MACHINERY
MONITORING
SYSTEMS, LLC

Machinery Monitoring Systems, LLC
Fairview Technology Center
11020 Solway School Road
Suite 105
Knoxville, TN 37931

MMS Product Overview

10/13/2022

Bryan Stewart – VP of Sales and Operations

Kent Petersen – VP of Product Management

Steve Follmar – CEO

MACHINERY
MONITORING
SYSTEMS, LLC

Agenda

MACHINERY MONITORING SYSTEMS, LLC

- MMS Management Introduction
- Alliance Partners
- Technology Partners
- Current Product Portfolio Overview
  - Snapshot Engine Balancer
  - MachineryRX Web Application
  - Sentinel Compressor Monitoring
  - ProBalance and ProBalance Plus
  - What's Next
- MMS\RCT

MMS Management

MACHINERY MONITORING SYSTEMS, LLC

Steve Follmar, President
- Windrock (Co-Founder)
- Cook Compression
- Beta Monitors
- Bentley Nevada

Glenn Mincher, VP Engineering
- Windrock (Co-Founder)
- CSI (Emerson)
- Bentley Nevada

Kent Petersen, Product Manager
- Windrock
- MAARS
- Nuclear Power Industry

Donna Stewart, VP Marketing & Training
- Medical Administration & Training

Bryan Stewart, VP Sales & Operations
- Hoerbiger
- Digicon
- KCI (Exterran)
- Ingersoll-Rand

Warren Laible, Subject Matter Expert
- Windrock
- Weatherford Global Compression
- Ro-Cip

John Biondolillo, VP Business Development
- Linde (Praxair)
- JM Canty Process Technology

Rachel Clark, Manufacturing Manager
- Windrock
- Siemens

Alliance Partners

MACHINERY MONITORING SYSTEMS, LLC

Exline

- Exclusive Distributor & Installation Services
- Packing Leak Sensor Manufacturer

ACI Services

- Software
- Compressor Models

STI Vibration Monitoring

- Monitoring Products
- Machining Services

Radical Combustion Technologies

- Clean Energy Solutions
- Advanced Engine Controls

Technology Partners

MACHINERY MONITORING SYSTEMS, LLC

Monico
- Industrial Computing
- Software & Edge

monico™
SIMPLE SOLUTIONS. POWERFUL MONITORING.

IMES
- Pressure Sensors
- Engine Monitoring

imes
the cylinder pressure people

PCB Piezotronics
- Accelerometers
- Impact sensors
- Ultra-Sonic Sensors

PCB PIEZOTRONICS
AN AMPHENOL COMPANY

Shinkawa
- Proximity Products
- Vibration Monitoring

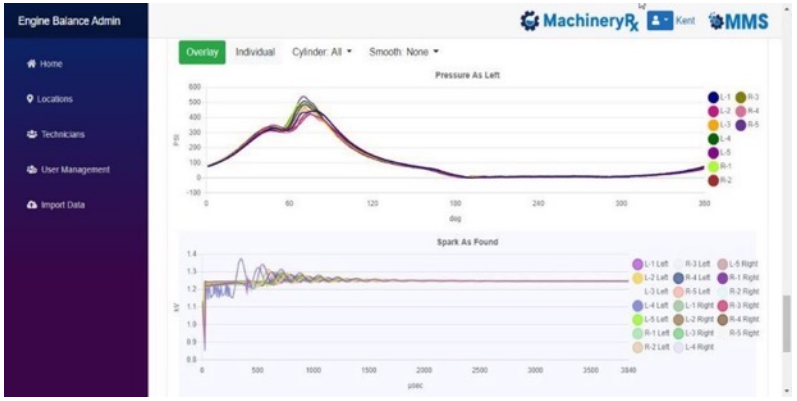
SEC SHINKAWA

Current Product Portfolio

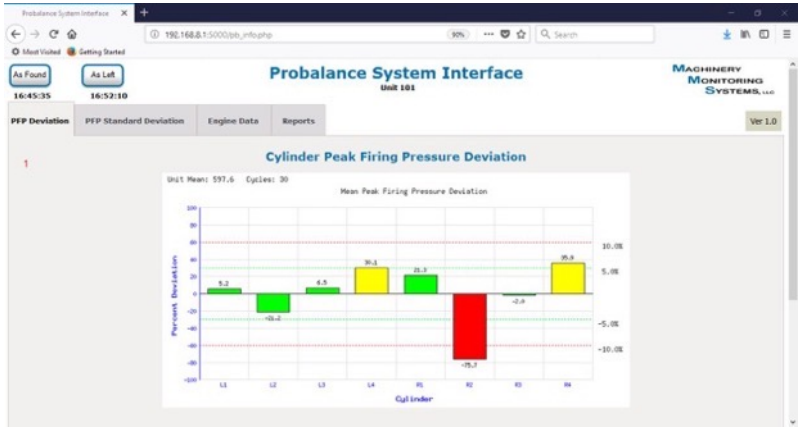
MACHINERY MONITORING SYSTEMS, LLC

Snapshot® - Portable Engine Balancer
Pressure and Ignition Analyzer

MachineryRX Web Application



ProBalance - 24/7 Monitoring



Sentinel Compressor Monitoring
Embedded ACI eRCM Model

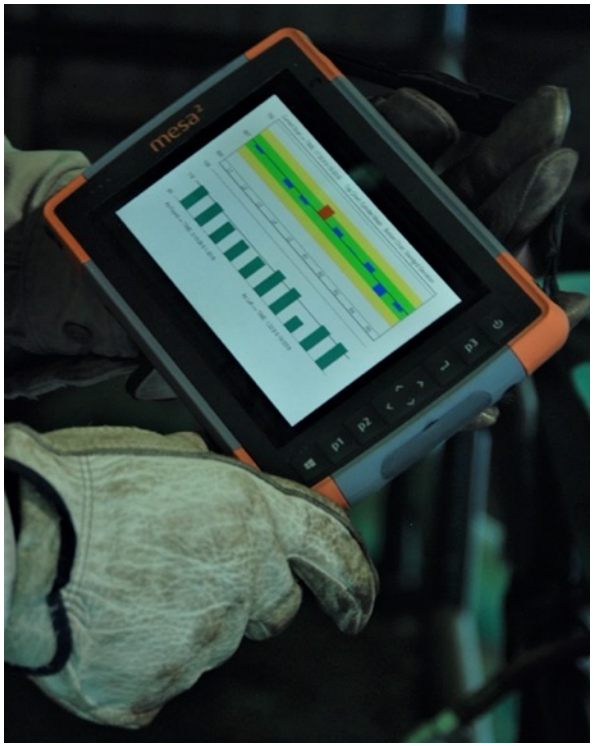
- Dynamic Pressure sensors
  - Alarms on Safety limits
  - Automated Diagnostic alarms
- Vibration and Impact sensors
  - Xhead, frame, cylinder and bearings
- Packing Vent Leakage sensor
  - Aid in Packing diagnostics
- Rod Drop sensor
  - Rider Band wear

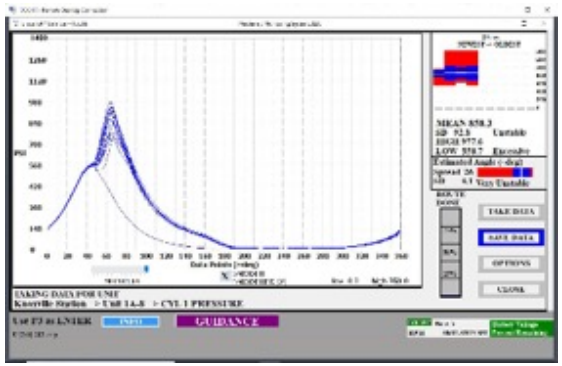
Snapshot® Portable Engine Balancer

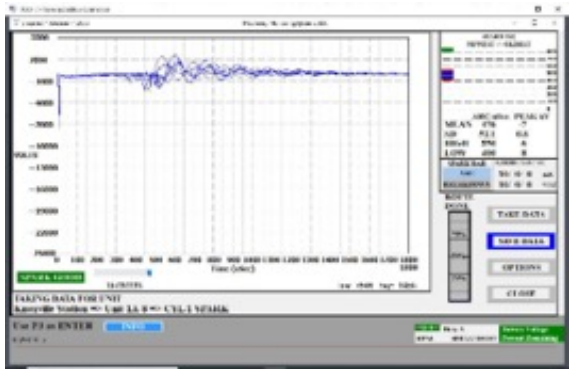
MACHINERY MONITORING SYSTEMS, LLC

Dynamic Engine Pressure

Ignition







MachineryRx™

Machinery Monitoring Systems, LLC

MachineryRx Admin

- Home
- Locations
- Technicians
- User Management
- Sys Admin
- Import Data

MachineryRx Kent MMS

MachineryRx™

Moore Gas Pipeline

Balance Job Status

	Summary Level	Total Machines	Total Balances	Balanced Early	Balanced Late	Avg Hours Between Balances	Avg Minutes to Balance	Percent Left Good	Personnel Involved	Total Rated Power
↓	Division 1	5	8	100.0%	0.0%	305.6	56.5	100.0%	2	10,550
↓	Division 9	9	44	0.0%	2.0%	5067.0	1858.3	27%	3	19,400
		14	**52**	**15.4%**	**1.92%**	**2686.3 hrs**	**1421.5 min**	**38.5%**	**3**	**29,950**

Recent Balance Jobs

	Location	Rated Power	Model Number	Manufacturer	Balanced By	Balance Date	Time To Balance (Minutes)	As Found Balance	As Found Condition	As Left Balance	As Left Condition
	Unit 1	1500	410-KVR	Ingersoll Rand	PaulW	Sep 28, 2021	56 min	?	Fair	3.0%	Good
	Unit 3A	1650	HBA-6T	Clark	Kent	Sep 24, 2021	0 min	?	Unknown	n/a	Unknown
	Test 4 Cylinder	1000	Model Number	Cooper	Kent	Sep 22, 2021	0 min	2.6%	Good	n/a	n/a
	Test 4 Cylinder	1000	Model Number	Cooper	Kent	Sep 22, 2021	6 min	2.6%	Good	2.6%	Good
	Test 4 Cylinder	1000	Model Number	Cooper	Kent	Sep 10, 2021	0 min	2.6%	Good	n/a	Unknown

