Papers for the 23rd Gas Machinery Conference
October 5-8, 2014, Nashville, TN, USA

KEY PERFORMANCE INDICATORS FOR RECIPROCATING ENGINE/COMPRESSORS

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ABSTRACT

There are many ways to evaluate the performance of reciprocating engine driven reciprocating compressors. Some metrics are easily calculated, others are more complex. Developing meaningful key performance indicators can allow operators to readily trend operating performance to help minimize fuel consumption, ensure air emission compliance, maximize capacity throughput, improve reliability, and better manage equipment maintenance outages.

This paper explores some of the most commonly used metrics and evaluates their applicability and limitations. The performance indicators are intended to show the overall health of the compressor unit (accounting for both the engine and the compressor) in an easy to identify way. A brief discussion on the required measured parameters, engine/compressor modeling required, and suggested acceptable bounds are also included.

Adopting standards and usage of these indicators can help optimize the operation and maintenance of compression equipment.

INTRODUCTION

Key performance indicators (KPIs) are often used to quickly indicate the performance against a goal. In the natural gas transportation industry, there are many different types of KPIs used to indicate compressor unit health. Meaningful KPIs for compressor units can allow operators to readily trend operating performance to help minimize fuel consumption, ensure air emission compliance, maximize pipeline capacity, improve reliability, and better manage equipment maintenance outages. This paper will explore some of the more commonly used KPIs used for reciprocating engine driven reciprocating compressor units and discuss their advantages and disadvantages. The purpose is to attempt to establish common KPIs that can be used throughout the industry and standardize their calculation methods.

For the purposes of this paper, it is assumed that the compressor unit is operated by a digital control system configured with typical input and output (I/O) based on the author's experience. [1] The I/O required will be discussed in general for each metric. Most of the KPIs presented can all be calculated in the unit's digital control system with the assumption the system has sufficient memory and processor speed.

This paper will discuss four broad types of KPIs; runtime based, performance based, reliability based, and cost based. Applicability and limitations of each metric is discussed. Detailed information on how each metric is calculated is also provided.

DISCUSSION

Many common compressor unit KPIs are selected because they are easy to calculate. For example, fuel usage as a percentage of the volume of gas transported. Others are more complicated in that some degree of modeling of the engine and/or compressor may be required. The main KPIs discussed in this paper are:

- Runtime based
  - Unit Utilization (UU)
  - Unit Availability – Gross (UAG)
  - Unit Availability – Net (UAN)
- Performance based
  - Fuel Transport Index (FTI)
  - Brake Specific Fuel Consumption (BSFC)
  - Compressor Efficiency – Thermal (CET)
  - Compressor Relative Efficiency – Thermal (CRET)
  - Compressor Gas Power (CGP)
  - Compressor Relative Efficiency (CRE)
  - Fuel Power (FP)
  - Fuel Torque (FT)
  - Power Range (PR)
  - Unit Relative Efficiency (URE)
  - Unit Overall Efficiency (UOE)
- Reliability based
  - Number of Starts (NS)
  - Unsuccessful Start Rate (USR)
  - Uninitiated Shutdown Rate (USDR)
- Cost based
  - Average Annual Operating Cost (AAOC)
  - Specific Maintenance Cost (SMC)
  - Specific Operating Cost (SOC)

There are many more possible KPIs. These have been selected based on the most commonly used and the ones that provide a good insight into the performance of compressor units. More detail on each of these will be discussed below. Additional subsets of these KPIs may be discussed where it is appropriate.

Runtime based

Runtime based metrics are useful in identifying the compressor units that are most frequently used and their availability for operation. These metrics are useful in identifying compressor units that are most likely to negatively impact pipeline capacity if the units are unavailable to be operated. These KPIs can be applied across all compressor units regardless of the driver/compressor type but some of the specific equations outlined in this paper would have to be modified.

Unit Utilization

Unit Utilization (*UU*) is the percentage that a compressor unit is operating. It is expressed as a percentage of the time the compressor unit is operating online vs. the total time in the measurement period. It is calculated from the equation:

$$UU = \frac{OperatingTime}{PeriodTime} * 100 \tag{1}$$

Where

OperatingTime	The total unit operating time during the *PeriodTime* in seconds
PeriodTime	The total time in a given period in seconds

It should be noted that the *OperatingTime* is intended to be the actual time that the compressor unit is actively compressing gas. This is commonly triggered by the indication that the compressor unit bypass valve is closed.

Because the utilization is dependent on the *PeriodTime*, there are several subsets of compressor unit utilization that can be performed. For example, it could be accumulated hourly, daily, monthly, and/or annually. Subscripts should be used to indicate the *PeriodTime* used in the calculation (e.g., UU_D for daily compressor unit utilization) Note that daily utilization can be calculated from the average of the hourly accumulation, monthly utilization is the average of the daily accumulation, and the annual average is the weighted average (accounting for the different number of days per month) of the monthly accumulation. Hourly accumulations may be more frequent than some operators need.

Compressor units with high utilization generally need to be more closely monitored for performance and maintenance issues. Also, maintenance outages for high utilization compressor units usually need to be carefully managed.

UU can also be expanded to accumulate warm-up time and cool-down/shutting-down time where those parameters are needed for air permit reporting purposes. In those modes, the engine is running but not actively compressing gas. Appropriate subscripts should be used such as UU_{DW} and UU_{DS} for daily accumulation of warm-up and shutdown times respectively.

It is recommended that this KPI is calculated and trended on both a monthly and annual basis. The KPI can be reviewed to assess patterns of high utilization which can be helpful in optimizing the timing for maintenance outages.

Unit Availability – Gross

Unit availability – gross (*UAG*) indicates the amount of time a compressor unit was available to run in a given time period. It is expressed as a percentage of the time the compressor unit is operating online (including warm-up and cool-down) or available to run vs. the total time in the measurement period. It is calculated from the equation:

$$UAG = \frac{PeriodTime - UnvailableTime}{PeriodTime} * 100 \tag{2}$$

Where

PeriodTime	The total time in a given period in seconds
UnavailableTime	The total time a unit is unavailable to operate during the *PeriodTime* in seconds

For the purposes of this metric, *UnavailableTime* indicates the time that the compressor unit is down for the purposes of performing maintenance work or other reasons why it cannot be operated. Warm-up and cool-down/shutting-down time should not be included in the unavailable time. Likewise, the period of time when a compressor unit is shutdown but available should be excluded from the *UnavailableTime*. Periods of time when the compressor unit is shutdown with a lockout that prevents a restart and when the compressor unit is out of service for maintenance should be included in the unavailable time. A key lockout on the unit control panel or a configuration parameter set through the human/machine interface are commonly used to indicate when a compressor unit is unavailable for operation due to maintenance.

