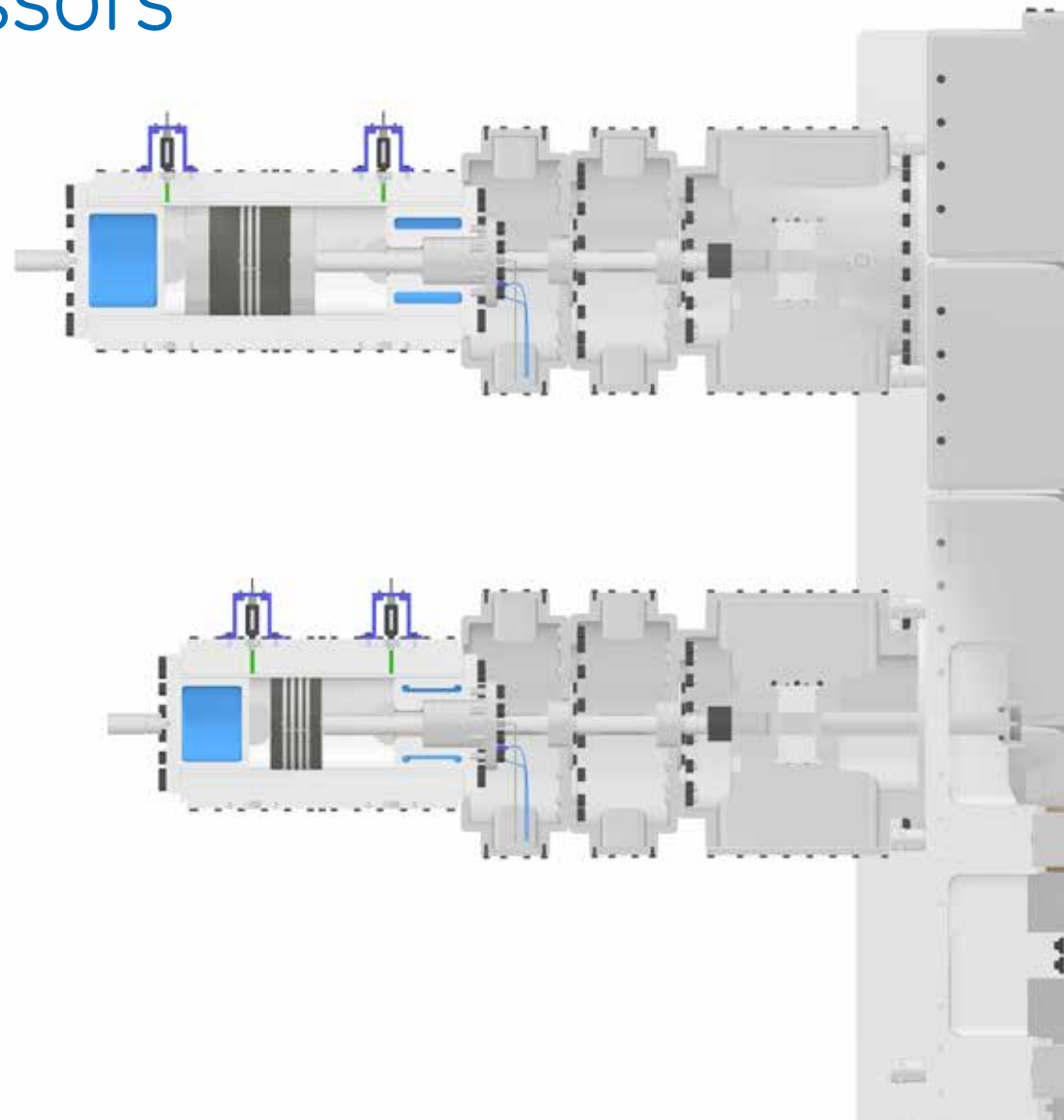


Condition Monitoring Solutions for Reciprocating Compressors





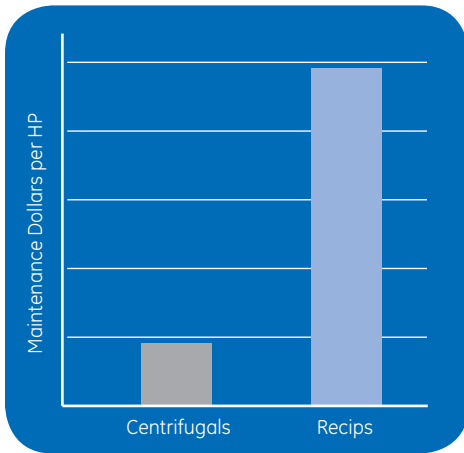
Why Monitor?