+10 Jobs

MachineryRx™

Machinery Monitoring Systems, LLC

A new way to track Machinery Health across the company

- Accessed with Browser
- Can be run in the Cloud or on a User's Network
- Type of Machine, OEM, Vintage or Sensor suite does not matter
- Data is encrypted
- SQL database is setup by Company, Division, Area, Station and Machine
- Adding, deleting and setting Users access\capabilities is done by Sys Admin
- Static, dynamic and calculated data can be collected, arranged and displayed as Management Reports, Dashboards or Trend graphs
- Technical Staff with proper credentials can drill down to individual sensor waveforms in a wide variety of typical formats

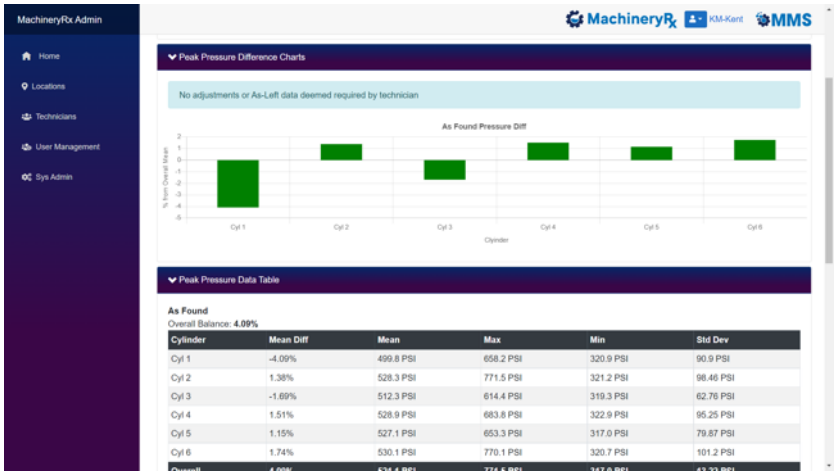
Typical Display of Reports and Plots

MACHINERY MONITORING SYSTEMS, LLC

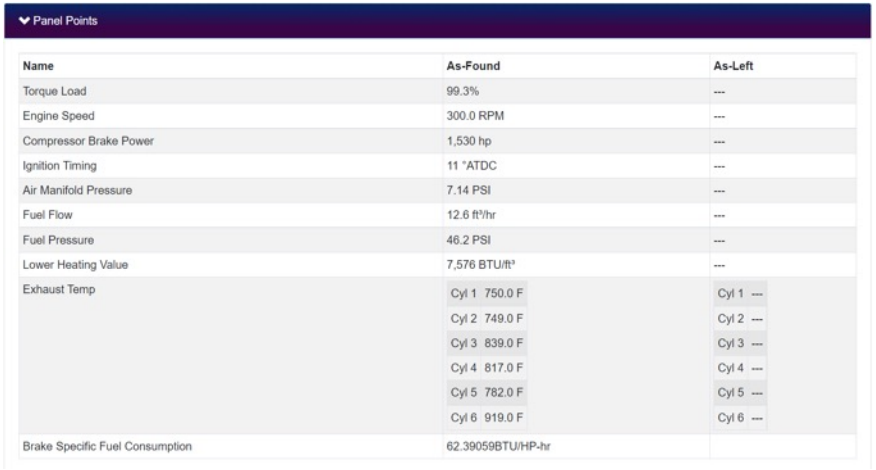
Pressure and Ignition waveforms

Vibration waveform and FFT

Engine Balance Plot



Panel Points



Panel Points

Name	As-Found	As-Left
Torque Load	99.3%	---
Engine Speed	300.0 RPM	---
Compressor Brake Power	1,530 hp	---
Ignition Timing	11 °ATDC	---
Air Manifold Pressure	7.14 PSI	---
Fuel Flow	12.6 ft³/hr	---
Fuel Pressure	46.2 PSI	---
Lower Heating Value	7,576 BTU/ft³	---
Exhaust Temp	Cyl 1 750.0 F Cyl 2 749.0 F Cyl 3 839.0 F Cyl 4 817.0 F Cyl 5 782.0 F Cyl 6 919.0 F	Cyl 1 --- Cyl 2 --- Cyl 3 --- Cyl 4 --- Cyl 5 --- Cyl 6 ---
Brake Specific Fuel Consumption	62.39059BTU/HP-hr	

Sentinel® Compressor Monitoring

MACHINERY MONITORING SYSTEMS, LLC

- Designed for high-speed data collection
  - Used for Safety alarming – startup issues, rod Loading, Vibration etc.
  - Real time IHP for control application
- 3 Versions available
  - CPM – compressor dynamic pressures
  - VM – Vibration and Flow sensors
  - EPM – Engine dynamic pressures ***
- Wide range of sensors for most applications
  - Voltage and current pressure sensors
  - Packing vent flow sensors
  - Rod Drop sensors
  - Vibration sensors
    - Accelerometers
    - Velometers
    - Proximity
    - Impact Sensors

*** EPM Not yet released

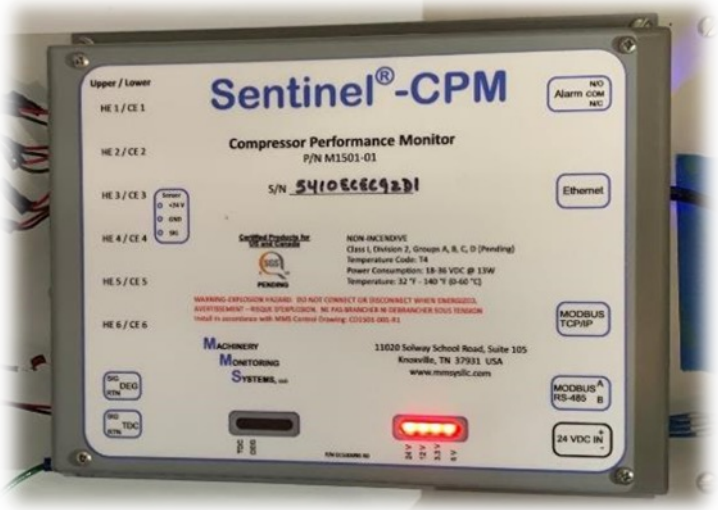
Sentinel®-CPM
Compressor Performance Monitor

MACHINERY MONITORING SYSTEMS, LLC

- 12 Input channels plus 2 phase trigger inputs
  Cylinder PVs & PTs

- Utilizes an ACI eRCM Kernel to calculate horsepower and additional performance parameters for each compressor cylinder.

- Results of the performance calculations are communicated to the customer PLC via TCP MODBUS or Serial RS485.



Embedded MMS version of the ACI eRCM Kernel

MACHINERY MONITORING SYSTEMS, LLC

- ACI eRCM Kernel with MMS enhanced performance calcs using *real time dynamic waveforms* (PVs & PTs).
- Compares theoretical calculated values from the eRCM Model with *actual measured* values in real time. Notable differences can help identify problems before they become failures.
- Real time measurements and alarming of rod loads, degrees of reversal, IHP and flow.

Additional Diagnostics

MACHINERY MONITORING SYSTEMS, LLC

The CPM automated diagnostic program alerts on all of the most common compressor faults

- Suction and Discharge valve leakage
- Piston ring leakage
- Packing leakage
- Unloader\Load step issues

The alert levels can be tuned for specific applications along with a User's tolerance for the amount of leakage that is acceptable