Like *UU*, the *PeriodTime* can be hourly, daily, monthly, annually etc. Subscripts should be used to indicate the *PeriodTime* used in the calculation. Compressor units with high *UAG* are generally well maintained and maintenance outages are minimized. It is recommended that this KPI is calculated and trended on both a monthly and annual basis.

Unit Availability – Net

Unit availability – net (*UAN*) is similar to *UAG* except credit is given for periods of time when there is no demand for the compressor unit. Thus it gives credit to the cases when maintenance is performed during periods of low demand to minimize the capacity impact to shippers. It is calculated from the equation:

$$UAN = \frac{PeriodTime - UnavailableTimeD}{PeriodTime} * 100 \quad (3)$$

Where

UnavailableTimeD The total time a unit is unavailable to operate while there is a system demand for the unit during the *PeriodTime* in seconds

The difficulty with this metric is determining when there is system demand for a compressor unit. In some cases, it can be done manually from the central dispatch center via a supervisory control and data acquisition (SCADA) system when pipeline capacity allocations are being made due to the outage and/or calculated locally when all of the available compressor units are operating at their maximum capability. The problem with manually setting an in-demand status is that they are often times overlooked both when setting and clearing. It is recommended that operators that use this metric utilize an automatic method to determine when a compressor unit is in demand.

Like *UU*, the *PeriodTime* can be hourly, daily, monthly, annually etc. Subscripts should be used to indicate the *PeriodTime* used in the calculation. Compressor units with high *UAN* indicate that outages are well managed such that do not negatively impact shippers. It is recommended that this KPI is calculated and trended on both a monthly and annual basis.

Performance based

Performance based metrics are intended to help the operator identify underperforming equipment. These metrics can help optimize the operation to maximize throughput/lower costs as well as planning maintenance activities.

Fuel Transport Index

The fuel transport index (*FTI*) is the percentage of the fuel consumed vs. the amount of gas being compressed. A low *FTI* generally indicates a fuel efficient compressor unit. It is calculated by:

$$FTI = \frac{QEngine}{QCompressor} * 100 \quad (4)$$

Where

QEngine	The fuel consumption rate in thousand standard cubic feet per day MSCFD
QCompressor	Compressor throughput in MSCFD

Although this metric is commonly used, it is not a reliable metric due to several limitations:

The heating value of the fuel often fluctuates due to gas composition changes. If the heating value drops, the engine fuel consumption (by volume) will increase for the same compressor power causing an increase in the *FTI*.

- The amount of power required by the engine (and therefore its fuel consumption) is dependent on the pipeline operating conditions. For example, an increase in the gas compressor discharge pressure will generally increase the amount of engine power required and. reduce the flow through the compressor (for a constant load step). The combined effect is an increase in the *FTI*.
- It is not typical to physically measure the flow through reciprocating compressors. In most cases, the compressor flow will have to be estimated based on geometric compressor models. Malfunctions, such as a failure of a compressor unloader pocket to close, can result in significant errors in the modeled compressor flow and therefore the *FTI*.

The limitations are exemplified in Figure 1. The *FPI* of this compressor unit shows a large variation in the *FPI* (minimum of 0.11%, maximum of 0.45%, average of 0.26%)[1]. The trend line indicates a general improvement in performance. However, the real reason for the decreasing trend line is a seasonal change in pipeline operating conditions resulting in generally lower compression ratios across the compressor. This increases the flow through the compressor for a given engine power which results in a lower *FPI*. Figure 2 shows the inverse relationship between compressor flow and the compression ratio on this compressor unit.

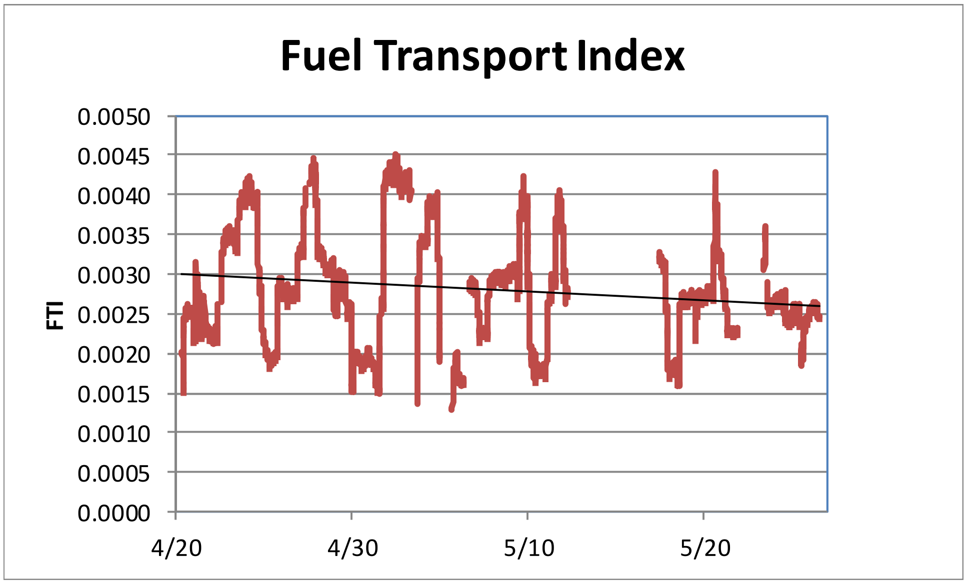

Figure 1 - FTI trend

[1] Based on over 10,700 data points in the sample on a well maintained compressor unit