As one of the oldest compressor designs, reciprocating compressors (recips) enjoy unique capabilities and are quite flexible with features such as broad capacity control ranges and the ability to compress gas regardless of mole weight or k value. Add multiple stages and they can compress a gas to extremely high compression ratios. Consequently, they are an ideal fit for selected applications—such as hydrogen compression in the de-sulfurization process of many refineries—and as part of the low-density polyethylene production process in chemical plants, to name just a few.

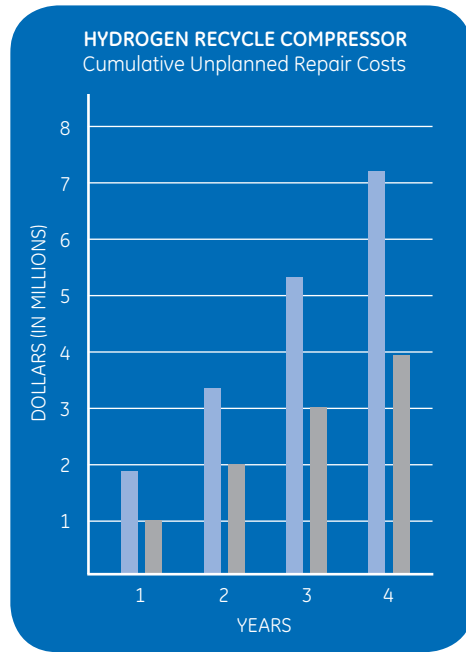
However, reciprocating compressors suffer from one very serious drawback: high maintenance costs. In fact, compared to similarly sized centrifugals, recips can consume as much as five times the amount of maintenance dollars.

That's why a continuous monitoring system is so important. Specifically designed to meet the unique machinery protection and condition monitoring needs of reciprocating compressors, our solutions, which include Safety Integrity Level (SIL) certified products can help close the gap, bringing your recip maintenance costs closer to the levels associated with centrifugals while simultaneously improving reliability, availability, and safety. And, with patented[†] technology, comprehensive services, and over 25 years of experience monitoring reciprocating compressors, no one is better equipped to help you.

[†] United States Patents 4,987,774; 6,421,571; 6,826,490; 6,937,941; 6,934,696 and 8,297,123. Great Britain Patent 2,408,338.



Recips can consume five times as many maintenance dollars as an equivalently sized centrifugal compressor.



■ Without monitoring ■ With monitoring

A monitoring system from GE will often more than pay for itself in the first year, and can save millions of dollars over the life of the compressor.



Recip Monitoring In Detail.

Pressure Packing Case Temperature
 Continuous monitoring of pressure packing temperature provides useful information on developing problems related to the packing, including excessive wear, insufficient cooling, and inadequate lubrication.

3500 Monitor: 3500/61 6-Channel or 3500/65 16-Channel Temperature Monitor
 Transducer: RTD or Thermocouple

Packing Vent Line Temperature
 Continuous monitoring of the vent line provides indication of leaking purge packing. With increase in process flow the vent line becomes hotter. For years, operators have used the subjective method of touching the line to see if gas is leaking.

Continuous Rod Load
 Combined (inertia and gas) rod loads calculated at the crosshead pin provides information about the lubrication condition of the crosshead pin. Insufficient reversal or excessive rod load can be identified and corrected before costly running gear damage occurs.

3500 Monitor: 3500/61 6-Channel or 3500/65 16-Channel Temperature Monitor
 Transducer: RTD or Thermocouple

Discharge Gas Temperature
 Continuous monitoring of discharge gas temperature can give an indication of worn valves, unloaders, excessive compression ratio, or insufficient cooling water.

Piston Rod/Plunger Position
 Horizontal and Vertical proximity probes observing the piston rod provide information on rod bow and rider band wear. Continuous monitoring gives maximum magnitude and direction of rod movement along with the crank angle at which the maximum occurs. The source of movement can be identified, enabling the proactive scheduling of maintenance for rider band replacement or crosshead repair. Monitoring plunger position in hyper compressors provides protection against deteriorating plungers.

