.10.1]
Zone	Limit local stream temperature differences to 50 ΔF (28 ΔC) [Section III. C. 3.]	Limit steady state, single-phase stream temperature differences to 50 ΔC (90 ΔF) [Section 5.8]
		For two-phase, cyclic, or transient events, limit local temperature differences to 20-30 ΔC (36-54 ΔF) [Section 5.8]
Cyclic	Limit cyclic temperature changes to ±1.8 ΔF/min (±1 ΔC/min) [Section III. C. 3.]	Limit cyclic temperature changes to ±1 ΔC/min (±1.8 ΔF/min) [Section 8.1.4]
		Limit pressure drop variation to +/- 30% of mean pressure differential ALPEMA IOW

Other sources of guidance on BAHX operation include the ALPEMA Integrity Operating Window (IOW) for BAHX (September, 2024) and the GPA Technical Bulletin GPA-TB-001 (December, 2020). These documents are based on the Chart IOM and ALPEMA guidelines, but they do introduce monitoring for pressure drop oscillations as an indicator of unstable boiling. API Standard 668 (November, 2018) contains an informative section on recommended operation, but this is based on ALPEMA and doesn’t offer any new guidance.

Interpretation

Transition temperature rate of change (ROC) guidelines apply when the BAHX is cooling down, warming up, or otherwise changing operating regimes. It governs how fast the stream inlet and outlet temperatures and local metal temperatures should change over 1 minute and over 1 hour time periods.

Zone guidelines apply during steady state operation and transient events such as when new streams are being introduced to the BAHX. During steady operation, the stream-to-stream temperature difference at any given location along the length of a BAHX should be within the ZONE guideline. When a new stream is being introduced (i.e. a stream starting at zero flow and increasing to full flow), if the temperature difference between the stream and the metal where the stream is being introduced is greater than the Zone guideline, then introduce the flow slowly.

The cyclic guidelines apply to steady state operation. They are intended to protect against high cycle fatigue, mostly due to unstable flow.

There are two reasons why the cyclic temperature rate of change guideline is more stringent than the 1 min Transition ROC guideline. The first is that a core experiencing steady state oscillations will accumulate orders of magnitude more of these cycles than it will transition events. The second reason is that damaging unstable boiling may be present without any streams exceeding the 1 min Transition ROC guideline, but fatigue damage may still be occurring due to a moving dry-out point that causes significant swings in heat transfer properties and local metal temperatures.

An alarm based on cyclic pressure drop fluctuations is also recommended, especially for thermosyphon loops. This is because unstable boiling can manifest as pressure oscillations without significant temperature oscillations appearing in stream outlet temperatures.

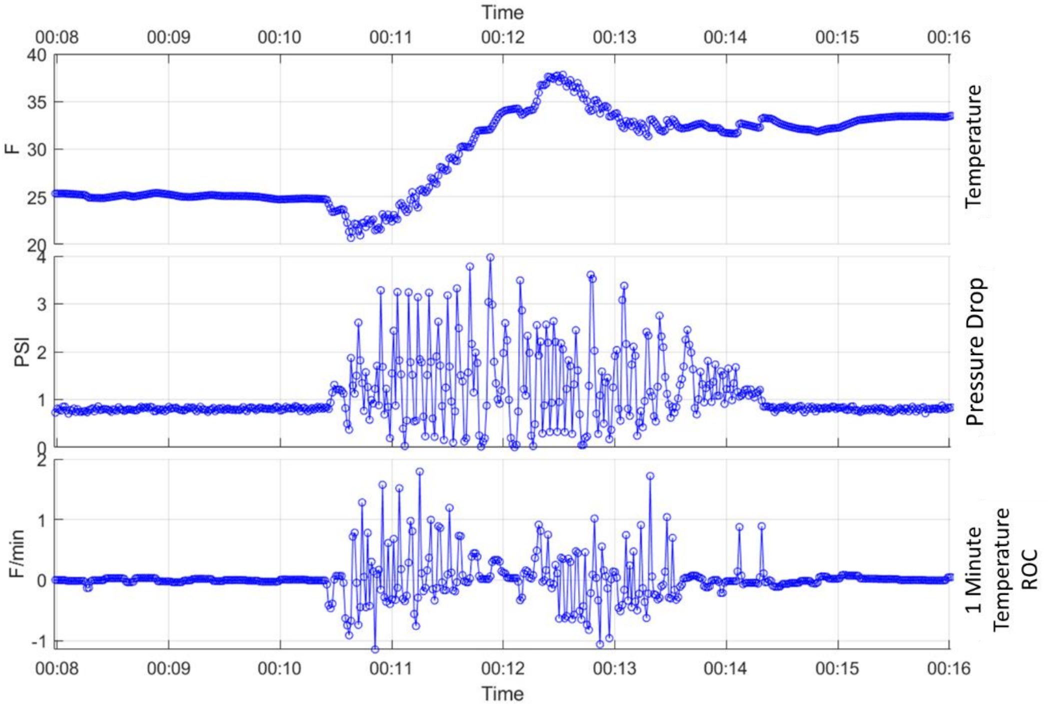

Figure 1: Demonstration of unstable flow that has a temperature rate of change within 9 ΔF/min, but a significant pressure drop signature.

Criteria

Table 2: Recommended Alarm Criteria

Alarm Name	**Process Value**	**Alarm Threshold**
MAWP	Inlet / Outlet Pressure	Exceeds Nameplate MAWP
MAWT	Inlet / Outlet Temperature	Exceeds Nameplate MAWT
1 min ROC	1 min Temperature Rate of Change	>= ±5 ΔC/min (9 ΔF/min)
1 hr ROC	1 hr Temperature Rate of Change	>= ±60 ΔC/hr (108 ΔF/hr)

2Φ Zone	Temperature Zone Differential for two phase, cyclic, or transient events	>= 28 ΔC (50 ΔF)
1Φ Zone	Temperature Zone Differential for single-phase steady state	>= 50 ΔC (90 ΔF)
Cyclic Temperature ROC	1 min Temperature Rate of Change	4 Cycles of ±1 ΔC/min within 24 minutes
Cyclic DP ROC	1 min DP Rate of Change	4 Cycles of -30/+50 %/min within 24 minutes

Explanation

MAWP, MAWT

MAWP is an acronym for Maximum Allowable Working Pressure, and MAWT an acronym for Maximum Allowable Working Temperature. These are critical values determined by ASME pressure vessel code and should never be exceeded except under special controlled circumstances. Each BAHX will typically have a single MAWT for all streams (65 C [150 F] is most common, 100 C [210 F] is less common). The MAWP is specific to individual streams. Values for both can be found on the heat exchanger nameplate.