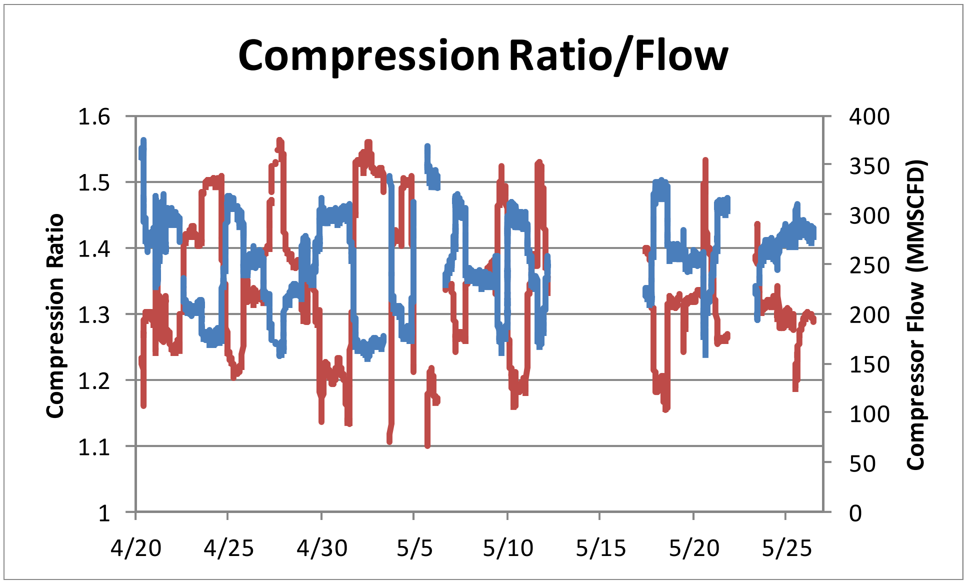

Figure 2 - Compression ratio (red) and compressor flow rate (blue) trend

The *FTI* is calculated on an instantaneous basis. It can be averaged over various time periods (hourly, daily, weekly, etc.) to help filter out noise. Out-of-bounds indicators could be triggered on *FTI* to indicate abnormal operation; however, use of this performance indicator is not recommended except for constant compression ratio applications that have a uniform fuel gas composition due to the limitations outlined above.

A related but only slightly better metric is calculating a transport index based on the fuel in dekatherms. This resolves the issue of fuel gas compositions of varying heat value but still does not resolve the issues associated with varying operating conditions on the compressor and, therefore, is not recommended as a reliable KPI. It is a suitable metric for constant compression ratio applications.

Brake Specific Fuel Consumption

Brake specific fuel consumption (*BSFC*) is commonly used by engine manufactures to provide the relative indicator of fuel efficiency. A low *BSFC* generally indicates an efficient engine. It is calculated by:

$$BSFC = \frac{10^6 * QEngine * BTUlhv}{24 * BHP} \qquad (5)$$

Where

BTUlhv	Lower heating value of the fuel in BTU/SCF[2]
BHP	Brake horsepower
QEngine	The fuel consumption rate in thousand standard cubic feet per day (MSCFD)

The brake horsepower should be measured if at all possible by a torque meter between the compressor and the engine. As most compressor units are not equipped with torque meters, it is recommended that *BHP* be based on compressor modeled power (discussed below).

[2] The most common usage of the heating value is in higher heating value. For most natural gas compositions, the lower heating value is approximately 90.5% of the higher heating value.

BSFC is calculated on an instantaneous basis. There are some practical limitations to this metric:

- Most compressor units are not equipped with a method to directly measure the engine brake power (such speed and a torque meter or integrated compressor pressures). Generally, an estimated power is calculated using compressor models and the compressor operating conditions. Operating deviations in the compressor model (such as a compressor pocket failing to actuate) will result in significant errors in the calculated *BSFC*.
- *BSFC* is not constant for an engine. Generally, the *BSFC* will increase as speed and torque are reduced from their rated values as shown in Figure 3. Figure 4 shows the *BSFC* trend history of a well maintained engine. Note the apparent erratic *BSFC* calculation.

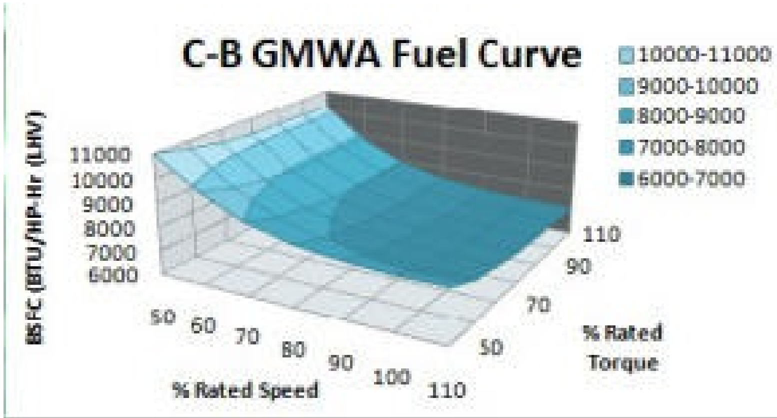

Figure 3 - Typical engine fuel curve

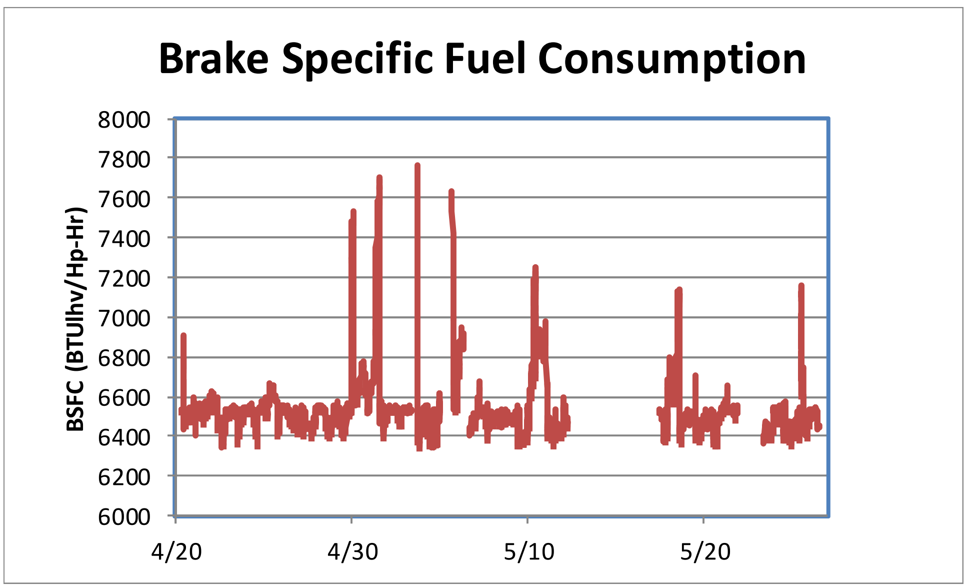

Figure 4 - Brake Specific Fuel Consumption

Without a comparison of the calculated *BSFC* to an expected *BSFC* for the same operating conditions, it is difficult to determine if the calculated *BSFC* value is good or not. As such, it is not recommended that out-of-bound limits be used for this KPI. Likewise, this should only be used as a KPI to indicate the relative performance to other similar engines operating under similar conditions (i.e., identical units on the same compression service).

