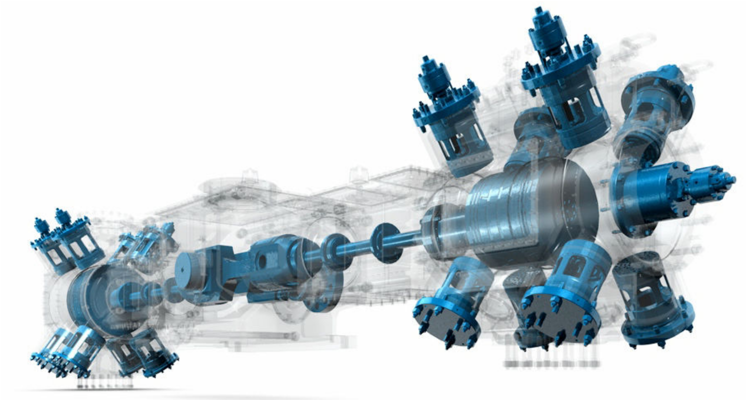

Monitoring and Diagnostics

- Effects of Compressor Controls become visible -

PROGNOST Systems GmbH

Thorsten Bickmann

Customer Support

thorsten.bickmann@prognost.com

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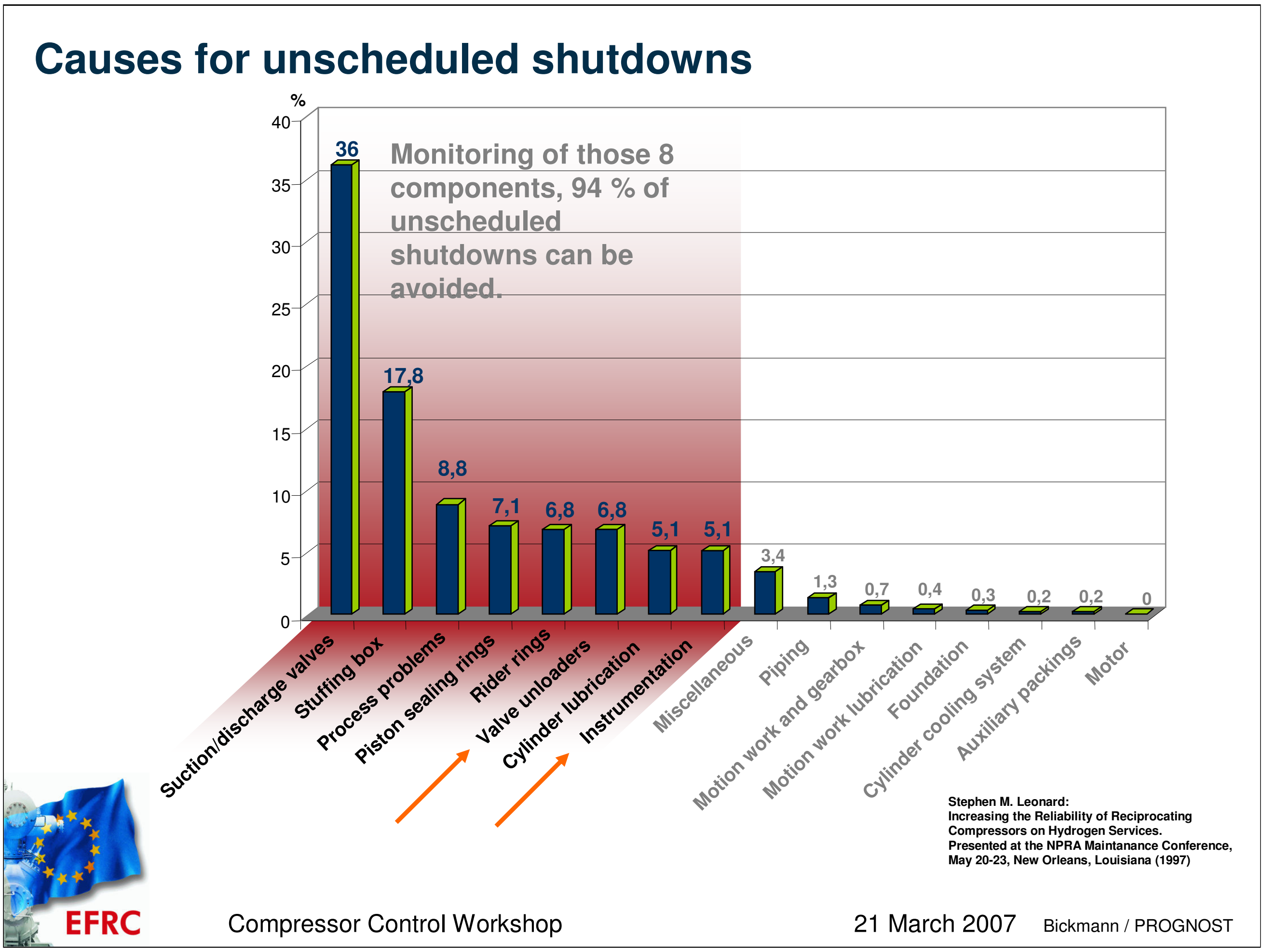
Whereas measurement equipment allows to the collect data as a basis for the evaluation of the condition of reciprocating compressors, acquired data - combined with operator´s experience - is used to identify problems as a basis for maintenance and operation decisions.

The development of electronic sensor technology along with increased performance of computer equipment has led to electronic measurement and digital data storage. Although threshold monitoring for trend data became the standard in the past for numerous applications, experience shows that a higher level of analysis and data interpretation is necessary to gain "information" instead of "data".



In order to design an effective monitoring strategy for condition monitoring systems especially for reciprocating compressors the mechanical features (weaknesses) must be analysed in terms of maintenance.

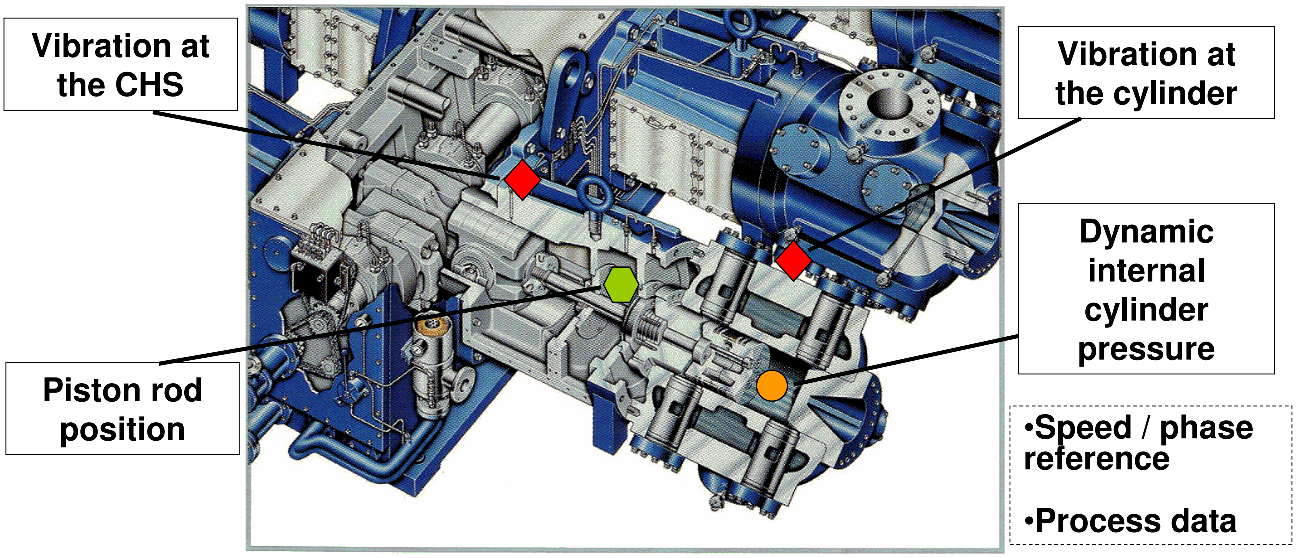
A survey conducted in 1997 by Dresser-Rand of 200 operators and designers on the causes of unscheduled shutdowns of reciprocating compressors clearly shows the main points in terms of maintenance technology.

Statistics show that eight component groups were responsible for 94% of unscheduled shutdowns. First and foremost defects in the suction/discharge valves are obviously responsible for unscheduled maintenance. More recent experience indicates similar results, even though the absolute involvement ratio of valves has dropped slightly due to the use of new materials.

Regulation of reciprocating compressor´s capacity in recent years has attained ever increasing priority through changing production requirements and increased efforts to save energy.

Effective function monitoring of these control devices like valve unloaders and reverse flow systems (instrumentation) is possible by pV-diagram and cylinder vibration analysis. By measured pressure curve the installed control device of each individual cylinder compression chamber can be checked.

How can the condition of a reciprocating compressor be monitored?

