EFRC Training Workshop

Condition Monitoring for Reciprocating Compressors

Block II – Standards/Performance/Big Data

Mr. Guillaume Christin – Baker Hughes, a GE Company

Mr. Jan Löken – PROGNOST Systems GmbH

EFRC

Topics

- Industry standards
- Performance monitoring
- Industry 4.0
- Big Data

CM Standards: Recip compressors

- Limited information from standards for Condition Monitoring

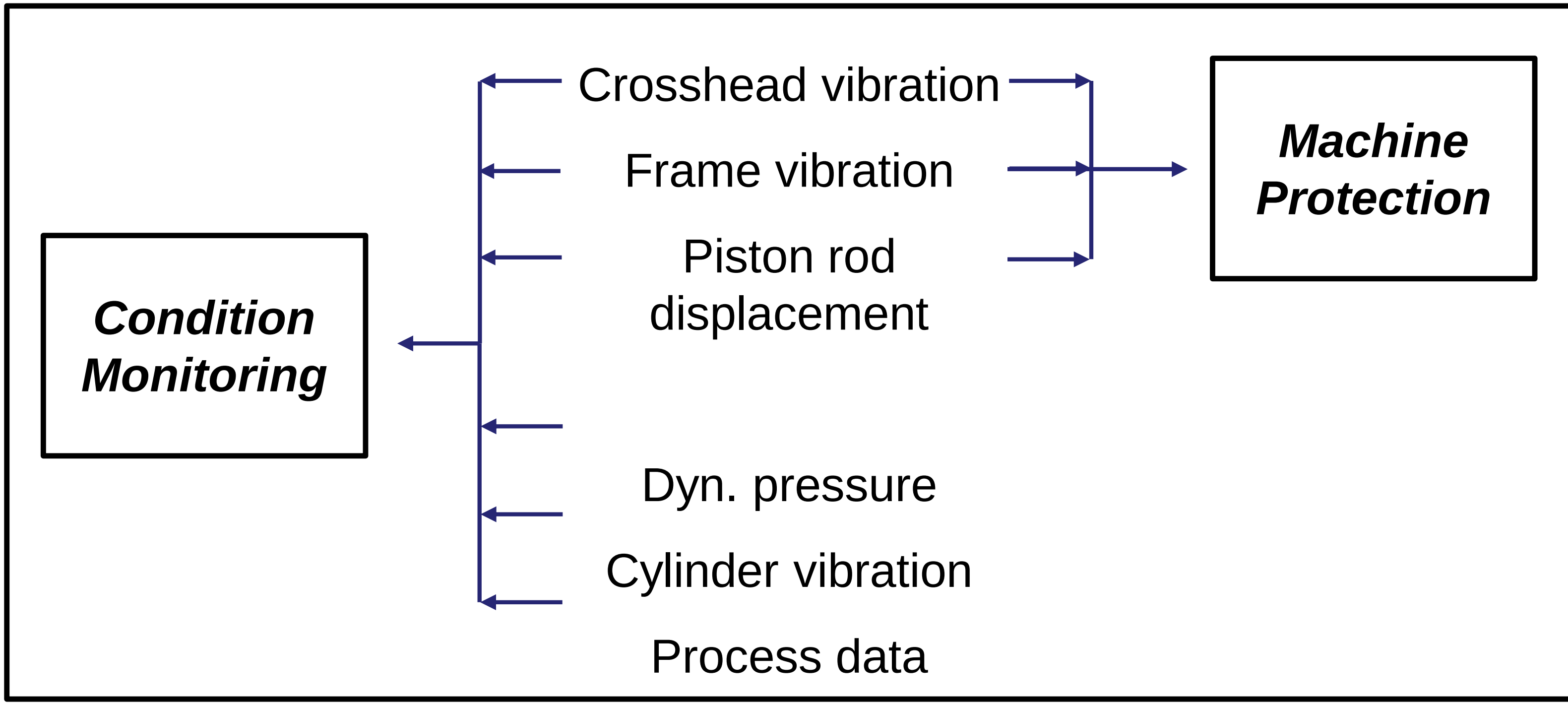
  - API 618: List of Machine Protection Parameters: Frame vibration, Crosshead vibration
  - API 670: Protection: Frame, Crosshead vibration, Rod Drop
  - EFRC: Evaluation: Frame, Cylinder (rod & lateral), Foundation
  - ISO: standards for acceptable vibration levels for reciprocating machinery

Standards: API 618/API 670

Condition	API-618 5th Edition (Table 5)		API-670 5th Edition Table P1	
	Alarm	Shutdown	Alarm	Shutdown
High Gas discharge Temperature	X	X	X	
Low Frame Lube-oil Pressure	X	X	X	X
Low Frame Lube-oil Level	X	-	X	-
Cylinder Lubricator System Failure	X	-	X	-
High Oil-Filter differential Pressure	X	-	X	-
High Frame Vibration	X	X	X	X
High level in Separator	X	X	X	X
Jacket Water System Failure	X	-	X	-
High Crosshead Pin, Main Bearing, Vent Packing Temperature	1	1	-	-
High Crosshead Vibration	-	-	X	X
Rod Drop	-	-	X	X

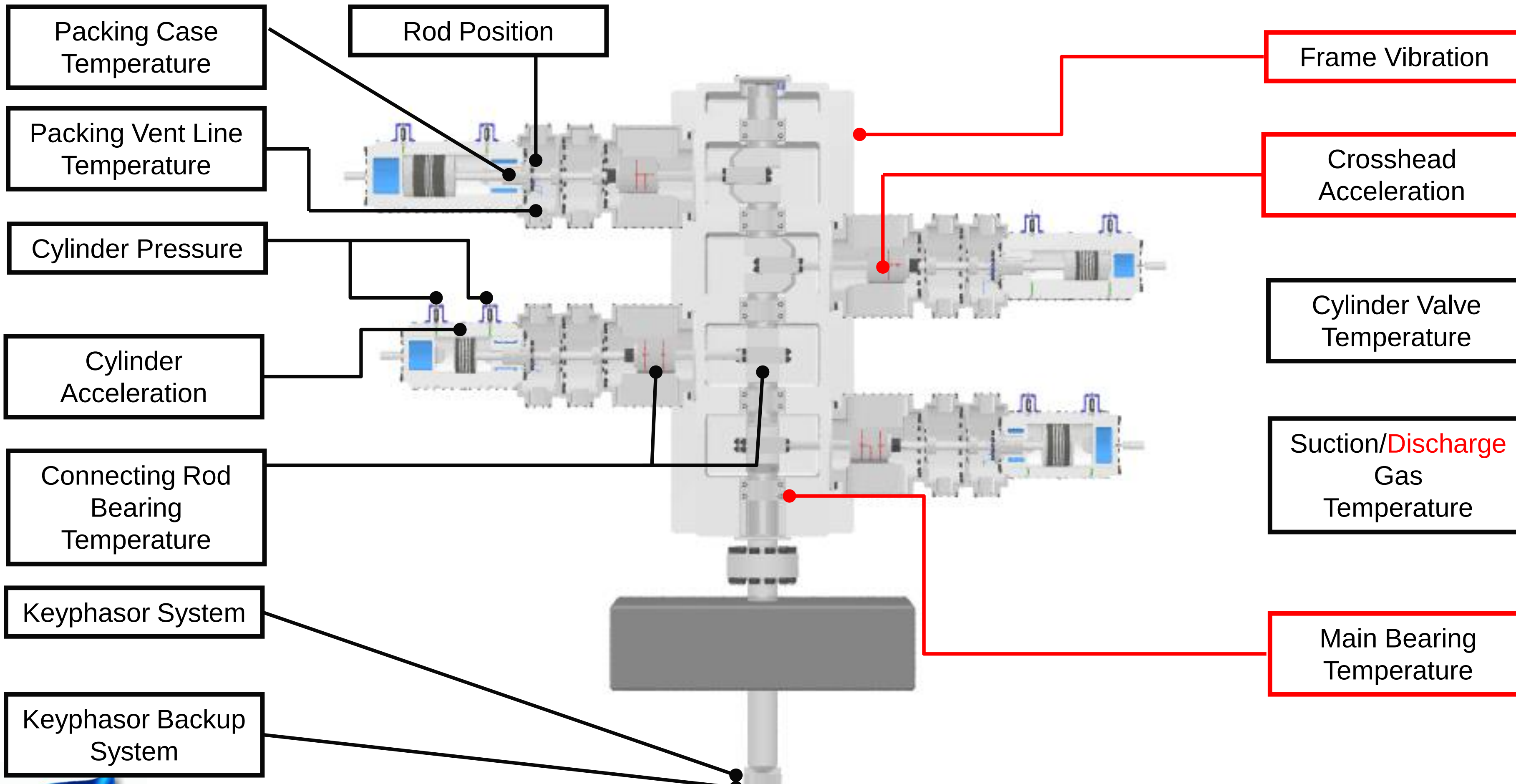
1 –API 618 5th Edition 7.6.6.7 – if specified and is present

Standards: Experience



Technology developments and practical experience over recent years lead to additional recommended measurements for monitoring and diagnostics.

Best practice / Sensors



Cylinder pressure sampling enables processing of performance parameters: Degrees Rod Reversal, Discharge & Suction Power Loss, Gas Rod Load, Indicated Horsepower, Peak Rod Loads, etc.

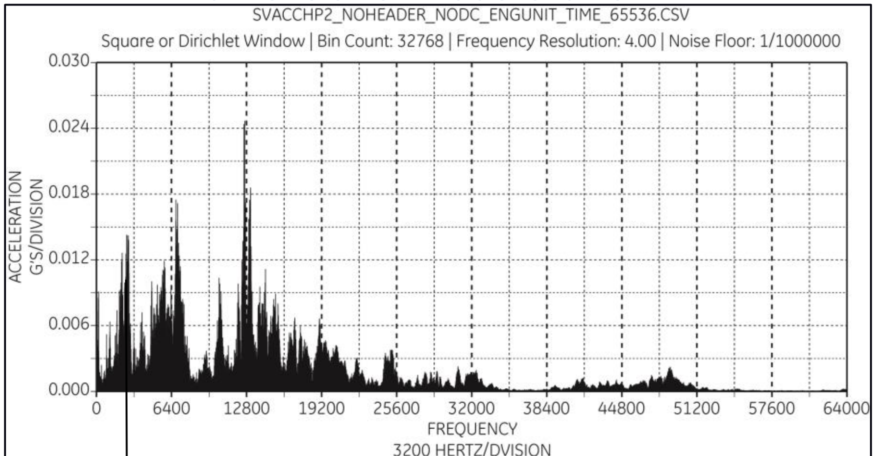
Best practice / Crosshead

Accelerometers can detect the typical malfunctions as loose running gear components, liquid ingestion, that generate impact-type vibration response better than a velocity sensor due to the high frequencies generated by impact events.

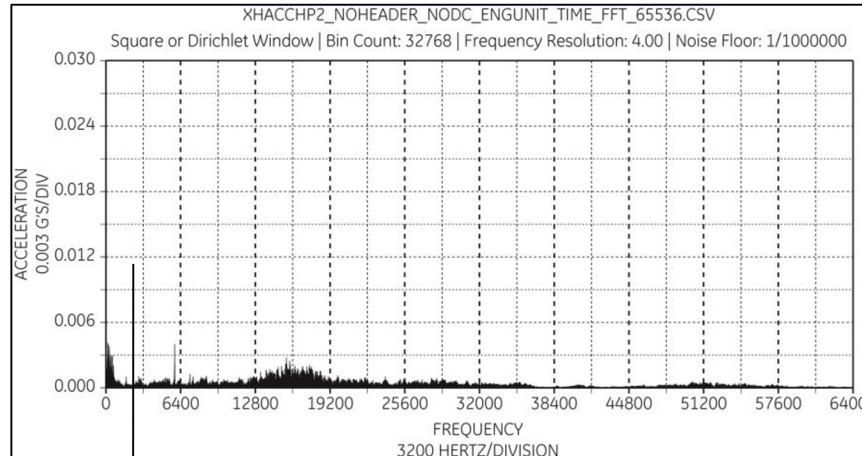
- Measurement should be acceleration units / Do not integrate the signal to velocity
- Possible Analyses: Peak or RMS
- Which band pass filter to apply for protection ?

Best practice / Crosshead

Valve Cover Acceleration



Crosshead Acceleration



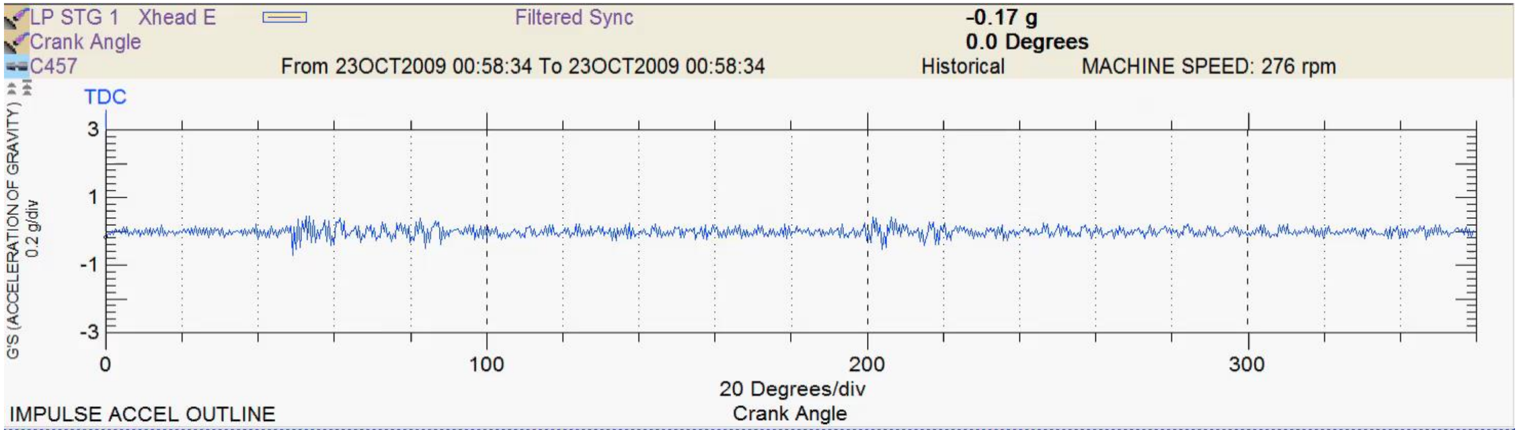
Mechanical ⟷ Valve Noise + Mechanical

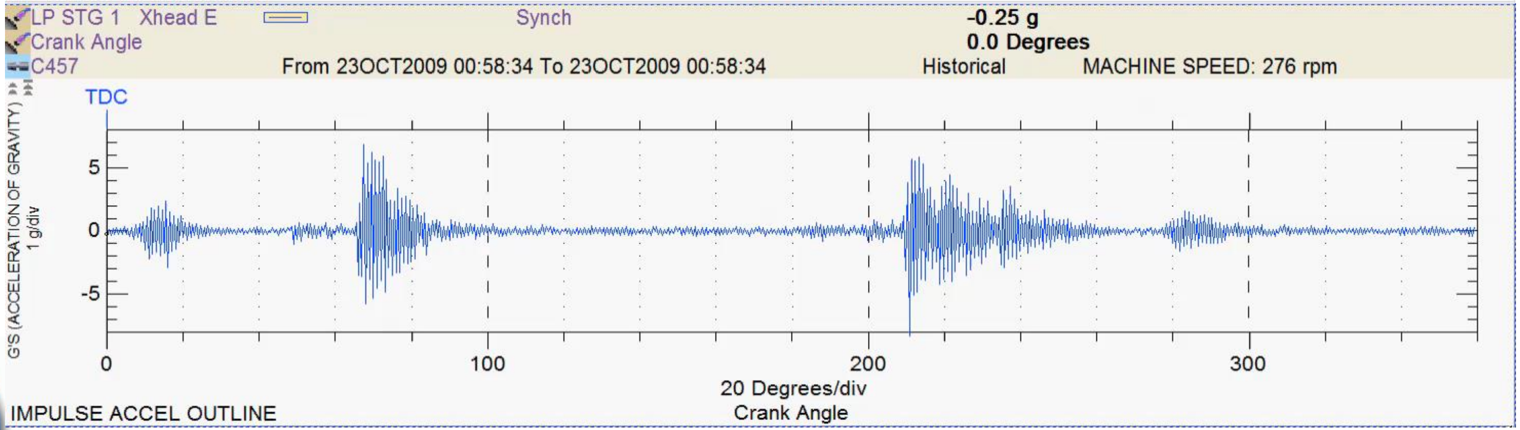
Mechanical ⟷ Valve Noise + Mechanical

Best practice / Crosshead

Filtered and unfiltered crosshead during development of failure

(loose piston rod connection)