CPM Sensor Suite

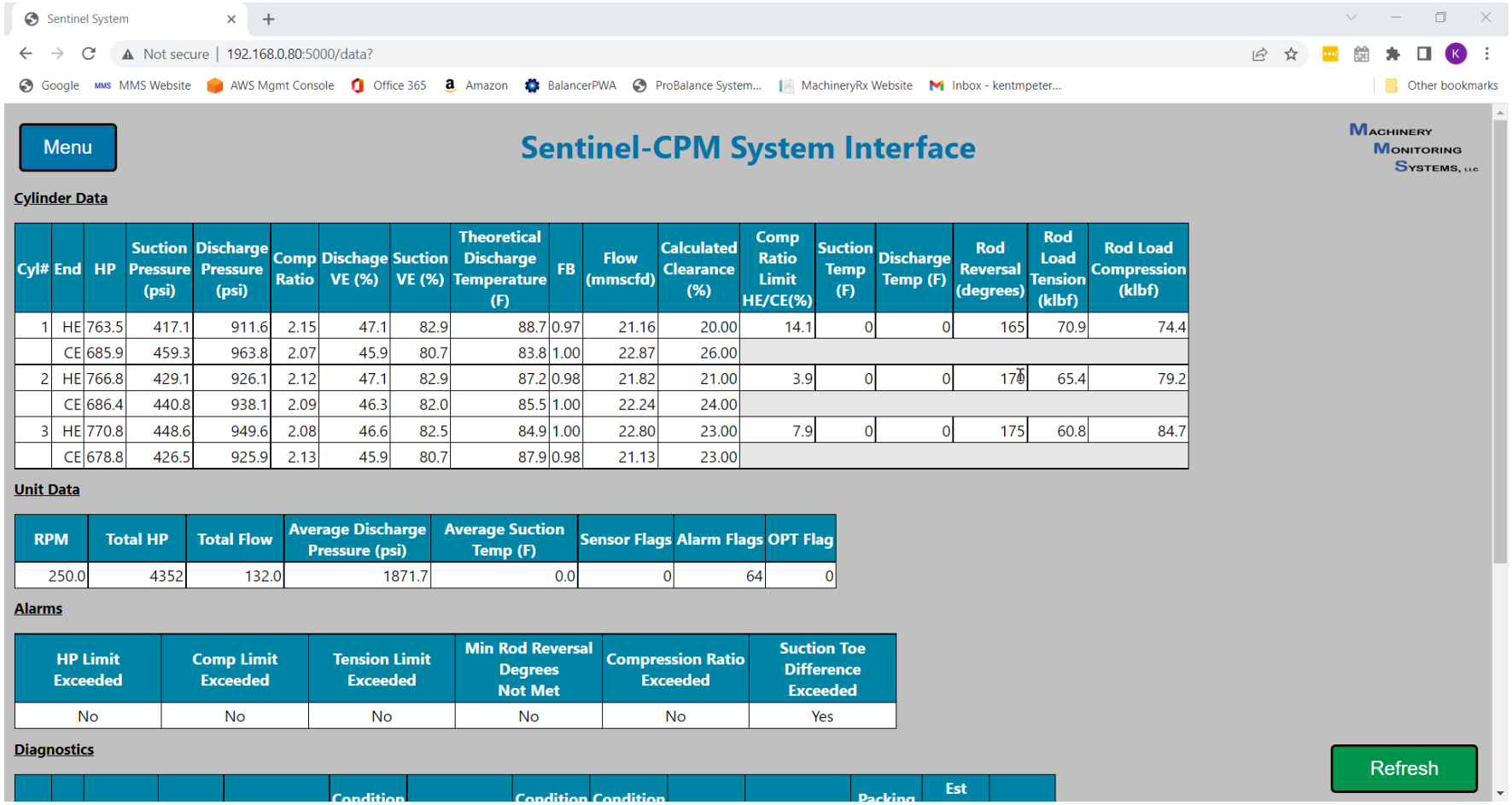
MACHINERY MONITORING SYSTEMS, LLC

- DC pressure sensors
  - IMES DC pressure sensors
- Magnetic Pickups
  - Altronic Magnetic pickups
- Packing Vent Flow Sensor
  - Used to enhance the embedded diagnostic program to differentiate between suction valve and packing leakage

Detail Cylinder Data

MACHINERY MONITORING SYSTEMS, LLC

Data available via Modbus and Web Browser



Cylinder Data

Cyl#	End	HP	Suction Pressure (psi)	Discharge Pressure (psi)	Comp Ratio	Dischage VE (%)	Suction VE (%)	Theoretical Discharge Temperature (F)	FB	Flow (mmscfd)	Calculated Clearance (%)	Comp Ratio Limit HE/CE(%)	Suction Temp (F)	Discharge Temp (F)	Rod Reversal (degrees)	Rod Load Tension (klbf)	Rod Load Compression (klbf)
1	HE	763.5	417.1	911.6	2.15	47.1	82.9	88.7	0.97	21.16	20.00	14.1	0	0	165	70.9	74.4
	CE	685.9	459.3	963.8	2.07	45.9	80.7	83.8	1.00	22.87	26.00						
2	HE	766.8	429.1	926.1	2.12	47.1	82.9	87.2	0.98	21.82	21.00	3.9	0	0	171	65.4	79.2
	CE	686.4	440.8	938.1	2.09	46.3	82.0	85.5	1.00	22.24	24.00						
3	HE	770.8	448.6	949.6	2.08	46.6	82.5	84.9	1.00	22.80	23.00	7.9	0	0	175	60.8	84.7
	CE	678.8	426.5	925.9	2.13	45.9	80.7	87.9	0.98	21.13	23.00						

Unit Data

RPM	Total HP	Total Flow	Average Discharge Pressure (psi)	Average Suction Temp (F)	Sensor Flags	Alarm Flags	OPT Flag
250.0	4352	132.0	1871.7	0.0	0	64	0

Alarms

HP Limit Exceeded	Comp Limit Exceeded	Tension Limit Exceeded	Min Rod Reversal Degrees Not Met	Compression Ratio Exceeded	Suction Toe Difference Exceeded
No	No	No	No	No	Yes

Diagnostics

					Condition		Condition	Condition			Packing	Est	

Sample Diagnostic Data

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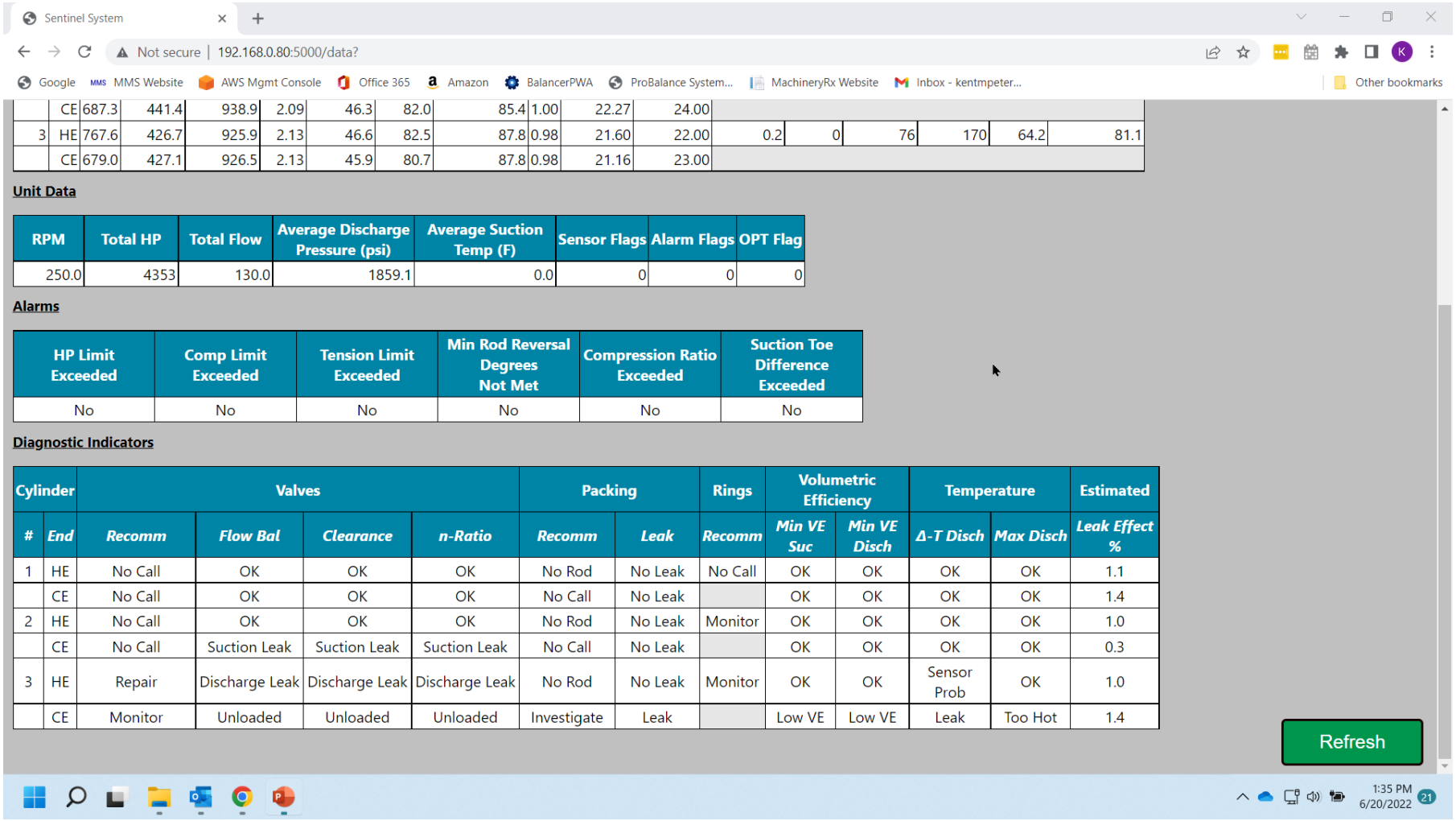


	CE	687.3	441.4	938.9	2.09	46.3	82.0	85.4	1.00	22.27	24.00						
3	HE	767.6	426.7	925.9	2.13	46.6	82.5	87.8	0.98	21.60	22.00	0.2	0	76	170	64.2	81.1
	CE	679.0	427.1	926.5	2.13	45.9	80.7	87.8	0.98	21.16	23.00						

Unit Data

RPM	Total HP	Total Flow	Average Discharge Pressure (psi)	Average Suction Temp (F)	Sensor Flags	Alarm Flags	OPT Flag
250.0	4353	130.0	1859.1	0.0	0	0	0

Alarms

HP Limit Exceeded	Comp Limit Exceeded	Tension Limit Exceeded	Min Rod Reversal Degrees Not Met	Compression Ratio Exceeded	Suction Toe Difference Exceeded
No	No	No	No	No	No