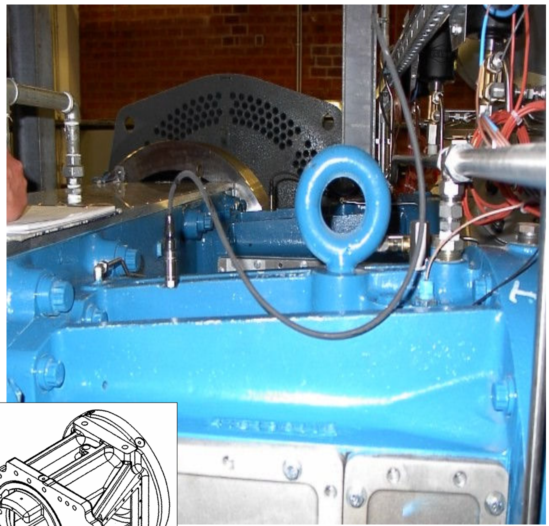


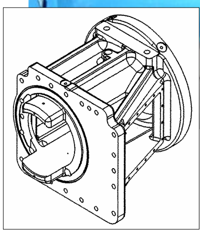
Measurement of vibrations at crosshead slides

with acceleration sensors

- mechanical damage
- clearance in the reciprocating drive train
- loose crosshead-piston rod connection

can be recognised





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When monitoring the condition of a compressor´s running gear and its components, various methods are employed.

For wear monitoring of bearings (crankshaft, connecting rod) temperature measurement points are used as a rule which are advantageous because of their simple assembly and low acquisition costs. These are frequently supplemented by flow measurements and temperature measurements of the lubricating oil.

For a general operational monitoring of the machine and to avoid mechanical consequential damage vibration monitoring is used. Here, vibration sensors are mounted at the crosshead slide.

For vibration processes segmented analyses have proven their worth in terms of rapid diagnosis. This means that vibration peaks, e.g. at characteristic load change points, can be effectively monitored.

To avoid consequential damage it is important to conduct continuous contemporaneous analysis and quickly alert operating staff or shut down the machine. These requirements are met by a special continuous monitoring which subjects the vibration signals of each crank revolution - individually and segmented - to a safety limit check (safety monitoring).

Average vibration values are displayed in the trend and compared with operation dependent warning thresholds. By this, an increase of slow developing failures like a loosening crosshead-piston connection can be detected in an early stadium.

Measurement of vibrations at cylinders

with acceleration sensors

- valve impacts can be recognised
- broken valve plate
- loose valve cage

can be detected

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Additional information on valve condition is provided by vibration accelerations measured at the cylinder. This involves installing accelerometers on the cylinders which cover a high frequency range in order to record the mechanical vibrations caused by opening and closing the valve.

Above all this method provides information on the valve opening and closing processes where large vibration peaks occur. As the opening and closing of the suction/discharge valves only takes place at certain intervals at different points on the crank revolution, the vibrations measured at the cylinder - apart from the peaks of valve action - also show wide areas with relatively low amplitudes.

In order to provide effective vibration monitoring and to be able to separate the low vibration areas and the vibration peaks caused by valve action and to monitor them separately, a special analysis is required. Here the vibration signal of a crank revolution of 360° is split into 36 segments each of 10°. Characteristic values are calculated for each segment, e.g. for peak and RMS values. To each segment its own threshold value is allocated.

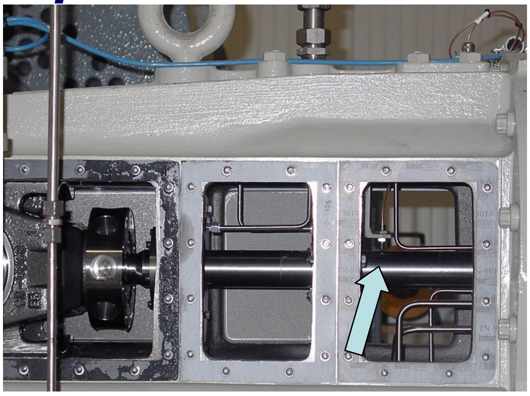
Usually only one sensor is mounted per cylinder.

Measurement of piston rod position

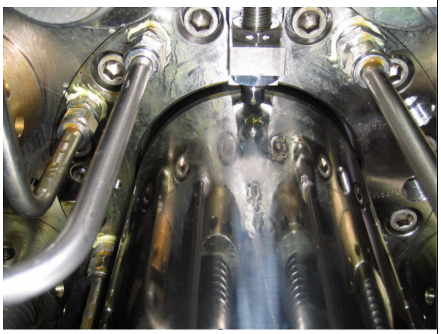
with proximity sensors

- The vertical change in position of the piston rod allows conclusions with reference to foreign matter in the compression chamber

  piston ring or valve fragments, oil or condensate accumulation in the compression chamber



- The condition of the piston rod (incipient fracture)
- Monitoring of rider ring wear



For this purpose an induction proximity sensor is fitted to the packing.

To determine the wear of piston and rider rings, the piston rod drop is continuously measured by a proximity sensor. In the course of its life wear of the piston ring leads to measurable piston rod drop. Determining rider ring wear requires monitoring of the measured values over a long period of time to show of a trend.

For signal analysis either individual interval values at specific points on the piston head are measured and segmented analyses are conducted over the whole revolution. These are particularly advantageous as possible interruptions caused, for instance by particles or lubricant residues on the piston rod, can be identified and therefore can prevent faulty interpretations.

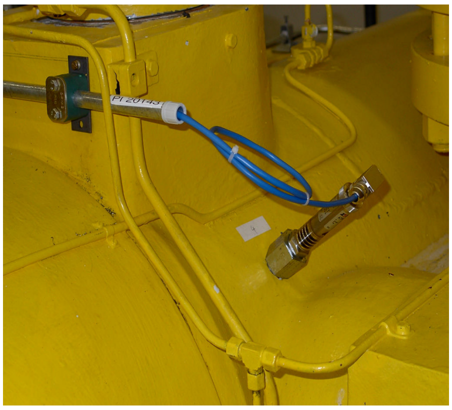
In addition, when there is damage to the piston rod connections, the piston or the crosshead, information can be gained from the total rod position signal as the piston rises. Due to a loose connection the rod position signal shows strong movement in certain areas.

A cracked rod shows a similar behaviour, as mentioned. Significant changes in the movement in the area of the rodload reversal points are visible up to eight minutes before the rod breaks.

Measurement of the internal dynamic cylinder pressure

- **with pressure sensors**
- **with strain rings**
- **with strain plates**

- Valve conditions
- Condition of the sealing elements such as piston rings and stuffing boxes
- Efficiency / Losses



In pV-diagram analysis the dynamic march of pressure inside the cylinder is being measured. This requires that special pressure sensors with a high frequency sensitivity are to be installed in a bore leading directly into the cylinder.

The pV-diagram analysis is one of the most important methods in valve condition monitoring. The analysis of a recorded signal allows conclusions to be drawn on conditions of the seal elements in the cylinder area. Damage to valves that result in leaks cause characteristic changes in the measured march of pressure. The measured pressure flow is converted into a pressure - volume diagram for which characteristic values are calculated at certain fixed points. These values (e.g. valve losses, polytropic exponents or crank angle at which the suction pressure is reached) undergo automatic threshold monitoring to identify if the suction or discharge valve is defective.

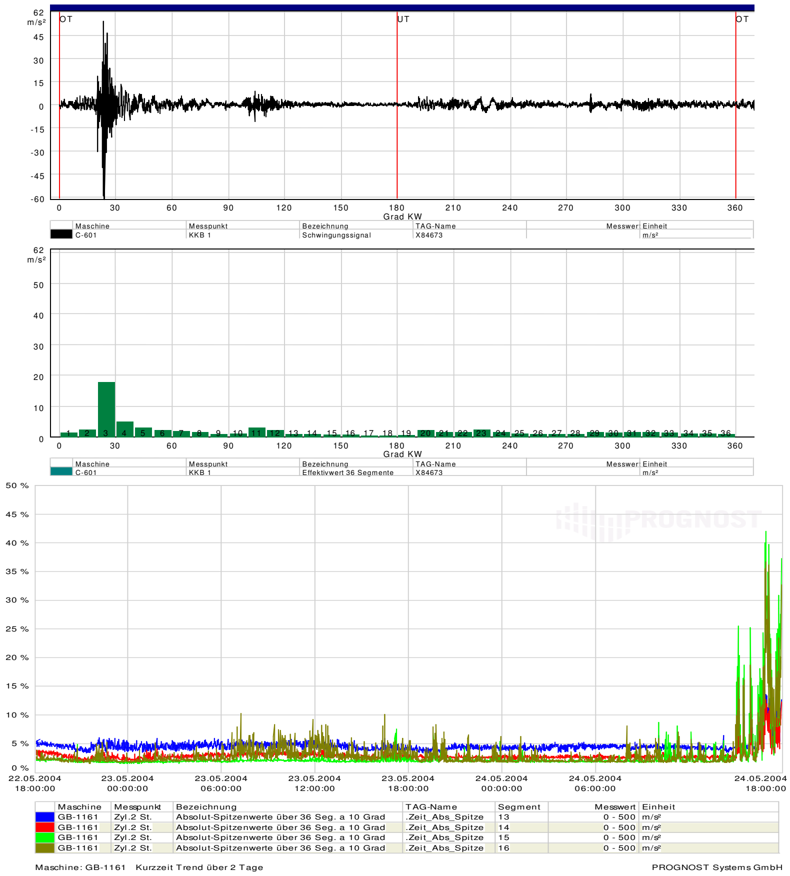
Cylinder pressure is a very good condition indicator as it reflects the real situation inside the cylinder. The user not only obtains clear local and function-oriented information on the condition but can also identify the precise effects on the compression process of the machine, for example the extent of a capacity reduction caused by damage.