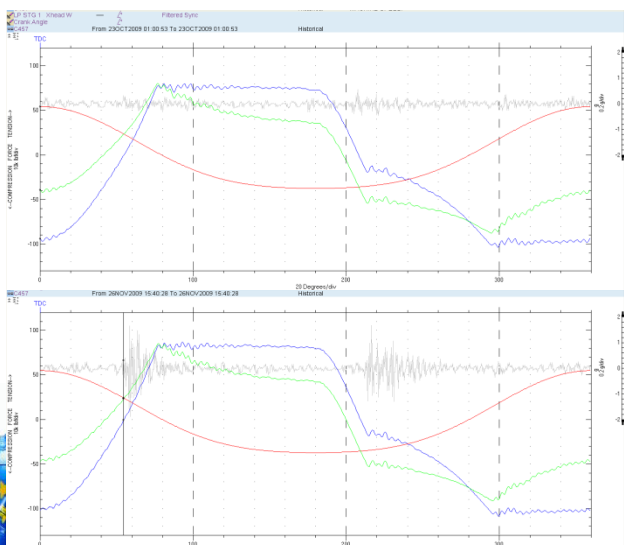


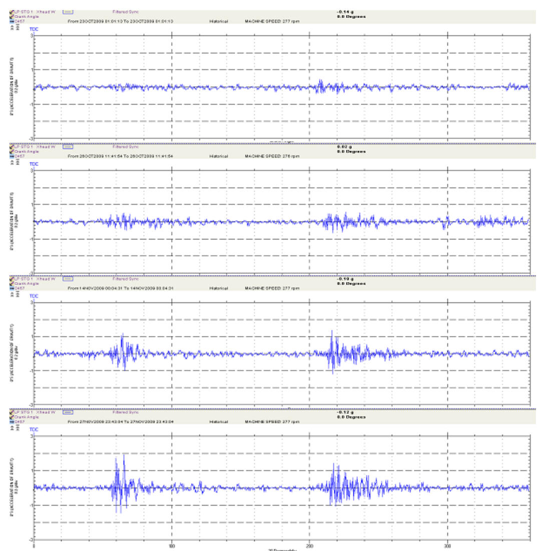


Best practice / Crosshead

Case with Loose Piston

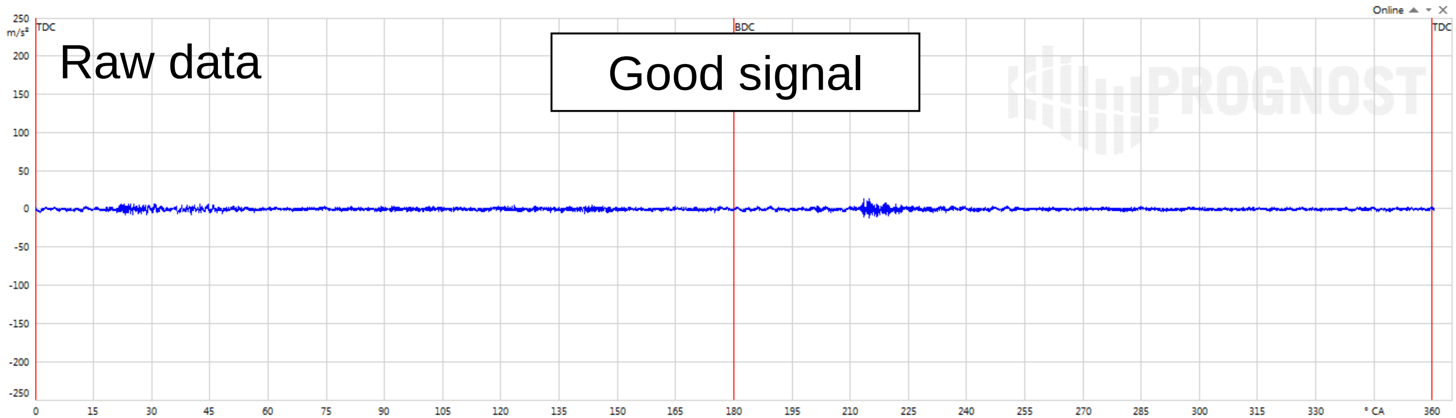
- Crosshead acceleration normal conditions 0.5 g pk
- Diagnostic alarm “Alert - Piston Looseness” 0.8 g pk
- Diagnostic alarm “Danger - Piston Looseness” 1.2 g pk
- First Alert was four weeks before the protection alarm (2 g pk)
- Inspection: broken roll pin, loose nut



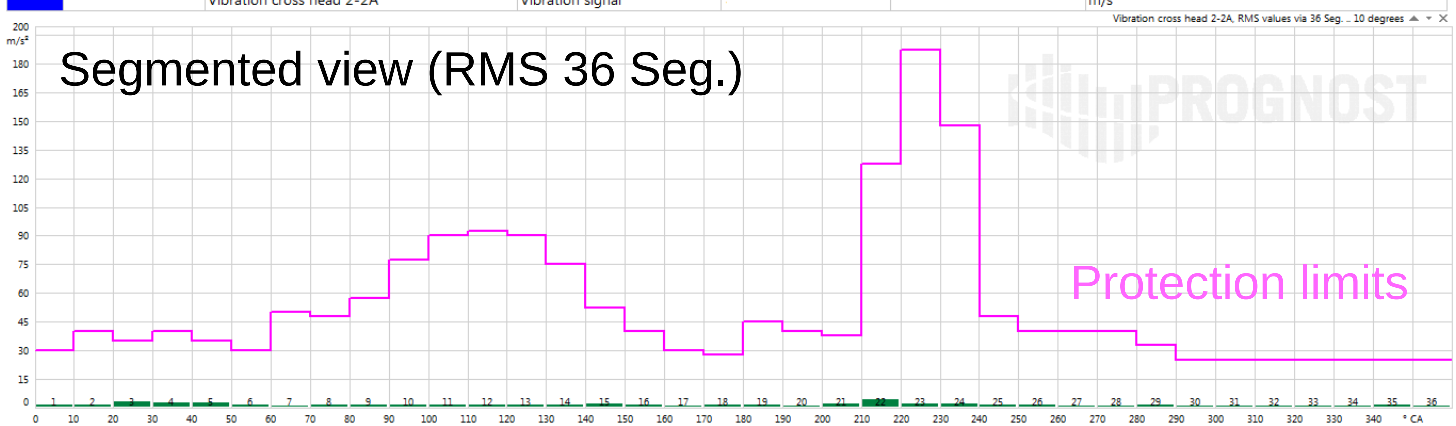


Best practice / Crosshead

Case with lubrication issue



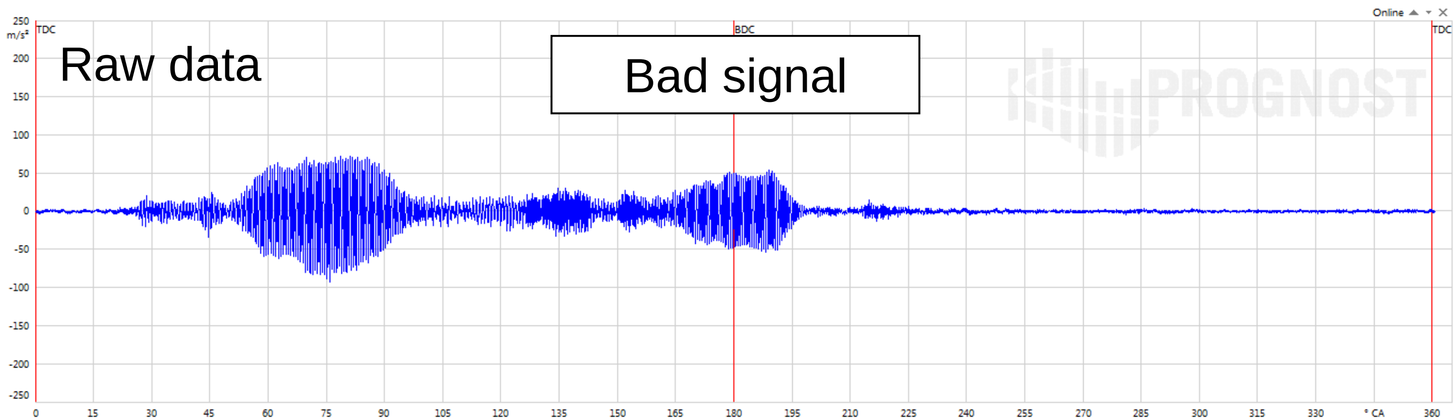
	Machine	Measuring Point	Data name	TAG-Name	Value	Unit
		Vibration cross head 2-2A	Vibration signal			m/s²



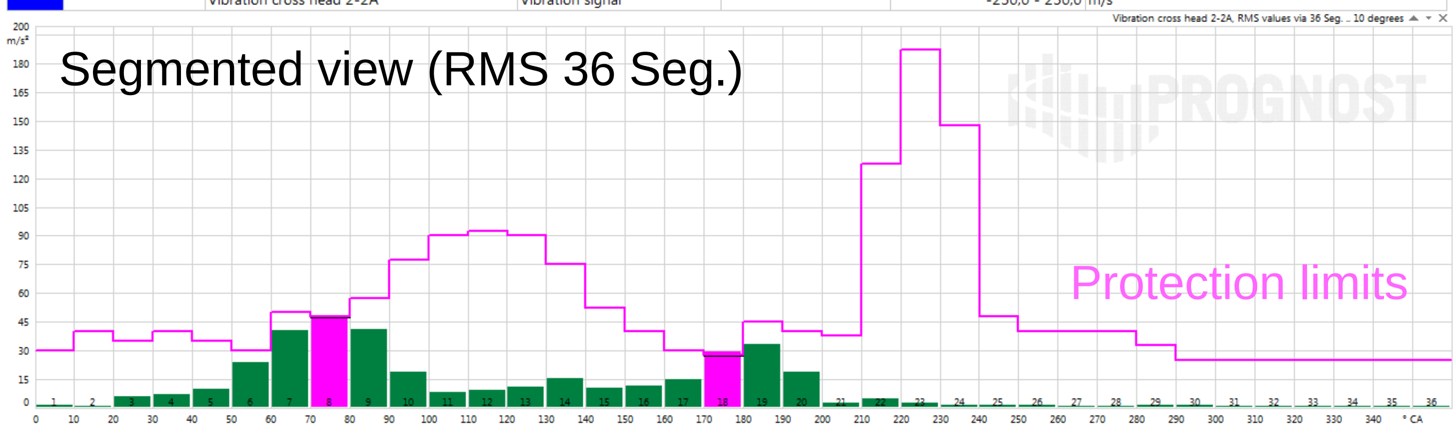
	Machine	Measuring Point	Data name	TAG-Name	Value	Unit
		Vibration cross head 2-2A	RMS values via 36 Seg. .. 10 degrees		0 - 250,0	m/s²

Best practice / Crosshead

Case with lubrication issue



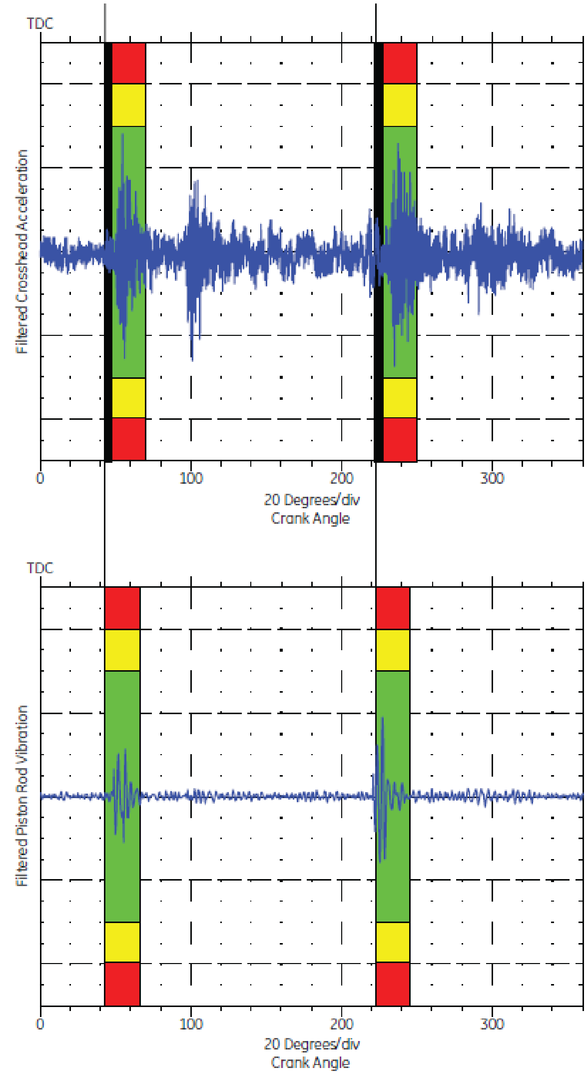
	Machine	Measuring Point	Data name	TAG-Name	Value	Unit
		Vibration cross head 2-2A	Vibration signal		-250,0 - 250,0	m/s^2



	Machine	Measuring Point	Data name	TAG-Name	Value	Unit
		Vibration cross head 2-2A	RMS values via 36 Seg. .. 10 degrees		0 - 250,0	m/s^2

Best practice / Crosshead

- Alert & Shutdown based on reference period
- Crank Angle bands alarming (fixed or custom width)
- 1 alarm threshold per segment

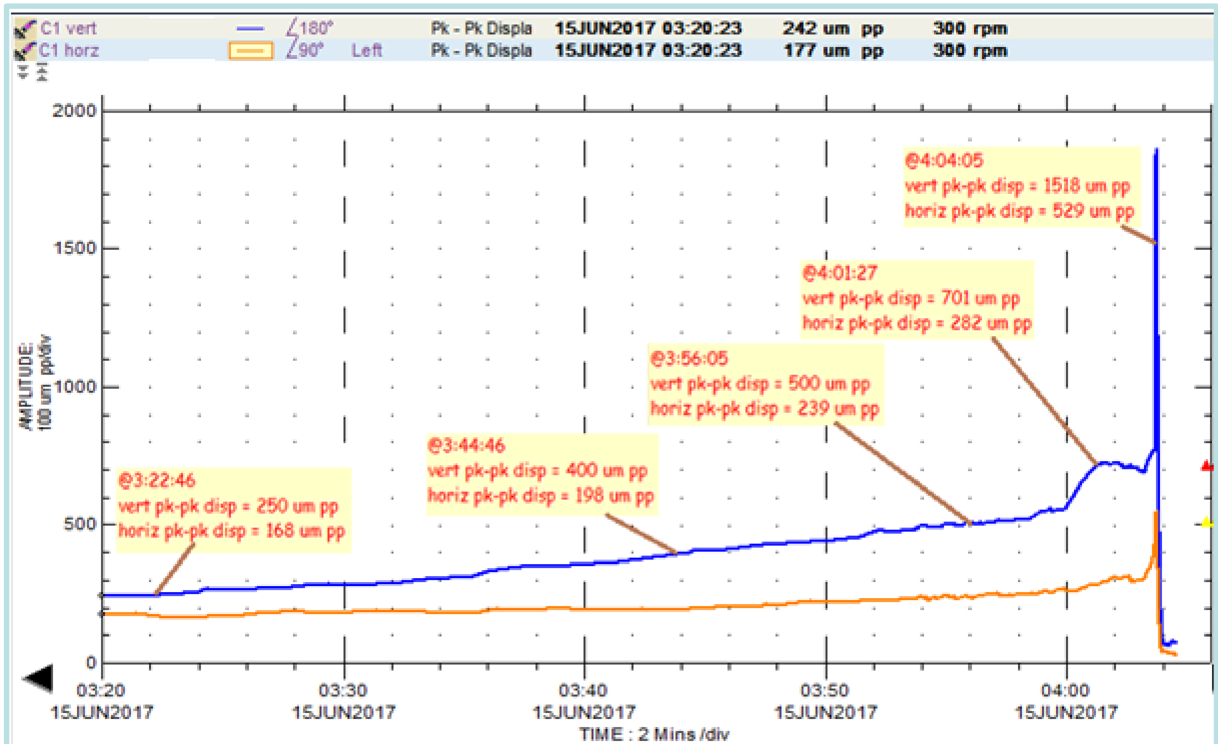


<u>Use crosshead vibration for shutdown</u>

Best practice / Rod position

Rod Position continuously monitors the crosshead looseness, piston rod vibration and rider band condition of each cylinder in a reciprocating compressor. Rod position shall be used as shutdown parameter