Diagnostic Indicators

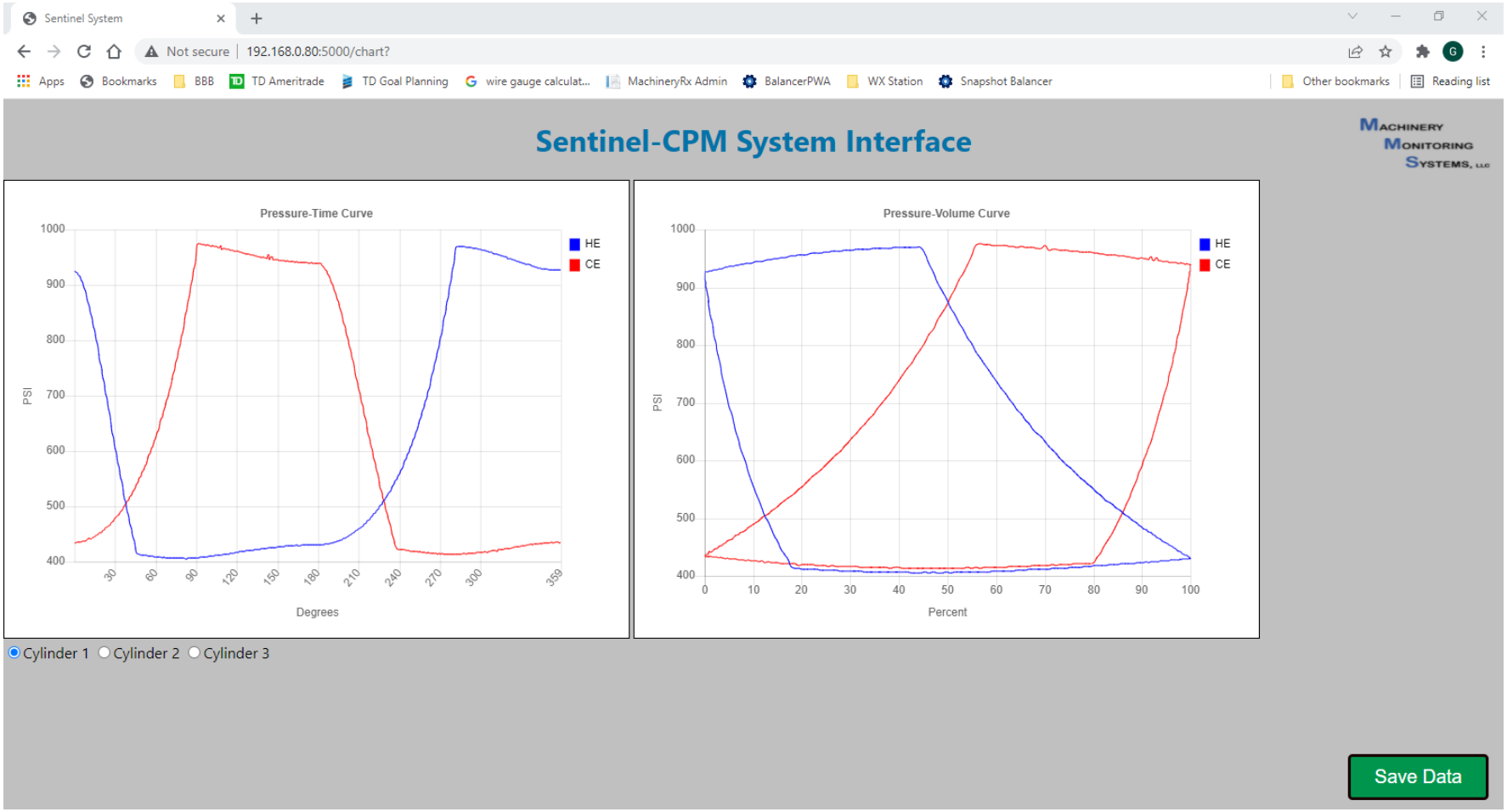
Cylinder		Valves				Packing		Rings	Volumetric Efficiency		Temperature		Estimated
#	End	Recomm	Flow Bal	Clearance	n-Ratio	Recomm	Leak	Recomm	Min VE Suc	Min VE Disch	Δ-T Disch	Max Disch	Leak Effect %
1	HE	No Call	OK	OK	OK	No Rod	No Leak	No Call	OK	OK	OK	OK	1.1
	CE	No Call	OK	OK	OK	No Call	No Leak		OK	OK	OK	OK	1.4
2	HE	No Call	OK	OK	OK	No Rod	No Leak	Monitor	OK	OK	OK	OK	1.0
	CE	No Call	Suction Leak	Suction Leak	Suction Leak	No Call	No Leak		OK	OK	OK	OK	0.3
3	HE	Repair	Discharge Leak	Discharge Leak	Discharge Leak	No Rod	No Leak	Monitor	OK	OK	Sensor Prob	OK	1.0
	CE	Monitor	Unloaded	Unloaded	Unloaded	Investigate	Leak		Low VE	Low VE	Leak	Too Hot	1.4