This information again is a basis for a decision whether servicing in mechanical and production engineering terms is economical in respect of any production commitments.

Analysis

- **On-line**
  every revolution (360 °CA) for compressor protection

- **Trend**
  to evaluate a development for early failure detection



Precise vibration analysis is a crucial element of any monitoring system. For this purpose, vibration (acceleration) signatures of the crosshead guides and cylinders are measured continuously.

Time signals of the measured vibrations are subdivided for **one crank rotation into 36 segments with a 10° crank angle each**. In this way, a relation is established to correlate the vibration events with the crank angle dependent machine functions.

Individual RMS and peak amplitude values are determined for each segment. Unlike a centrifugal compressor that is continually loaded per rotation, the reciprocating compressor undergoes major fluctuation with each rotation. However, the varying weak loadings are stable at the same load for each crank angle. It is therefore necessary to subdivide the time signal of the measured vibrations for one crank rotation into 36 segments, each having a 10° crank angle.

The **Trend** has an effective early failure warning capability and covers faults / failures that develop over a period of minutes, hours or days. The average values of a minute are compiled to a mean minute value and compared to the pre-specified operating-condition-depending 1st and 2nd warning level.

The trend is based on the following values collected over one minute:

- Vibration analysis values (RMS and absolute peak value of each of the 36 segments of one rotation)
- Rod-Position analysis values (for each of the 8 segments a 45 °CA per rotation)
- pV-diagram analysis values
- DCS-values

Compressor capacity control

The *compressor output* can be controlled in several ways:

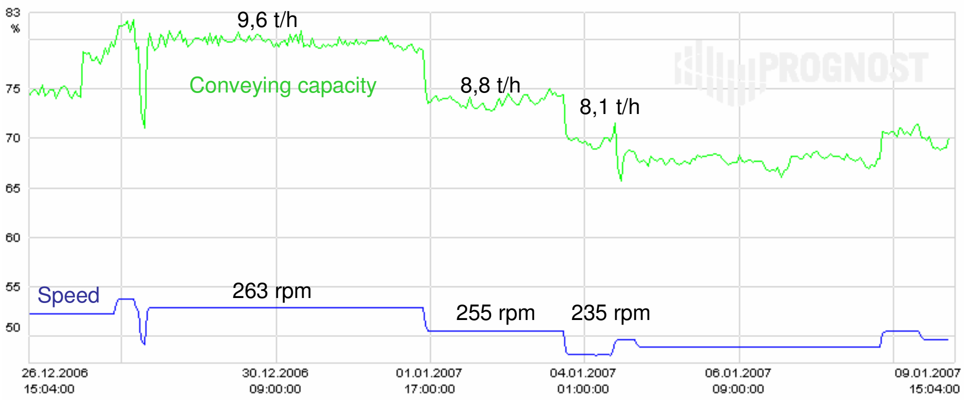
- ***by controlling the drive speed***
- ***reverse flow control (e.g. HydroCOM)***
- ***variance in cylinder end clearance***
- ***unloading of suction valves***
- ***suction pressure regulation***
- ***bypass (gas recycling around compressor or around 1st stage)***

Further detailed explanations can be found in the other presentations of this workshop.

Compressor capacity control

- **by controlling the *drive speed***

  especially for compressors with turbine drives and gas engines
  increasingly used for electric motor drives
  (frequency control with a thyristor motor: expensive)



	Machine	Measuring Point	Data name	TAG-Name	Segment	Value	Unit	Status
(blue)	GB-6702 A	Trigger	Rotation speed	X6750	1	0 - 500	1/min	
(green)	GB-6702 A	FM 2. St.	Conveying capacity	F6816	1	0 - 12,0	t/h	

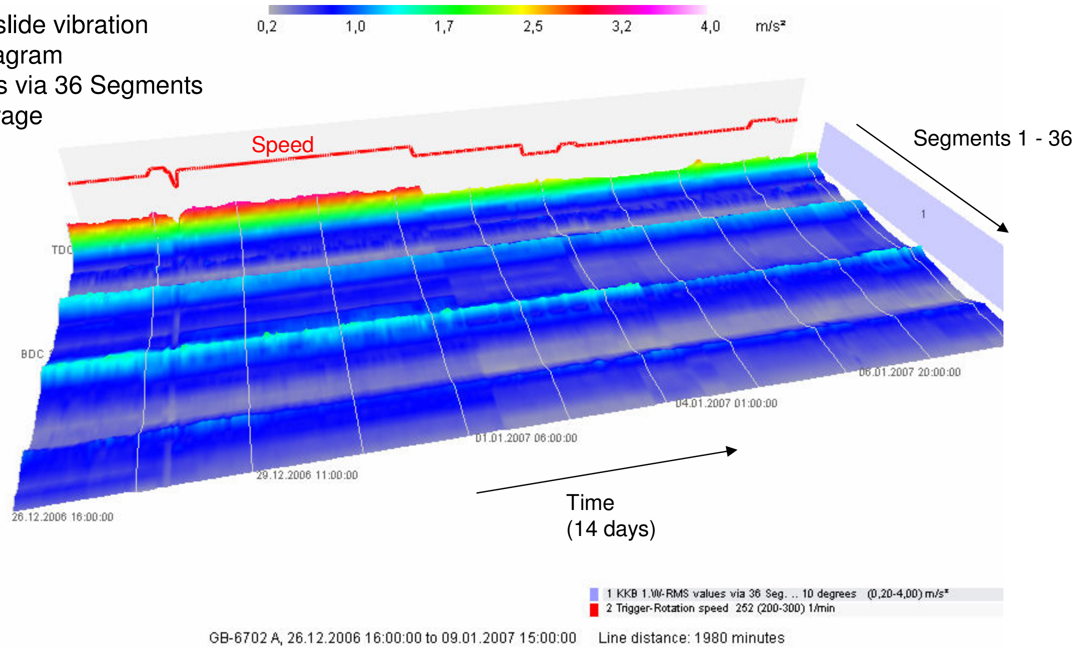
A four throw compressor with two stages is operated in a refinery in Germany. The drive of the compressor is a steam turbine.

The trend view displays the speed of the compressor and the conveying capacity. It is visible, that the flow changes proportional by the the speed.

Compressor capacity control

- **by controlling the *drive speed***

Crossheadslide vibration
Waterfalldiagram
RMS values via 36 Segments
Hourly average



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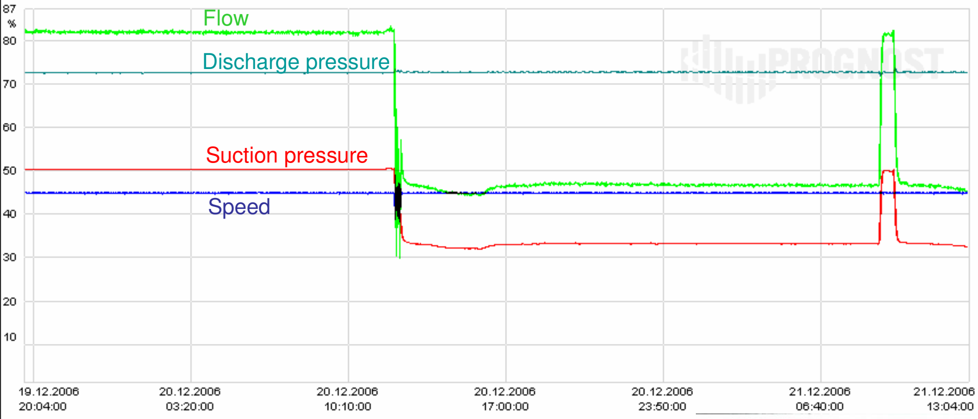
This slide shows the waterfall plot of the CHS vibration at the same compressor.

The amplitudes of the vibrations correlate with the speed.