Compressor Efficiency – Thermal

Compressor thermal efficiency (*CET*) can be calculated from the suction and discharge temperatures at a given compression ratio. The *CET* is relatively easy to calculate using the compressor suction and discharge pressures and temperatures. These parameters should be measured reasonably close to the compressor cylinders and always on the compressor side of any coolers or heaters. It is calculated on an instantaneous basis in percent by:

$$CET = \frac{Ts * (Rc^{\frac{(k-1)}{k}} - 1)}{(Td - Ts)} * 100 \qquad (6)$$

Where

Rc	The compression ratio as calculated below
Ts	The suction temperature in °R
Td	The discharge temperature in °R
k	The ratio of specific heat for the gas

The compression ratio is calculated as:

$$Rc = \frac{Pd}{Ps} \qquad (7)$$

Where

Pd	The discharge pressure in PSIA
Ps	The suction pressure in PSIA

A note of caution: the suction and discharge temperatures will be nearly the same when the compressor unit is shut down. This can cause a divide by zero error in Equation 5. To avoid this, the *CET* calculation should be inhibited when the compressor unit is not actively compressing gas.

There are some precautions that need to be considered when using this KPI. First, the ratio of specific heat of the compressed gas can change with changing operating conditions (pressures/temperatures and gas composition). If these parameters change significantly, the ratio of specific heat should be recalculated based on the average of the suction and discharge conditions. Secondly, accuracy in *CET* is very dependent on the accuracy of the temperature measurement; a small error in temperature can create a large change in the calculated efficiency, especially at low compression ratios. The *CET* can be expected to change as a function of compression ratio. Monitoring *CET* for real-time out-of-bound limits is therefore difficult to perform unless the expected compressor efficiency is known. To avoid divide by zero errors, the calculation of *CET* should be inhibited and set to 100 when the compressor unit is not actively compressing gas.

While *CET* can be calculated for each compressor stage, it is highly recommended that individual cylinder discharge temperatures be measured so *CET* can be calculated at the cylinder level.[3] If *CET* is calculated for each compressor cylinder, the efficiency can be compared between cylinders operating on the same stage. Cylinders showing lower efficiencies are more likely to have mechanical operating problems (such as compressor valve failures or loss of coolant flow). Cylinders that have a deactivated compressor end will also tend to show a lower *CET* than a double acting cylinder on the same stage. Figure 5 shows a trend of *CET* for a well maintained compressor unit.

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[33] Subscripts should be used to represent the cylinder number. For example CET_3 would be the compressor thermal efficiency for cylinder 3.

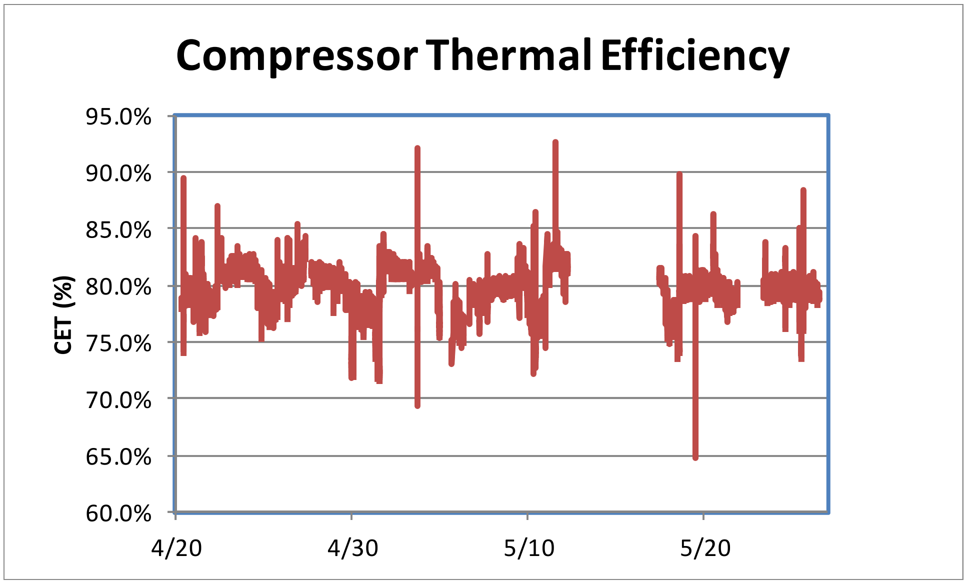

Figure 5 - Compressor thermal efficiency

Because of the variability *CET*, it is difficult to establish out-of-bound limits except for very high and very low levels. Gas temperature changes typically lag changes in pressure; as such, the use of a lag filter is recommended on this KPI.

Compressor Relative Efficiency - Thermal

The compressor relative thermal efficiency (*CRET*) normalizes the *CET* to the expected efficiency for a given operating condition. It is calculated on an instantaneous basis by:

$$CRET = \frac{CET}{CETe} * 100 \qquad (8)$$

Where

CETe The expected thermal efficiency in percent

CETe is a modeled parameter of *CET*, typically as a function of compression ratio. It is commonly back calculated from a large dataset of operating data when the compressor unit is known to be in good mechanical condition. It is commonly modeled as a second order polynomial but an interpolated one-dimensional lookup curve is recommended along the lines of the author's article [2].

CRET is relatively easy to model and takes little computing resources and is calculated on an instantaneous basis. As such, it is a good KPI for the use of real-time out-of-bound notifications to identify performance deviations. As noted above, the uncertainty in *CET* increases at low compression ratios. Therefore, it is recommended that out-of-bound limits be dynamic based on the measurement uncertainty to minimize false alerts. This is demonstrated in Figure 6. The *CRET* should be continuously outside of the expected bounds for at least 10 minutes before an out-of-bounds indicator is set on this KPI. To avoid divide by zero errors, the calculation of *CRET* should be inhibited and set to 100 when the compressor unit is not actively compressing gas.

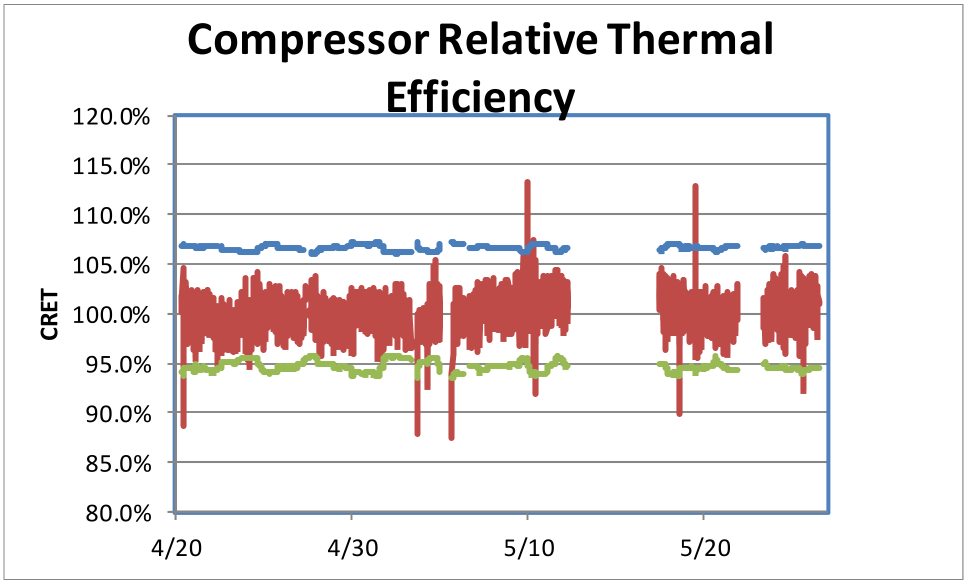

Figure 6 - CRET (red) with dynamic upper (blue) and lower (green) bounds for limits