3500 Monitor: 3500/72M 4-Channel Rod Position Monitor
 Transducer: 3300XL Series Proximity Transducer

3500 Monitor: 3500/77M 4-Channel Cylinder Pressure Monitor
 Transducer: 165855 Cylinder Pressure Transducer

Cylinder Pressure Profile
 The single most effective way of determining the overall health of a reciprocating gas compressor is by examining the cylinder pressure profile. Online access to the internal pressure for each compressor chamber enables continuous monitoring of cylinder pressures, compression ratios, peak rod loads, and rod reversal. This provides valuable information on the condition of suction valves, discharge valves, piston rings, packing glands, and crosshead pin. And, interfacing the 3500 System with System 1* software provides valuable diagnostic plots such as Pressure versus Volume (P-V), Log P versus Log V, and Pressure versus Crank Angle (Theta- θ) (P-T).

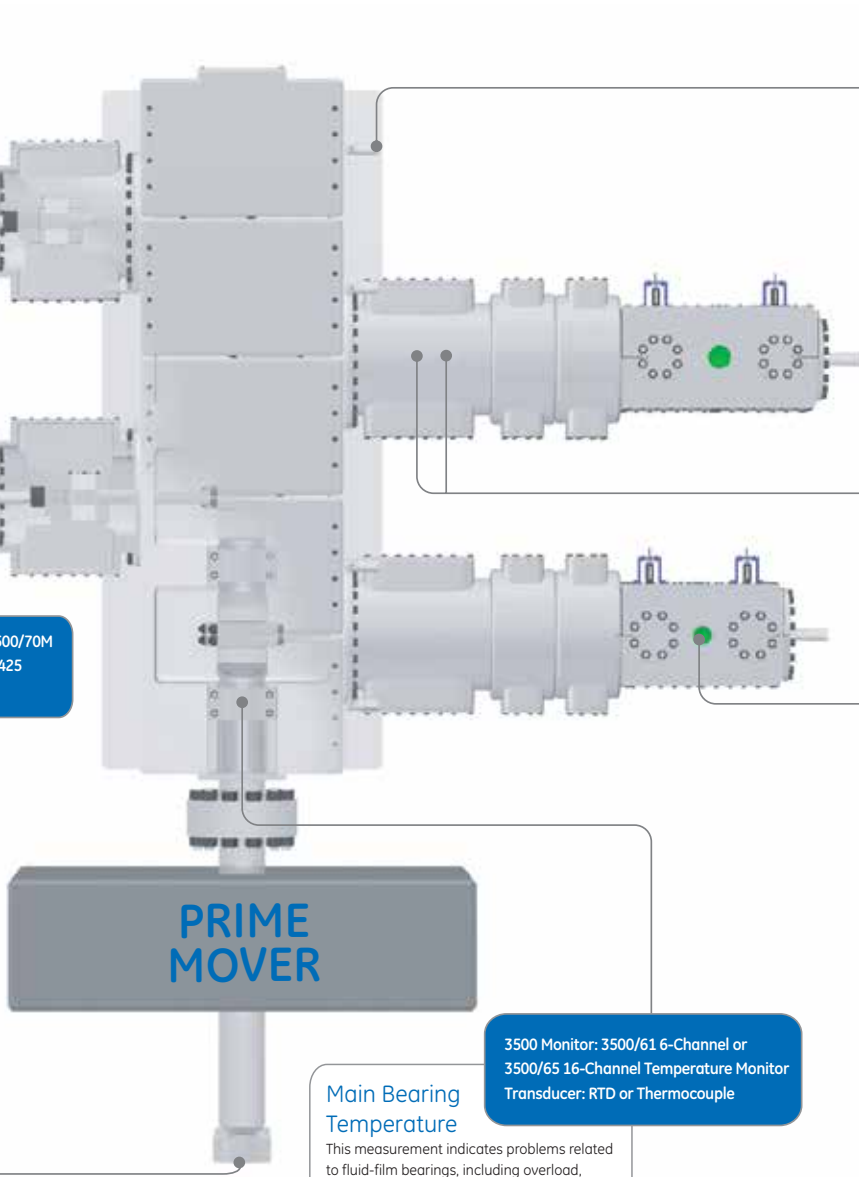
3500 Monitor: 3500/77M 4-Channel Cylinder Pressure Monitor
 Transducer: 165855 Cylinder Pressure Transducer

Cylinder Acceleration
 Placing accelerometers on the cylinder provides waveform information that can be combined with cylinder pressure data to assess the health of the cylinder valves. This information has significant value when hydraulically actuated valves (stepless unloaders) have been installed on a compressor. For compressors so equipped, cylinder acceleration is strongly recommended.