Compressor capacity control

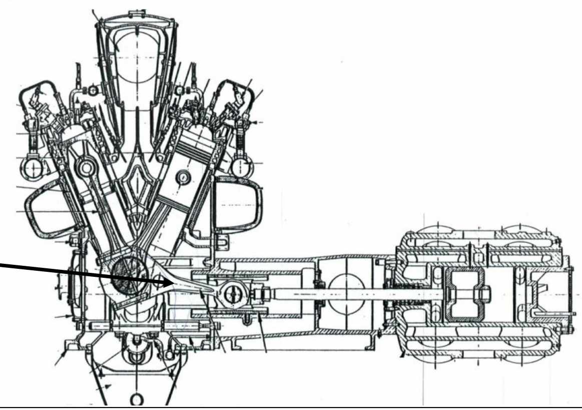
- by ***suspension***



Trend view
Hourly average of 1,5 days

	Machine	Measuring	Data name	TAG-Name	Se	Value	Unit
	SD-W-K02	K02 Trigge	Rotation speed	S2331	1	0 - 1000	U/mir
	SD-W-K02	Saugdruck	Suction pressure	P0102	1	0 - 100	bar g
	SD-W-K02	Enddruck	Discharge pressure	P0103	1	0 - 100	bar g
	SD-W-K02	Durchflußm	Process Data	F2201	1	0 - 30000	m³/h

Integral Compressor
The crankshaft of the gas motor has an additional connecting rod for driving the piston for compression



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Compressor Control Workshop

An Integral Compressor consists of a gas engine and compression components. They are usually operated in fields where gas is delivered.

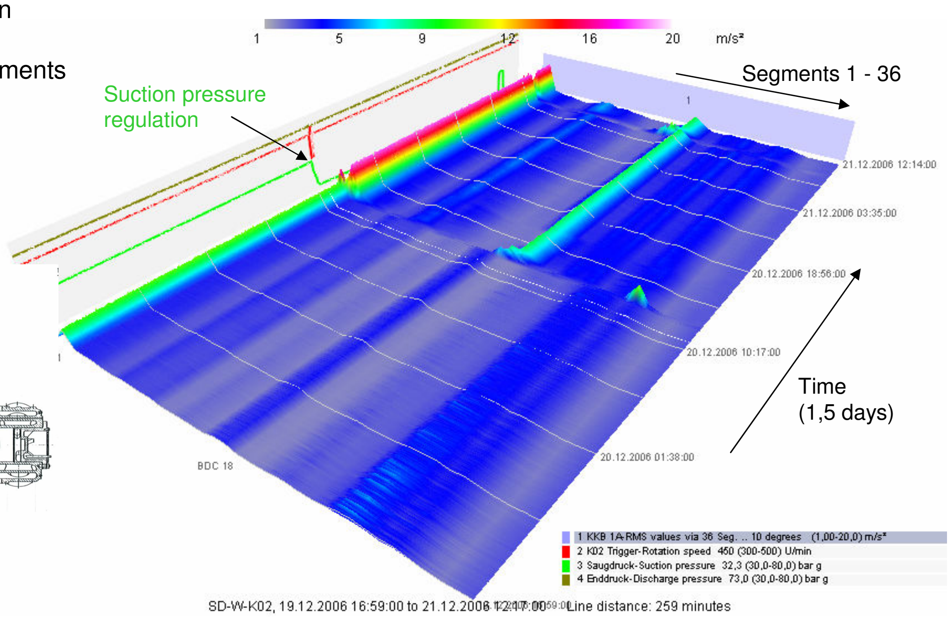
The capacity control is regulated by the suction pressure.

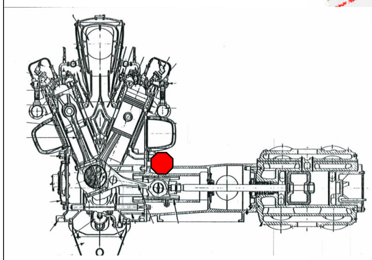
If the suction pressure decreases (with the same discharge pressure and speed), the flow is reduced.

Compressor capacity control

- by ***suspection pressure regulation***

Crossheadslide vibration
Waterfalldiagram
RMS values via 36 Segments
Hourly average



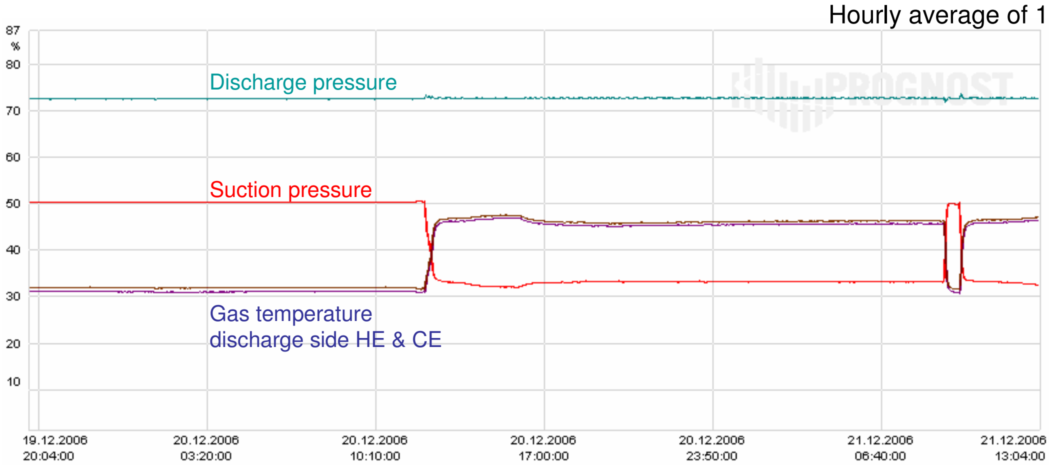


The reduced suction pressure with the same discharge pressure causes a higher compression ratio. Thus, the load of the compressor is higher, which leads to higher vibrations at the crosshead slide.

Compressor capacity control

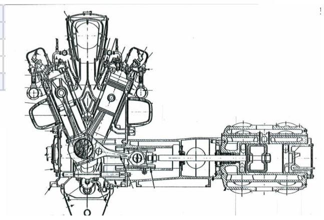
- by ***suspection pressure regulation***

Trend view
Hourly average of 1,5 days



Machine	Measuring Poir	Data name	TAG-Name	Se	Value	Unit
SD-W-K02	Saugdruck	Suction pressure	P0102	1	0 - 100	bar g
SD-W-K02	Enddruck	Discharge pressure	P0103	1	0 - 100	bar g
SD-W-K02	Zyl.temp 1A DS	Medium temperature discharge side	T2226	1	0 - 200	°C
SD-W-K02	Zyl.temp 1A KS	Medium temperature discharge side	T2227	1	0 - 200	°C

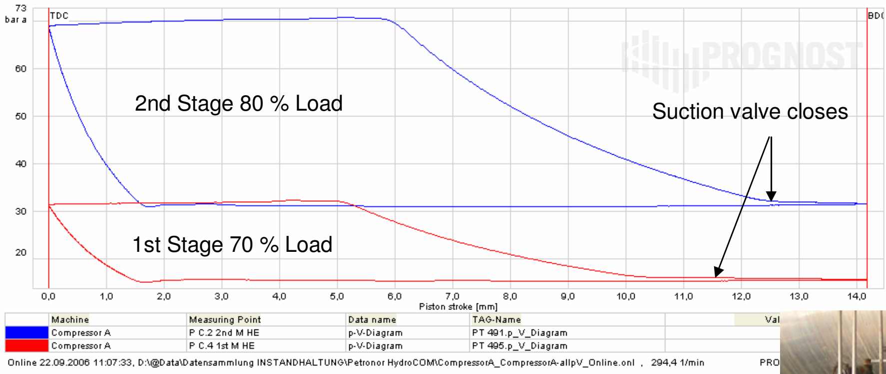
Machine: SD-W-K02 Trend 1 day 17 hours, Zyl.temp 1A KS - 8



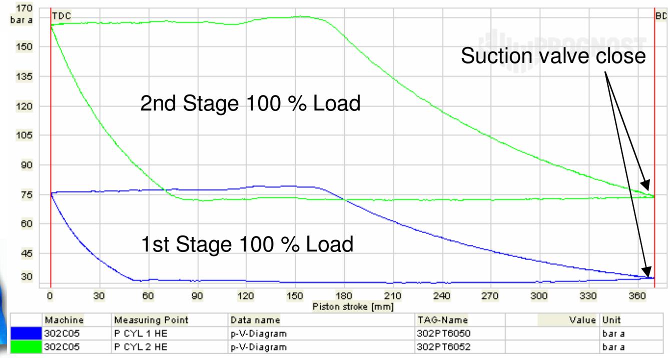
Due to the higher compression ratio (= discharge pressure / suction pressure), the gas temperatures increase.

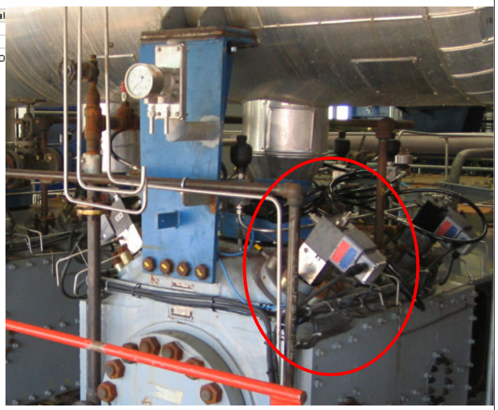
Compressor capacity control

- ***by reverse flow control (e.g. HydroCOM)***



On-line
pV Diagram





With the pV-diagram analysis, the dynamic pressure curve inside of the cylinder is measured.

The pV-diagram analysis is one of the most important methods to monitor valve conditions.