1 Min ROC

The rate of change of stream inlet and outlet temperatures should not exceed ±5 ΔC/min. This is constrained by the ±60 ΔC/hr limit, as explained below. This should be calculated by taking the difference in temperature at time T and T-1 minute. A common mistake made when calculating temperature ROC is to take the difference in temperature at consecutive readings and dividing by the time difference of the readings. This can lead to erroneously high rates of change if the time difference is smaller than 1 minute, as seen in Table 3.

Table 3: Demonstration of correct and incorrect temperature rate of change calculation

Time [mm:ss]	00:00	00:15	00:30	00:45	01:00	01:15	01:30	01:45
Temp [C]	40	40	41	41	42	42	43	43
Correct ΔC/min Calculation	-	-	-	-	2	2	2	2
Incorrect ΔC/min Calculation	-	0	4	0	4	0	4	0

1 Hr ROC

The rate of change of stream inlet and outlet temperatures should not exceed ±60 ΔC/hr. This should be calculated by taking the difference in temperature at time T and T-60 minutes, for the reasons explained above. This limits the amount of time that could be spent at a constant ROC of ±5 ΔC/min to 12 minutes per hour.

Zone

The zone temperature differences are calculated by subtracting the maximum stream temperature at a given point along the exchanger length by the minimum stream temperature at that same point. Since stream temperatures are typically only known at inlets and outlets, a more practical application of this alarm is to calculate the stream temperature difference for headers that overlap along the exchanger length, as seen in Figure 2. 2Φ refers to two phase, but also applies to transient and cyclic events. 1Φ applies to single-phase steady state.

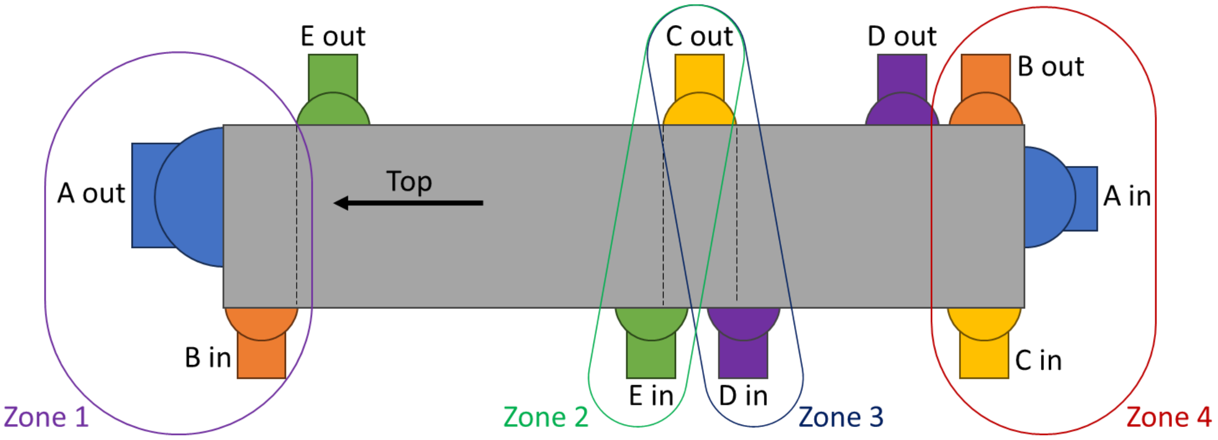

Figure 2: Demonstration of appropriate temperature zones

Zone 1	Zone 2	Zone 3	Zone 4
Max(A out, B in) – Min(A out, B in)	Max(E in, C Out) – Min(E in, C out)	Max(C out, D in) – Min(C out, D in)	Max(A in, B out, C in) – Min(A in, B out, C in)

For BAHX installed in batteries (parallel units with common inlets and outlets connected with manifolds), it is common to have temperature sensors installed in common piping and not in the branches that feed and collect from individual units. In these situations, the common inlet temperature can be assumed to be the temperature that each unit experiences. Individual BAHX outlets should be instrumented before the streams are recombined. In the case where there is only a common mixed outlet temperature, it should not be assumed to reflect the temperature of any individual unit. Each unit may have different flow rates that affect the heat transfer and outlet temperatures of the unit's streams, but the common outlet temperature will only report the mixed fluid temperature. However, the zone alarms should still apply, in that an alarm that is triggered from the common outlet temperature means at least one unit is exceeding the alarm criteria, but a non-alarm does not necessarily mean all units are within the zone guidelines.

Cyclic ROC

The cyclic alarm should be configured to only alarm after a set number of cycles are detected. The recommended configuration is to alarm if 4 cycles occur within 24 minutes. To calculate this, look for a signal above the THRESHOLD (+1 ΔC/min for temp, +50% for DP), followed by a signal below the negative THRESHOLD (-1 ΔC/min, -30% DP). This constitutes one cycle. Alarm if 4 CYCLES occur within SPAN of 24 minutes. This method is demonstrated for temperature ROC in Figure 3 below. For the relative DP change, use the mean DP value from the previous rolling 60 minutes.