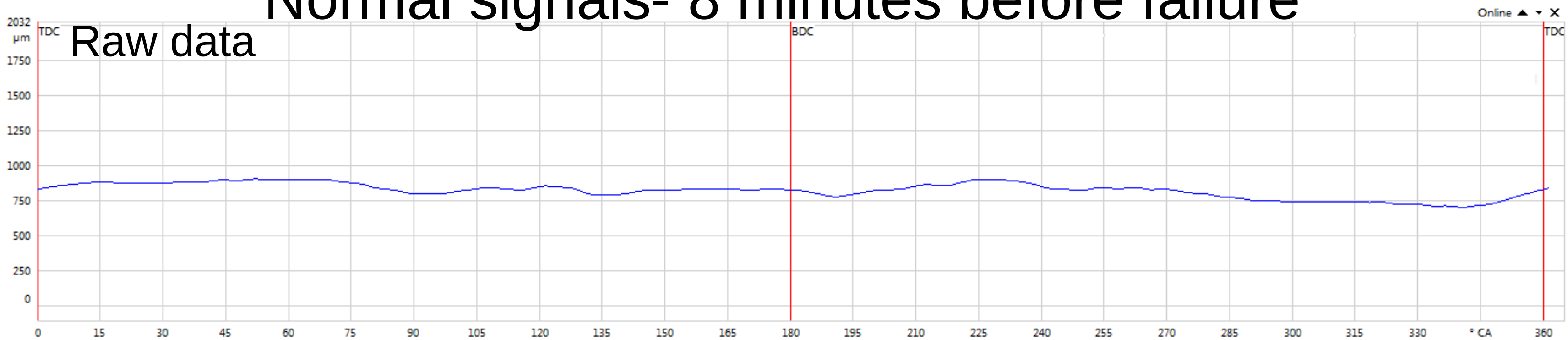
Broken Rod case. Early detection with Pk-pk rod displacement



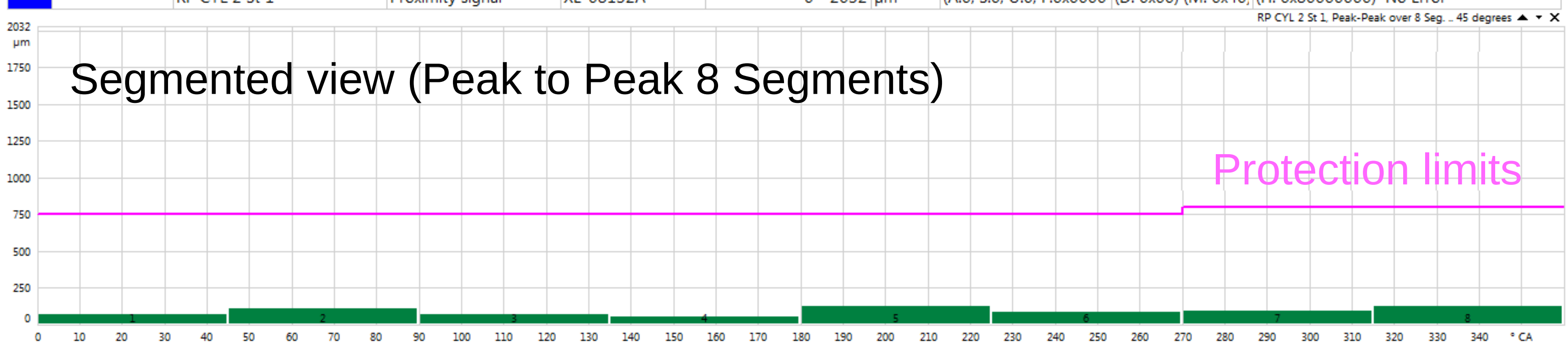
Best practice / Rod position

Case with broken rod

Normal signals- 8 minutes before failure



	Machine	Measuring Point	Data name	TAG-Name	Value	Unit	Safety (Beta)	MP Status	Channel Status
		RP CYL 2 St 1	Proximity signal	XE-08132A	0 - 2032	µm	(A:0, S:0, U:0, F:0x0000	(D: 0x00) (M: 0x40)	(H: 0x80000000) No Error

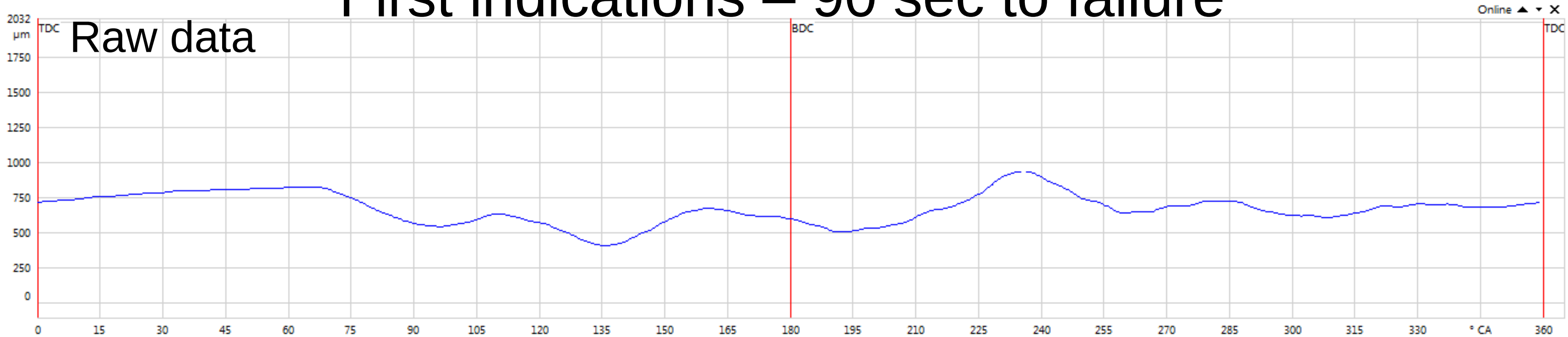


	Machine	Measuring Point	Data name	TAG-Name	Value	Unit	Safety (Beta)	MP Status	Channel Status
		RP CYL 2 St 1	Peak-Peak over 8	XE-08132A		µm			

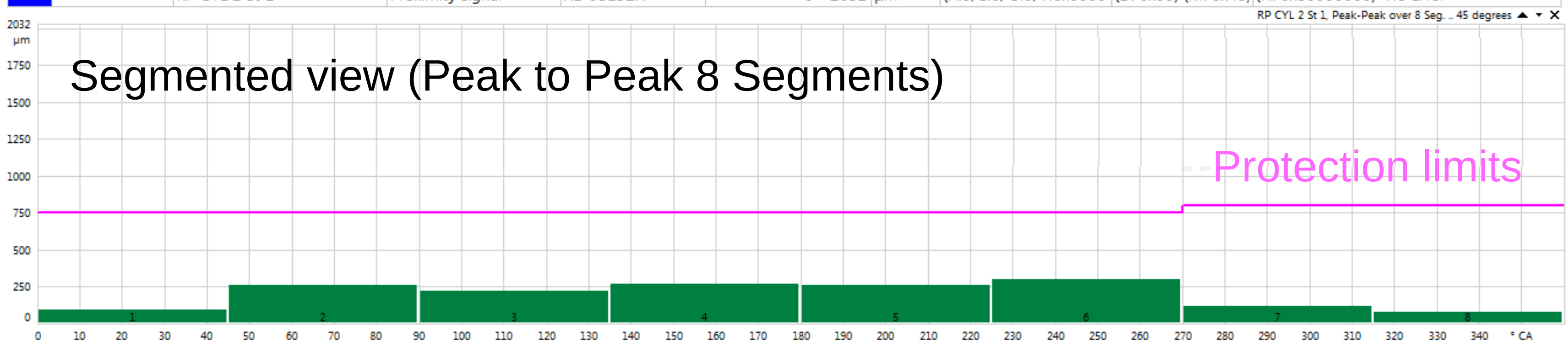
Best practice / Rod position

Case with broken rod

First indications – 90 sec to failure



	Machine	Measuring Point	Data name	TAG-Name	Value	Unit	Safety (Beta)	MP Status	Channel Status
	--	RP CYL 2 St 1	Proximity signal	XE-08132A	0 - 2032	µm	(A:0, S:0, U:0, F:0x0000	(D: 0x00) (M: 0x40)	(H: 0x80000000) No Error



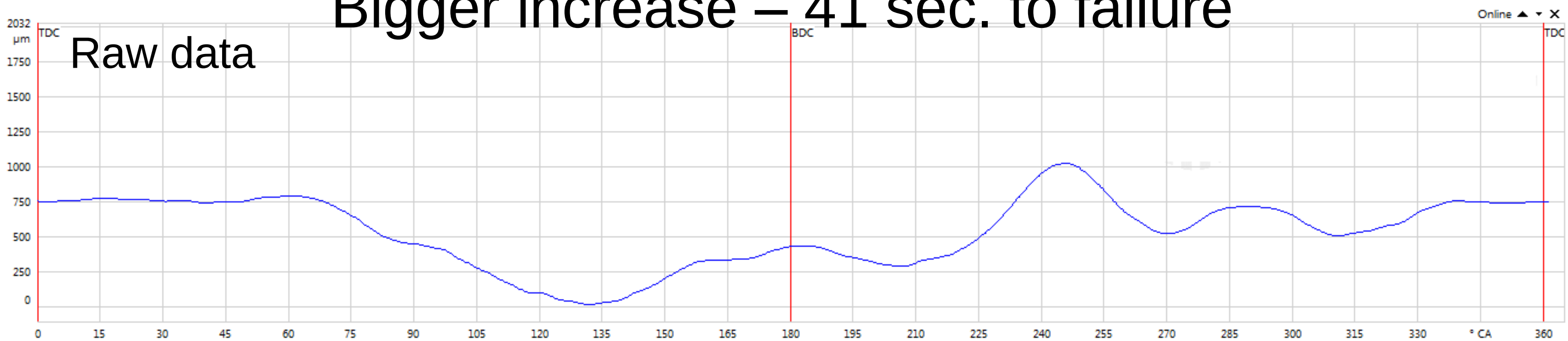
	Machine	Measuring Point	Data name	TAG-Name	Value	Unit	Safety (Beta)	MP Status	Channel Status
		RP CYL 2 St 1	Peak-Peak over 8	XE-08132A		µm			

EFRC

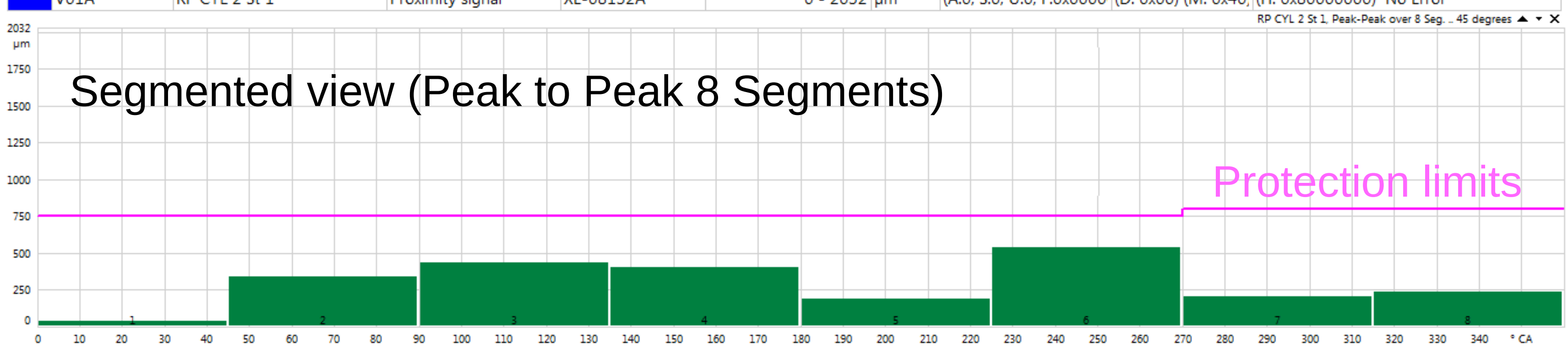
Best practice / Rod position

Case with broken rod

Bigger increase – 41 sec. to failure



	Machine	Measuring Point	Data name	TAG-Name	Value	Unit	Safety (Beta)	MP Status	Channel Status
	V01A	RP CYL 2 St 1	Proximity signal	XE-08132A	0 - 2032	µm	(A:0, S:0, U:0, F:0x0000	(D: 0x00) (M: 0x40)	(H: 0x80000000) No Error



	Machine	Measuring Point	Data name	TAG-Name	Value	Unit	Safety (Beta)	MP Status	Channel Status
	V01A	RP CYL 2 St 1	Peak-Peak over 8	XE-08132A		µm			

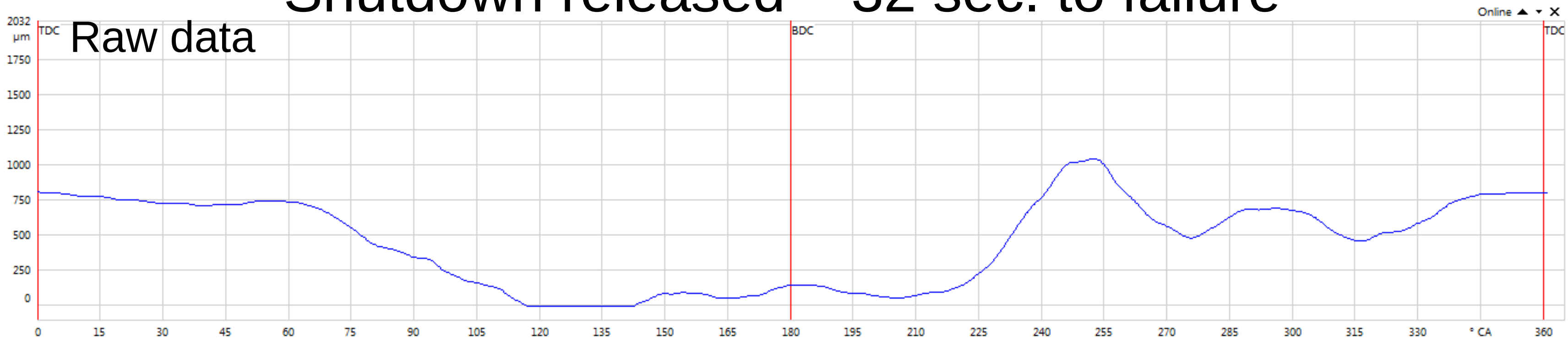
Ring Buffer 08.02.2016 23:08:24,417 (08.02.2016 23:08:24,417 BLOCK#5081451-5084817(3366)) , 892,3 1/min

PROGNOST Systems GmbH

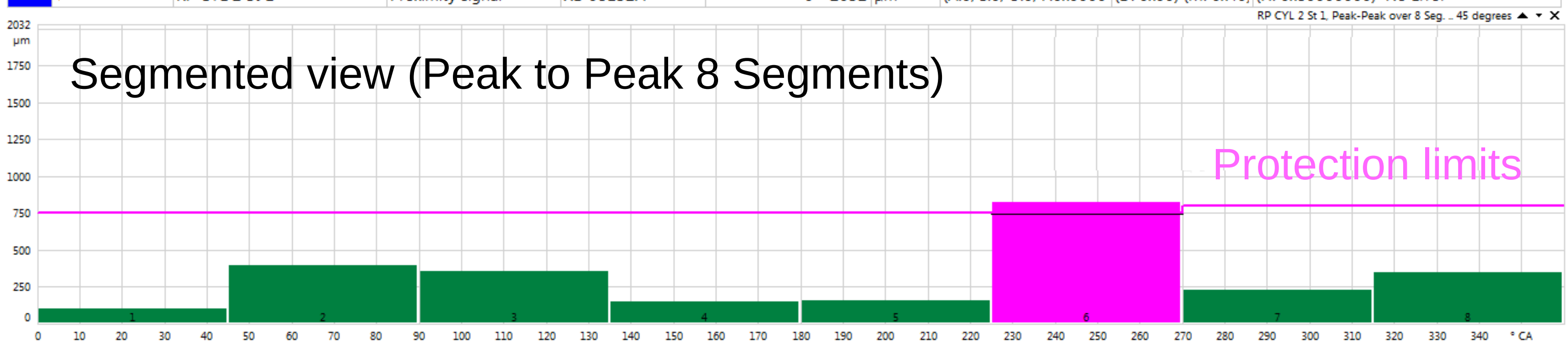
Best practice / Rod position

Case with broken rod

Shutdown released – 32 sec. to failure



	Machine	Measuring Point	Data name	TAG-Name	Value	Unit	Safety (Beta)	MP Status	Channel Status
		RP CYL 2 St 1	Proximity signal	XE-08132A	0 - 2032	µm	(A:0, S:0, U:0, F:0x0000	(D: 0x00) (M: 0x40)	(H: 0x80000000) No Error