3500 Monitor: 3500/70M
 Transducer: 330425 Accelerometer

Multi-Event Keyphasor Signal
 A proximity probe observing a multi-toothed wheel on the crankshaft provides a precise reference timing signal every 30 degrees of rotation in addition to a once-per-turn reference point. This allows measurements such as rod position and cylinder pressure to be correlated with a highly accurate crank angle measurement. Rod position can be captured at the same point in the piston rod stroke, and cylinder volume can be computed precisely at each point in the stroke for highly accurate P-V curves.

3500 Monitor: 3500/25 Keyphasor Module
 Transducer: 3300XL Series Proximity Transducer



Main Bearing Temperature
 This measurement indicates problems related to fluid-film bearings, including overload, bearing fatigue, or insufficient lubrication.

3500 Monitor: 3500/61 6-Channel or 3500/65 16-Channel Temperature Monitor
 Transducer: RTD or Thermocouple

Malfunction/Measurement In Detail.



Frame Vibration

Increases in frame vibration can indicate problems such as imbalance due to unusual pressure differential or inertial unbalance, looseness in the foundation attachment (such as deteriorating grout or shims), and high moments caused by excessive rod load.

3500 Monitor: 3500/70M 4-Channel Impulse/ Velocity Monitor
Transducer: 330500 Velomitor* or 190501 Velomitor CT
Piezo-Velocity Transducer

3500 Monitor: 3500/70M
Transducer: 330425
Accelerometer

Crosshead Vibration

Crosshead-mounted accelerometers can detect machinery problems due to impact-type events such as excessive crosshead clearance, liquid ingestion into the cylinder, excessive clearance in the crosshead pin bushing and loose or cracked nuts, bolts, liners or pistons.

3500 Monitor: 3500/61 6-Channel or 3500/65 16-Channel
Temperature Monitor
Transducer: RTD or Thermocouple

Crosshead Shoe Temperature

Continuous monitoring of crosshead shoe (slipper) temperature provides useful information on developing slipper problems such as overload, fatigue, and insufficient lubrication.

3500 Monitor: 3500/61 6-Channel or 3500/65 16-Channel Temperature Monitor
Transducer: RTD or Thermocouple

Suction/Discharge Valve Temperature

Suction and discharge valves are typically the highest maintenance items on recip. Faulty valves can significantly reduce the compressor's efficiency as well as increase combined rod load. By recompressing the same gas, a leaky valve becomes hotter than normal, causing the valve cover plate temperature to increase. By monitoring both absolute valve temperature, and differential temperature between a group of valves, valve problems can be spotted early and repaired before efficiency losses mount.

3500 Monitor: 3500/61 6-Channel or 3500/65 16-Channel
Temperature Monitor
Transducer: RTD or Thermocouple

Suction Gas Temperature

Continuous monitoring of suction gas temperature provides a useful baseline against which to compare suction valve temperature. Relative changes in the temperature between suction valves and suction gas can give an indication of the worn suction valves. In addition, suction gas temperature, combined with the integrated equation of state engine in System 1 software, provides the information necessary to calculate capacity at suction conditions and cylinder flow balance numbers.

	See Note ²			MALFUNCTION ¹												
	API-618 (Fourth Ed.)	Protection Solution	Management Solution	Excessive Crankcase and Cylinder Vibration	Excessive Main Bearing Temperature (loss of lubrication)	Rod Load Faults (including reversal, excessive loading, etc.)	Faulty Cylinder Suction Valves	Faulty Cylinder Discharge Valves	Leaking Pressure Rings	Worn Rider Bands	Pressure Packing Case Leaks & Seizures	Excessive Clearance in Crosshead Bushing/Pin	Excessive Crosshead Slipper Clearance	Liquid Ingestion	Mechanical Looseness (piston, liner, piston rod)	
MEASUREMENT																
Frame Vibration	■	■	■	■											■	
Main Bearing Temperature		■	■		■											
Crosshead Acceleration		■	■	■		■	■	■				■	■	■	■	
Multi-Event-Per-Revolution Keyphasor® Signal		■	■	■		■	■	■	■	■	■	■	■	■	■	
Cylinder Pressure		■	■			■	■	■	■		■	■	■	■		
Combined Rod Load ³		■	■			■	■	■			■				■	
Piston Rod Position			■							■			■		■	
Hyper Plunger Position			■								■				■	
Suction Valve Temperature			■				■									
Discharge Valve Temperature			■					■								
Pressure Packing Case Temperature			■								■					
Crosshead Shoe Temperature			■										■			
Suction Gas Temperature			■				■									
Discharge Gas Temperature	■	■	■					■	■							
Online Gas Analyser Data Input			■				■	■	■					■		
Trending & Analysis Software			■	■	■	■	■	■	■	■	■	■	■	■	■	

1 The red-marked ■ measurements are recommended for auto-shutdown machinery protection.

2 All of the measurements marked in each column are highly recommended to detect the malfunction.

3 Combined rod load is calculated from cylinder pressure sensors measurement in the pressure monitor but is used for specific malfunction and protection functions.