Refresh

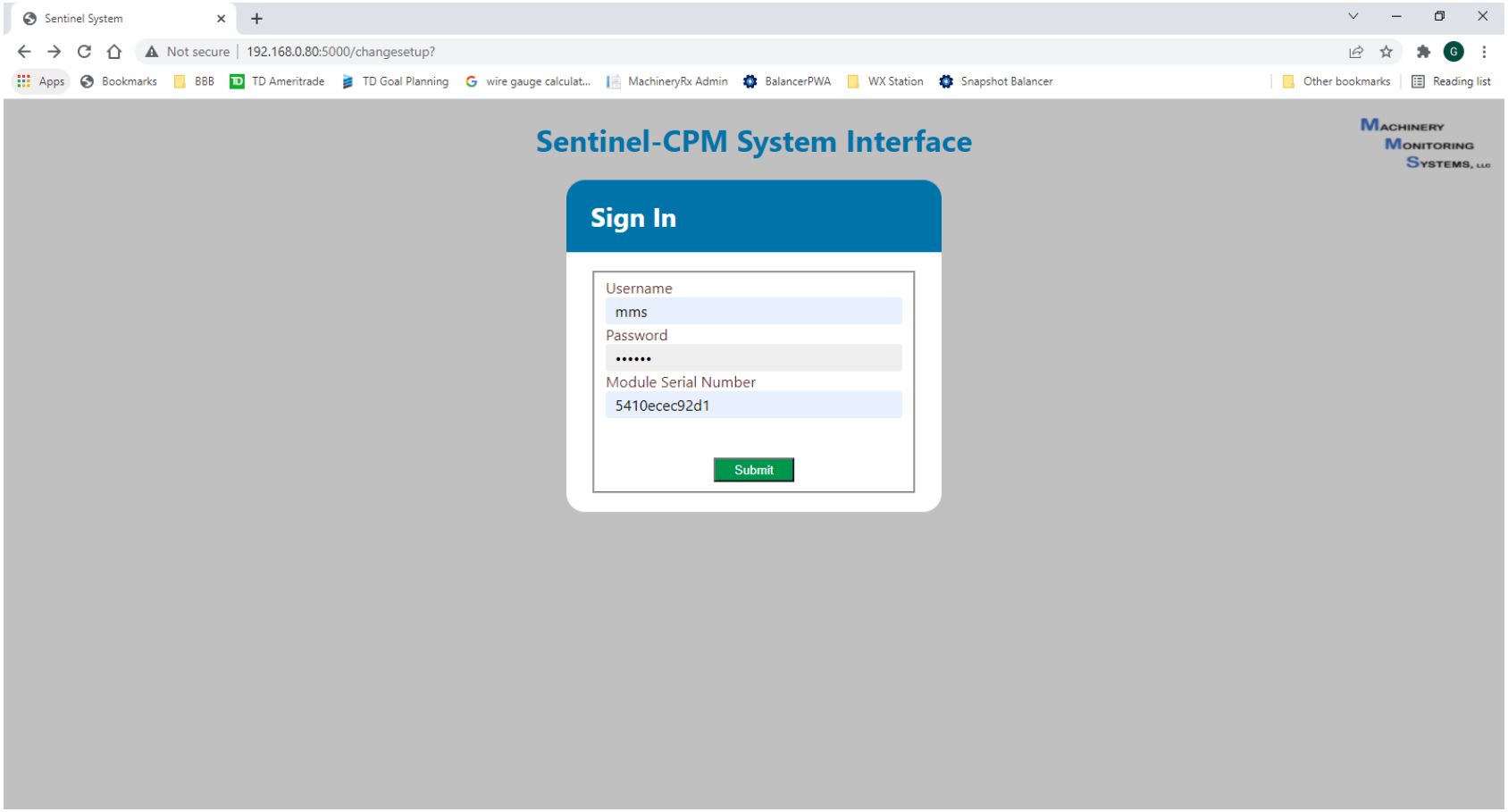
Phased P-T & P-V Curves

Machinery Monitoring Systems, LLC

Dynamic waveforms available via Network connection

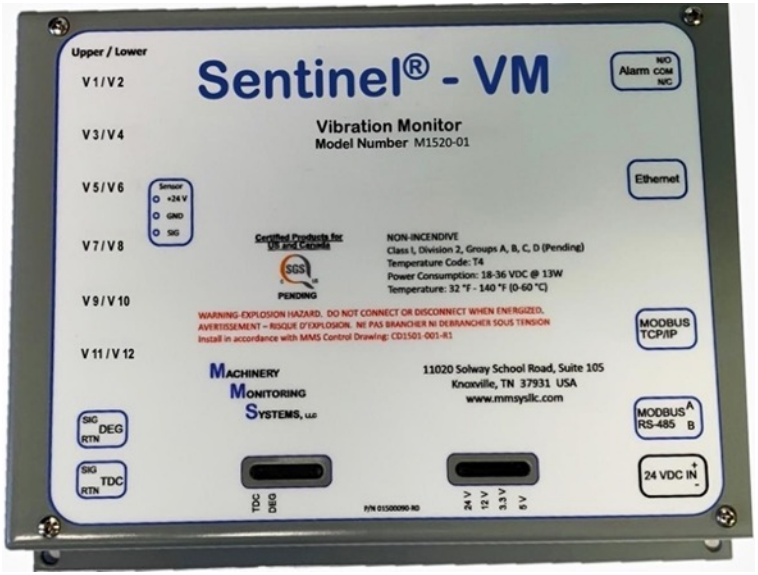


TSA Compliant Log-In



Sentinel®-VM
Vibration Monitor

MACHINERY MONITORING SYSTEMS, LLC

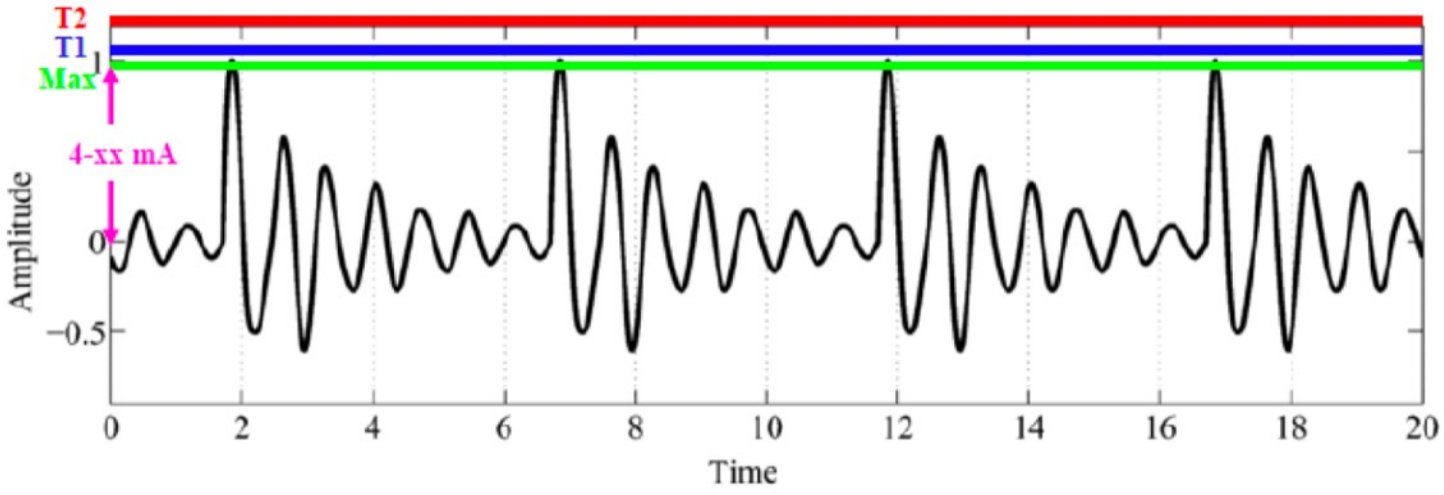


- 12 Vibration sensor inputs
  - Accelerometers
  - Velocity pickups
  - Proximity probes
- Crosshead vibration/impacts
- Frame/Bearing vibration
- Cylinder/Frame Movement
- Rod Drop\Rod Runout
- Communicate to Unit PLC
  - Modbus TCP
  - Modbus RS-485
- Web interface

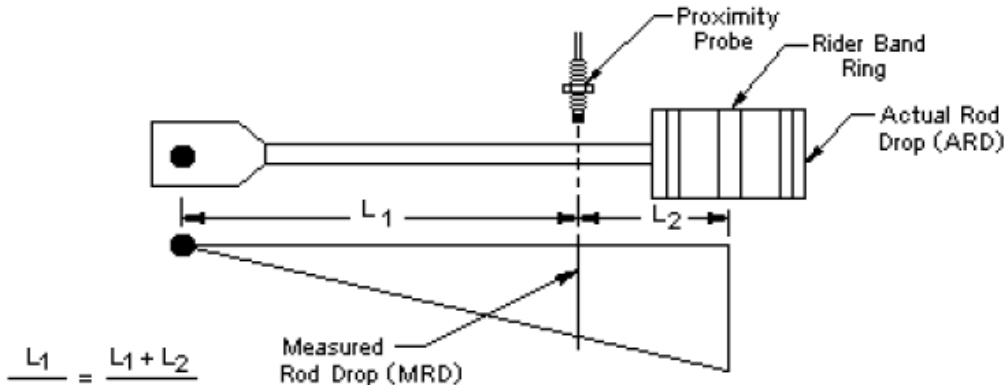
Sample of new Sentinel-VM input devices

MACHINERY MONITORING SYSTEMS, LLC

New method to detect Xhead mechanical impacts



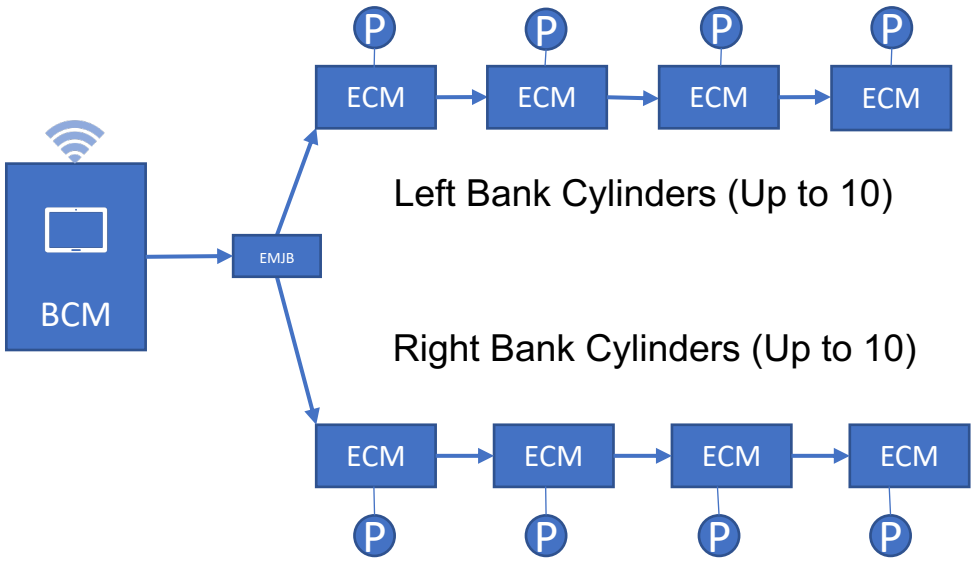
- Rod Drop = Rider Band Wear
- Rod Runout = Mechanical looseness



$$\frac{L_1}{MRD} = \frac{L_1 + L_2}{ARD}$$

$$\text{Actual Rod Drop} = \frac{\text{Measured Rod Drop}\,(L_1 + L_2)}{L_1}$$

ProBalance / ProBalance Plus



- BCM (Balance Control Module) mounted to UCP (Magnet or Bolted)
- Customer provided conduit BCM – EMJB (Engine Mounted Junction Box)
- MMS-supplied cables EMJB – ECMs (Engine Cylinder Module)
  - Armored
  - 6-Pin Amphenol Connectors
- MMS-supplied cables ECM-ECM
- Dual Port Kiene valves on each cylinder
- IMES or Kistler pressure sensors on each cylinder

ProBalance Components

MACHINERY MONITORING SYSTEMS, LLC

BCM mounted to UCP

ProBalance Components

MACHINERY MONITORING SYSTEMS, LLC

Wireless antenna

BCM mounted to UCP

ProBalance Components

MACHINERY MONITORING SYSTEMS, LLC

Wireless antenna

BCM mounted to UCP

Conduit to EMJB

ProBalance Components

MACHINERY MONITORING SYSTEMS, LLC

Wireless antenna

BCM mounted to UCP

Conduit to EMJB

Power (24VDC) and communications (MODBUS IP or RS-485)

ProBalance Components

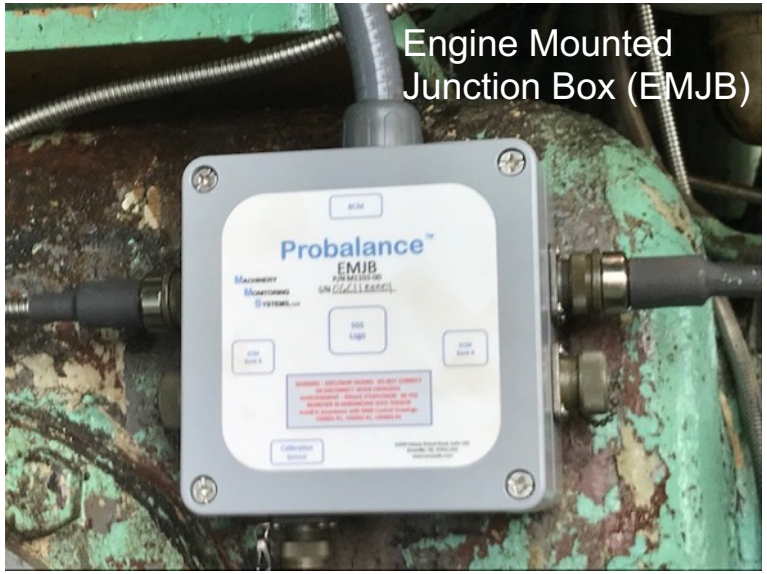
MACHINERY MONITORING SYSTEMS, LLC

Wireless antenna

BCM mounted to UCP

Conduit to EMJB

Power (24VDC) and communications (MODBUS IP or RS-485)



ProBalance Components

MACHINERY MONITORING SYSTEMS, LLC

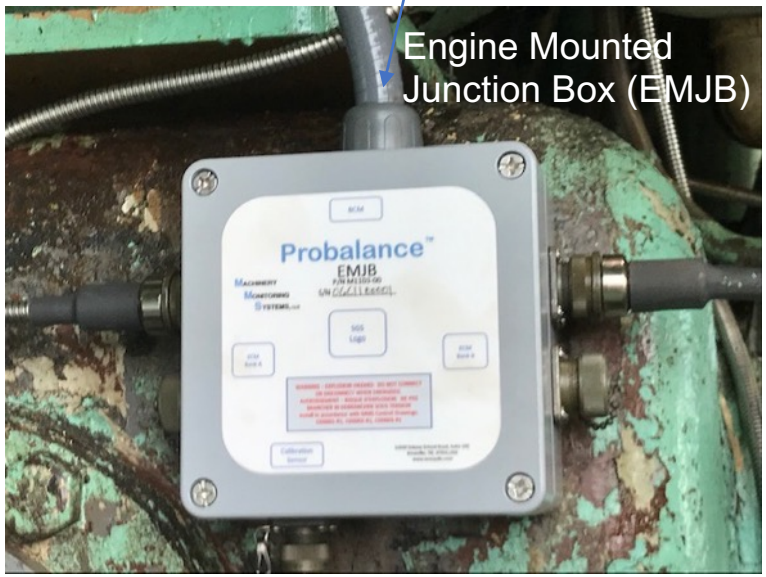
Wireless antenna

BCM mounted to UCP

Conduit to EMJB

Power (24VDC) and communications (MODBUS IP or RS-485)