As *CRET* is normalized, [3] it is easily used to interpret the performance of a compressor. Low efficiencies are most commonly caused by mechanical issues while high efficiencies are most typically a measurement error most commonly associated with gas temperature measurement (as with *CGT*) or in the modeling of the compressor efficiency.

Compressor Gas Power

Compressor gas power (*CGP*) is calculated based on the net power that went into the pipeline with adjustments for thermal and mechanical efficiency. It is calculated on an instantaneous basis in horsepower by:

$$CGP = \frac{Had * Qs * 1{,}000{,}000 * SG}{1.44 * 13.08 * 33 * CET * CEV * Meff} + AXP \qquad (9)$$

Where

Had	The adiabatic head across the compressor in Ft-lbf/lbm
Qs	The measured flow rate through the compressor in percent
SG	The specific gravity of the gas being compressed relative to air
CEV	The compressor valve efficiency in percent
Meff	The mechanical efficiency of the compressor in percent
AXP	Any power used for auxiliary loads not accounted for in the engine base power rating such as external cooling fans in horsepower

CEV accounts for the losses across the compressor valves. *Meff* accounts for friction losses in the compressor packing and bearings where 95% is commonly used. The methods for calculating adiabatic head are excluded here for brevity because it is commonly available elsewhere.

This KPI should be directly comparable to other power calculations discussed below. *CGP* requires the physical measurement of the flow rate through the compressor which is not commonly quantified on most reciprocating compressors. *CGP* is calculated on an instantaneous basis.

There are two significantly different ways to measure the flow through the compressor for this KPI. The first is to use a conventional flow measurement device such as an averaging pitot tube, orifice plate, or clamp-on ultrasonic meter.[4] The second method involves calculating the flow rate based on the fraction of time the suction valve is opened based on continuous compressor cylinder pressure monitoring and the associated compressor cylinder displacement. Of the two methods, the in-cylinder pressure measurement method tends to be the more expensive option. However, it also offers the potential to pinpoint issues to a specific compressor cylinder end. Conversely, the first method can identify a deviation but additional manual data gathering and data evaluation may be required to pinpoint the underlying problem. This should be inhibited and set to zero when the compressor unit is not actively compressing gas.

It is recommended that operators adopt *CGP* as a KPI as it can be compared to other power metrics outlined in this paper as a method to continuously monitor and diagnose problems.

Compressor Relative Efficiency

Compressor relative efficiency (*CRE*) is the normalization of *CGP* compared to the compressor modeled power. It is calculated on an instantaneous basis as:

$$CRE = \frac{CGP}{CMP} * 100 \tag{10}$$

Where

CMP Is the modeled compressor power in horsepower

CMP is commonly modeled by estimating the flow rate through the compressor based on the compressor clearance and displacement volumes and modeling the power required per unit of compressor flow rate. There are many different methods used to perform this modeling such as those outlined by Matthews [4]. *CETe* can be used as part of these models. The *CMP* should include any *AXP* loads so it is directly comparable to the other power calculation methods in this paper.

This KPI is very good at identifying mechanical problems with the compressor, including that one or more compressor valves have failed or that a compressor unloader/pocket is not actuating correctly. As a normalized parameter, it is easy to interpret at a glance. Like *CRET*, it is recommended that out-of-bound limits be dynamic to minimize false notifications as shown in Figure 7. *CRE* should be continuously outside of the expected bounds for at least 10 minutes before an out of limits event should be triggered. To avoid potential divide by zero errors, the calculation of *CRE* should be inhibited and set to 100 when the compressor unit is not actively compressing gas. It is highly recommended that operators adopt this KPI as it is an effective tool to continuously monitor and diagnose compressor problems.

[4] In some cases, a differential pressure between the suction valve inlet to the compressor pulsation bottle can be used as a primary flow measurement device. To use the compressor piping as a primary flow element requires the calibration of a flow coefficient, which can be back calculated from the estimated compressor flow based on a compressor cylinder performance test or a temporary flow measurement device (such as tracer gases, insertion averaging pitot tubes, or clamp-on ultrasonic meters). The differential pressure transmitter has to be of a relatively high accuracy, calibrated for a low range of differential pressures, and damped or filtered to minimize pulsation effects. Care must be taken in installing the transmitter's gauge lines to prevent the accumulation of liquids.

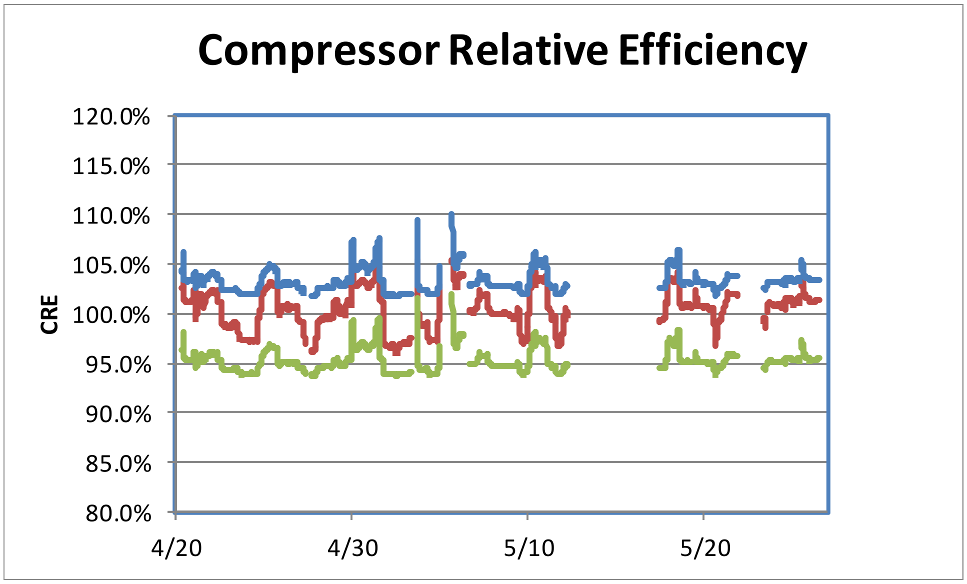

Figure 7 - CRE (red) with dynamic upper (blue) and lower (green) bounds for limits