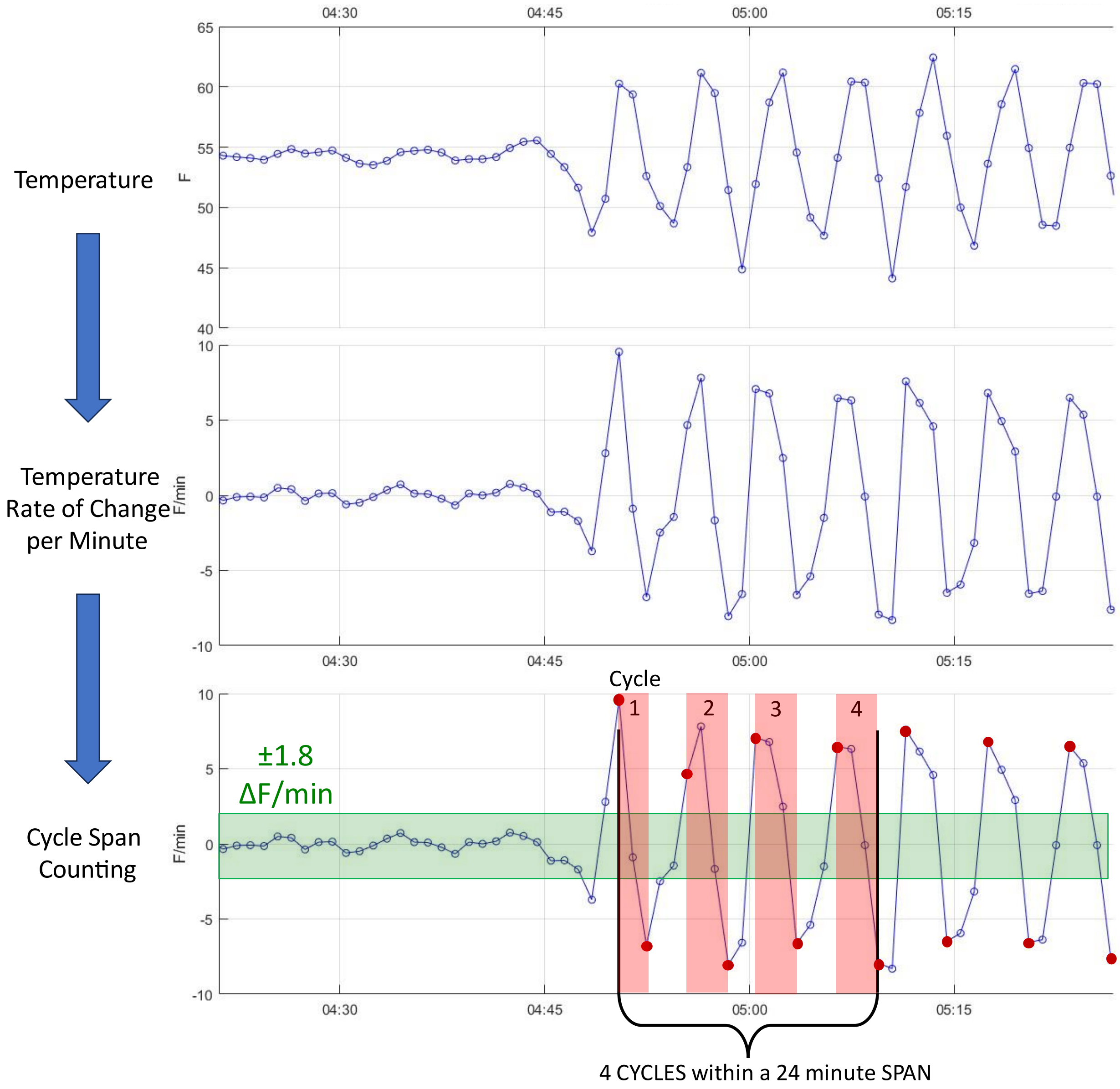

Figure 3: Demonstration of temperature cycle identification

Alarm Tuning

The recommended alarms are derived from the operating guidelines, which are intended to be conservative. Although the assessment shown in “Appendix D - Alarm Assessment” shows that most of these alarms will be infrequent, there are likely some instances where they will be overly conservative. If an installation is triggering a lot of alarms, it may be appropriate to decrease the sensitivity to prevent the alarms from becoming a nuisance, as this quickly leads to them being ignored or dismissed without consideration. If this is happening regularly, then the sensitivity should be decreased. It is better that some events that should be alarmed are missed rather than all alarms are ignored.

Alarms may be tuned by the following methods:

1. Adjust the triggering threshold
2. Delay the alarm until the threshold is exceeded by a minimum time duration
3. Deactivate the alarm during no or low flow conditions
4. Limit the applicable streams

The easiest way to control the alarm sensitivity is to adjust the triggering threshold. Maximum recommended thresholds are provided in Table 4 below.

Table 4: Maximum recommended alarm thresholds

Alarm Name	**Recommended Threshold**	**Maximum Threshold**
1 min ROC	>= ±5 ΔC/min (9 ΔF/min)	>= ±10 ΔC/min (18 ΔF/min)
1 hr ROC	>= ±60 ΔC/hr (108 ΔF/hr)	>= ±90 ΔC/hr (162 ΔF/hr)
2Φ Zone	>= 28 ΔC (50 ΔF)	>= 40 ΔC (72 ΔF)
1Φ Zone	>= 50 ΔC (90 ΔF)	>= 75 ΔC (132 ΔF)
Cyclic Temp ROC	THRESHOLD = ±1 ΔC/min [±1.8 ΔF/min] N=4 SPAN = 24 min	THRESHOLD = ±3 ΔC/min [±5.4 ΔF/min] N=5 SPAN = 24 min
Cyclic Temp ROC	THRESHOLD = -30/+50% /min N=4 SPAN = 24 min	THRESHOLD = -50/100% /min N=5 SPAN = 24 min

The next easiest way to decrease alarm sensitivity is to delay activation until the threshold is exceeded for a minimum amount of time. A minimum duration of 5 minutes is a recommended starting point.

False positives can occur when the BAHX is isolated from flow and the sensor is located far upstream or downstream of the unit. Logic can be added to deactivate an alarm based on flow, inlet pressure, pressure drop, valve position, or compressor/expander speed. Additionally, the alarm tuning can be customized for each individual stream.

The cyclic temperature alarm is the one most likely to need tuning. The typical cycle time of an unstable stream can vary significantly based on the specific installation. Cycle times can vary from 2 minutes per cycle (this is a common time resolution of a DCS historian, so faster cycles were not caught by this analysis) to 20 minutes per cycle. Longer cycles may also be caused by other phenomena besides unstable flow, such as poor controller tuning. See Figure 4 below for examples.