Conduit from BCM



Engine Mounted Junction Box (EMJB)

ProBalance Components

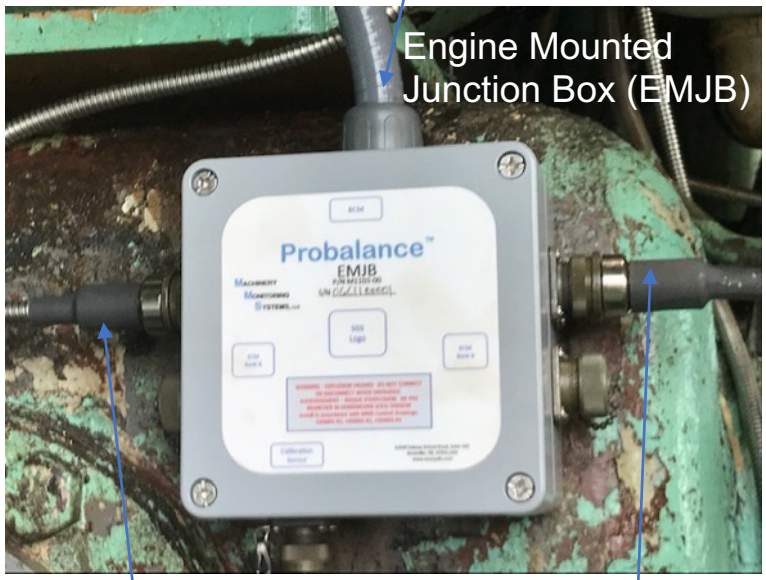
Wireless antenna

BCM mounted to UCP

Conduit to EMJB

Power (24VDC) and communications (MODBUS IP or RS-485)

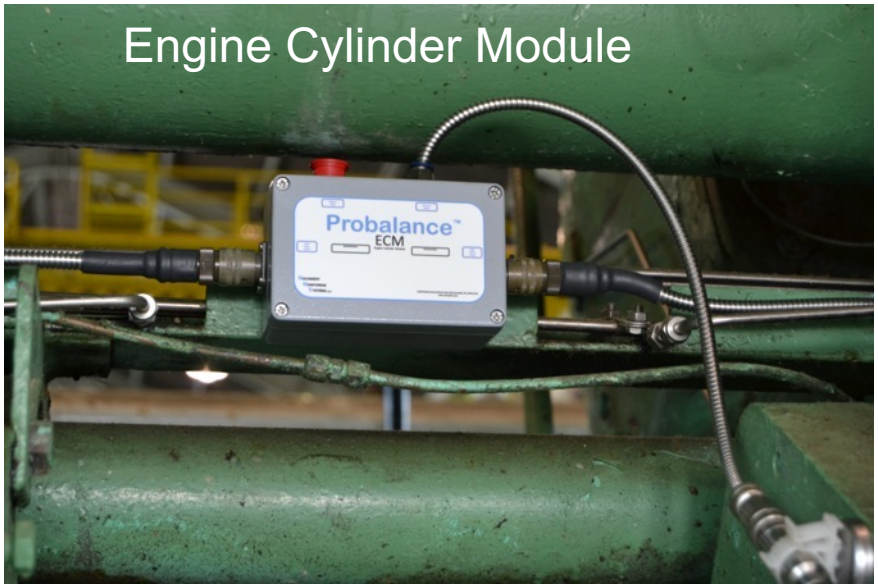
Conduit from BCM



Armored Cables to Bank A & B ECMs

ProBalance Components

MACHINERY MONITORING SYSTEMS, LLC



One per cylinder
Daisy-chained Communications & Power

Dual-port Kiene valve
w/ pressure sensor

ProBalance Use

MACHINERY MONITORING SYSTEMS, LLC

- Live, continuous PFP data wirelessly to tablet
- Adjust balancing valve on cylinder
- See effect on balance for all cylinders immediately
- Operator verifies balance anytime on the BCM (at UCP)

ProBalance Use

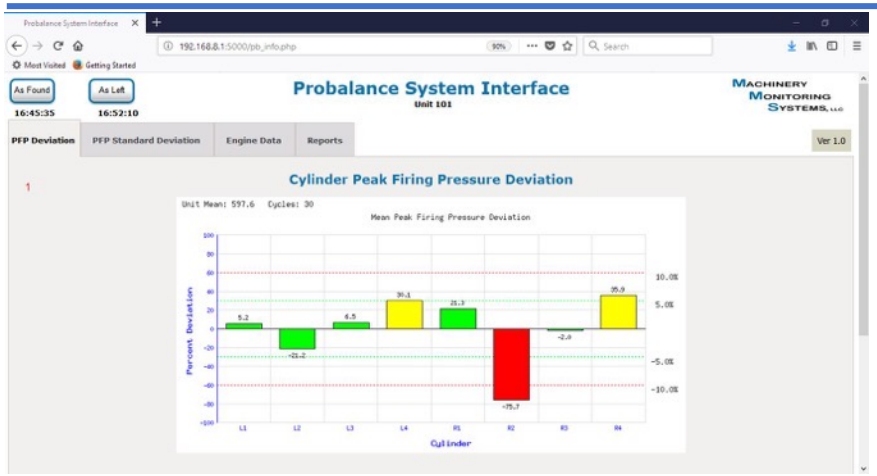
MACHINERY MONITORING SYSTEMS, LLC

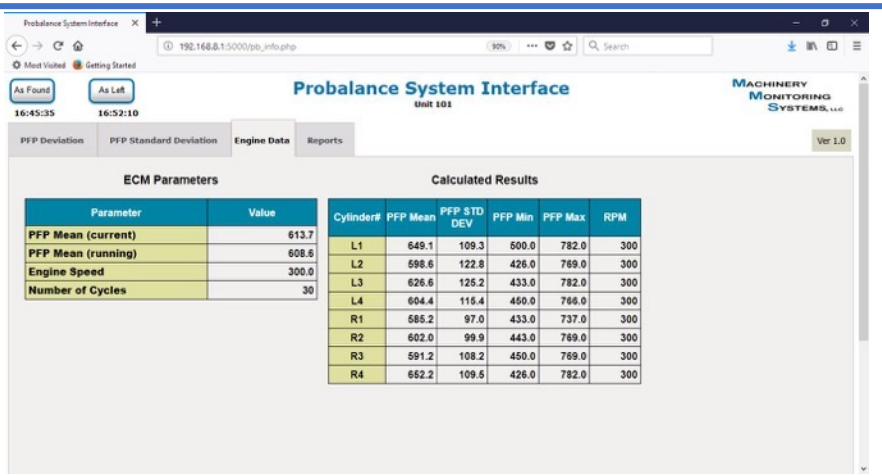
- Live, continuous PFP data wirelessly to tablet
- Adjust balancing valve on cylinder
- See effect on balance for all cylinders immediately
- Operator verifies balance anytime on the BCM (at UCP)

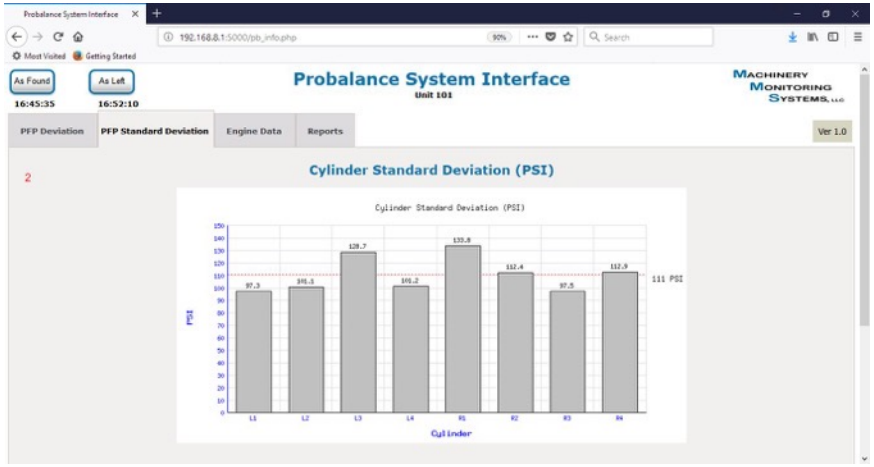
10
~~45 – 90~~ *Minutes for an 8-cylinder engine*