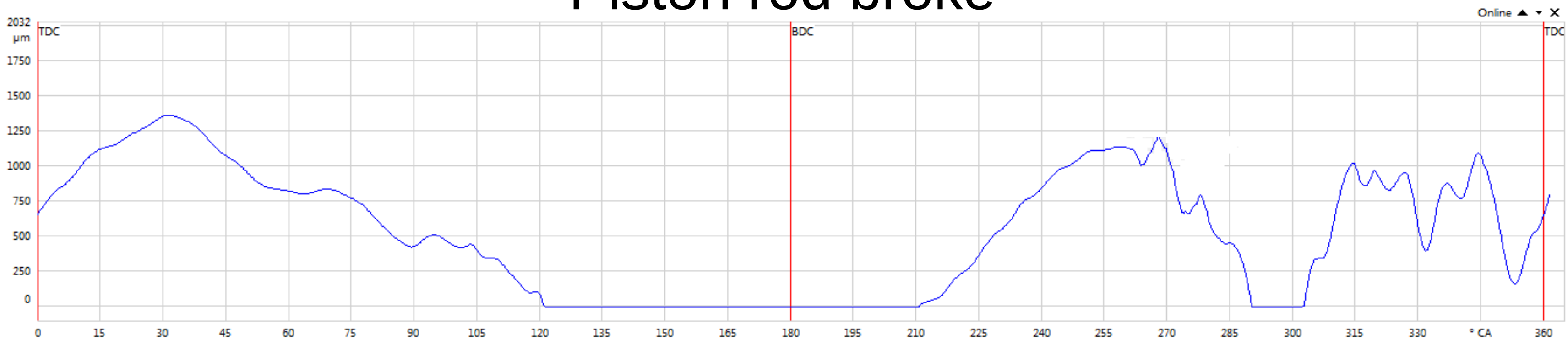


	Machine	Measuring Point	Data name	TAG-Name	Value	Unit	Safety (Beta)	MP Status	Channel Status
		RP CYL 2 St 1	Peak-Peak over 8	XE-08132A		µm			

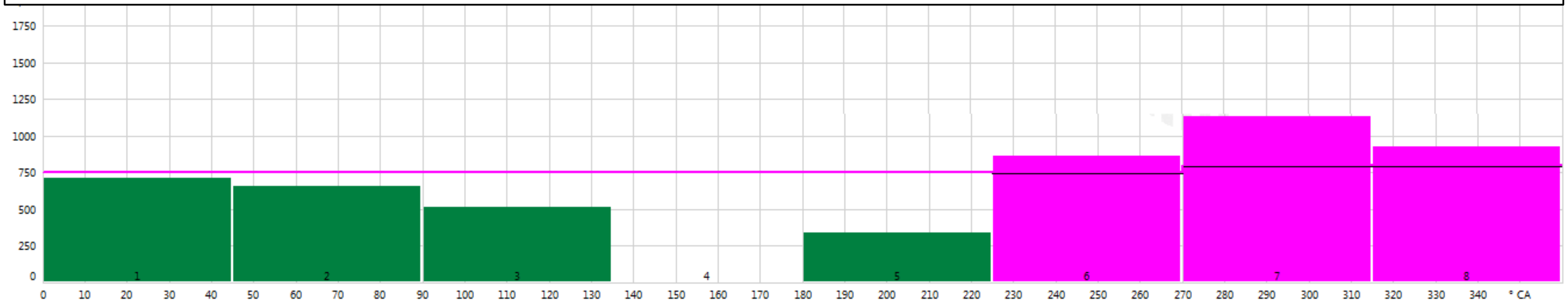
Best practice / Rod position

Case with broken rod

Piston rod broke



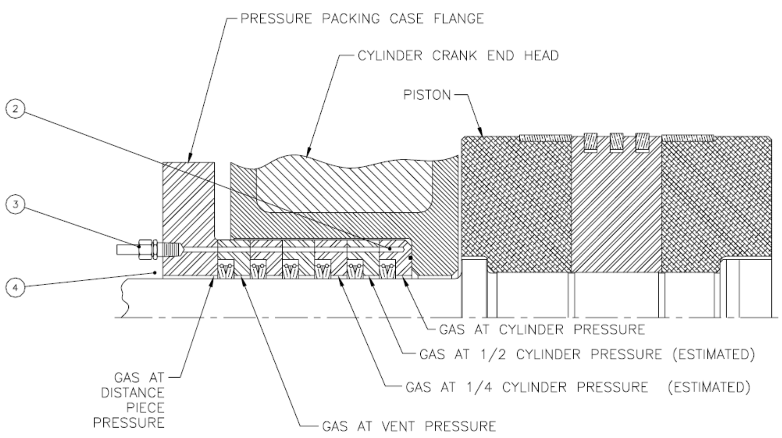
Automatic trip was no active!

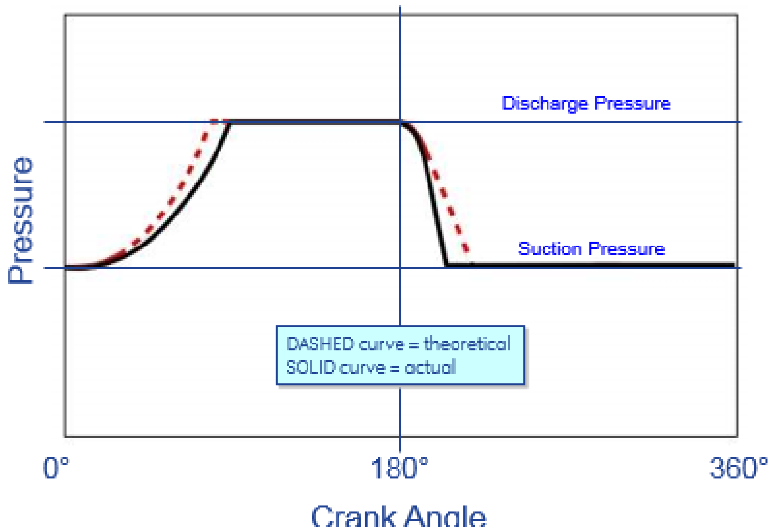


	Machine	Measuring Point	Data name	TAG-Name	Value	Unit	Safety (Beta)	MP Status	Channel Status
		RP CYL 2 St 1	Peak-Peak over	XE-08132A		µm			

Emissions

- Gas emission are a critical issue for recips
- Solution: monitoring packing case status, adopting better sealing solutions.
- Condition monitoring can help identifying such leakages and provide corrective actions.
- Pressure packing leaks detection with temperature, vent temperature, cylinder pressure





Performance Indicators

- Volumetric Efficiency
  - Fraction of stroke used by suction or discharge process
- Capacity
  - Amount of gas processed per specified unit of time
- Flow Balance
  - Ratio of suction capacity to discharge capacity
- Indicated Horsepower
  - Power required for the cycle (area inside P-V curve)
- Power Losses
  - Power lost to flow restrictions in suction and discharge path

Volumetric Efficiency – Defined

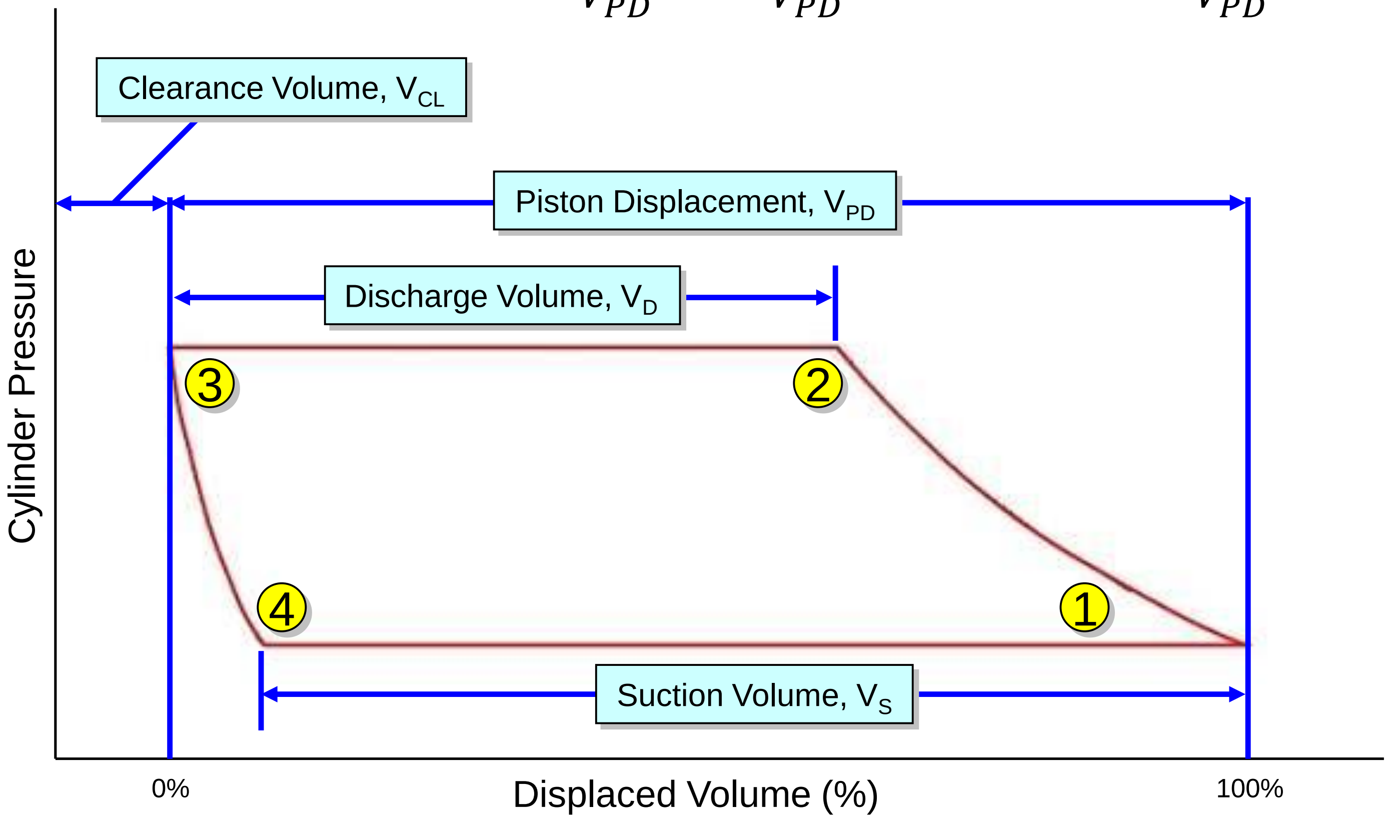
Performance Indicators

Discharge Volumetric Efficiency

$$VE_D = \frac{V_D}{V_{PD}} = \frac{V_2 - V_3}{V_{PD}}$$

Suction Volumetric Efficiency

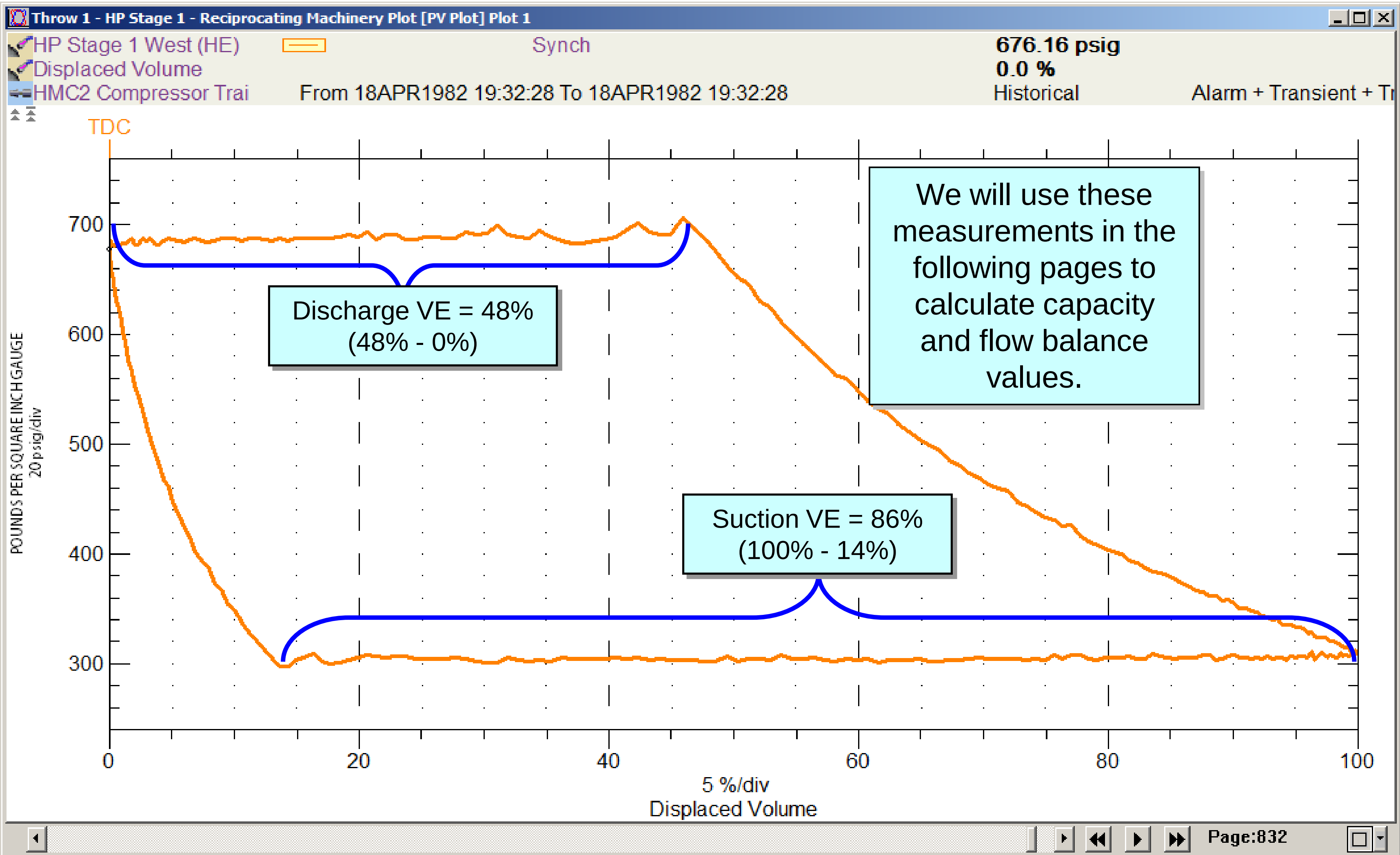
$$VE_S = \frac{V_S}{V_{PD}} = \frac{V_1 - V_4}{V_{PD}}$$



Link to page 16

Volumetric Efficiency – Measured

Performance Indicators



Capacity

Performance Indicators

- Capacity is the amount of gas (mass or volume) that is processed by a compressor per specified unit of time.
  - Mass Units (kg/hr, lbmol/stroke, etc.)
  - Volume Units (mmscfd, CFM, etc.)
- Capacity can be measured by flow instruments or calculated from measured values of volumetric efficiency, pressure, cylinder volume, and compressor speed.

Suction Capacity Calculation (SI)

Performance Indicators

- Information for cylinder on page 42:
  - P_s = 310 psig = 2137.4 kPa = (2137.4+ 101.3) kPa abs = 2239 kPa abs
  - V_s = (86%)(2.83m^3) = 2.44 m^3
  - Z = 1.0136 (dimensionless)
  - R = 3784 J/mol K
  - T_s = 84.7º F = 29.28º C = (29.28 + 273.15) K = 302.43º K

- Calculation

$$PV = ZnRT$$

$$n_s = \frac{PV}{ZRT}$$

$$n_s = \frac{\left(\frac{2\,239\,000\ N}{m^2}\right)(2.44\ m^3)}{(1.0136)\left(\frac{3784\ N \cdot m}{mol \cdot K}\right)(302.43\ K)}$$

$$\boxed{n_s = 4.71\ mol\ (per\ stroke)}$$

Flow Balance

Performance Indicators

- Flow Balance is defined as Suction Capacity divided by Discharge Capacity.