At the heart of our Recip Monitoring Solution is the Bently Nevada* 3500 Series Machinery Protection System...

Integrated Machinery Protection and Machinery Management

Our powerful 3500/22M TDI Rack Interface Module eliminates the need for bulky external data acquisition hardware or special interface modules between the monitor rack and software. Simply plug an Ethernet cable into the 3500/22M and you're ready to communicate with our powerful System 1 software for advanced diagnostics, condition monitoring, and other plant asset management functionality. The result is a zero-footprint solution requiring absolutely no additional rack or cabinet space when augmenting your basic machinery protection system with System 1 connectivity. And, the enhanced data collection technology of our 3500/22M TDI allows earlier and improved diagnosis of previously difficult-to-ascertain transient events (such as cylinder liquid ingestion).

- Fully compliant with the requirements of American Petroleum Institute (API) Standard 670 for Machinery Protection Systems and Standard 618 for Reciprocating Compressors.
- Available in 19" 14-slot EIA rack or space-saving 12" 7-slot mini-rack.
- Available with a variety of high-quality display options ranging from self-configuring VGA touch screens to remote workstations to LCD panels that mount directly on the rack face.
- Monitor modules available with 4-20 mA recorder output signals for interfacing with strip chart recorders and other analog based control and automation equipment.
- Safety Integrity Level (SIL) certified monitor modules are available for use in Functional Safety applications.



Single-cable Ethernet connectivity to our System 1 software for advanced diagnostics and condition monitoring functionality.

Capabilities for assessing piston rod vibration and position at precisely defined crank angles for repeatable, useful information on rider band wear, rod bow/flex, and other conditions. Also applicable to hypercompressors using plungers instead of conventional pistons.

6- or 16-channel temperature monitors accept a variety of RTDs or thermocouples. Absolute and differential alarming capabilities allow the monitors to be used for valve temperatures, gas or other process temperatures, bearing temperatures, crosshead shoe (slipper) temperatures, pressure packing case temperatures, and a variety of other machinery or process temperature measurements.

All monitor modules are totally software configurable via the 3500's Rack Interface Module—key lockable to prevent unauthorized tampering.

Keyphasor module accepts multi-event-per-turn signals for greater accuracy—required for reciprocating compressor applications where crank angle must be precisely determined.



Highly reliable power supplies accept worldwide AC/DC voltages/frequencies and can be ordered as fully redundant to assure uninterrupted performance.

Powerful cylinder pressure measurements now available for the most complete picture of reciprocating compressor health. Dynamic P-V curves, rod reversal measurements, and much more.



Cylinder Pressure

Where the Action Is.

Special-purpose 4-channel vibration modules are designed to address the casing vibration, crosshead acceleration and cylinder acceleration measurement requirements unique to reciprocating compressors by providing reliable machinery protection without false or missed alarms. Filtering, alarm delay, full-scale range, transducer input type, and a host of other options are fully software configurable on a per-channel basis.

Generic 4-channel vibration modules accept velocity, acceleration, and proximity transducers. Filtering, alarm delay, full-scale range, transducer input type, and a host of other options are fully software configurable on a per-channel basis. Used for a variety of measurements on the recip's prime mover.

A variety of relay modules are available for actuation upon user-configurable alarm and status events. Relays are highly reliable and intended for connecting the monitoring system to external annunciators and machinery control systems for auto-shutdown.

Fully digital communications of all monitored parameters and statuses using a variety of industry-standard protocols—ideal for connection to process and machine control systems rather than using analog (4-20 mA) outputs. Supports time-stamping of alarms and clock synchronization.

The single most important measurement for condition monitoring of reciprocating compressors is cylinder pressure. Armed with accurate cylinder pressure at each point in the piston's stroke, a Pressure-Volume (PV) curve can be constructed that provides indispensable information on your machine's health.