ProBalance Tablet Screens

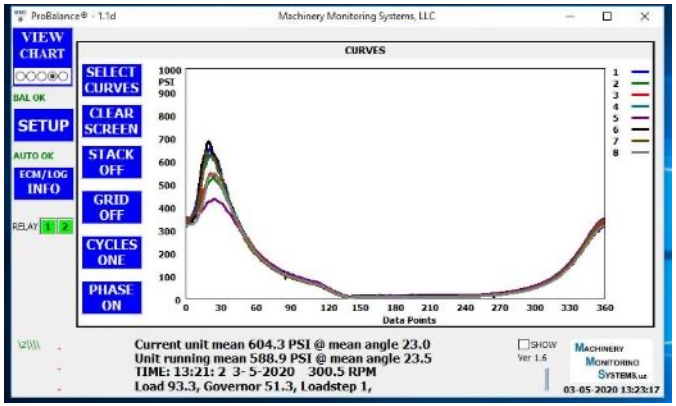
MACHINERY MONITORING SYSTEMS, LLC

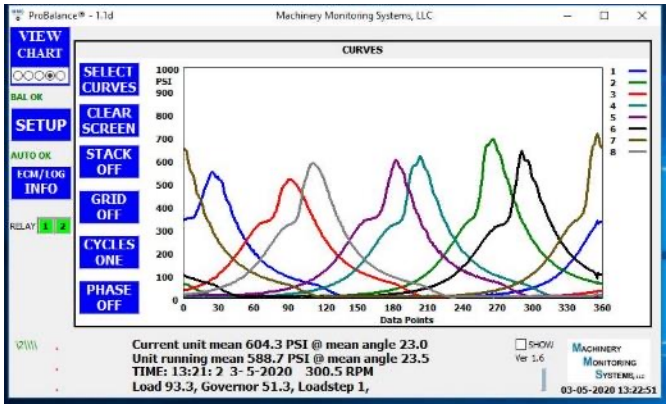


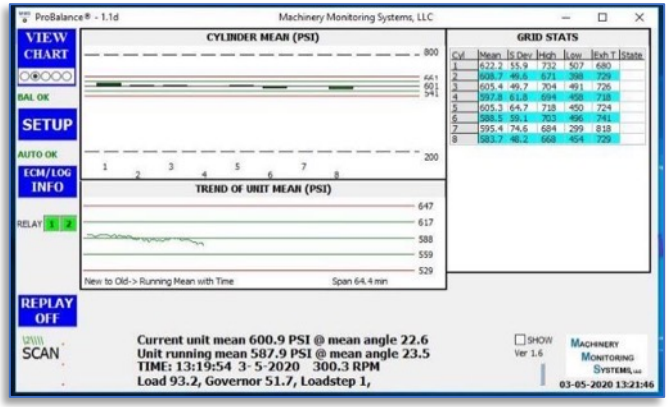




ProBalance BCM Screens







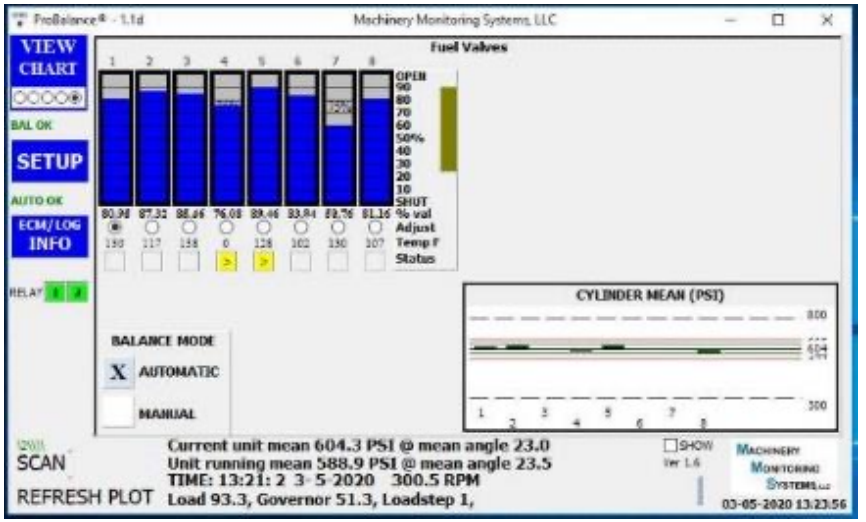
Version 2.0 updated User Interface to be released soon

ProBalance Plus Upgrade

MACHINERY MONITORING SYSTEMS, LLC

Automatic Balancing w/ ProBalance Plus

- Add electronically controlled fuel balancing valves
- Comm cable from each ECM
- Daisy-chained power from EMJB



Electronic Balancing Valve Features

MACHINERY MONITORING SYSTEMS, LLC

Comparison of MMS ProBalance Plus Balancing Valve to Others		
MMS eFGM	**Others**	**Comments**
Position feedback	None	No calibration of valves necessary
Stepper motor directly coupled to valve	Rubber belt	Reliability
Temperature sensor in valve	None	Identifies hi temp valve body Common valve failure is from a failure of the cam operated fuel valve
Retrofittable to existing manual CECO FGMs	No	Years of operating experience with CECO balancing valves
EMI & Vibration ruggedized	No	Reliability
Simplified wiring (Power – 24VDC & Serial Pair)	6 conductor cable from UCP to each valve	Reliability, ease of installation & cost
Manual override adjustability	No	Stem on top of stepper motor
High torque stepper motor	No	Supports manifold pressures up to 125 PSI

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ProBalance Experience

MACHINERY MONITORING SYSTEMS, LLC

- TLA-8
- TLAD-5
- GMW-8
- GMVH-12
- HBA-6
- HBA-10
- TCV-16
- W-330
- Z-330
- KVR-8 (PO Pending) – will be 1st 4 stroke engine

Optional Balancing Methods

MACHINERY MONITORING SYSTEMS, LLC

- **Peak Firing Pressure (PFP)** is the most common balancing method – probably due to the history of balancing – it was easy to measure.
- It is accomplished by measuring the firing pressures of all the cylinders, calculating the mean of those pressures, and adjusting the firing pressures as close to that mean pressure as possible.

OR

Peak Pressure Ratio (PPR) is a method suggested in EPPL / SWRI / DOE study in 2008. In this method, the PFP and the unfired Compression Pressure (Cp) of each cylinder is measured.

The compression pressure is an indication of how much air is trapped in the cylinder. Since we cannot change that, by inputting the proper amount of fuel into each cylinder, we can control the equivalence ratio, which profoundly influences the combustion process.

Peak Pressure Ratio Balancing

MACHINERY MONITORING SYSTEMS, LLC

- The PFP is divided by the Cp establishing the PPR.

$$\boldsymbol{PPR = PFP \div Cp}$$

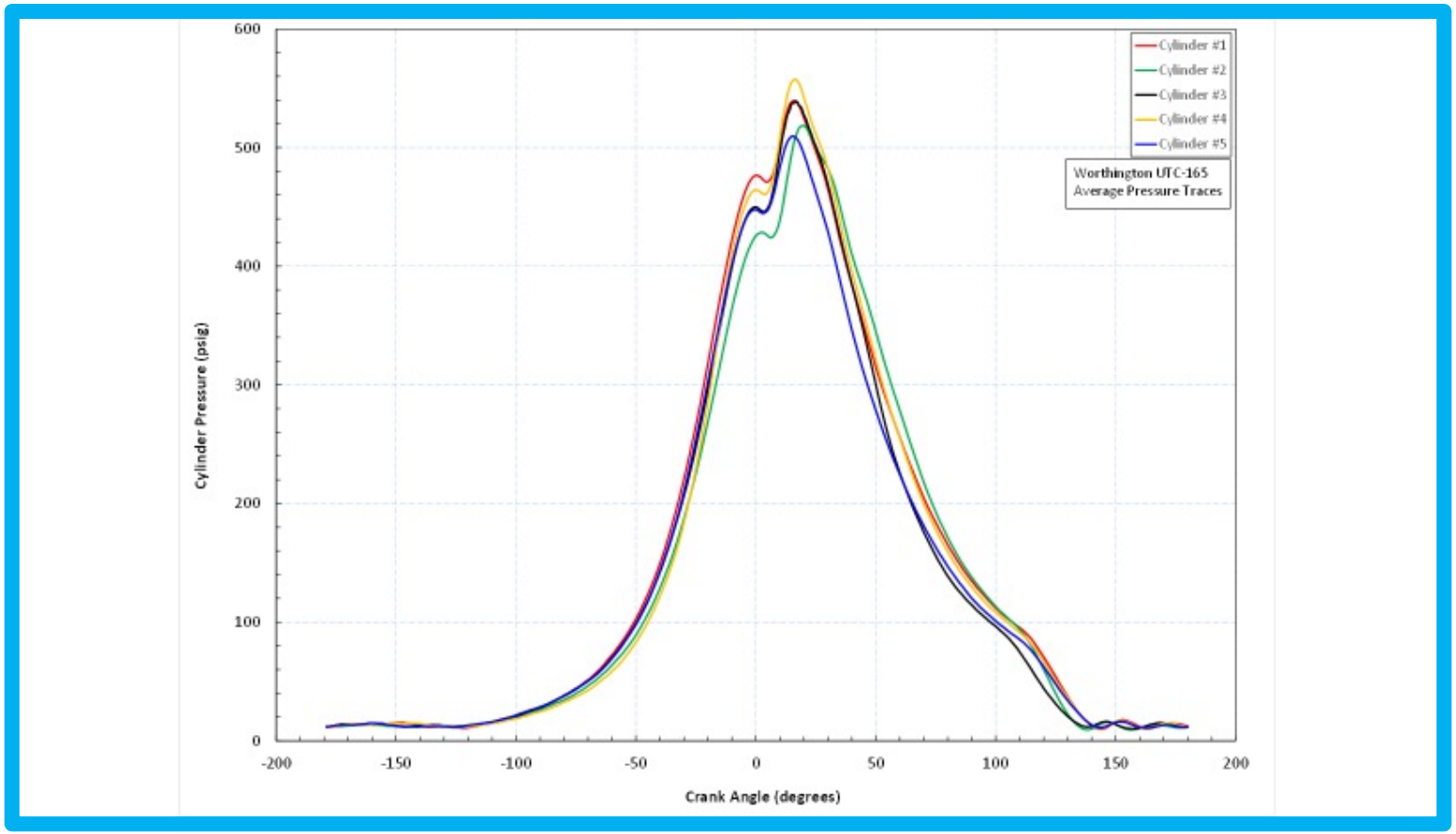
- Multiplying the Average PPR by the individual cylinder Cp's generates the target PFP for that cylinder.

- Research has proven that utilization of the PPR method reduces NOx, COV's and associated crankshaft stresses induced by rapid variations in angular velocities imparted by unbalance and misfires*.