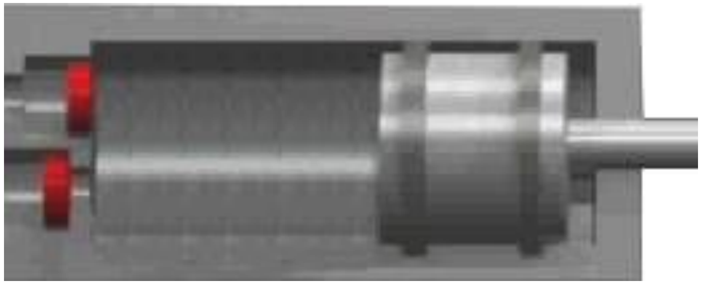
$$Flow\ Balance = \frac{n_s}{n_d}$$

- If the cylinder is in perfect condition, with no leakage past the valves, packing or rings, Flow Balance is exactly 1.

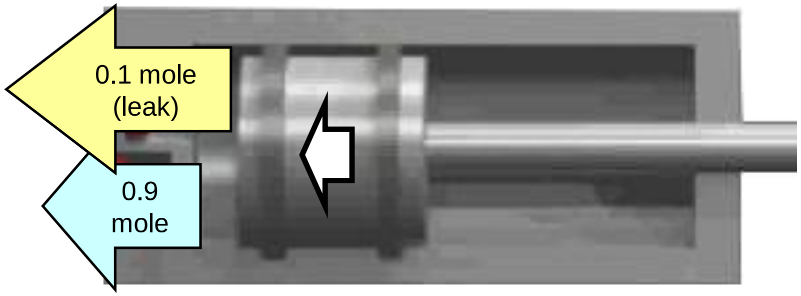
Suction Valve Leak Example

Performance Indicators

- Some of the gas leaks out of the chamber through the suction valve during the compression process.



- Fewer moles of gas are discharged than are brought in during the suction process.



Discharge Capacity = 0.9 mole

- $n_S > n_D$, so Flow Balance >1

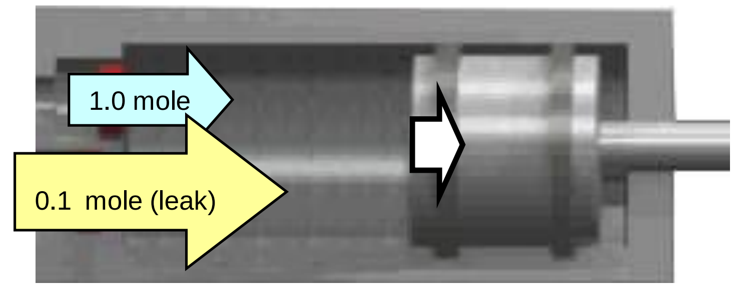
Discharge Valve Leak Example

Performance Indicators

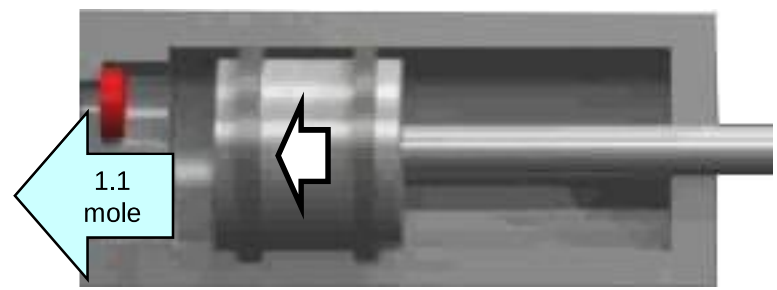
- Additional gas leaks into the chamber through the discharge valve during the suction process.

- This “extra” gas is discharged along with the gas that was admitted through the suction valve.

- $n_S < n_D$, so Flow Balance < 1



Suction Capacity = 1.0 mole

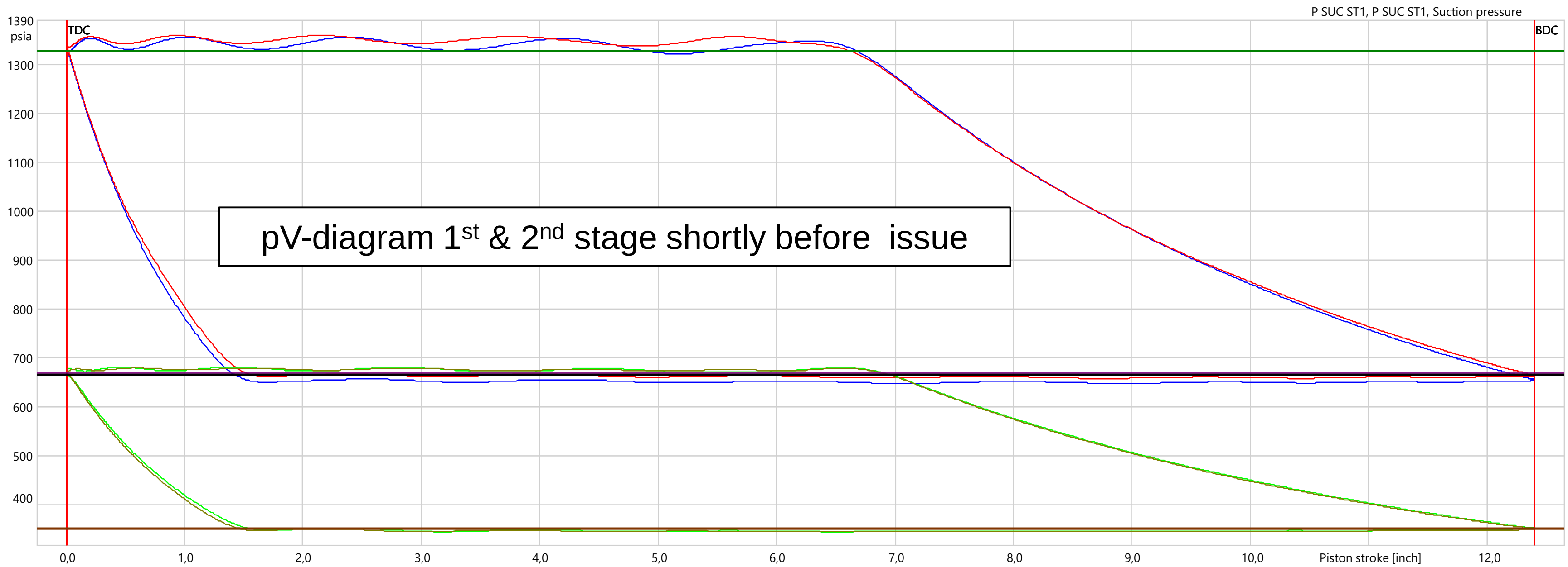


Discharge Capacity = 1.1 mole

Flow Balance = 1.0 / 1.1 = 0.9

Discharge Valve Leak Example

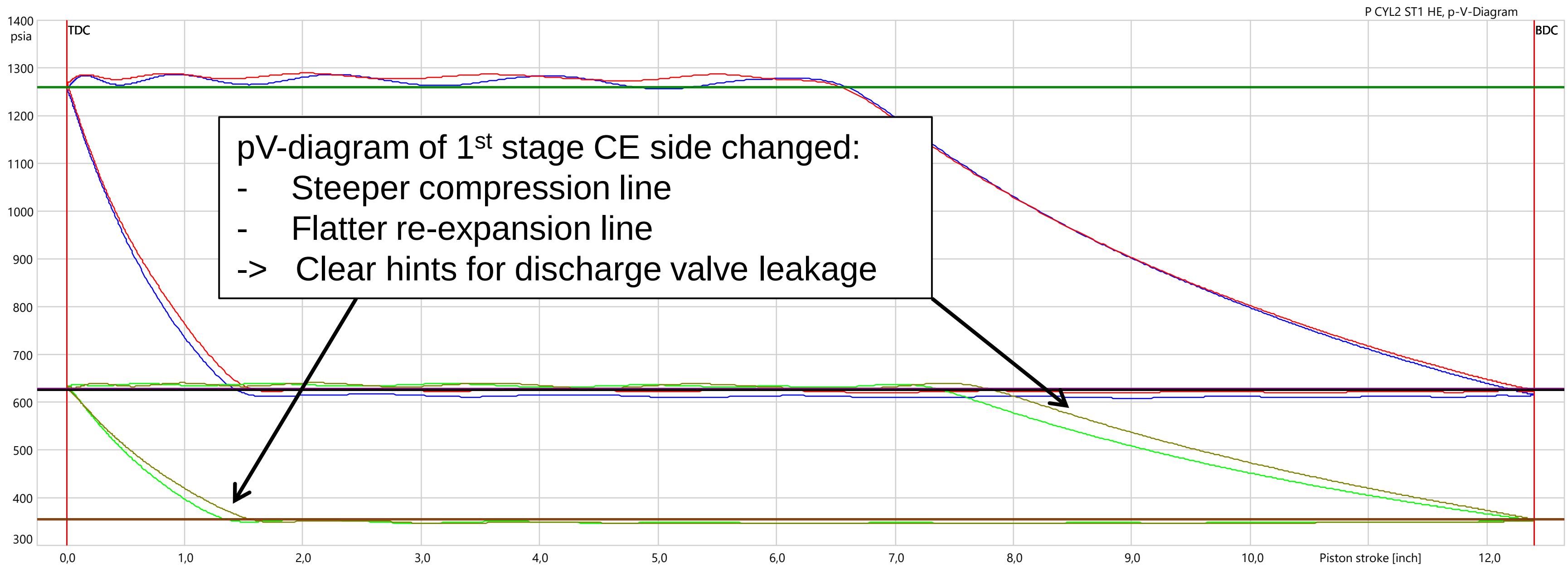
Performance Indicators



	Machine	Measuring Point	Data name	TAG-Name	Value	Unit
		P CYL1 ST2 HE	p-V-Diagram	302 PT 7015	14,50 - 2335	psia
		P CYL1 ST2 CE	p-V-Diagram	302 PT 7016	18,02 - 2339	psia
		P CYL2 ST1 HE	p-V-Diagram	302 PT 7013	12,60 - 882,8	psia
		P CYL2 ST1 CE	p-V-Diagram	302 PT 7014	15,42 - 885,6	psia
		P SUC ST1	Suction pressure	302 PT 7001A	0 - 580,2	psia
		P DIS ST1	Discharge pressure	302 PT 7001B	0 - 870,2	psia
		P SUC ST2	Suction pressure	302 PT 7004A	0 - 870,2	psia
		P DIS ST2	Discharge pressure	302 PT 7004B	0 - 2321	psia

Discharge Valve Leak Example

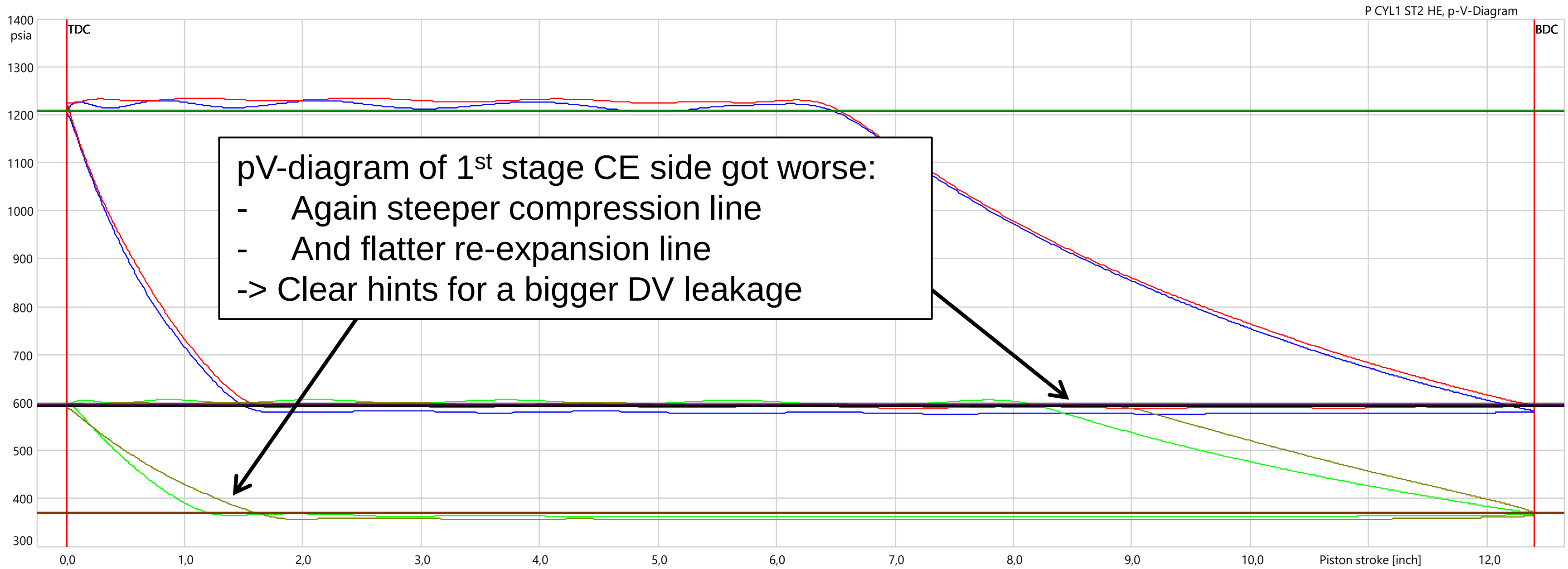
Performance Indicators



	Machine	Measuring Point	Data name	TAG-Name	Value	Unit
		P CYL1 ST2 HE	p-V-Diagram	302 PT 7015	14,50 - 2335	psia
		P CYL1 ST2 CE	p-V-Diagram	302 PT 7016	18,01 - 2339	psia
		P CYL2 ST1 HE	p-V-Diagram	302 PT 7013	12,58 - 882,8	psia
		P CYL2 ST1 CE	p-V-Diagram	302 PT 7014	14,28 - 884,5	psia
		P SUC ST1	Suction pressure	302 PT 7001A	0 - 580,2	psia
		P DIS ST1	Discharge pressure	302 PT 7001B	0 - 870,2	psia
		P SUC ST2	Suction pressure	302 PT 7004A	0 - 870,2	psia
		P DIS ST2	Discharge pressure	302 PT 7004B	0 - 2321	psia