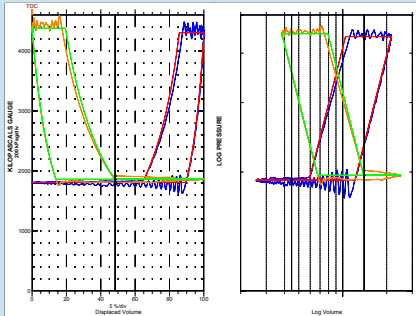
That's why we've given particular attention to this vital measurement. With a robust sensor, advanced signal processing functionality in our 3500/77M Recip Cylinder Pressure Monitor, and a suite of graphical plots in System 1 software specifically for analyzing cylinder conditions, there's simply no better way to get inside your cylinders—where the action is.

Historically, measuring these conditions meant temporarily attaching transducers to indicator valves on each cylinder. Although cumbersome, this practice was necessary because pressure transducers simply couldn't survive under long-term exposure to the harsh environment of cylinder chambers. We knew that the key to reliable and effective assessment of machinery health—not to mention convenience—was to design a sensor that could endure 24/7 exposure to such an environment, eliminating the burden of constantly connecting and disconnecting every time you wanted data. With our proven Bently Nevada 165855 Cylinder Pressure Transducer, we've done just that. It provides continuous static and dynamic pressure data and is specifically designed for use with our 3500/77M Recip Cylinder Pressure Monitor. Innovative materials and construction techniques[†] allow it to deliver reliable measurements in the extreme temperatures, pressure cycling, and harsh chemical environments (such as H₂S) inherent in reciprocating compressor cylinder applications.

Available in a variety of pressure ranges from 100 psia to 10,000 psia (68947 kPa / 689 bar), the 165855 has undergone extensive testing. In fact, we're so confident of its performance that we offer something unique to the industry: **a three-year warranty.**

[†] U.S. Patent 6,955,090



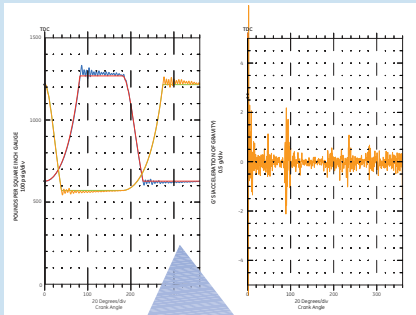
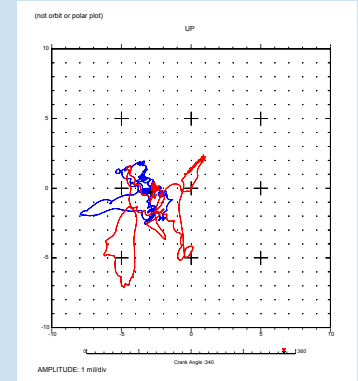


Pressure Versus Displaced Volume

Plotting indicated and ideal cylinder pressure versus displaced volume enables detection of malfunctioning seals (rings, valves and unloaders). Use of log-log scales permits earlier detection of leaks. For cylinders with stepless unloaders a patented algorithm detects the valve closure point and adjusts the theoretical curves.

Rod Position Plots

Rod position plots display the total movement of the plunger or piston rod at the pressure packing case. Typically, effects of changes in mechanical clearances, such as plunger to guide bearing, crosshead to crosshead guide, etc., and changes in average position, such as the thermal growth of a piston rod at cold conditions and operating conditions can be seen in this format. In this example the unloaded condition (red curve) is being compared with the loaded condition (blue curve) of the cylinder.

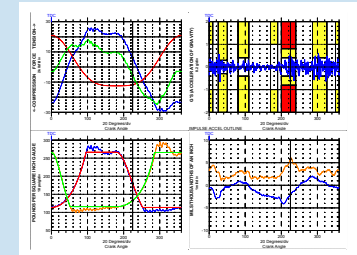


Y Versus Crank Angle

Leveraging the 3500 architecture, which simultaneously captures data across multiple channels, this plot format enables users to correlate events across different measurements and to correlate events with piston position inside the cylinder. For example, the large filtered acceleration impulse event at the cursor near 240 degrees along with the impulse event near 40 degrees probably suggests a loose piston condition exists.

Rod Load Plots

Plotting gas and combined rod load (shown in the top left pane) with other measurements such as crosshead acceleration and rod position provides the ability to detect problems such as mechanical looseness, excessive loading and inadequate reversal. Additionally, the impulse acceleration (upper right plot) has segment bands that are user configurable for start and duration and these can be programmed for alarm conditions which can be seen in the plot. For example, the cursor at the impulse event in the acceleration waveforms correlates to a looseness in the running gear, probably resulting from a loose piston/crosshead connection nut.