*FINAL REPORT
SwRI® Project No. 18.06223
DOE Award No. DE-FC26-02NT41646

Cylinder Pressure v Crank Angle
0 to 600 psi Scale

MACHINERY MONITORING SYSTEMS, LLC



Cylinder Pressure v Crank Angle
400 to 580 psi Scale

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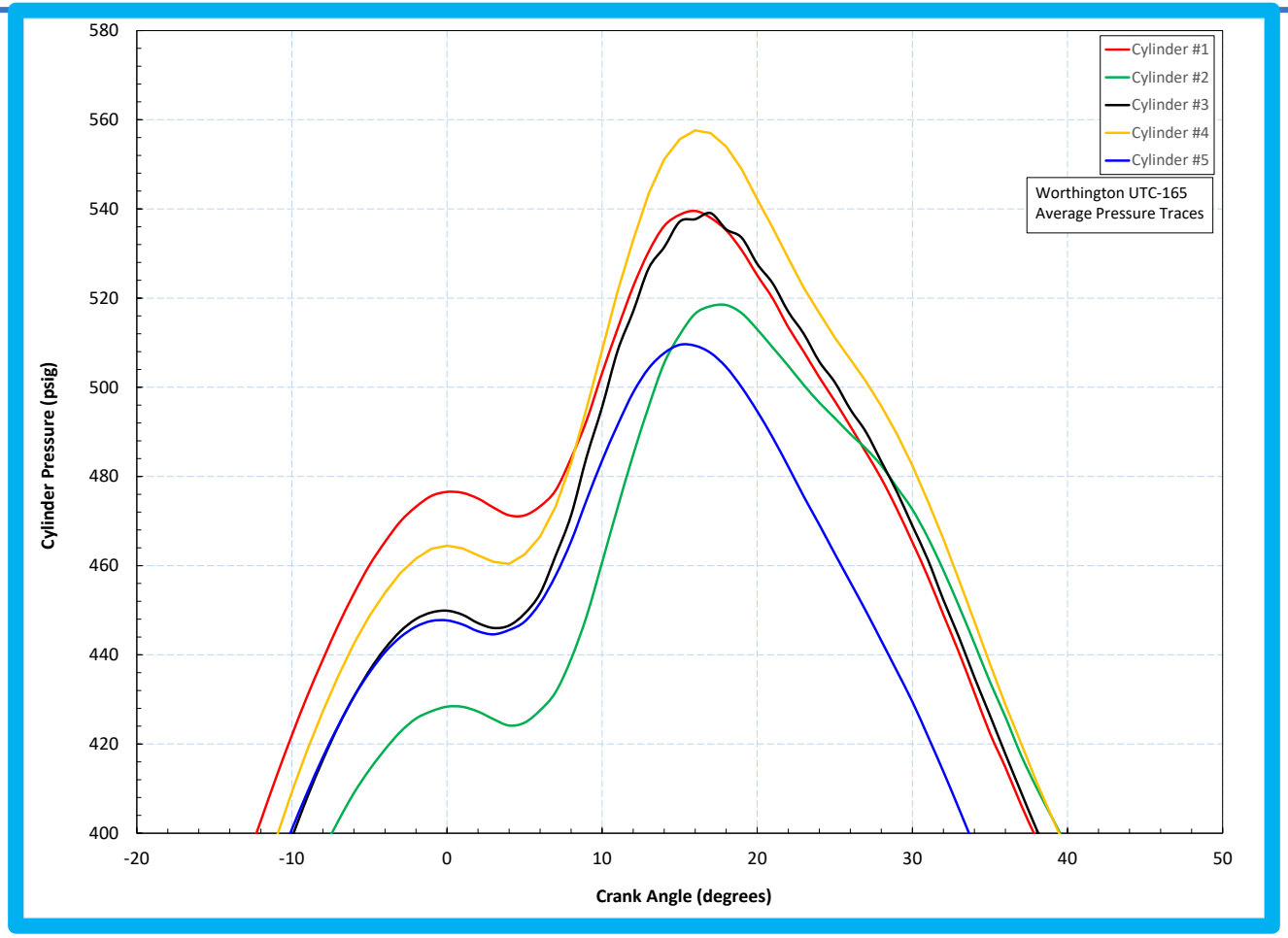

PFP vs PPR

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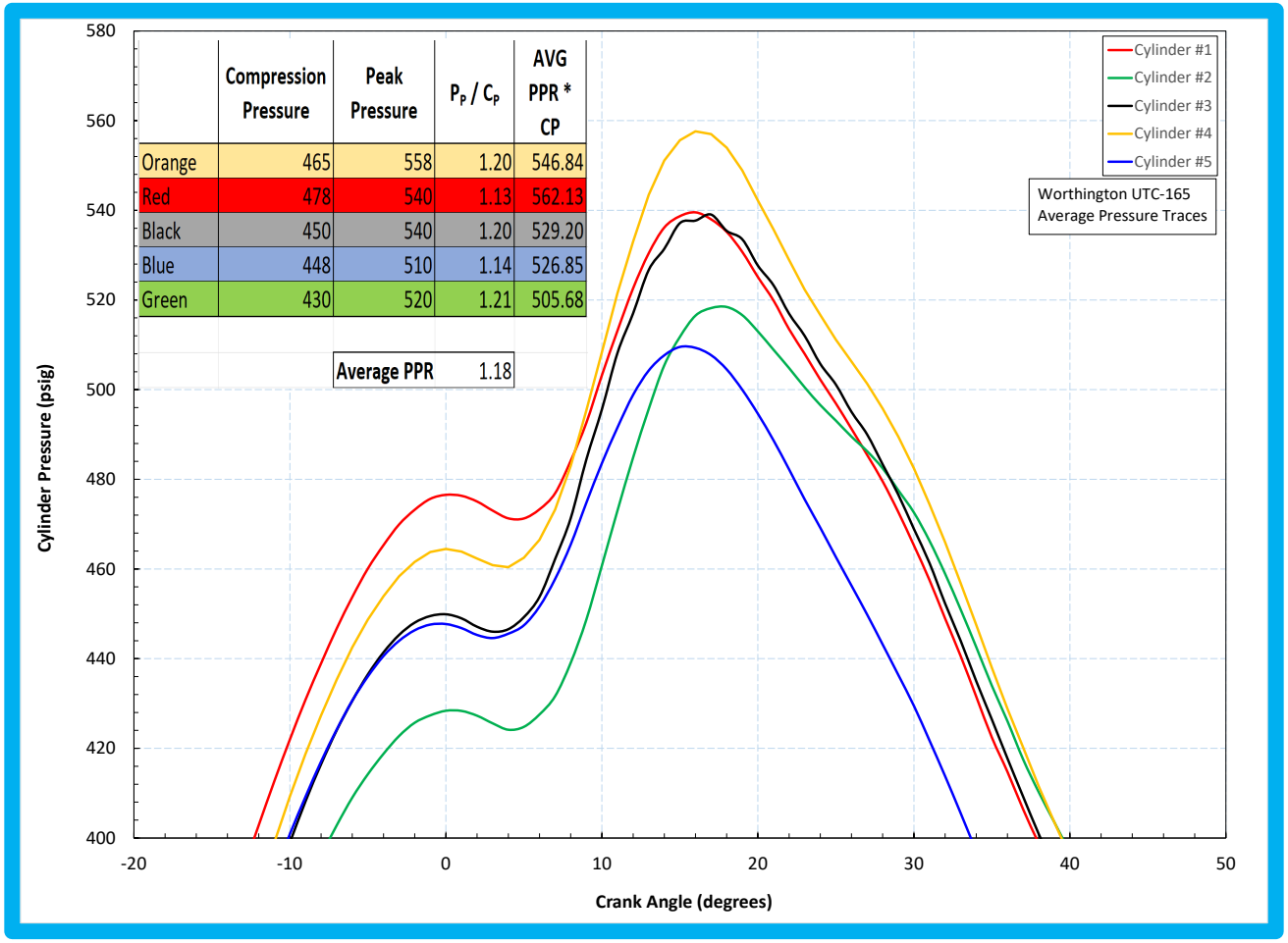

What's Next

MACHINERY MONITORING SYSTEMS, LLC

- New ProBalance Software Release
- Add PPR as an optional balancing method
- Integration of ProBalance into the MachineryRX app
- New Automatic Balancing Valve
- New Balance of Plant System

RCTClean 3.0 gr Solution(1) for GMV Engines

MACHINERY MONITORING SYSTEMS, LLC

Does not require turbocharger OR HPFI installation/upgrades.

- ***RCTClean*** vs Competition:
  1) 40-50% Lower in Cost
  2) Performs Better
  3) Project time cut in half (6 mos vs 12 mos)

- ***RCTClean*** retrofit for GMV-class engines enables:
  1) Compliance with EPA NOx limit of 3.0 gr/bhp-hr.
  2) Compliance with EPA CH4 (Methane) limit of 5.3 gr/bhp-hr.
  3) Engine stability improvement over 50% (COVs < 6.0%).
  4) A $1.5mm cost savings vs the traditional industry solutions.

  - Note (1) *RCTClean* 3 OgrSolution is Patent Pending

RCT
Radical Combustion Technologies

3.0 gr Solution Demonstration(1)(2)(3)

Machinery Monitoring Systems, LLC

GMV-4 Parameters	Baseline GMV	*RCTClean* 3.0gr(3)	Change (+/-%)
Load (HP)	480	492.6	na
AMP ("Hg)	9.45	11.81	na
AMT (°F)	129.7	138.8	na
NOx (gr/bhp-hr)	8.10	1.09	-86.5%
CO (gr/bhp-hr)	5.92	3.54	-40.2%
THC (gr/bhp-hr)	10.73	6.47	-39.7%
VOC (gr/bhp-hr)	1.46	1.51	+3.4%
CH4 (gr/bhp-hr)	8.18	4.98(2)	-39.1%
CH2O (gr/bhp-hr)	1.29	1.32	+2.3%
BSFC (BTU/bhp-hr)	9145.70	9258.02	+1.2%
Misfires (%)	0.225	0.000	-100%
COV (%)	12.4	5.51	-55.6%

CSU Energy Institute
GMV-4 Cooper Bessemer
Test Engine

Note: (1) Data results CSU GMV-4 test conducted 9/27-28/2022
(2) All data taken at LOPP 18 ATDC. Advancing LOPP will reduce CH4, THC, CH20 and improve BSFC.
(3) RCTClean 3.0gr Solution is Patent Pending

Questions ?

MACHINERY MONITORING SYSTEMS, LLC

Thank You!

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