Fuel Power

Fuel power (*FP*) estimates the net power developed by the engine based on the fuel consumption. It requires a model of the fuel usage as a function of speed and torque (as shown in Figure 2). This parameter is calculated on an instantaneous basis by:

$$FP = \frac{1{,}000 * QEngine * BTUlhv}{24 * (BSFCe + BSFCit)} \quad (11)$$

Where

BSFCe The expected (modeled) compressor power in horsepower

BSFCit The expected change in brake specific fuel consumption if the actual ignition timing is different than the optimum ignition timing

It is recommended that an interpolated two-dimensional (speed and torque) look-up curve be used to determine the baseline *BSFCe* and a one-dimensional interpolated curve be used for *BSFCit*. This equation assumes that the engine is configured to operate at its trapped equivalence ratio (TER); otherwise, an adjustment to the BSFC is required to account for off optimum engine air flow.

The calculation of *FP* is usually a recursive calculation in that *FP* is required to calculate torque used to determine the *BSFC* which is required to calculate *FP*. This is generally not problematic. To avoid potential divide by zero errors, the calculation of *FP* should be inhibited and set to zero when the compressor unit is below idle speeds and not actively compressing gas.

Fuel Torque

Fuel torque (*FT*) is the engine torque based on fuel consumption compared to the engine's rated torque in percent. Engine makers often do not specify the rated torque but rather rated power and rated speed so *FT* is actually calculated from power and speed. It is calculated on an instantaneous basis by:

$$FT = \frac{FP * RPMr}{BHPr * RPM} * 100 \quad (12)$$

Where

RPMr	The rated engine speed in RPM
RPM	The actual engine speed in RPM
BHPr	The site rated engine power in horsepower

The unit's torque can also be calculated based on the load power. It is preferable to use this *FP* for load control rather than load based torque, as mechanical problems with the engine tend to cause the actual brake specific fuel consumption to increase. This will cause the *FT* to be higher than the actual mechanical torque on the engine. Thus, a mechanical problem with the engine will automatically result in a deration of the engine to prevent accelerated mechanical damage to the engine.[5] The operator will be made aware of this condition through the compressor unit relative efficiency parameter discussed below.

As a KPI, *FT* indicates how highly loaded a compressor unit is operating. Alarms and shutdowns should be used on *FT*. For shutdowns, it is recommended that a time delay alarm be used at moderate overloads (e.g., *FT* > 103%) and an immediate shutdown occur on high overload (*FT* > 110%). To avoid potential divide by zero errors, the calculation of *FT* should be inhibited when the engine is operating below idle speeds.

For compressor units that are ambient uprated,[6] the *FT* should be calculated as above but the allowable control set-point for loading, alarms, and shutdowns should be adjusted based the allowable maximum torque for the current ambient conditions. This will result in *FT*>100% during the times of ambient uprate. For ambient uprated units, a sister parameter, ambient fuel torque, can be calculated based on the *FT* as a percentage of allowable torque at the current ambient conditions. The ambient fuel torque should only have minimal excursions above 100%.

Power Range

The power range (*PR*) is the power being generated by a compressor unit as a percentage of the range of power possible at the current operating conditions. This parameter is calculated on an instantaneous basis by:

$$PR = \frac{(FT * RPM - FTmin * RPMmin)}{(FTmax * RPMr - FTmin * RPMmin)} * 100 \quad (13)$$

Where

RPMmin	Minimum allowable engine speed in RPM under the current conditions[7]
FTmax	Maximum fuel torque capable under current operating conditions
FTmin	Maximum fuel torque capable under current operating conditions

PR is useful for pipeline system operators to determine where additional power can be increased (or decreased) on the system without starting (stopping) additional compressor units.

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[5] Torque load control based on compressor modeled power may be desirable for very lightly loaded engines where significant misfires are likely as the actual BSFC can vary widely under those conditions.

[6] Some engines are allowed to operate at higher loads at lower ambient temperatures when there is more cooling capacity. For example, a unit rated at 90 °F may allow a 10% higher torque level at 40 °F.

[7] In some cases, the minimum speed will be based on mechanical limits (avoiding torsional resonance, minimum oil pressure requirements) and, in some cases it will be based on having sufficient combustion air. In the latter case, models are typically required to determine the allowable minimum speed based on engine torque and ambient conditions.

Unit Relative Efficiency

The compressor unit relative efficiency (*URE*) compares the fuel power to modeled compressor power. This is a normalized parameter and is a good indicator of the overall compressor unit health. *URE* is calculated on an instantaneous basis by:

$$URE = \frac{FP}{CMP} * 100 \tag{14}$$

It is suitable for real-time out-of-bounds checking provided the bounds are dynamic to accommodate the uncertainty in the underlying models (specific fuel consumption and/or compressor models) and are temporarily inhibited during significant operations changes (such as compressor load step changes) as depicted in Figure 8. *URE* should be continuously outside of the expected bounds for at least 10 minutes before an out-of-bounds indicator is triggered on this KPI. To avoid divide by zero errors, the calculation of *URE* should be inhibited and set to 100 when the compressor unit is not actively compressing gas.

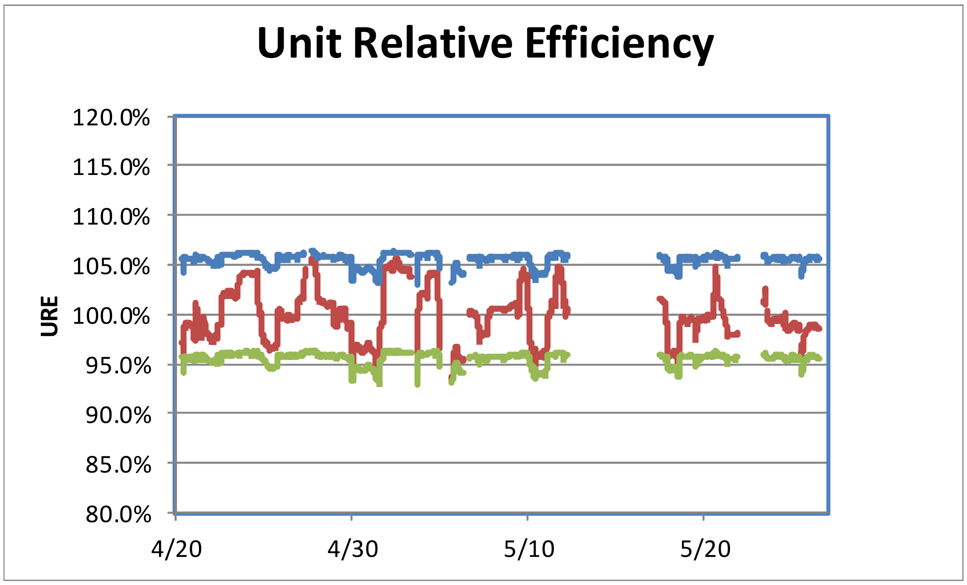

Figure 8 – URE (red) with dynamic upper (blue) and lower (green) bounds for limits

URE is a very good KPI for continuous performance monitoring. For example, if there is an ignition problem with one of the power cylinders, the fuel will increase to the other power cylinders to maintain the load. This will result in an increase in the fuel power and/or a decrease in the compressor power (if a load step was changed as a result of the apparent increase in engine torque) resulting in a drop in *URE*.