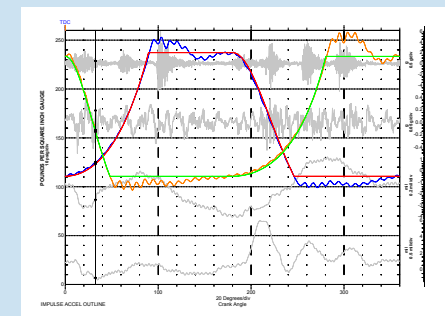
Reciprocating Software Variables	
Plot	Value
P326A CYL 1 PRS CE	
Discharge Volumetric Efficiency	49.6%
Suction Volumetric Efficiency	77.7 %
Indicated Horse Power	600 hp
Adiabatic Discharge Temp	252 deg F
Discharge Capacity	15.0 mmscfd
Suction Capacity	13.9 mmscfd
Median Capacity	14.5 mmscfd
Adiabatic Median Capacity	14.3 mmscfd
Flow Balance	0.93
Adiabatic Flow Balance	34.4
Power / Median Capacity Ratio	41.4 hp/mmscfd
Indicated Clearance Volume	34.4
Discharge Power Loss	7.24 hp
Suction Power Loss	8.72 hp
Suction Temperature	110 deg F
Discharge Temperature	240 deg F
Suction Pressure	210 psig
Discharge Pressure	451 psig
P326B CYL 1 PRS HE	
Discharge Volumetric Efficiency	49.9 %
Suction Volumetric Efficiency	80.9 %
Indicated Horse Power	655 hp
Adiabatic Discharge Temp	251 deg F
Discharge Capacity	15.0 mmscfd
Suction Capacity	15.4 mmscfd

Performance Variables at a Glance

Right click on a pressure curve to bring up this handy software variable reference box that displays the performance variables for each chamber in the cylinder. Changes in these performance variables, such as cylinder flow balance, can confirm diagnosis of valve, piston ring or pressure packing failures. These values can be collected and trended to identify long-term degradation.

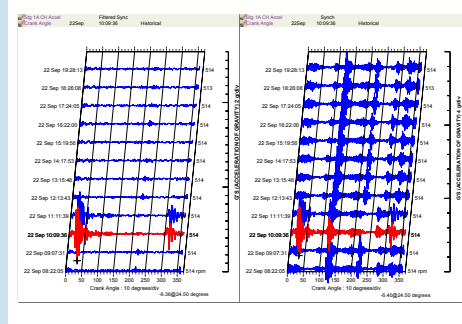
Crank Angle Overlay

Leveraging the 3500 architecture, which simultaneously captures data across multiple channels, this plot format enables users to correlate events across different measurements within a single plot pane. The plot format incorporates graphics optimization algorithms to enhance data presentation quality. This helps the user to more quickly and accurately correlate events across multiple measurements.



Crank Angle Waterfall Plots

A crank angle waterfall plot allows the user to see how events in one cycle of compression compares with other cycles over a long period of time. As such, the pressure, crosshead or cylinder acceleration, and piston rod vibration waveforms can be configured for such a plot. This enables the user to observe operational changes to the events in the waveforms. The plot on the left shows a filtered crosshead Accel signal (3-2000 Hz) and reveals that a possible mechanical looseness event occurred with a particular load step for two samples, while the overall crosshead signal on the right (3-20000 Hz) reveals the overall impact energy of the time interval. Another plot of the pressure waveform could reveal the closing point of a stepless unloader changing rapidly over a short time period—providing indication of poor process control or incomplete control loop tuning.



Decision Support* Software: A Powerful Difference

In addition to System 1 software's powerful plotting, trending, and manual data analysis capabilities, you'll find something unique: Decision Support is the component of the System 1 software platform that enables an automatic audit of its collected data against user-embedded rules and knowledge, detect mechanical or thermodynamic problems, and generate informative advisories that we call Actionable Information*.

Actionable Information advisories are configured by you, to reflect your specific operating practices and procedures. When a specific malfunction or condition is detected, System 1 software informs plant personnel what the problem is, how severe it is, and what to do about it—in real time. Cell phone, pager, PDA, e-mail, desktop and process control system pop-up windows—even conventional annunciator panels—they are all supported as ways to communicate Actionable Information advisories to the right people at the right time.