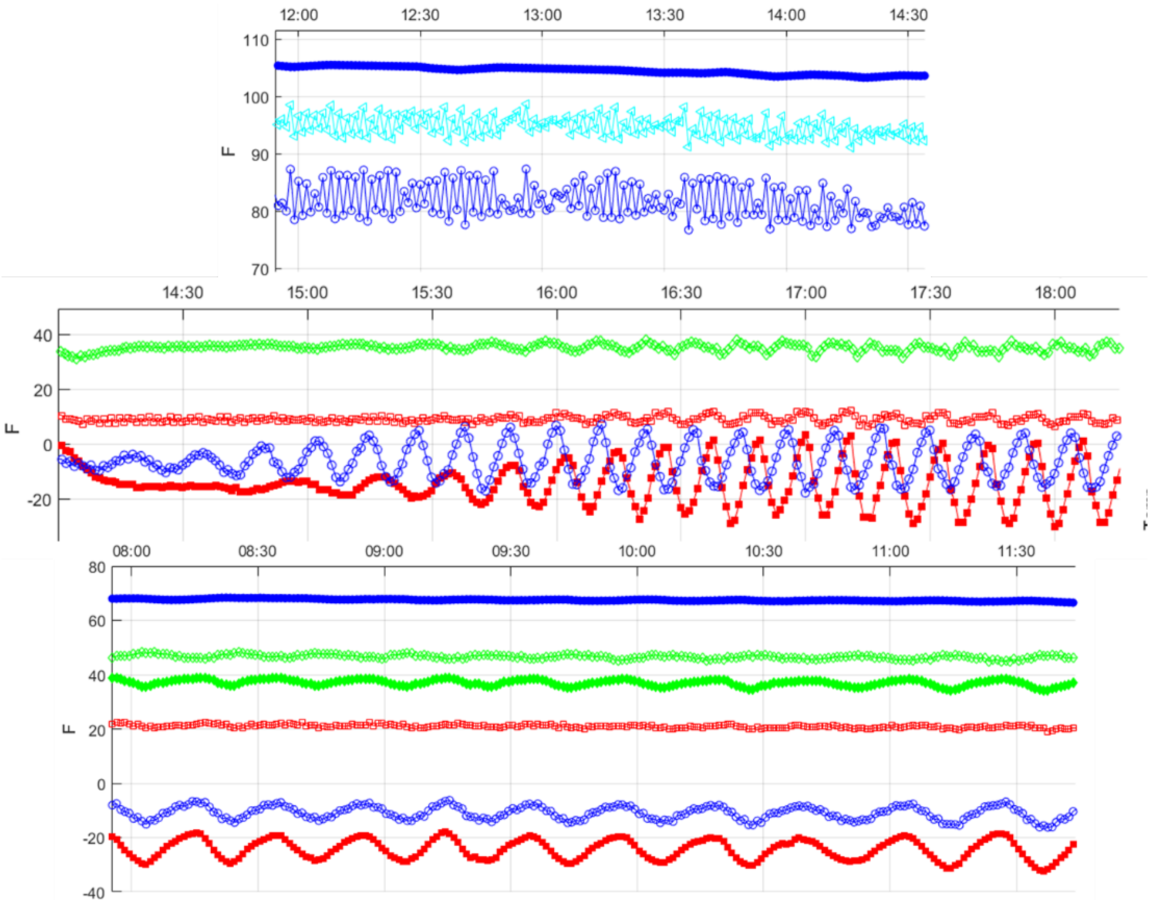

Figure 4: Demonstration of different temperature cycling periods. Top plot shows a period of 2 min, middle shows a period of 12 minutes, and bottom a period of 20 minutes.

Strategy 2: Metrics

Metrics are distinct from alarms in that they aren't intended to provide immediate feedback to operators and don't require immediate action. They are intended to be reviewed on a regular basis as a mechanism to improve operating procedures and identify gaps in operator training. It is possible that metrics could eventually be correlated with leaks and be used to predict an individual unit's risk of developing a leak, but such efforts are not discussed here.

Criteria

A starting basis for the metrics is calculating the number of minutes alarms are triggered in a time period. These values should then be weighted to account for the severity of the events. An event where the 1 minute temperature rate of change is 10 ΔC/min is not as damaging as an event where the rate of change is 20 ΔC/min. The weightings that are proposed in Table 5 are somewhat arbitrary, and other sources have proposed differing weightings, but until a correlation can be made between the metrics and BAHX damage all weightings will be speculative.

One additional metric that should be included is pressure drop. Excessive pressure drop is not included as an alarm because it rarely needs immediate attention, and is more indicative of plugging or fouling that requires cleaning or deriming.

Table 5: Weightings for calculating metrics

Metric	Level	Weighting
MAWP, MAWT	Nameplate	99
1 min ROC	>= ±5 ΔC/min (9 ΔF/min)	1
	>= ±10 ΔC/min (18 ΔF/min)	2
	>= ±15 ΔC/min (27 ΔF/min)	4
1 hr ROC	>= ±60 ΔC/hr (108 ΔF/hr)	1
	>= ±90 ΔC/hr (162 ΔF/hr)	2
	>= ±120 ΔC/hr (216 ΔF/hr)	4
Zone	>= 28 ΔC (50 ΔF)	1
	>= 50 ΔC (90 ΔF)	2
	>= 75 ΔC (132 ΔF)	4
Cyclic ROC	±1 ΔC/min [±1.8 ΔF/min], N=4, SPAN=24 min	1
	±2 ΔC/min [±3.6 ΔF/min], N=4, SPAN=24 min	2
	±3 ΔC/min [±5.4 ΔF/min], N=4, SPAN=24 min	4
Cyclic DP	-30, +50 % DP/min, N=4, SPAN=24 min	1
Pressure Drop	>= 4x design DP	1

The weighted cyclic temperature rate of change metric is the most difficult metric to implement. ASTM standard E1049, "Standard Practices for Cycle Counting in Fatigue Analysis" explains several different methods that could be used to convert a rate of change signal to cycle magnitude counts.