As a normalized KPI, *URE* is easy to interpret. Deviations outside the expected bounds can be traced back to modeling errors, instrument calibration errors, or (most likely) engine and/or compressor mechanical problems. Its use is highly recommended. When used in conjunction with *CRE*, these KPIs can help pinpoint if the deviations in expected performance are associated with the engine or the compressor.

Unit Overall Efficiency

The compressor unit overall efficiency (*UOE*) compares the net power that enters the pipeline as compressed gas to the energy rate entering the engine as fuel. This parameter is calculated on an instantaneous basis. This KPI can (and should) be calculated for all compressor units regardless of driver type. For reciprocating compressors, *UOE* is calculated by:

$$UOE = \frac{24 * 2{,}544.43 * CGP * CET * Meff}{100{,}000 * QEngine * BTUlhv} \qquad (15)$$

While *UOE* will fluctuate with operating conditions, it is still a good KPI to monitor as it can be compared from compressor unit to unit to identify the most efficient compressor units on a pipeline system to operate. *UOE* is used best when it is compared against other compressor units operating in similar conditions (e.g., compressor units on the same compression service or similar compression ratios). Care must be given not to make decisions based on *UOE* calculated at one operating condition to the *UOE* at significantly different operating conditions. For example, at low compression ratios, Unit A might have a higher *UOE* than Unit B, which doesn't indicate that Unit A should always be started before Unit B because Unit B might have a higher *UOE* at high compression ratios.

Out-of-bound limits should not be used on the *UOE* KPI. To avoid divide by zero errors, the calculation of this KPI should be inhibited when the compressor unit is not actively compressing gas and set to 100.

Reliability based

Reliability based metrics are intended to help identify opportunities to improve compressor unit reliability. Improvements in reliability can reduce total operating costs through the reduction in unplanned work activity and overtime. These KPIs can be applied across all compressor units regardless of the driver/compressor type.

Number of Starts

The number of starts (*NS*) counts the number of times that a compressor unit reaches online status (actively compressing gas). This should be an accumulation register that always increments. They should be tracked on at least a monthly basis and rolled up to an annual basis. *NS* should utilize the appropriate subscripts to indicate the corresponding time period basis.

Compressor units with a high number of starts in a given period are either unreliable compressor units (which will also have a high number for uninitiated shutdowns) or have widely varying system load demands. In either case, further evaluation is warranted on these engines to assess mechanical modifications that would improve the reliability and/or increase the operating range of the compressor unit(s) to reduce the number of shutdowns required.

In some cases, the number of starts is used to estimate the amount of purge/blow-down gas emitted. This isn't always a reliable metric for that purpose as in some cases the compressor unit was not blown down. A better approach is to directly estimate and accumulate the estimated purge volumes in the compressor unit control system.[8]

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[8] Purge volumes can vary significantly depending on the operation of the purge/vent valves and the upstream pressure. The purge flow rate can be estimated based on the purge valve position, the valve flow coefficients, source pressure and the time that the purge valve is open while the vent valve is opened. The purge calculations can also be based on unit piping flow coefficients and the suction pressure. When calculating purge volumes, it is important to subtract the gas volume that remains in the compressor at the time the vent valve is closed from all of the gas estimated as having flown through the purge valve.

The number of starts is within one of the number of shutdowns. Therefore, it can be used in the estimation of blow-down volumes. Not all shutdowns involve blow-downs and not all blow-downs are initiated at the same operating pressure. The compressor unit control systems can more reliably and accurately estimate these volumes than can be performed manually from the number of starts.

If the gas composition of the compressed gas is known or can be reliability estimated, the estimated purge/blow-down emissions can further be enhanced by directly calculating and accumulating the greenhouse gas equivalent, especially for gases that contain large portions of non-methane/non-carbon dioxide.

Unsuccessful Start Rate

The unsuccessful start rate (*USR)* metric is the percentage of all start attempts that did not reach the stage where the compressor unit was online compressing gas during a period of time. It is calculated by:

$$USR = \frac{NS}{NSA} * 100 \tag{16}$$

Where

NSA The number of start attempts (both successful and unsuccessful)

It is important to note that the values for *NS* and *NSA* must be for the same time period (i.e. current month, current year, life of compressor unit, etc.)

This KPI is useful for identifying underlying issues that can adversely impact the reliability of the compressor unit. As the number of start attempts may be relatively low, it is recommended that this KPI be calculated (and reset) over the period of one year.

It is a best practice to gather root causes of unsuccessful starts and compile that information into a central database. That information can be mined to initiate modifications to compressor units that are critical to the pipeline throughput. For example, if a common cause of unsuccessful starts is incomplete sequence trips due to valve position failure, valve flushing and lubrication maintenance (or replacement in the worst case) or valve position limit switch/wiring work can reduce the frequency of unsuccessful starts.

If the *USR* is reset (i.e., at the beginning of each calendar year), a divide by zero error can occur. When *USR* is reset, the calculation should be inhibited and set to 100 until another start is attempted.

Uninitiated Shutdown Rate

The uninitiated shutdown rate (*USDR*) is the percentage of all compressor unit shutdowns that are associated with automatic protection trips (i.e., not associated with an operator initiated shutdown for no demand or planned maintenance). This also excludes shutdowns associated with unsuccessful starts. High values for this KPI generally indicates a less reliable compressor unit. It is calculated by:

$$USDR = \frac{NUSD}{NSD} * 100 \tag{17}$$

Where

NUSD The number of uninitiated shutdowns in a given period

NSD The number of all shutdowns in a given period

The values for *NUSD* and *NSD* must be for the same time period (i.e. current month, current year, life of compressor unit, etc.) As the number of shutdowns may be relatively low, it is recommended that this KPI be calculated (and reset) over the period of one year.