The indicated energy is used to describe the actually applied energy per time unit for the compression of the gas from suction to discharge pressure. The energy used and power for the compression process can be read directly from the area of the measured pV-diagram, making it possible to directly determine the efficiency.

The flow regulation has a direct influence on the shape of the pV-diagam.

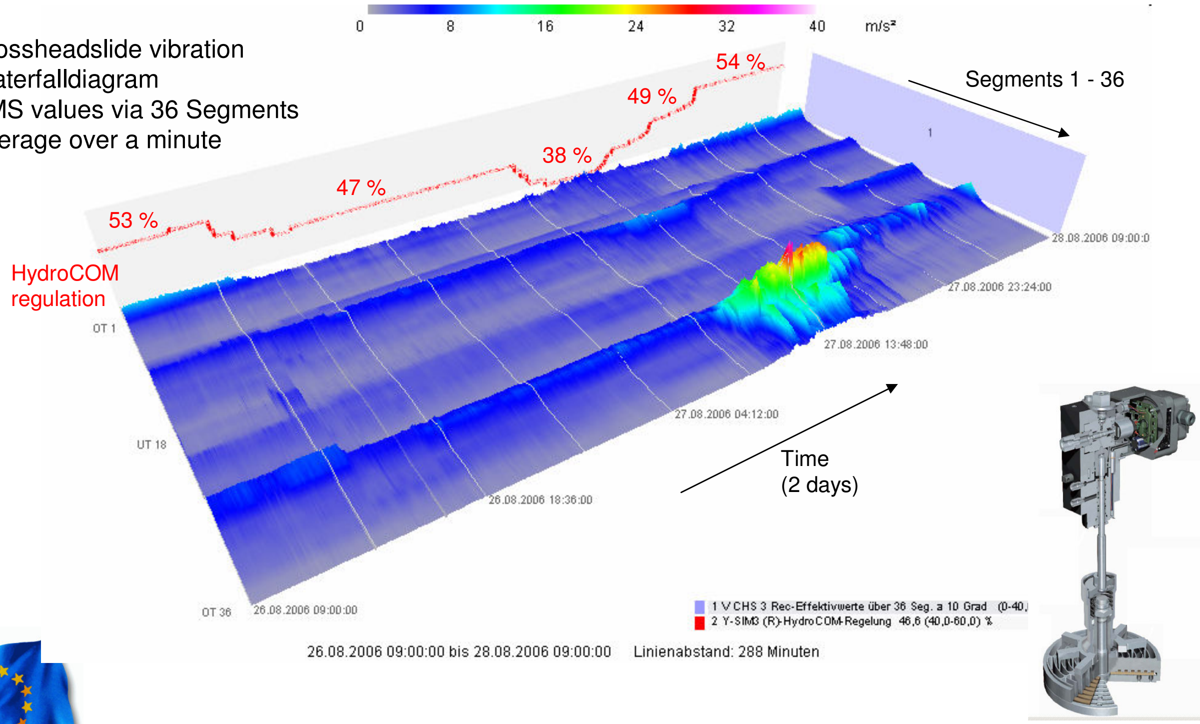
Due to the late closing of the suction valve within the reverse flow control, the compression starts later.

In fact, the design of the pV and the surface (equals indicated energy) is changing.

Compressor capacity control

- ***by reverse flow control (e.g. HydroCOM)***

Crossheadslide vibration
Waterfalldiagram
RMS values via 36 Segments
Average over a minute



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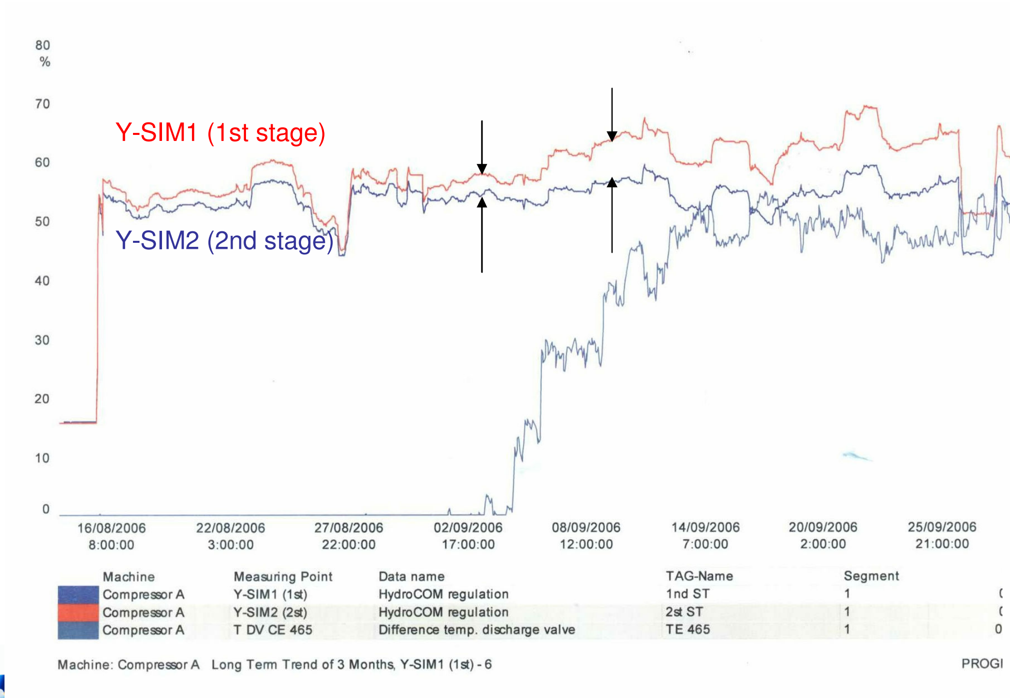
Changes in the reverse flow regulation have a direct influence in vibrations.

The waterfall diagram of the crossheadslide vibrations shows hard knocks, when this compressor has a low load of 38 %.

The RMS values are up to four times higher than at a load of 47%.

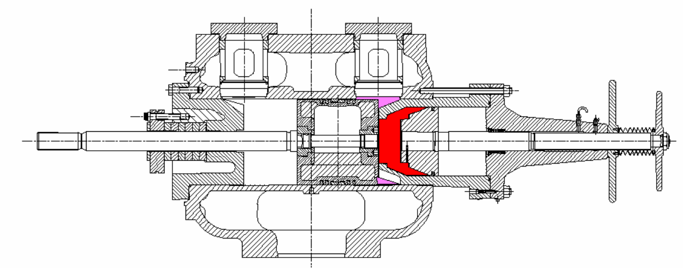
Compressor capacity control

- ***by reverse flow control (e.g. HydroCOM)***

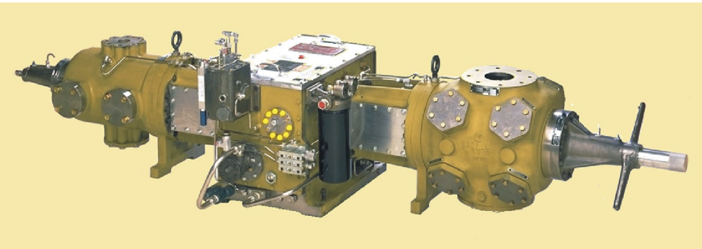


Compressor capacity control

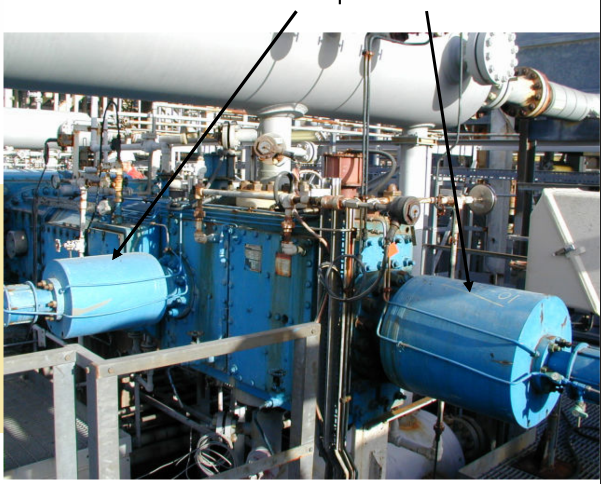
- **by variances in cylinder end clearance**