Review

The weighted metrics should be reviewed on a regular basis, typically monthly or quarterly. One way to do this is to report the weighted number of minutes each alarm type is active on daily or weekly basis. This is helpful to investigate how specific operating modes are affecting BAHX operation, or how different operators run the units.

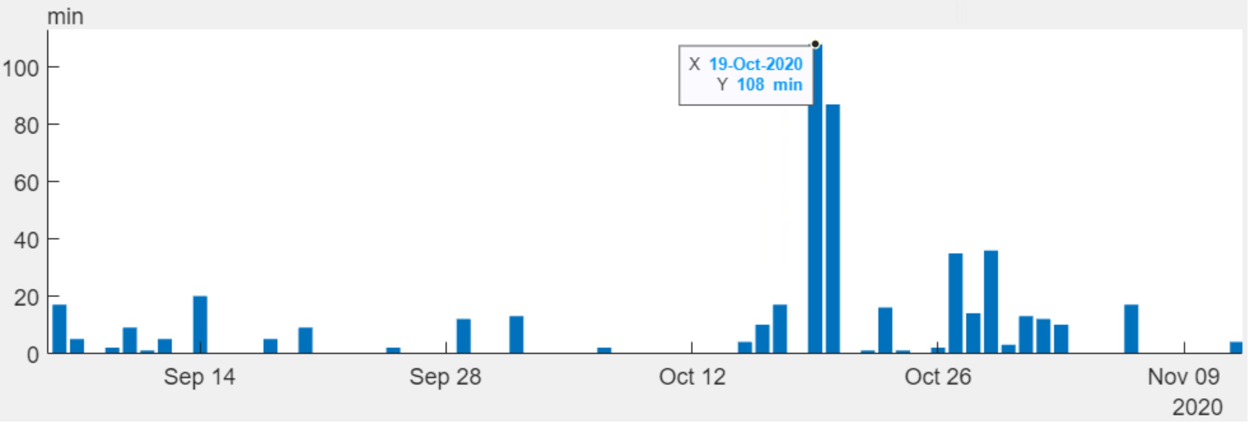

Figure 5: The above graph shows the amount of time a specific alarm was active on a daily basis. October 19 and 20th have anomalous operation that warrants further investigation.

It is also valuable to compare the cumulative amount of weighted alarm time between different units. This is valuable for comparing identical units in or units in equivalent applications to determine if one is experiencing rougher service or is at higher risk for requiring replacement.

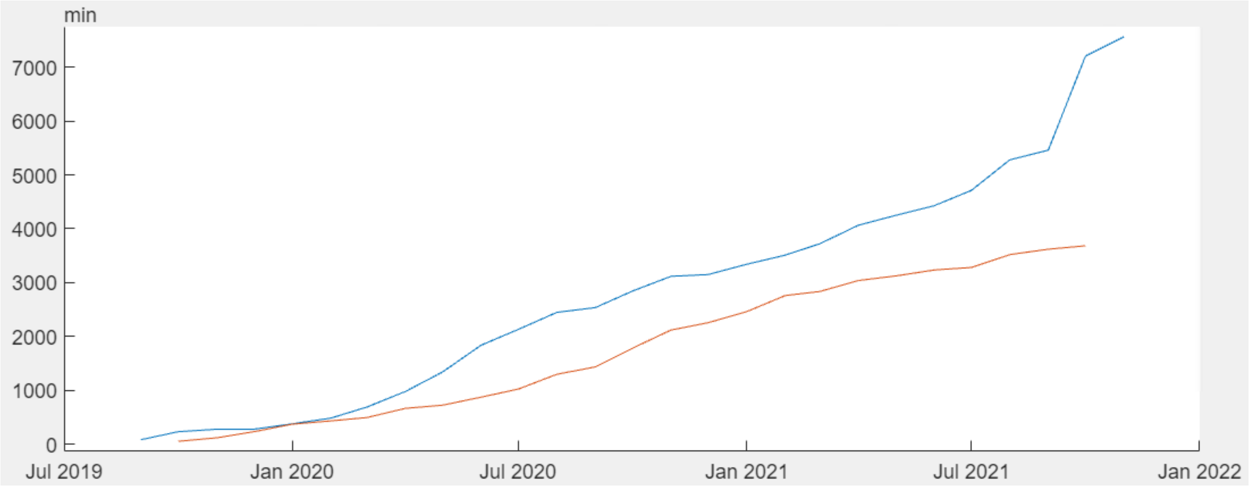

Figure 6: Unit 4 (blue) vs Unit 5 (orange) cumulative weighted alarm times for exceeding 9 F/min.

The metrics alone aren't useful without context, which can come from several different sources.

1. Current operation vs past operation
2. Comparing the metrics of different trains in the same plant
3. Comparing the metrics of different plants
4. Comparing the metrics of a specific unit against fleet averages

Difficulty Correlating with Leaks

One difficulty with correlating metrics based on operational data with leaks is that there is a complex relationship between the two. There are many variables that affect how a given thermal event will translate into stress, including parting sheet thickness, stacking pattern, layer layout, pre-existing temperature profile, etc.

Another difficulty is obtaining the required training data to develop a correlation. Many BAHX are not fully instrumented, so critical information about a unit's operating history is often missing. For example, flow rate and pressure drop information is often not available, which is important in order to rule out false positives, such as when there appear to be high zone temperature differentials but no flow.

Lastly, each leak that occurs in a BAHX only represents one data point, where hundreds of data points at minimum are typically needed to construct correlations with extremely noisy data. However difficult it may be to connect between operating excursions and leaks, we are confident that leaks are ultimately caused by operating conditions, and thus worthy of more investigation.

There may be value in comparing the cumulative metrics of similar BAHX designs operating in similar applications to the cumulative metrics when similar BAHX designs in similar applications leaked.

There may be value in calculating the cumulative metrics of individual BAHX units that have developed leaks, and using these as a basis of comparison for similar BAHX designs operating in similar applications. However, until a large number of leaking and non-leaking BAHX are analyzed, this relationship is not expected to be very robust.