It is a best practice to gather root causes of uninitiated shutdowns and compile that information into a central database. That information can be mined to initiate modifications and/or maintenance to compressor units that are critical to the pipeline throughput.

If the *USDR* is reset (i.e., at the beginning of each calendar year), a divide by zero error can occur. When *USDR* is reset, the calculation should be inhibited until and set to 100 a shutdown is encountered.

Cost based

These KPIs can be applied across all compressor units regardless of the driver/compressor type. Unlike the KPIs above, these metrics cannot be calculated in the compressor unit control system as the unit control system generally does not have access to maintenance costs. Accurate calculations of these KPIs require maintenance costs to be tracked (or at least reasonably estimated) by compressor unit. These KPIs are used to aid operators in identifying compressor units with high cost of operation and allow them to optimize the pipeline system to minimize operating costs.

Average Annual Operating Cost

The average annual operating cost (*AAOC*) is based on the cost of service to operate and maintain a compressor unit ignoring any fuel or power costs. It is calculated by:

$$AAOC = SRU + AAOMC \tag{18}$$

Where

SRU The share of fixed station resource usage (general facility maintenance costs, electrical power fixed demand charges, base labor, etc.)

AAOMC Average annual operating (lube oil, electricity, etc.) and maintenance cost

Long term costs should be adjusted to an annual basis. For example, if the compressor unit is overhauled every 25,000 operating hours and the compressor unit averages 2,500 hours per year, 1/10 of the overhaul costs would be included in the *AAOC*.

Care must be given when analyzing *AAOC* information. Specifically, significant differences in *AAOC* can be expected between compressor units with significantly different *UU*. This KPI can be a good tool for estimating the cost of service for a given compressor unit and can be rolled up to the compressor station level. It can be used to help estimate projected maintenance costs.

Specific Maintenance Cost

The specific maintenance cost (*SMC*) is the variable portion of the *AAOC* converted to a horsepower-hour basis. It is calculated by:

$$SMC = \frac{AAOMC}{HPHR} \tag{19}$$

Where

HPHR The annual accumulated horsepower-hours

The KPI is useful in estimating the expected change in maintenance costs that can be expected due to changes in equipment runtime.

This can aid in developing maintenance budgets.

Specific Operating Cost

The specific operating cost (*SOC*) includes *SMC* and the cost of fuel.[9] It is calculated by:

$$SMC = SMC + FOC \tag{20}$$

Where

FOC The fuel operating costs in $/horsepower-hour

This KPI is useful in helping to optimize system operation to the minimum cost of operation to the operator.

[9] Some operators have fuel trackers. In those cases, the cost of the fuel (or some portion thereof) should be excluded from this calculation.

CONCLUSIONS

The KPIs presented in this paper can be useful in monitoring the reliability and performance of compressor units. While the specific focus in this case is reciprocating engine driven reciprocating compressors, many of these KPIs are directly applicable or adaptable to other types of compressor equipment as well. It is important to adopt standard conventions for the usage of these KPIs if they are to be deployed at a corporate or industry level. Calculating, monitoring, and analyzing these KPIs can help an operator optimize the operation of their compression fleet to maximize throughput, minimize maintenance costs, and/or increase equipment reliability.

With the exception of the cost based KPIs, the parameters should be calculated at the compressor unit level in the unit control panel. The cost based KPIs must be calculated offline and should be updated on an annual basis.

ACKNOWLEDGMENTS

The author would like to acknowledge the assistance of Kent Beebe in developing many of these KPIs and Mary Beth Whitfield for her review and comments.

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NOMENCLATURE

AAOC	Average annual operating cost in $/year
AAOMC	Average annual operating and maintenance cost in $/year
AXP	Auxiliary power in horsepower
BHP	Brake horsepower
BHPr	Site rated engine power in horsepower
BSFC	Brake specific fuel consumption in BTUllv/BHP-Hr
BSFCe	Expected brake specific fuel consumption in BTUllv/BHP-Hr
BSFCit	Ignition timing adjustment to brake specific fuel consumption in BTUllv/BHP-Hr
BTUlhv	Lower heating value of the fuel in BTU/SCF
CET	Compressor efficiency, thermal
CETe	Expected compressor thermal efficiency
CEV	Compressor valve efficiency in percent
CGP	Compressor gas power in horsepower
CMP	Modeled compressor power in horsepower
CRET	Compressor relative efficiency, thermal
CRE	Compressor relative efficiency
FOC	Fuel operating cost in $/horsepower-hour
FT	Fuel torque in percent
FTmax	Maximum potential fuel torque under current operating conditions in percent
FTmin	Minimum potential fuel torque under current operating conditions in percent
FTI	Fuel transport index in percent
FP	Fuel power in horsepower
HPHR	Annual accumulated horsepower-hours
k	Ratio of specific heat
Meff	Mechanical compressor efficiency in percent
MSCFD	Thousand standard cubic feet per day
NS	Number of starts
NSA	Number of start attempts
NSD	Number of shutdowns
NUSD	Number of uninitiated shutdowns
OperatingTime	Total unit operating time during the *PeriodTime* in seconds
Pd	Discharge gas pressure in PSIA
PeriodTime	The total time in a given period in seconds

PR	Power range in %
Ps	Suction gas pressure in PSIA
QCompressor	Compressor throughput in MSCFD
QEngine	The fuel consumption rate in thousand standard cubic feet per day MSCFD
Qs	Compressor flow rate in MMSCFD
Rc	Compression ratio
RPM	Actual engine speed in RPM
RPMr	Rated engine speed in RPM
RPMmin	Minimum engine speed in RPM
SG	The specific gravity of the gas being compressed relative to air
SOC	Specific power operating costs in $/BHp-Hr
SRU	The share of fixed station resource usage in $/year
SMC	Specific Maintenance Cost in $/BHp-Hr
SOC	Specific Operating Cost in $/BHp-Hr
Td	Discharge gas temperature in °R
TER	Trapped equivalence ratio
Ts	Suction gas temperature in °R
UAG	Unit availability – gross in percent
UAN	Unit availability – net in percent
UOE	Unit overall efficiency in percent
URE	Unit relative efficiency
USDR	Uninitiated shutdown rate in percent
USR	Unsuccessful start rate in percent
UU	Unit utilization in percent
UU_D	Daily unit utilization in percent
UU_{DS}	Daily unit cool-down/ shutting-down utilization in percent
UU_{DW}	Daily unit warm-up utilization in percent
UnavailableTime	Total time a unit is available to operate during the *PeriodTime* in seconds
UnavailableTimeD	Total time a unit is available when there is a system demand for the unit during the *PeriodTime* in seconds