Variable pocket



fixed pocket volume



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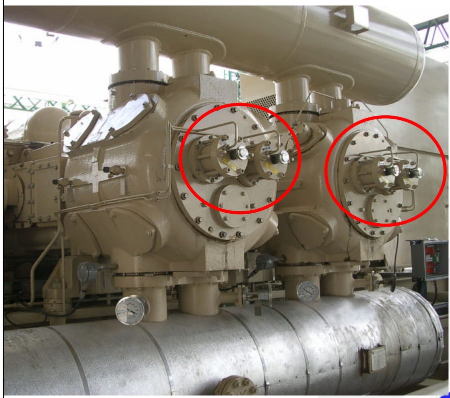
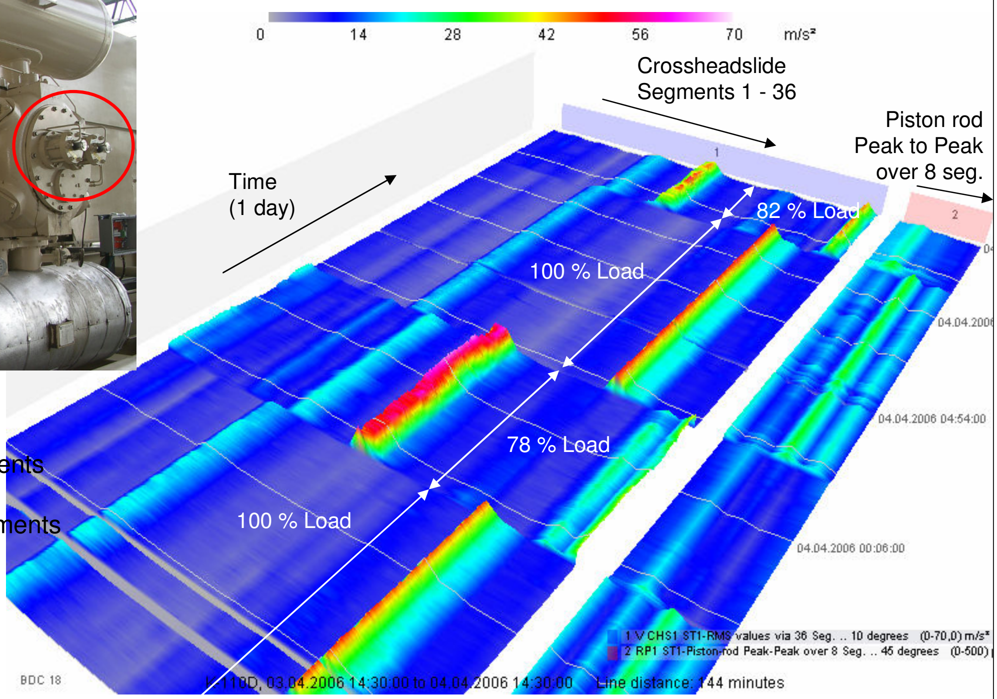
By additional clearances in the compression chamber, the capacity is regulated.

The clearance pocket adds fixed clearance to the cylinder and enables additional capacity control that cannot be achieved through cylinder end unloading. When clearance is added to the cylinder, the throughput of the cylinder and engine performance is decreased.

Compressor capacity control

- **by variances in cylinder end clearance**





Waterfalldiagrams
- Crossheadslide vibration
  RMS values via 36 Segments
- Piston rod
  Peak to Peak over 8 Segments

Average over a minute

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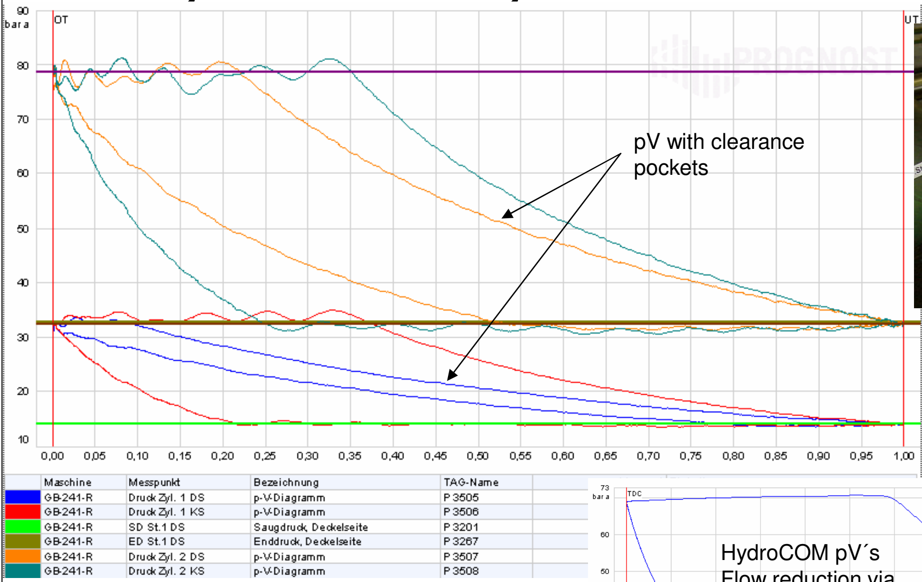
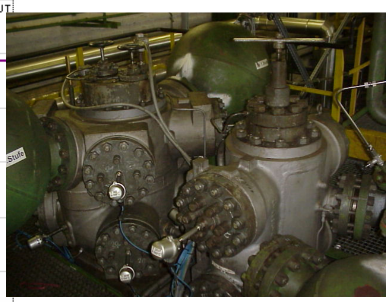
The direct influence of the regulation via clearance pockets is visible in this waterfallplot of the crosshead slide vibrations.

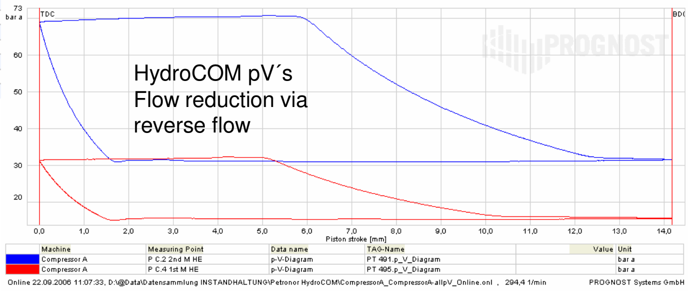
The peak to peak movement of the rod changes, too.

Compressor capacity control

- **by variances in cylinder end clearance**







On-line
pV Diagram

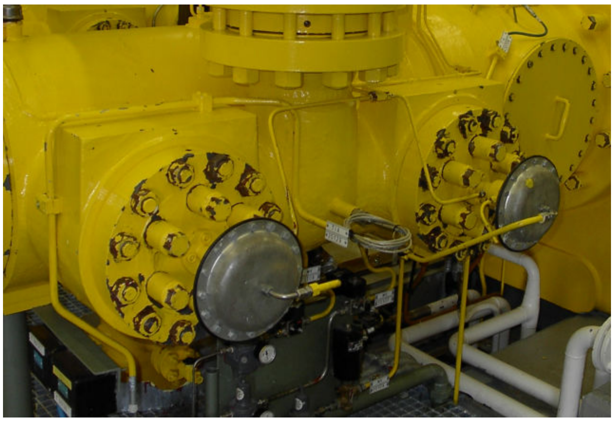
The flow regulation via additional clearance pockets is displayed in the upper pV-diagram.

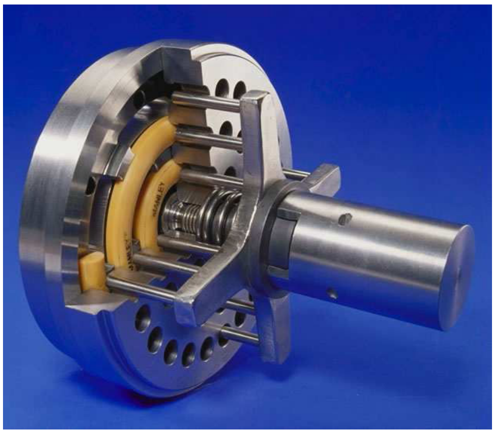
The clearance pocket adds fixed clearance to the cylinder and enables additional capacity control that cannot be achieved by cylinder end unloading. When clearance is added to the cylinder, the throughput of the cylinder and engine performance is decreased.

During compression stroke, the clearance volume must be filled before the gas reaches discharge pressure and opens the discharge valve, so less gas is discharged. This also leaves extra gas at discharge pressure trapped in the clearance pocket, which has to expand during the suction stroke and delays the opening of the suction valve.