Conclusion

Practical methods of implementing Chart recommended operating guidelines were presented. The guidelines are intended to keep thermal stress and thermal fatigue damage low enough that it will not adversely affect the typical 20-year service life of a BAHX. They can be implemented as immediate alarms for operators and aggregated as metrics for periodic review by operators and management. The periodic review provides an opportunity for continuous improvement of plant operation and to ensure correct and uniform operator response to upset events. It is important that the alarm parameters should be tuned for each specific installation based on field experience to prevent nuisance alarms. The difficulty of correlating metrics with leaks is very high, but if it could be done reliably, the value of such a correlation would also be very high, as it would allow for units to be classified according to their risk of leaking.

Appendix A – Alternative ROC Alarm/Metrix Calculations

A method that has been used by some operators to trigger the 1 C/min cyclic alarm has been described as using "counts" or cumulative absolute rate of change. This method involves summing up the total number of minutes that the absolute temperature rate of change exceeds the 1 C/min threshold, and if the sum is greater than a target value for a given time span (for example, 36 counts in an hour), then the alarm is triggered. This has the advantage of being easier to calculate than the cyclic ROC method proposed in this paper. A visual explanation can be seen in Figure 7, where the temperature data in the top graph is converted into 1 min temperature rate of change in the bottom graph. The points above the absolute threshold of 1 C/min are in the red areas.

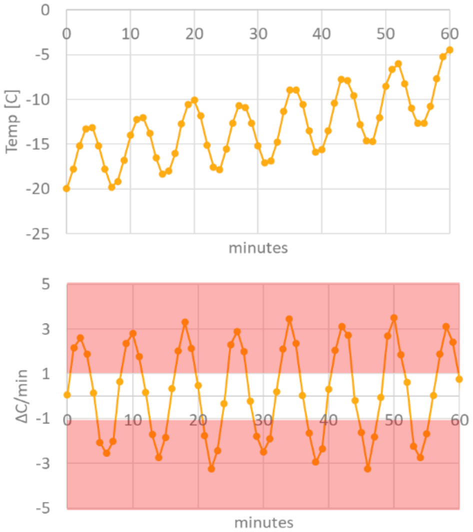

Figure 7: Cumulative absolute rate of change calculation would count the number of points in the red zones occurring every hour

A modification of this method that has been used is to weigh the temperature rate of change points by how far above the threshold they are. For example, for each minute the temperature rate of change is above 3 C/min, count it as 2 minutes for the purposes of this calculation.

The downside of these methods is that they will also trigger during monotonic changes in temperature, as seen in Figure 8.

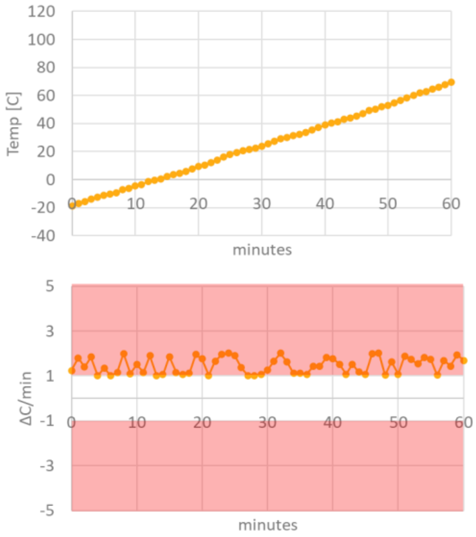

Figure 8: Cumulative absolute rate of change calculation will trigger on monotonic changes

A simple change to this method that would decrease the likelihood of false alarms is setting separate thresholds for the number of positive ROC counts and negative counts. This would ensure the temperature has gone up and down for a minimum duration during a span of time. An example of this would be triggering the cyclic alarm when the temperature ROC was above 1 C/min for at least 18 minutes in an hour and the ROC was below -1 C/min for at least 18 minutes in the same hour.

Appendix B – Identifying Unstable Boiling

Unstable flow can be a difficult phenomenon to detect. Per the GPA Technical Bulletin GPA-TB-001, it is best identified through differential pressure measurements across a stream. When this measurement is not available unstable boiling can be inferred from the temperature data. Unfortunately, there are examples of where each method fails to detect unstable boiling. Figure 9 shows unstable boiling arising without exceeding the 1 min Transition ROC guideline or the Cyclic ROC guideline. Figure 10 shows an example of thermal cycling without any apparent pressure drop impact.

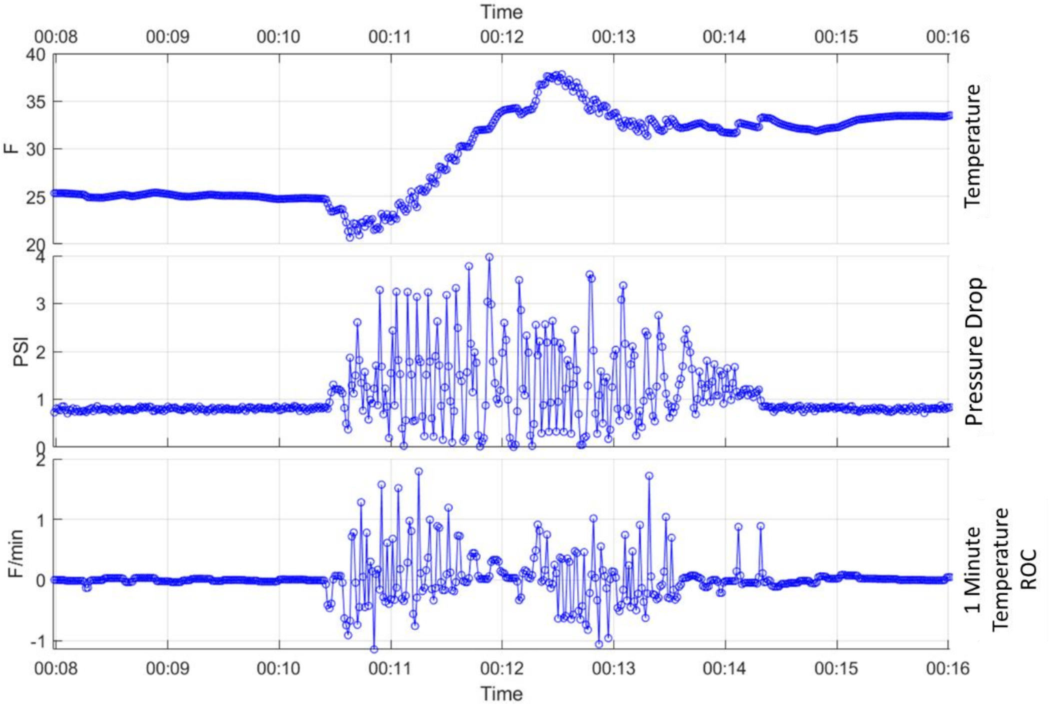

Figure 9: Demonstration of unstable flow that has a temperature rate of change within 1.8 ΔF/min, but a significant pressure drop signature.