Discharge Valve Leak Example

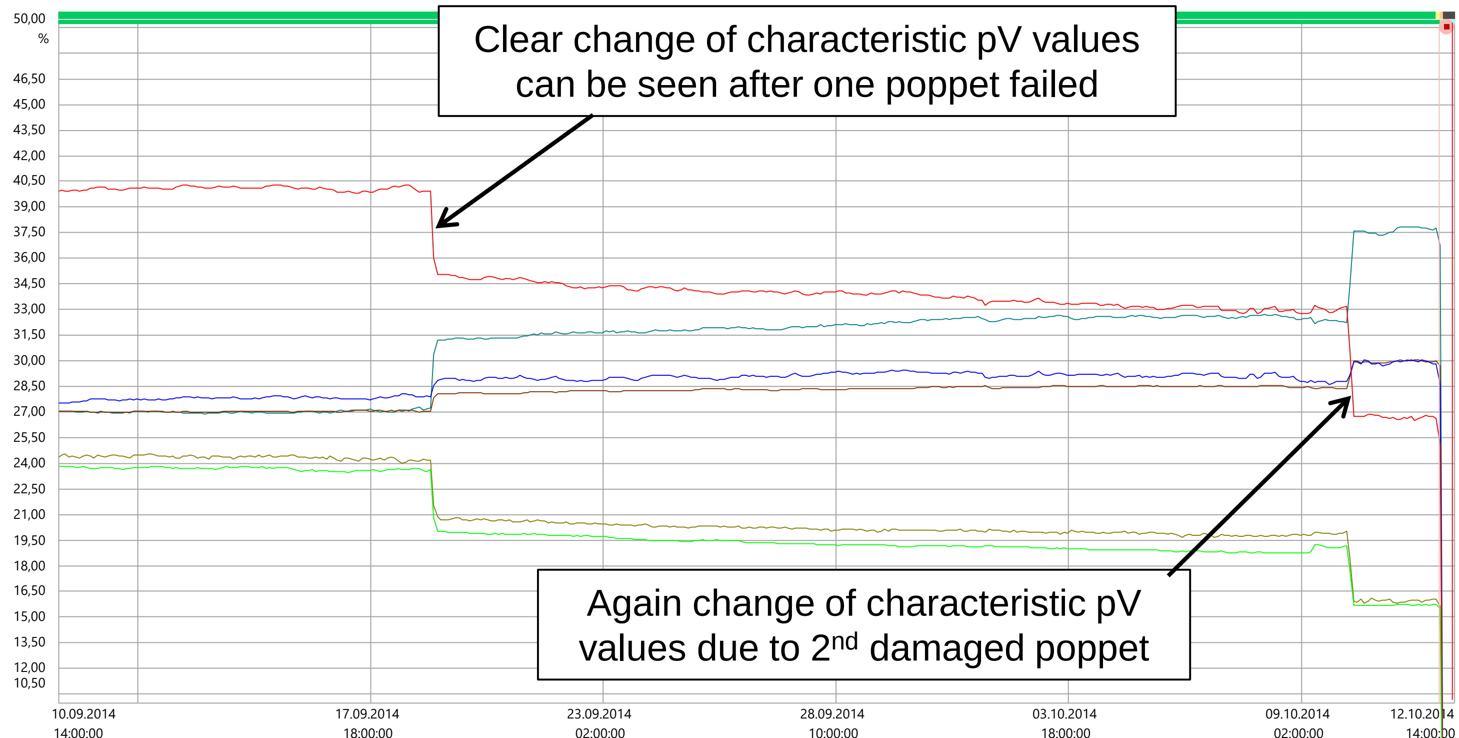
Performance Indicators



	Machine	Measuring Point	Data name	TAG-Name	Value	Unit
		P CYL1 ST2 HE	p-V-Diagram	302 PT 7015	14,50 - 2335	psia
		P CYL1 ST2 CE	p-V-Diagram	302 PT 7016	19,38 - 2340	psia
		P CYL2 ST1 HE	p-V-Diagram	302 PT 7013	13,35 - 883,6	psia
		P CYL2 ST1 CE	p-V-Diagram	302 PT 7014	8,977 - 879,2	psia
		P SUC ST1	Suction pressure	302 PT 7001A	0 - 580,2	psia
		P DIS ST1	Discharge pressure	302 PT 7001B	0 - 870,2	psia
		P SUC ST2	Suction pressure	302 PT 7004A	0 - 870,2	psia
		P DIS ST2	Discharge pressure	302 PT 7004B	0 - 2321	psia

Discharge Valve Leak Example

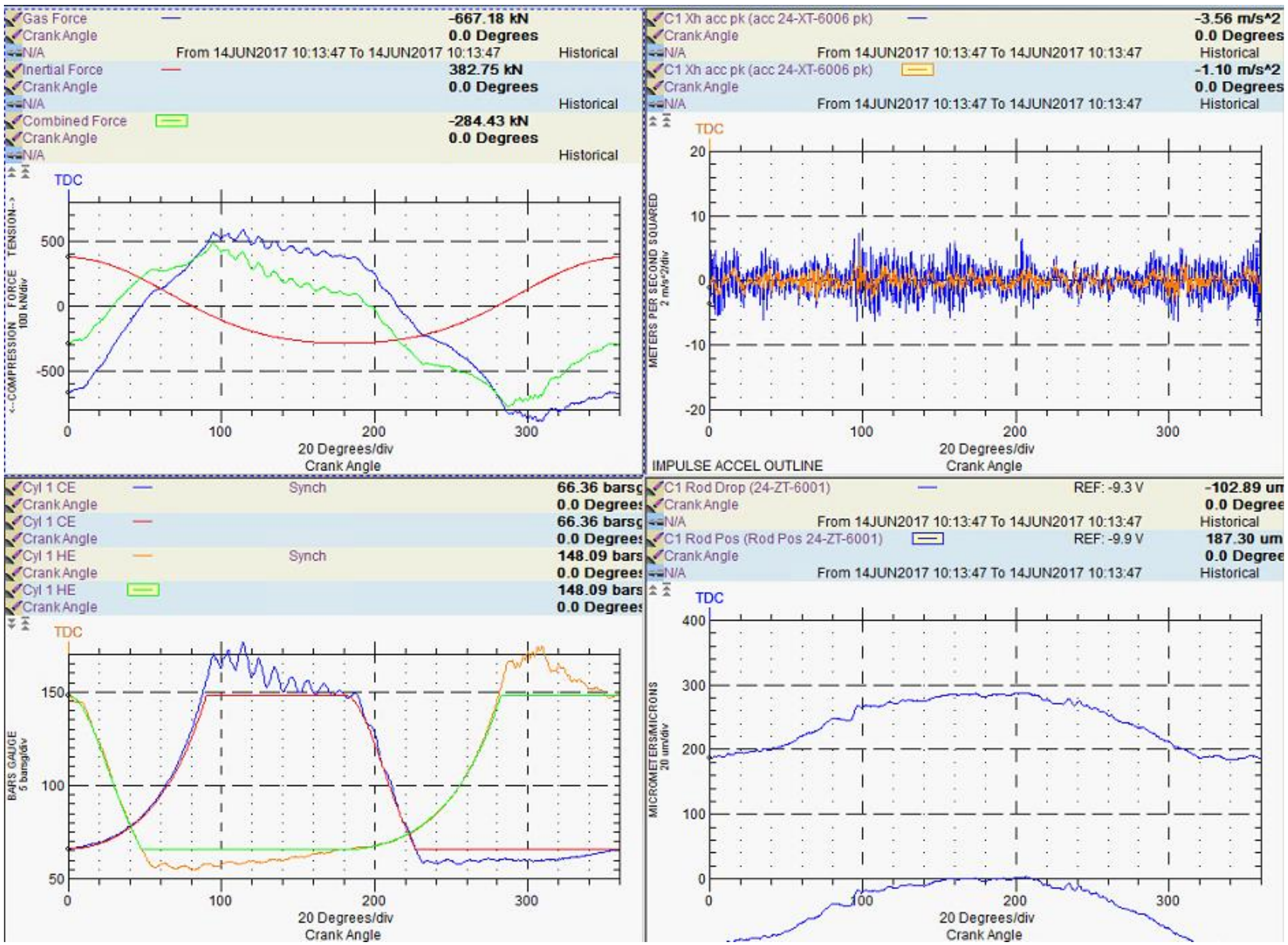
Performance Indicators



	Machine	Measuring Point	Data name	TAG-Name	Segment	Value	Unit	Status	Min and Max Values
		P CYL2 ST1 CE	Break through suction pressure	302 PT 7014	1	0 - 150,0	° CA		0 - 69,10
		P CYL2 ST1 CE	Break through discharge pressure	302 PT 7014	1	200,0 - 350,0	° CA		200,0 - 261,2
		P CYL2 ST1 CE	Polytropic exponent 1, Expansion line	302 PT 7014	1	0 - 5,000			0 - 1,207
		P CYL2 ST1 CE	Polytropic exponent 2, Expansion line	302 PT 7014	1	0 - 5,000			0 - 1,247
		P CYL2 ST1 CE	Polytropic exponent 1, Compression line	302 PT 7014	1	0 - 5,000			0 - 2,581
		P CYL2 ST1 CE	Polytropic exponent 2, Compression line	302 PT 7014	1	0 - 5,000			0 - 1,791