Compressor capacity control

- by valve lift control of compression chamber suction valves

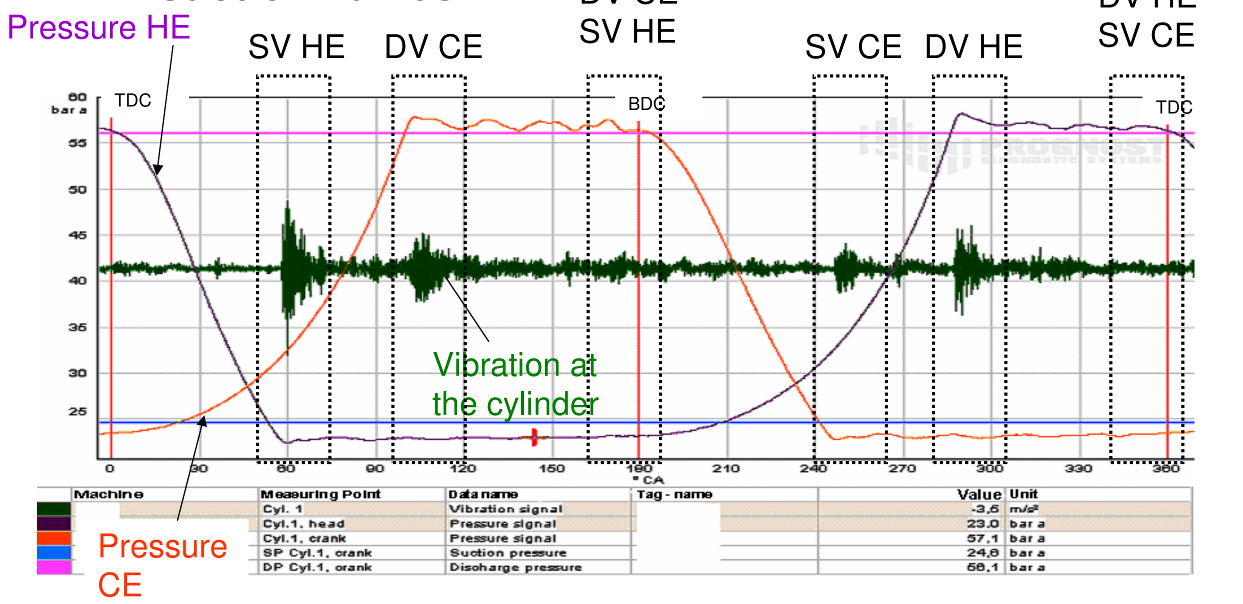




Suction Valve with
Gas Actuated Unloading Device

Compressor capacity control

- **by valve lift control of compression chamber suction valves**



These impacts always take place at the same time / °CA if the load is constant

1. Suction:

The suction phase begins just at when the pressure in the cylinder chamber is low enough that the differential pressure between suction vessel and compression chamber can open the suction valves, and not yet when dropping below suction pressure. The magnitude of the under-suctioning gives an indication as to the ease of movement of the suction valve plate. If the valves are open, the gas can flow into the cylinder.

In the cylinder chamber, and at the end of the suction stroke, suction pressure and pressure balancing prevails between suction vessel and compression chamber. The suction valve closes because there is no longer any pressure load acting on the valve plate, only the spring force. The suction phase ends here. The piston is now in the bottom dead center, meaning, the cylinder interior chamber has reached its maximum volume.

2. Compression:

After reaching at the bottom dead center, the direction of movement of the piston changes and the enclosed gas is compressed. When the discharge pressure is reached, compression continues for such a length of time until the pressure difference between the discharge pressure and the compression chamber is sufficient for opening the discharge valves.

3. Output:

Output of the gas commences when the valves are open.

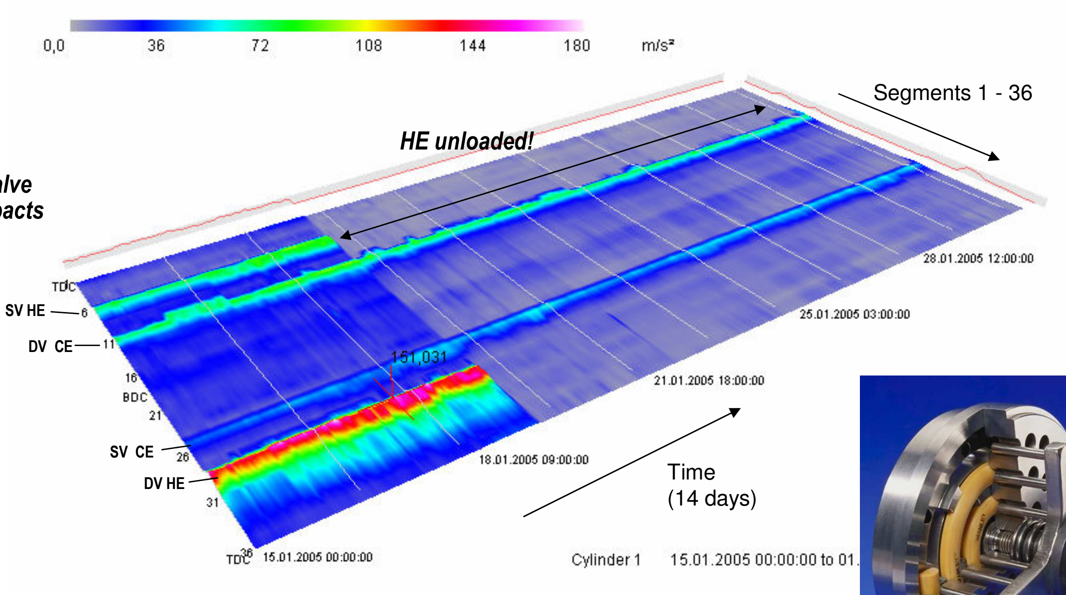
In the top dead center there is discharge pressure prevailing in the cylinder chamber, the discharge valves close and the output is completed. The cylinder chamber now has its smallest volume and compressed gas can only be found in the volumetric clearance.

4. Re-expansion:

After a reverse of the movement direction of the piston, the gas remaining in the volumetric clearance is now expanded from discharge pressure to suction pressure, until the suction valves open again and gas is suctioned in. This phase is also known as re-expansion.

Compressor capacity control

- by valve lift control of compression chamber suction valves



Cylinder vibration
Waterfalldiagram
RMS values via 36 Segments
Average over an hour

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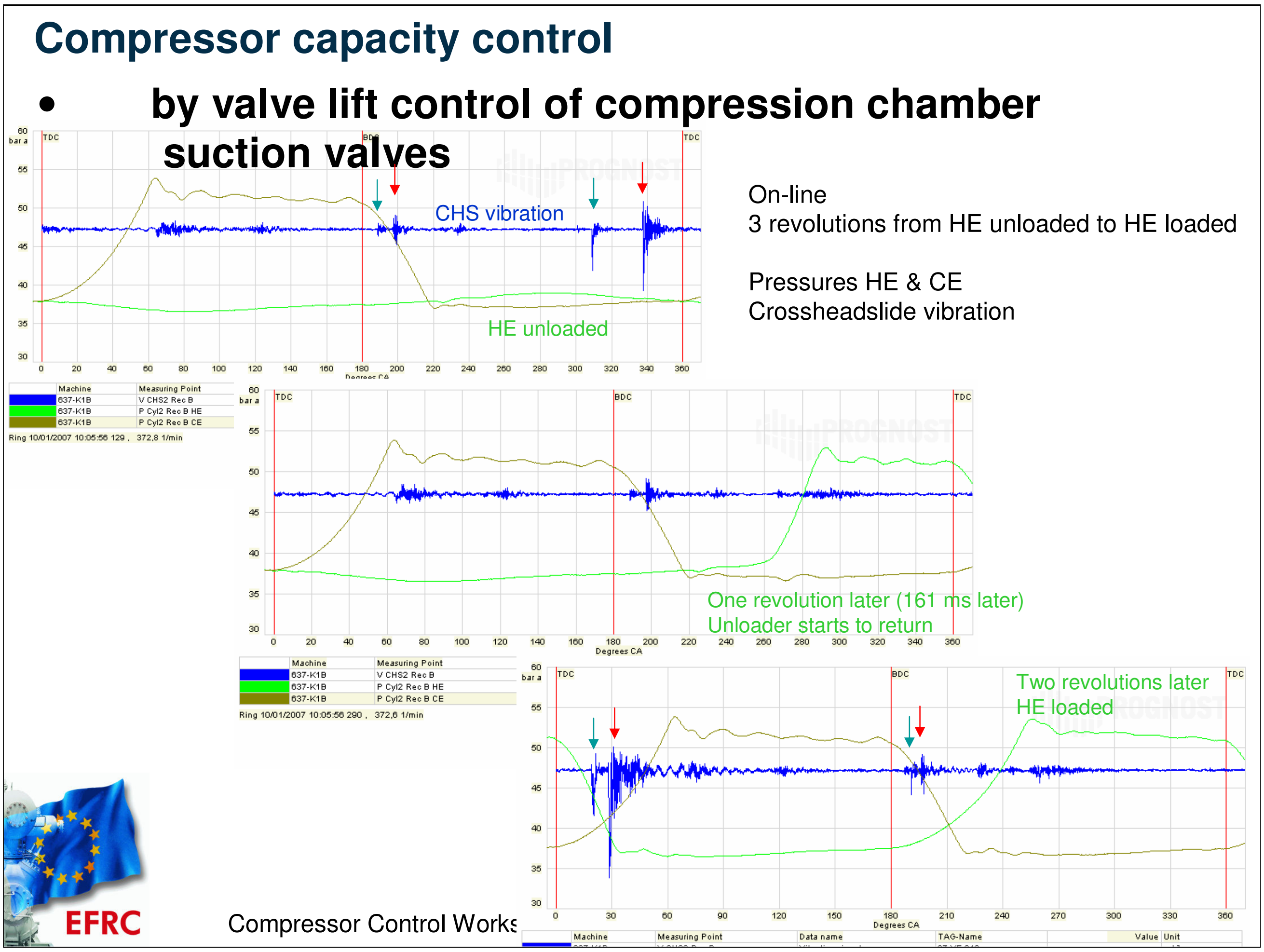
The waterfallplot of cylinder vibrations clearly dispays the opening and closing impacts of the valves.

By unloading the HE, no valve activities are present.

Effective function monitoring of these control devices is possible with cylinder vibration analysis.