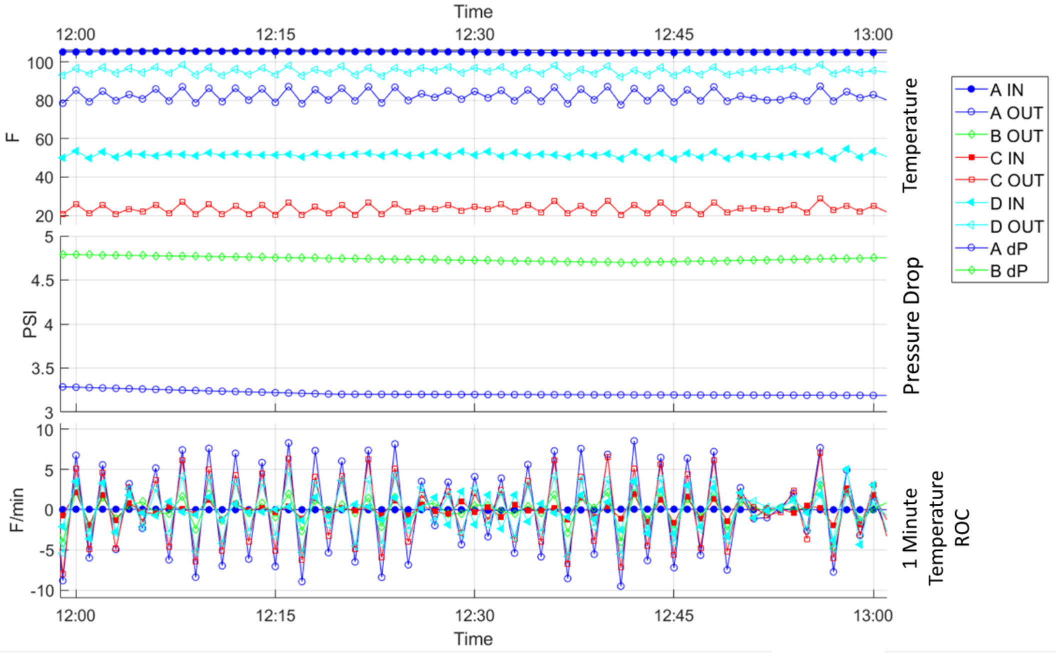

Figure 10: Demonstration of unstable flow that has a temperature rate of change exceeding 1.8 ΔF/min BUT no significant pressure drop signature, demonstrating that pressure drop cannot reliably detect unstable operation.

Appendix C – Implementing Alarms

Prerequisites

1. MAWP for each stream
2. MAWT for each stream
3. Inlet/outlet zones
4. Time series data of:
    a. Temperatures at inlets and outlets
    b. Pressure
        i. At inlets and outlets OR
        ii. At inlets or outlets, plus differential pressure
    c. Flow or flow indication (e.g. valve position, drum pressure, or compressor speed may sometimes be used as proxies for flow)

Preprocessing

Create 1 min temperature ROC

ROC_T_1min = Temperature(now) - Temperature(now - 1min)

Create 1 hr temperature ROC

ROC_T_1hr = Temperature(now) - temperature(now - 60min)

Create Zone Difference

For each zone:

Zone = max(Temperature(all zone streams)) - min(Temperature(all zone streams))

Create 1 min DP ROC

ROC_DP_1min = DP(now)-DP(now - 1min) / average(DP(now - 60min : now))

Programming Alarms

The ROC, Zone, and Cyclic alarms should have additional logic that disables them in cases where no-flow is detected.

Alarm Name	**Process Value**	**Alarm If**
MAWP	Stream Inlet / Outlet Pressure (P)	MAWP will typically vary by stream For each stream pressure: P >= MAWP_Stream
MAWT	Stream Inlet / Outlet Temperature (T)	MAWT is typically the same for all streams For each stream temperature: T >= MAWT
1 min ROC	1 min Temperature Rate of Change (ROC_T_1min)	ROC_T_1min_Limit = 5 [ΔC/min] (9 [ΔF/min]) For each stream temperature: abs(ROC_T_1min) >= ROC_T_1min_Limit

1 hr ROC	1 hr Temperature Rate of Change (ROC_T_1hr)	ROC_T_1hr_Limit = 60 [ΔC/hr] (108 [ΔF/hr]) For each stream temperature: abs(ROC_T_1hr) >= ROC_T_1hr_Limit
2Φ Zone	Temperature Zone Differential for two-phase, cyclic, or transient events (Zone_TwoPhz)	Zone_ TwoPhz_Limit = 28 [ΔC] (50 [ΔF]) For each two-phase Zone: Zone >= Zone_TwoPhz_Limit
1Φ Zone	Temperature Zone Differential for single-phase steady state (Zone_OnePhz)	Zone_OnePhz_Limit = 50 [ΔC] (90 [ΔF]) For each one-phase Zone: Zone >= Zone_OnePhz_Limit
Cyclic Temp ROC	1 min Temperature Rate of Change (ROC_T_1min)	For each ROC_T_1min: 4 cycles of ±1 ΔC/min occur within 24 minutes This assumes ROC_T_1min is populated with data at 1 minute intervals, with most recent data at the beginning.

```
ALARM_CYCLES = 4
THRESHOLD_HIGH = 1 [ΔC/min]
THRESHOLD_LOW = -1 [ΔC/min]
SPAN = 24 [min]
FOUND_CYCLES = 0
CYCLE_START_FOUND = false

for time_index = 1 : SPAN
   if not(CYCLE_START_FOUND)
       if ROC_T_1min(time_index) > THRESHOLD_HIGH
           CYCLE_START_FOUND = true
       end
   else
       if ROC_T_1min(time_index) < THRESHOLD_LOW
           FOUND_CYCLES = FOUND_CYCLES + 1
           CYCLE_START_FOUND = false
       end
   end
end

if FOUND_CYCLES > ALARM_CYCLES
       activate alarm
else
       disable alarm
end
```