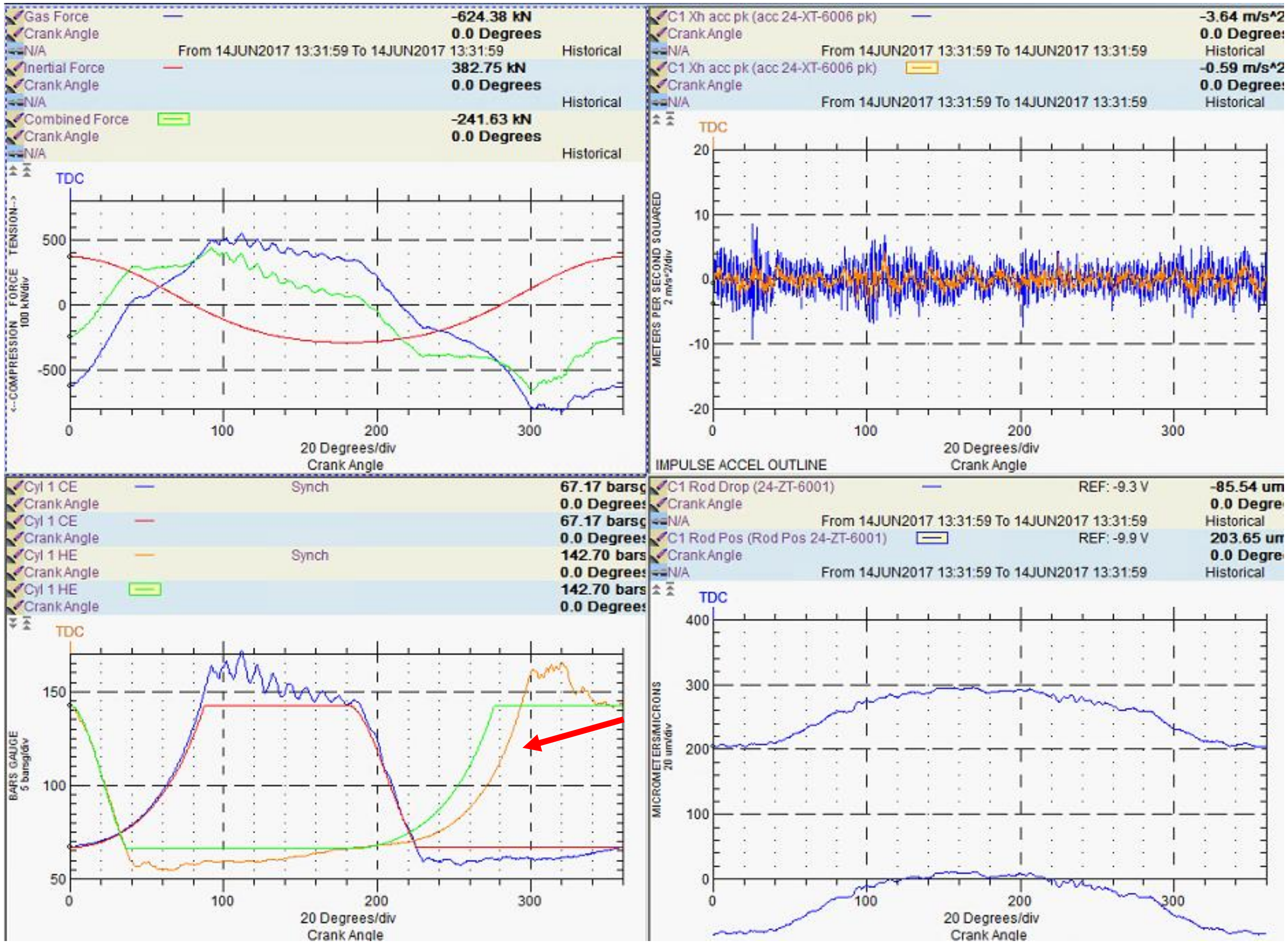
Suction Valve Leak Example

Performance Indicators



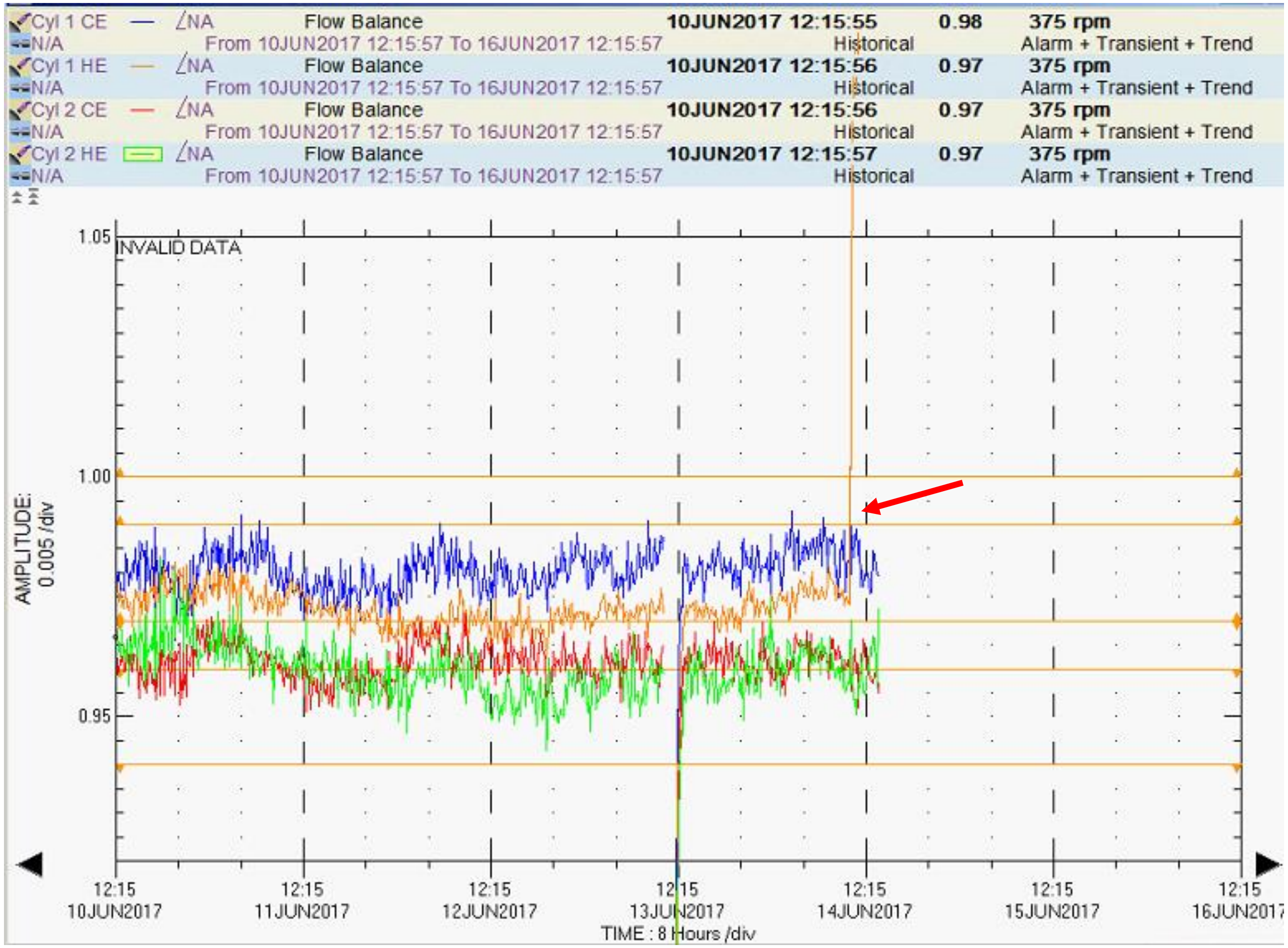
Suction Valve Leak Example

Performance Indicators



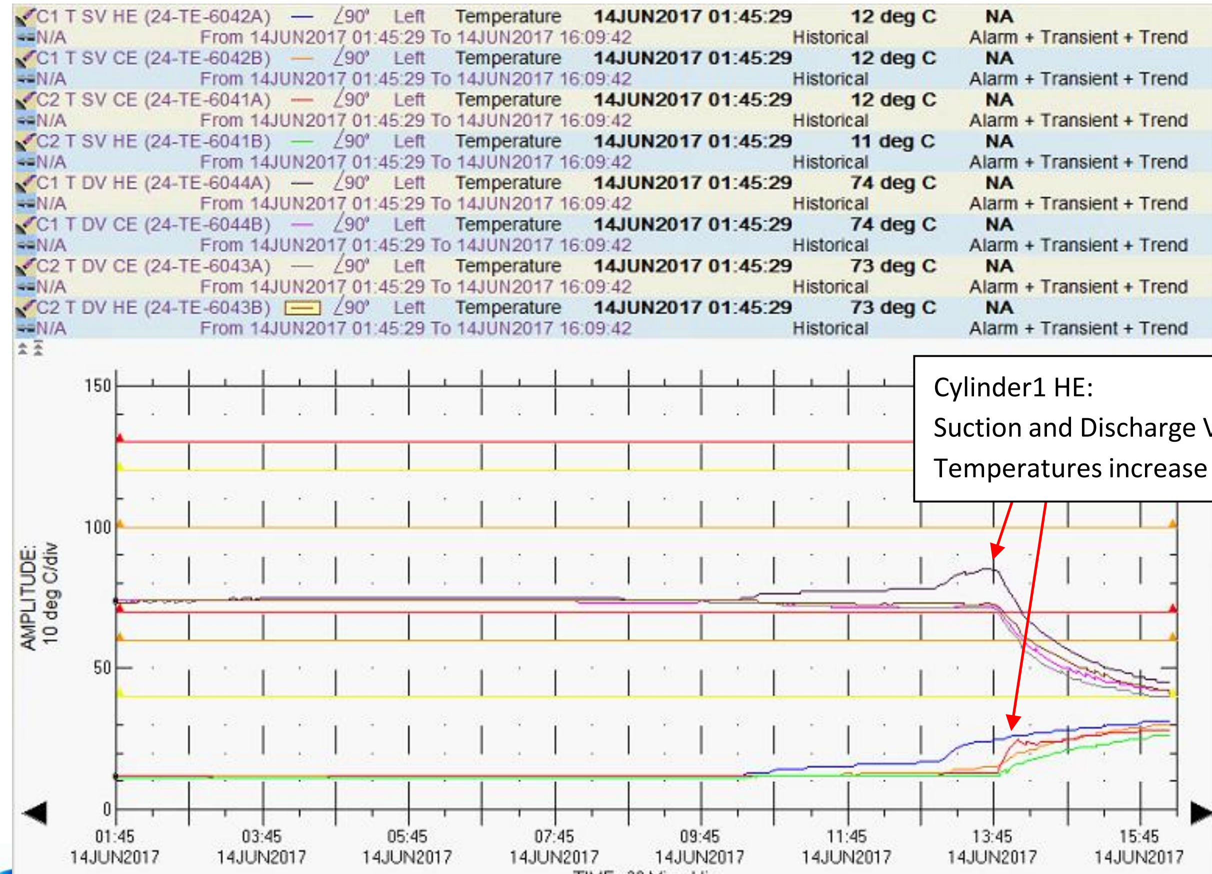
Suction Valve Leak Example

Performance Indicators

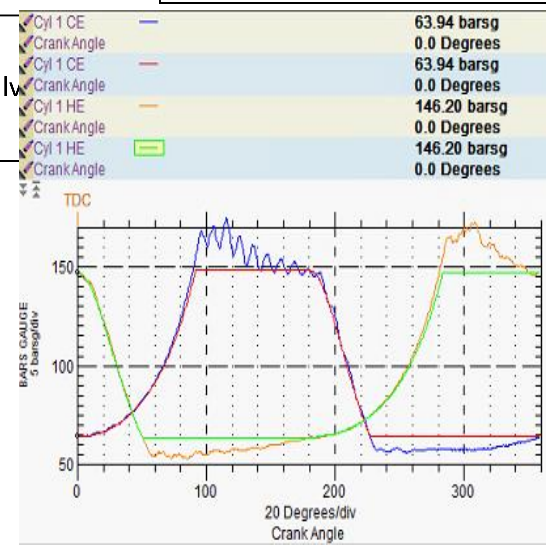


Suction Valve Leak Example

Performance Indicators

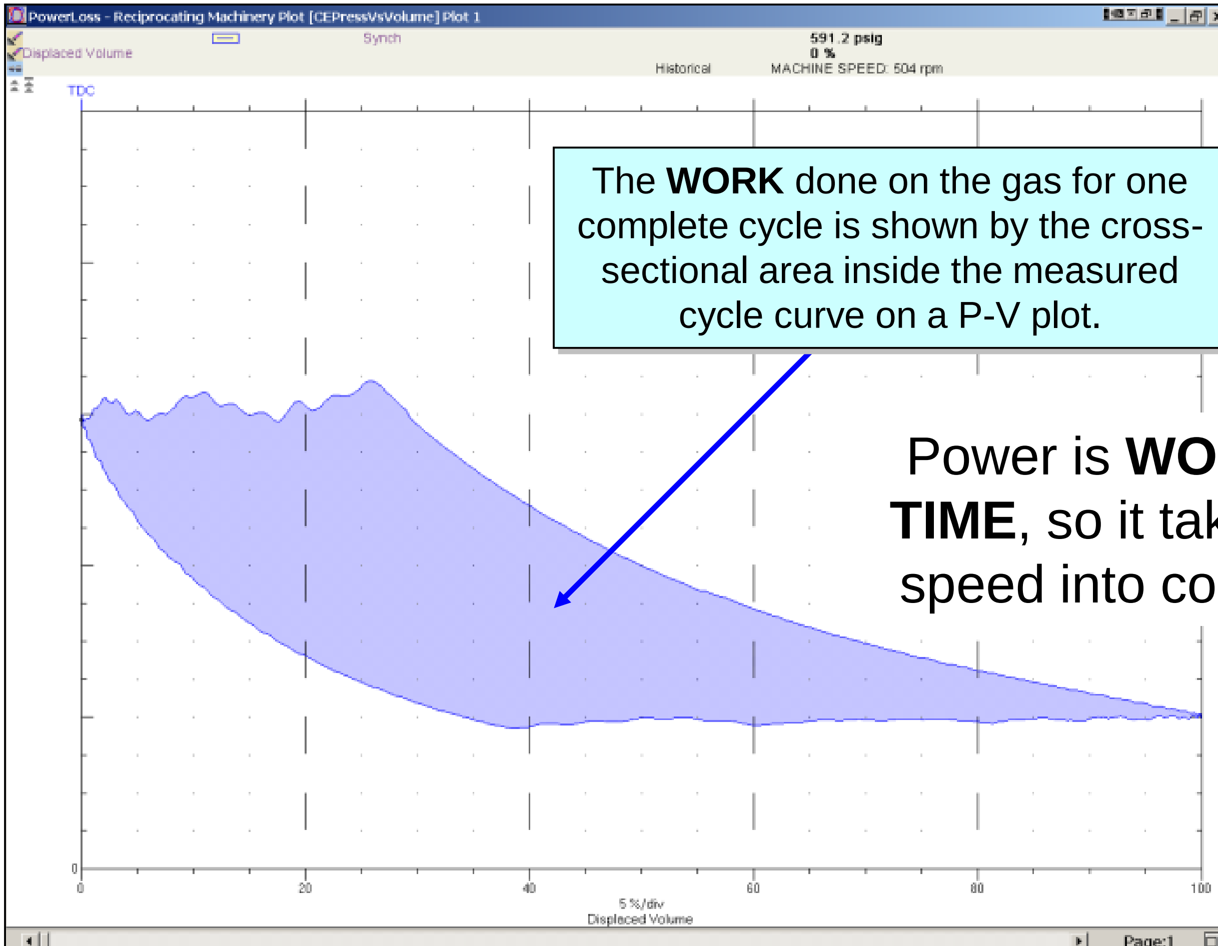


After Valve Replacement



Indicated Horsepower

Performance Indicators

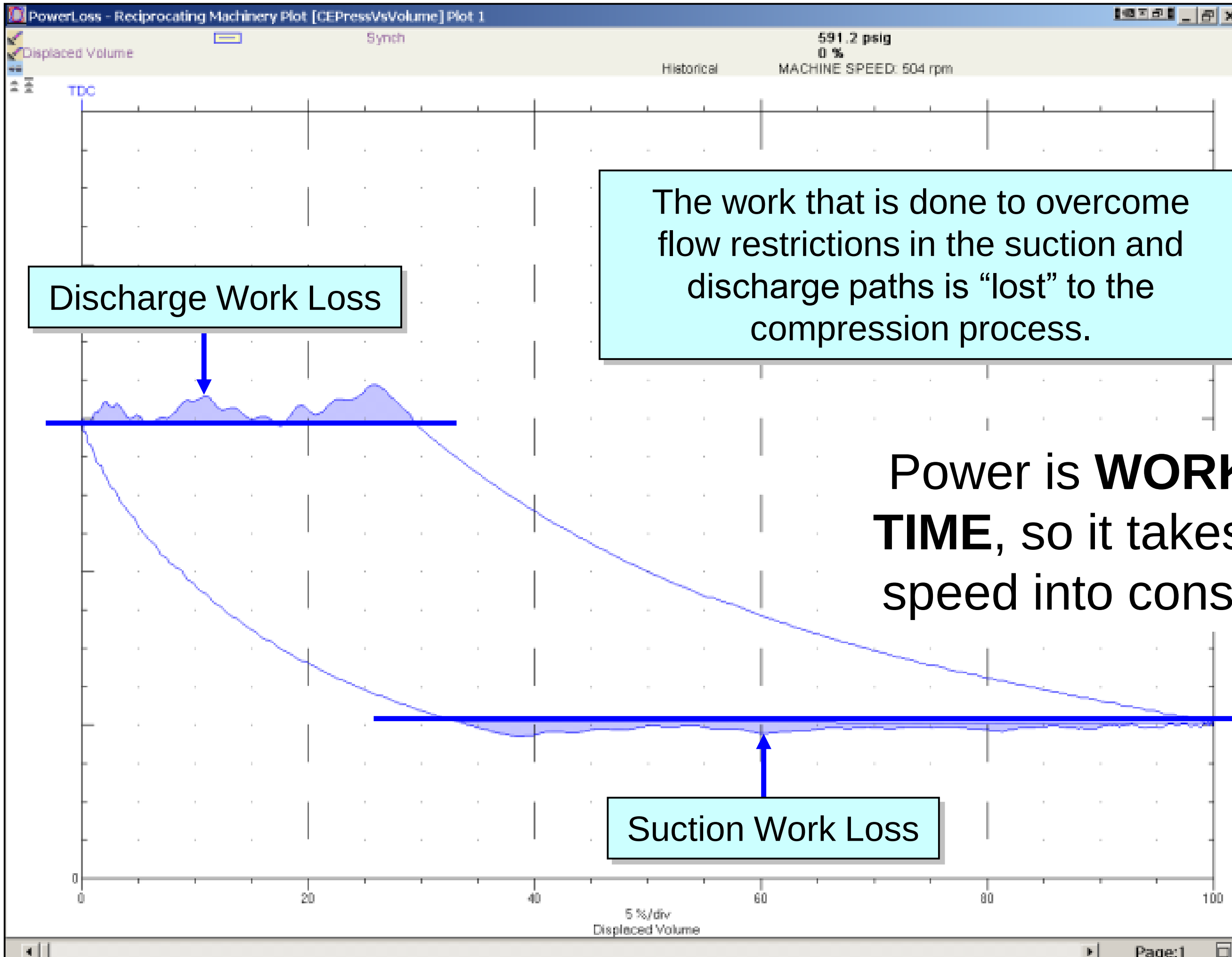


The **WORK** done on the gas for one complete cycle is shown by the cross-sectional area inside the measured cycle curve on a P-V plot.

Power is **WORK** per unit **TIME**, so it takes machine speed into consideration.

Power Losses

Performance Indicators

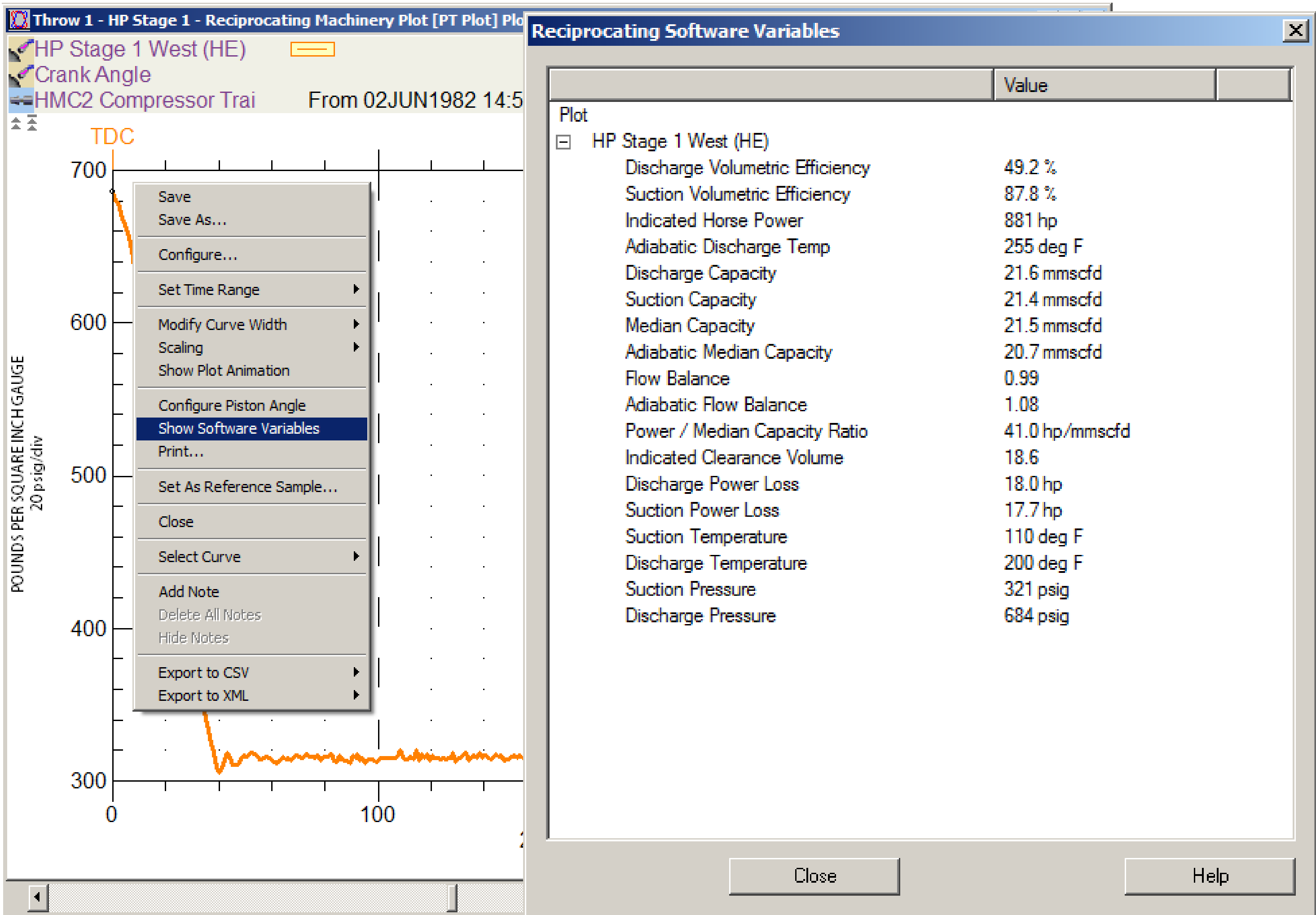


The work that is done to overcome flow restrictions in the suction and discharge paths is “lost” to the compression process.