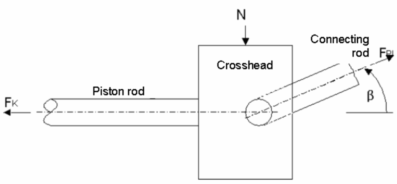
This slide shows three revolutions of the indicated pressures (headend and crankend) and crosshead slide vibration during the change from headend unlaoded to loaded.

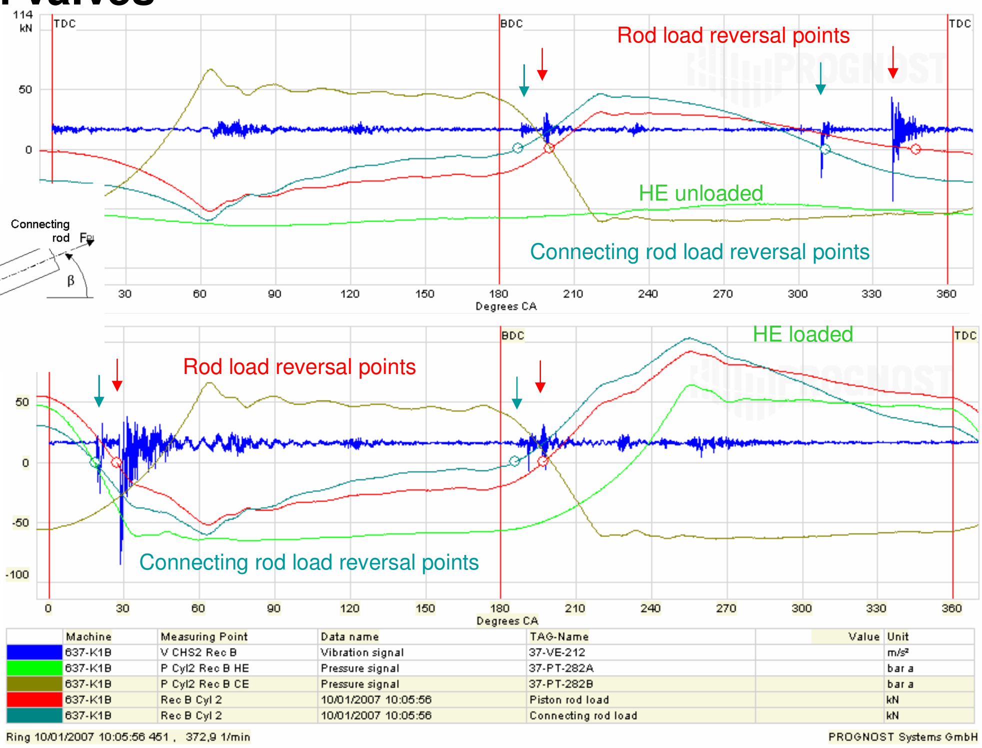
Compressor capacity control

- by valve lift control of compression chamber suction valves

On-line

Pressures HE & CE
Crossheadslide vibration
Piston rod load
Connecting rod load





	Machine	Measuring Point	Data name	TAG-Name	Value	Unit
	637-K1B	V CHS2 Rec B	Vibration signal	37-VE-212		m/s²
	637-K1B	P Cyl2 Rec B HE	Pressure signal	37-PT-282A		bar a
	637-K1B	P Cyl2 Rec B CE	Pressure signal	37-PT-282B		bar a
	637-K1B	Rec B Cyl 2	10/01/2007 10:05:56	Piston rod load		kN
	637-K1B	Rec B Cyl 2	10/01/2007 10:05:56	Connecting rod load		kN

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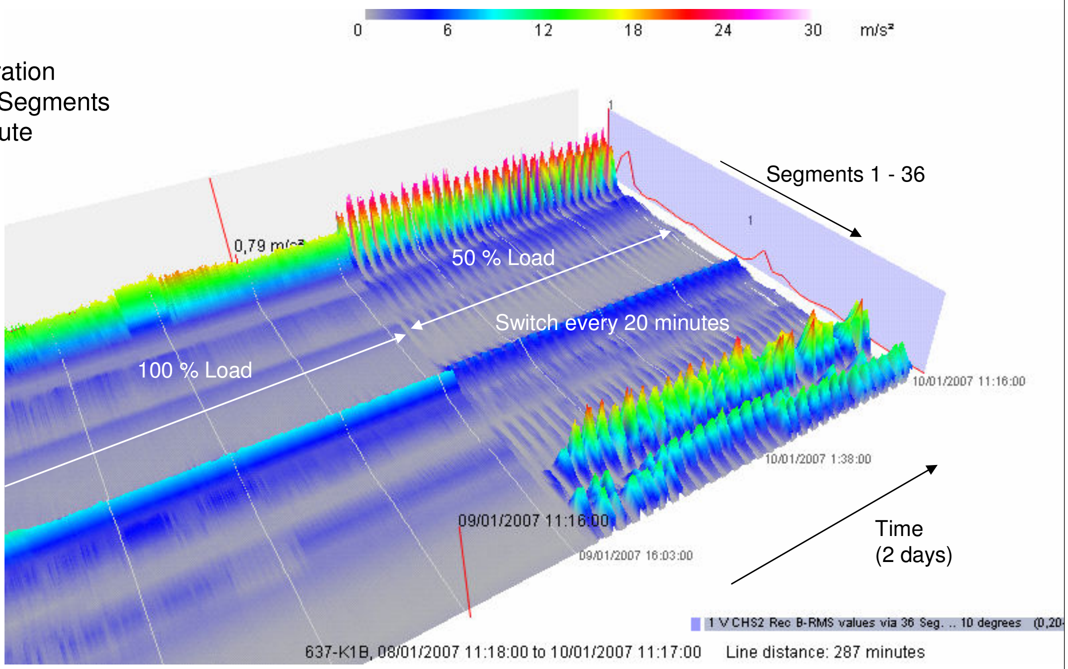
The position of rodload reversal points (change from tension to pressure forces) changes by unloading the headend.

The maximum tension and compression forces are reduced at unloaded HE.

Compressor capacity control

- **by valve lift control of compression chamber suction valves**

Waterfalldiagram
Crossheadslide vibration
RMS values via 36 Segments
Average over a minute



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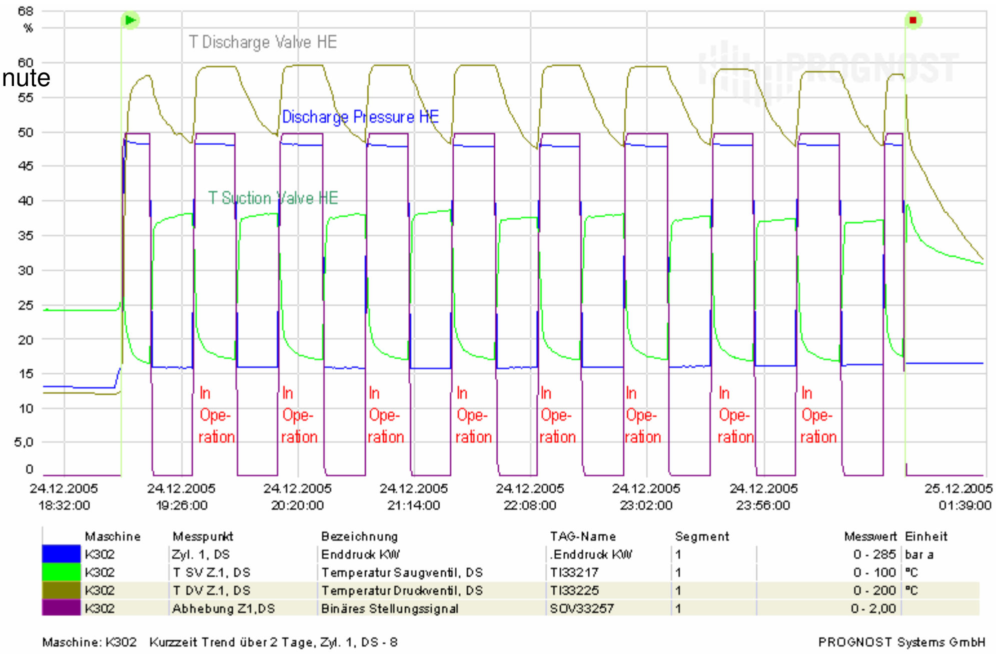
The waterfall diagram displays the crosshead slide vibrations of two days. At 100% load the maximum peaks are in the area of the reversal points, to to clearances in the reciprocating running gear.

During the 20 minutes switch from headend unladed to loaded (at 50% load), the vibrations at the crosshead slides are up to two times higher.

Compressor capacity control

- **by valve lift control of compression chamber suction valves**

Trend view
Average over a minute



This slide displays the behaviour of the suction and discharge gas temperatures while unloading the head end compression chamber.

When the headend compression chamber is loaded, the suction valve temperatures drop from 37°C to 17°C. Due to the compression in the HE chamber, the discharge temperature is rising.
When the suction valve is unloaded, the temperatures of the gas and the suction valves are the same.