Cyclic DP ROC	1 min DP Rate of Change (ROC_DP_1min)	For each ROC_DP_1min: 4 cycles of -30, +50% DP/min occur within 24 minutes This assumes ROC_DP_1min is populated with data at 1 minute intervals, with most recent data at the beginning.

```
ALARM_CYCLES = 4
THRESHOLD_HIGH = 0.50
THRESHOLD_LOW = -0.30
SPAN = 24 [min]
```

```
FOUND_CYCLES = 0
CYCLE_START_FOUND = false

for time_index = 1 : SPAN
   if not(CYCLE_START_FOUND)
       if ROC_DP_1min(time_index) > THRESHOLD_HIGH
           CYCLE_START_FOUND = true
       end
   else
       if ROC_DP_1min(time_index) < THRESHOLD_LOW
           FOUND_CYCLES = FOUND_CYCLES + 1
           CYCLE_START_FOUND = false
       end
   end
end

if FOUND_CYCLES > ALARM_CYCLES
       activate alarm
else
       disable alarm
end
```

Appendix D - Alarm Assessment

Field Data

DCS data from several plants representing different services were used to evaluate the different alarm criteria, which can be seen in Table 6. The Data Set column has three values. The first is the number of days of data, the second is the mode timestep (the most common interval between data points), and the third shows the number of temperature readings available over the number of stream inlets and outlets. For example, a data coverage of 5/8 would mean there are 8 ports (4 inlets, 4 outlets) and data is available for 5 of them.

Table 6: Data sets used to assess alarm frequency

Unit	**Data Set** Days of data Timestep [mm:ss] Coverage
1	209 days 01:00 8/8
2	461 days 01:00 8/8
3	365 days 01:00 6/6
4	804 days 01:00 8/8
5	726 days 01:00 6/6
6	365 days 01:00 7/8
7	454 days 01:00 5/6
8	365 days 01:00 12/12

Assessment Results

The alarm assessment demonstrates that with the recommended alarm settings, the alarms were acceptably infrequent for the sample data set.

Each alarm was assessed based on percentage of time the alarm was active, the average duration of each individual alarm event, and the average time between individual alarm events.

3.49 %	% Time Alarming
00:36:35	Avg. Duration of Each Alarm [hh:mm:ss]
16:48:44	Avg. Time Between Alarms [hh:mm:ss]

Figure 11: Example and explanation of alarm frequency data

Table 7: Alarm frequency assessment

Unit	MAWT	>= 60 ΔC/hr	>= 5 ΔC/min	>= 28 ΔC Zone	>= 50 ΔC Zone	4 cycles in 24 min ±1 ΔC	5 cycles in 60 min ±3 ΔC	Repair History
1	0 % 00:00:00 00:00:00	0 % 00:00:00 00:00:00	0.03 % 00:01:15 82:30:38	0.66 % 00:15:52 39:22:42	0.01 % 00:10:00 2517:08:00	3.13 % 00:45:25C 23:20:05	0.35 % 02:13:07 557:24:33	1 leak in 1 year
2	0 % 00:00:00 00:00:00	0.01 % 00:08:00 5532:53:30	0.02 % 00:01:20 133:18:07	33.57 % 05:39:12 11:10:21	0.02 % 01:05:00 3687:55:00	0 % 00:00:00 00:00:00	0 % 00:00:00 00:00:00	None in 20 years
3	0 % 00:00:00 00:00:00	0.15 % 00:25:38 282:29:25	0.11 % 00:03:01 44:14:34	30.15 % 03:31:31 08:09:25	0.16 % 00:13:20 136:48:45	0.79 % 01:03:03 129:51:37	0.03 % 01:29:30 2922:20:40	2 leaks in 9 years
4	0.005 % 00:05:48 1754:15:05	0.03 % 00:08:24 470:32:23	0.67 % 00:02:39 06:34:08	0.75 % 00:08:35 18:56:40	0.04 % 00:21:49 838:41:02	1.89 % 00:58:24 50:21:10	1.08 % 01:56:38 176:45:23	None in 4 years
5	0 % 00:00:00 00:00:00	0.01 % 00:01:36 2905:29:10	0.36 % 00:02:10 9:59:39	0.65 % 00:12:36 32:08:00	0.01 % 00:04:00 2905:27:10	1.13 % 00:40:55 59:13:39	0.39 % 01:10:23 289:23:50	3 leaks in 3 years
6	0.0067 % 00:35:00 4379:42:30	0.02 % 00:23:30 1751:41:12	0.05 % 00:02:00 67:21:05	0.43 % 00:15:16 58:56:10	0.03 % 00:32:36 1459:32:50	0.30 % 00:30:25 167:57:50	0 % 00:00:00 00:00:00	None in 30 years
7	0 % 00:00:00 00:00:00	0.01 % 00:05:21 906:17:42	1.62 % 00:01:38 01:39:25	0.56 % 00:20:25 60:25:27	0.01 % 00:02:58 1359:31:20	20.14 % 01:34:50 06:15:43	7.45 % 03:23:31 41:56:27	Unknown
8	0 % 00:00:00 00:00:00	0.12 % 00:31:02 397:38:35	1.35 % 00:01:06 01:21:34	98.5 % 454:05:03 07:19:03	0.53 % 01:52:14 335:05:11	74.24 % 01:50:52 00:38:27	7.91 % 01:58:21 22:54:59	Unknown