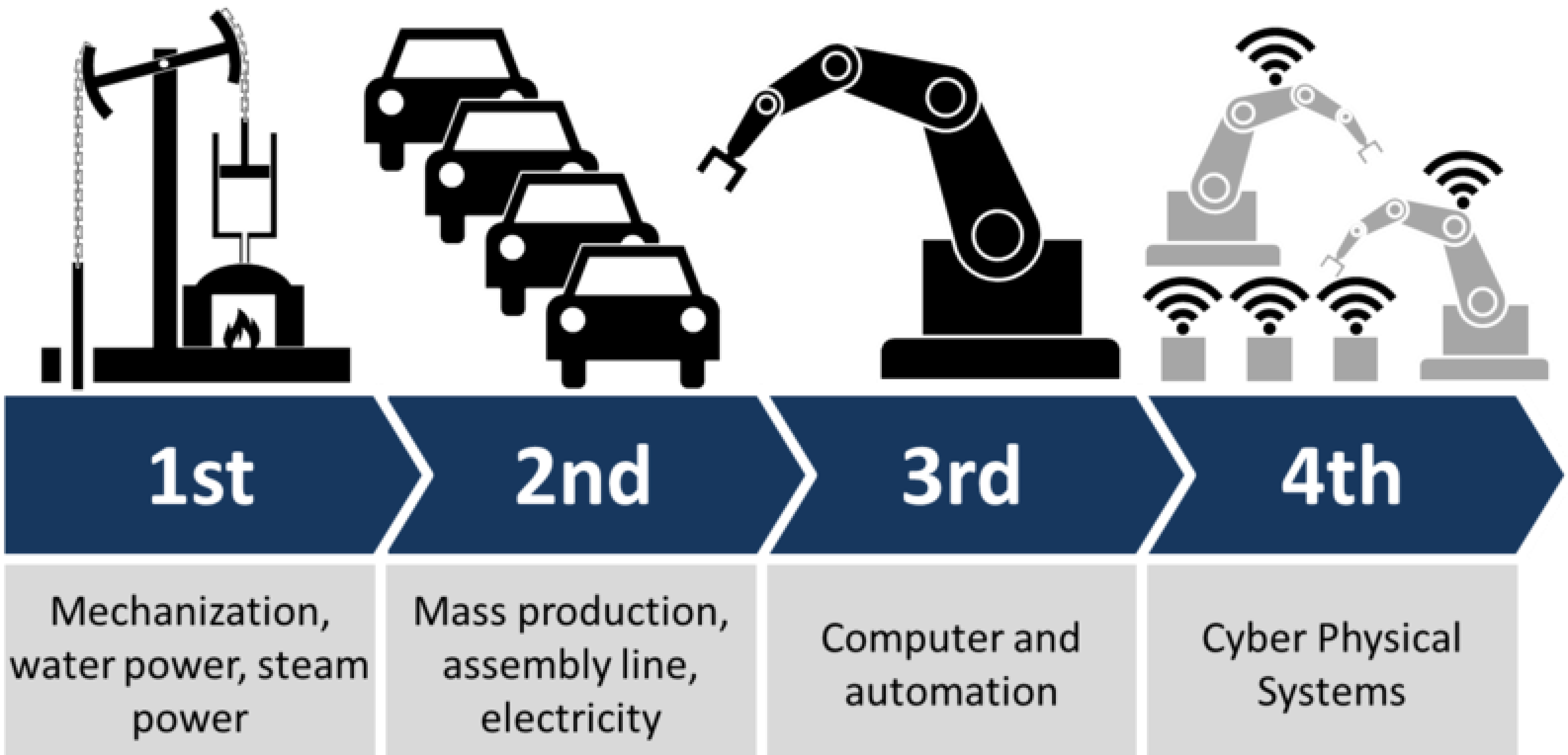
Power is **WORK** per unit **TIME**, so it takes machine speed into consideration.

Diagnostic Software Calculations

Performance Indicators



Industry 4.0



Source: http://www.allaboutlean.com/

What’s So Different?

Data

- Volumes
- Variety of sources
- Ubiquitous access & speed
- Low cost

Technology

- Smart devices & machines
- Connectivity
- Compute power

Big data – Example I

- Twin-engine civil aircraft
- 6 h flight NY → LA
- Produces 240TB data
- Analysed on-board with *Engine-indicating and crew-alerting system* (EICAS)

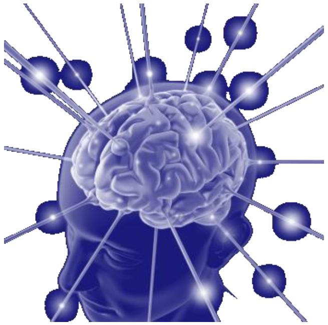
Big data – Example II

- 4-throw compressor
  – 21 probes
- 45 MB per minute
  = 64,8 TB per day
- Monitoring use software analytics methods

Characteristics of the Digital Enterprise

- **Information-driven**
  - Leverages data, advanced analytics, and modern platforms throughout enterprise
- **Core and contract**
  - Optimize around core strategic capabilities, outsource balance
- **Smart, connected ecosystem**
  - Dynamic, real-time information throughout value chain; adaptive business processes
- **Value-based products/services, smart environments**
  - Data–rich, outcome oriented, remote monitoring, as-a-service enabled
- **Service savvy**
  - Services as/more important than physical equipment; connected business models
- **Quickly adaptive to customer**
  - Solve customer problems through new services

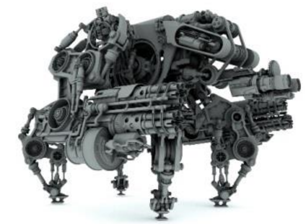
Tools of the Digital Enterprise



Visual Analytics

Machine Learning

Streaming Analytics



Smart Machines

Cognitive Computing/AI

Predictive Analytics

Augmented Reality

Enhanced Plant Apps

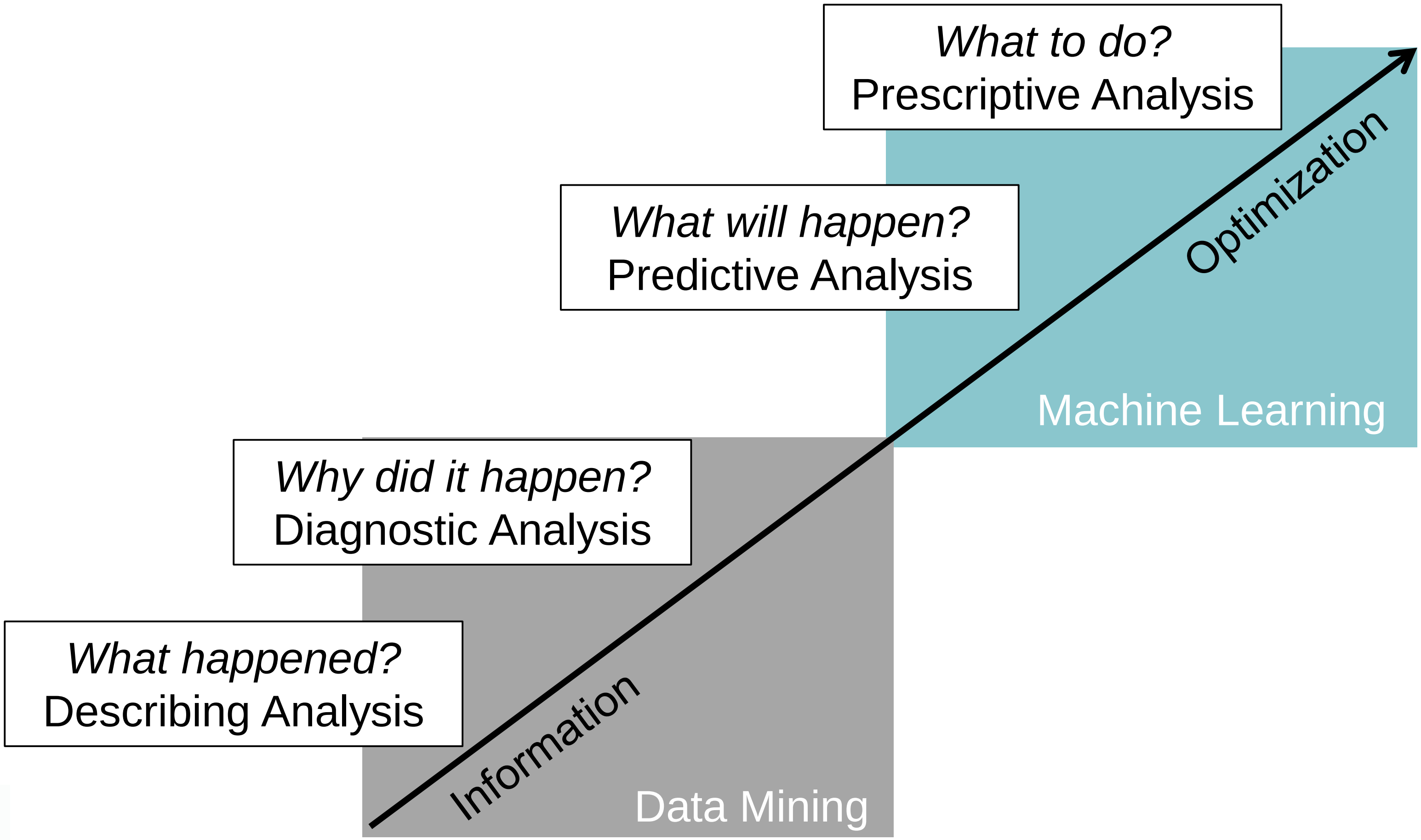
Big Data development

- Big Data is known as „Data Warehousing“ and „Data Mining“ since the late 1990´s
- First application was ERP/CRM
- Data analyses was performed with economically-oriented statistical methods
- *What happened?* (Description)
- *Why did it happen?* (Diagnostics)

Big Data development

- Future of Big Data is „Prediction“ of e.g. demographical developments or customer churn or traffic jam predictions
- Amazon & Co. are the drivers
- Engineering/mechanical statistical methods are in their early days
- *What will happen?* (Prediction)
- *What to do?* (Prescription)

Big Data development



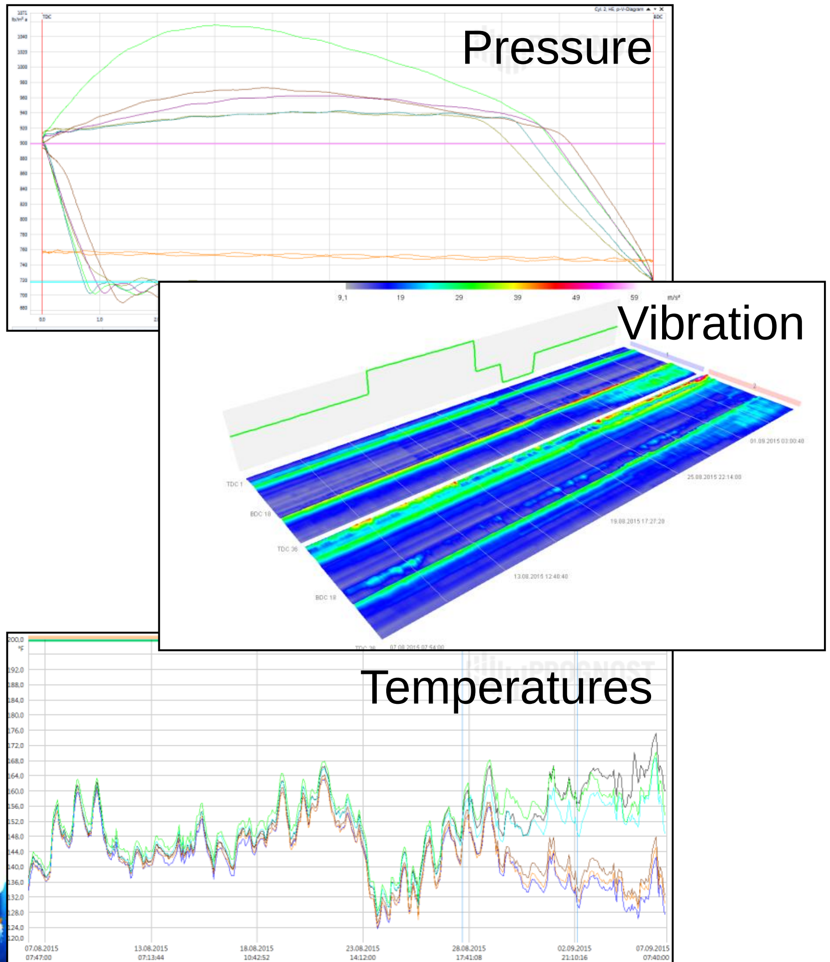
Machine Learning

- „Machine Learning“ = Knowledge from Experiences
- Different scientific methods are used to enable machines to make experiences, i.e. to learn
    - Supervised Learning
    - Regression cluster
    - Decision Trees
    - Support Vector Machines
    - Fuzzy Systems
    - Neuronal Networks

Big Data in CMS

- Diagnostics of machines, the reliable identification of failure pattern and the output of clear information is key for meaningful condition monitoring
- Today, some systems are in the beginning of the „Prediction“ phase
- Mostly linear developments, e.g. rider band wear

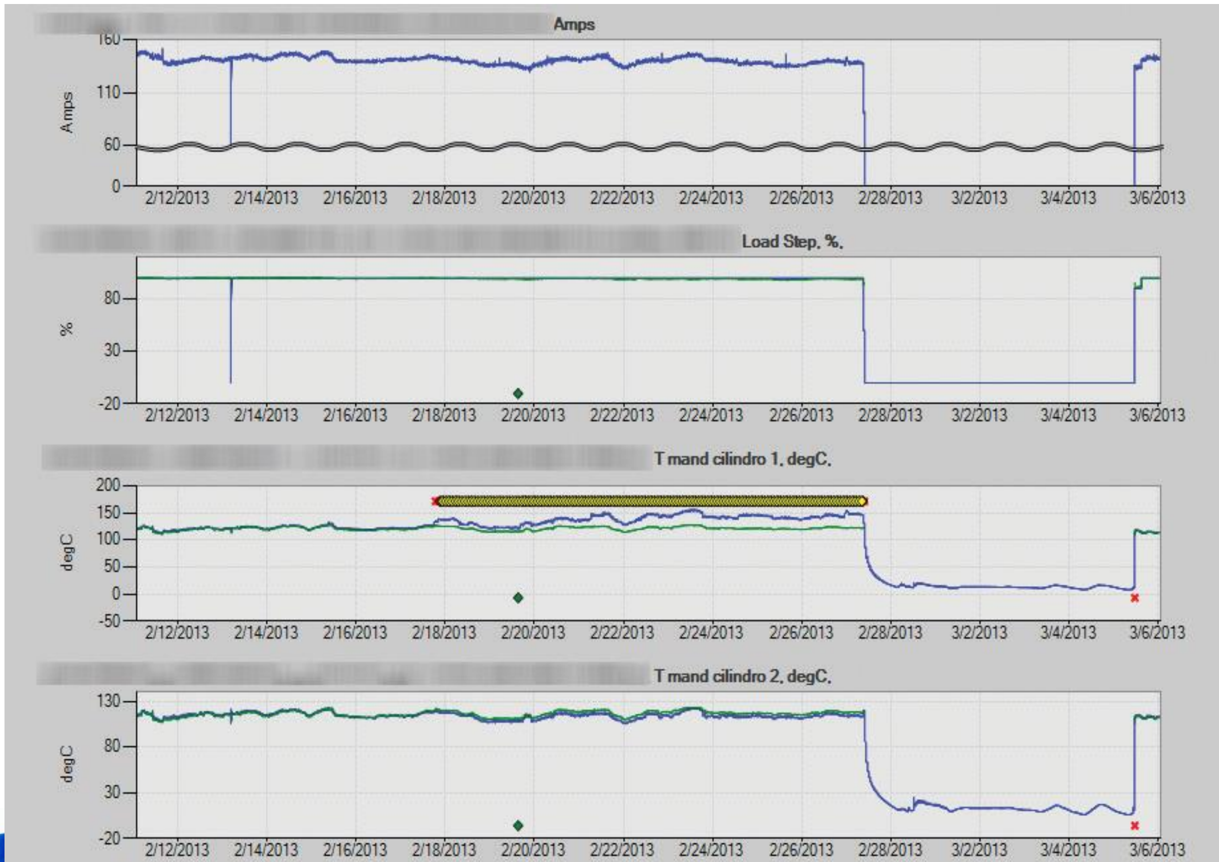
Big Data – Example of usage in Condition Diagnostics



Pattern recognition compares signals based on known cases and results in automatic message:

„Blocked discharge Valve issue Cyl. XY"

Big data – Example of usage in Condition Diagnostics



Multivariate predictive **empirical modeling** engine that uses the operating and environmental profile for each piece of equipment, combined with first principles **rules** and FMEA **patterns** to provide diagnostic advisories:

„Valve Leak Cylinder X"

Industry Goals

Need to make operation safer and more reliable while helping to ensure optimal performance at a lower sustainable cost.

An intelligent asset strategy for each asset is needed to collect and manage all data and information to make the best decisions that help maximize overall asset and operational performance.

Elements of Asset Performance Management Platform

- Collect, analyze, and visualize the data that is crucial to assets' health
- Prioritize work by determining which assets are most critical to the overall health of operation
- Understand the true status of each asset
- Predict equipment and process issues with greater accuracy before they occur
- Assure mechanical integrity of assets and compliance with regulations
- Learn from continuous, real-time analysis and visibility to understand the options for mitigating potential problems while balancing associated costs, risks, and benefits
- Define and manage asset strategies with a risk-based approach for improved planning and efficiency

Summary

By leveraging cutting-edge data science, domain experience and analytics technology, today's solutions for the Industrial Internet are able to balance traditionally competing priorities – reducing costs, improving availability, and managing risk—to provide intelligent asset strategies that help maximize asset performance and productivity.