You can employ powerful built-in rules with our Recip RulePaks, ready-to-run collections of intelligent rules just for recip, and/or you can build your own rules with our extraordinarily easy-to-use RuleDesk features—just drag and drop logical and mathematical operators into any sequence of conditions that correspond to a particular malfunction. The choice is yours through a totally flexible system that lets you design rules specific to your process and machinery, automate the data analysis function, and communicate required actions and urgencies instantly to the right people—whether across the hall or across the globe.

System 1 Optimization and Diagnostic Software

Don't just protect your recip, proactively manage them with the enhanced condition monitoring and Decision Support capabilities of System 1, our most advanced software ever.

System 1 is a platform for managing every asset in your plant. It brings together a variety of condition monitoring technologies, maintenance management applications, reliability tools, process control and historian data specifically for addressing the unique needs of reciprocating compressors.

The result is a total reciprocating compressor solution, capable of providing:

- Discharge pressure
- Suction pressure
- Minimum/maximum pressure for each crankshaft revolution
- Compression ratio
- Peak rod load for both compression and tension
- Number of degrees of rod reversal
- Suction volumetric efficiency
- Discharge volumetric efficiency
- Indicated horsepower
- Capacity at suction conditions
- Capacity at discharge conditions
- Suction power losses
- Discharge power losses
- Indicated clearance volume
- Flow balance of suction to discharge
- Adiabatic median capacity between suction and discharge capacity
- Adiabatic flow balance between theoretical suction and discharge flow

- Power to median capacity ratio
- Displaced volume
- Adiabatic discharge temperature
- Piston animation view
- Vertical force plot
- Automated plot sessions creation





Comprehensive Condition Monitoring **Services.**

Retrofits

We make retrofits of our instrumentation systems simple by managing the entire project. We handle everything, from drilling and tapping holes in the machine to accommodate our transducers, to packaging and configuring our monitoring systems into enclosures suitable for your plant's environment, to pulling field wiring, to integrating our software into your plant's IT infrastructure, to documenting every detail.

Training

Understanding the vibration and performance behavior of your machinery is the key for asset optimization. To achieve this we offer tailored training.

- Instrumentation and monitoring systems operation and maintenance: training for instrumentation Engineers, providing basic knowledge on Bently Nevada™ 3500 system and components, operation and troubleshooting procedures.
- System 1® for reciprocating compressor 'Getting Started' course: hands-on training on system usage, data management and interpretation to enable trainees to analyze malfunctions and use of supporting data for root cause analysis.
- Reciprocating compressor Monitoring and Diagnostic: in this course attendees learn reciprocating compressor components, mechanics, performance theory, and recip-specific diagnostic techniques. The course illustrates several failure patterns through hands-on workshops at our RecipKit and actual case histories. Completion of this course enables system users to understand the compression process and interpret vibration readings of reciprocating compressors.



Machinery Diagnostics

The mechanical and thermodynamic behavior of your reciprocating compressors is analyzed by our Machinery Diagnostics Experts; malfunctions on valves, piston rings, rider bands are analyzed as well as vibration on running gear components. Machinery Diagnostic Services (MDS) can be provided either remotely or on site, on call, periodically, or continuously. This includes:

- Start-up, commissioning and operational assistance. Data analysis, system optimization (hardware and software), fine tuning of settings and customization of data visualization and management (based on actual operations and users' needs).
- Alarm and Event Management (daily, weekly, 24/7): The "real time" disposition of alarms to indicate machine problems, process problems or instrumentation problems.
- Baseline Audits (on site/remote), asset "baseline" and report for diagnostic and alarming purposes, so that data is available for ongoing diagnostics, minimizing nuisance alarms or missed warnings.
- Periodic Audits (on site/remote), asset audit and diagnostic report. Assessing and reporting machine condition, providing recommended actions and, where applicable, performing root cause analysis.

Risk Assessment

We can audit selected assets, or your entire plant, and provide benchmarking data on which assets present the highest business interruption and other risks, which technologies and methodologies to use to mitigate risk, and the expected ROI of investments in our solutions.

Balancing & Alignment

We balance and align virtually every type of rotating machinery found in industrial plants.

Program Management

For customers that prefer to outsource all or part of their asset management activities, we can assist. Whether your needs are focused on a specific category of assets (such as reciprocating compressors), a specific condition monitoring technology (such as lubricant analysis), or a broader scope encompassing maintenance management, reliability, condition monitoring, and other asset management functions—we have the people, and experience, to deliver the results you're seeking.



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