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

# Resonance User's Group Meeting

Gatlinburg, Tennessee
August 2022

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

# Balancing Slow Speed Reciprocating Engines

*The Old and the New*

August 2, 2022

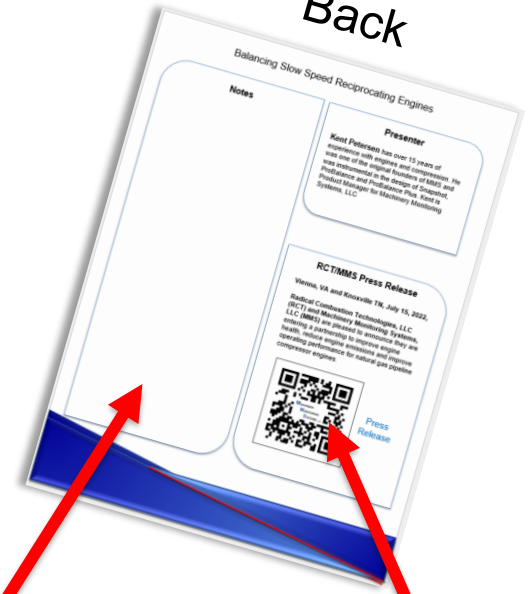
Kent Petersen, MMS LLC
Bryan Stewart, MMS LLC
Jim McCoy, Radical Combustion Technologies

# Participant Handout

Front


QR Code to download copy of presentation

Back




For notes if you hear anything interesting

QR Code to download Compressor Tech article on MMS/RCT partnership

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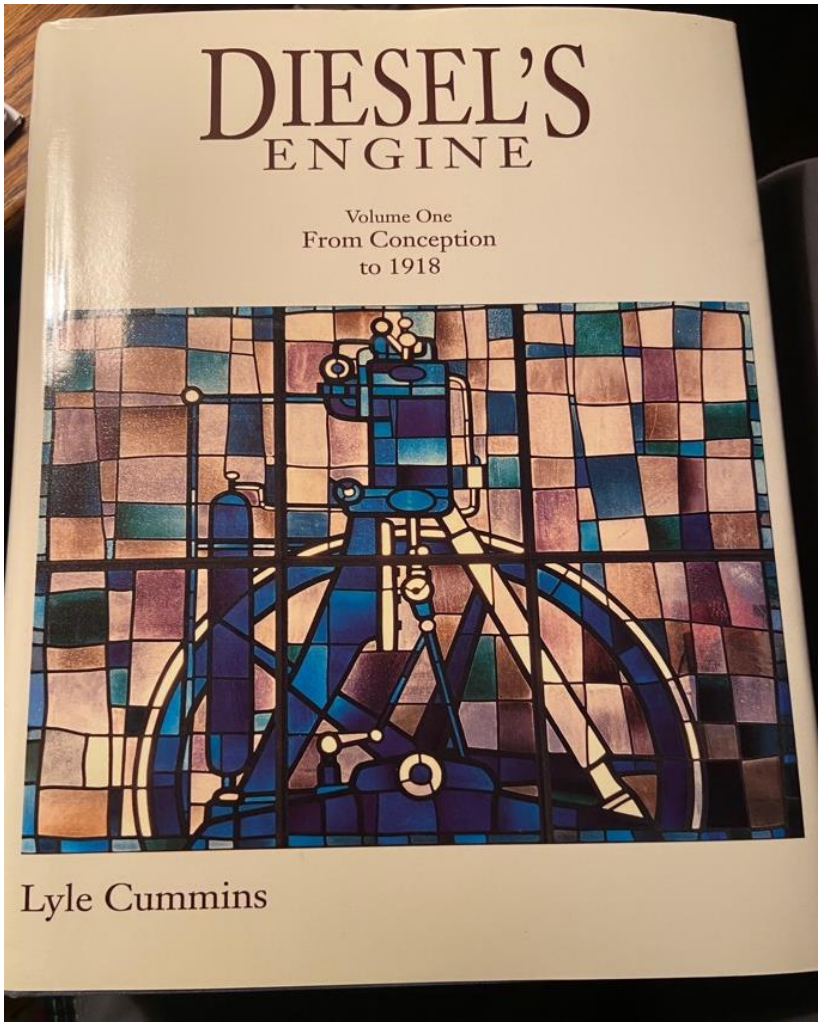
To begin, a little history!




# Historical Balancing Methods

*Great Book!!*

MACHINERY MONITORING SYSTEMS, LLC

# Historical Balancing Method

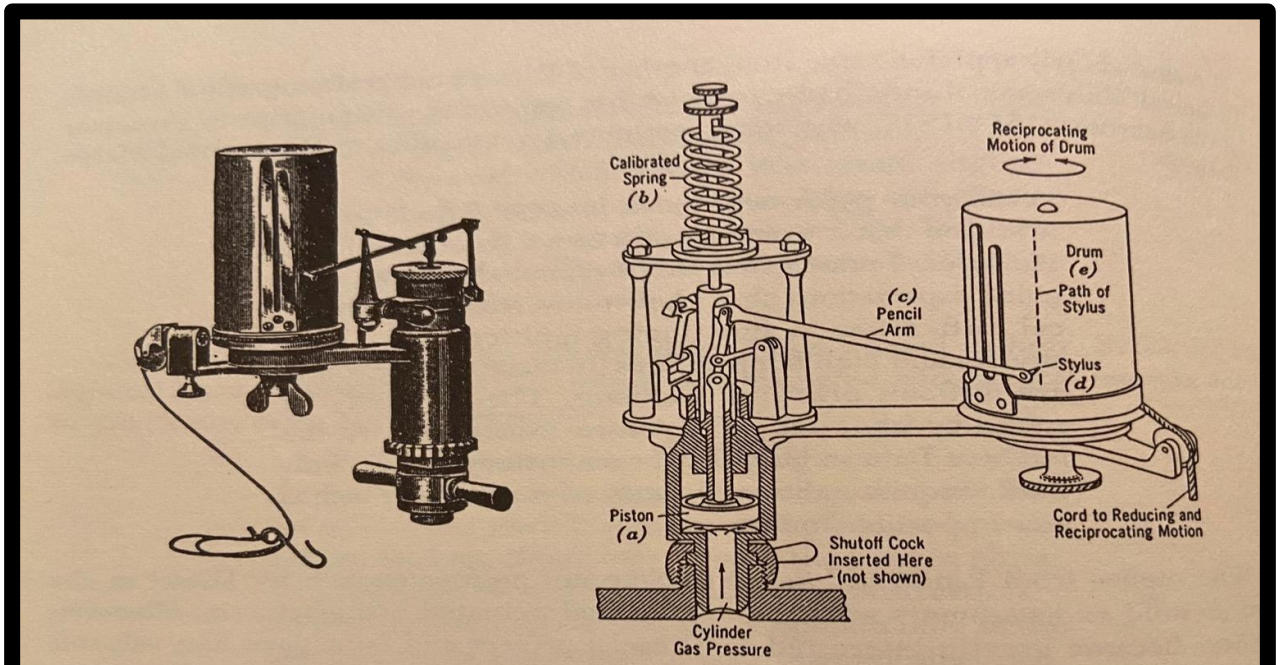
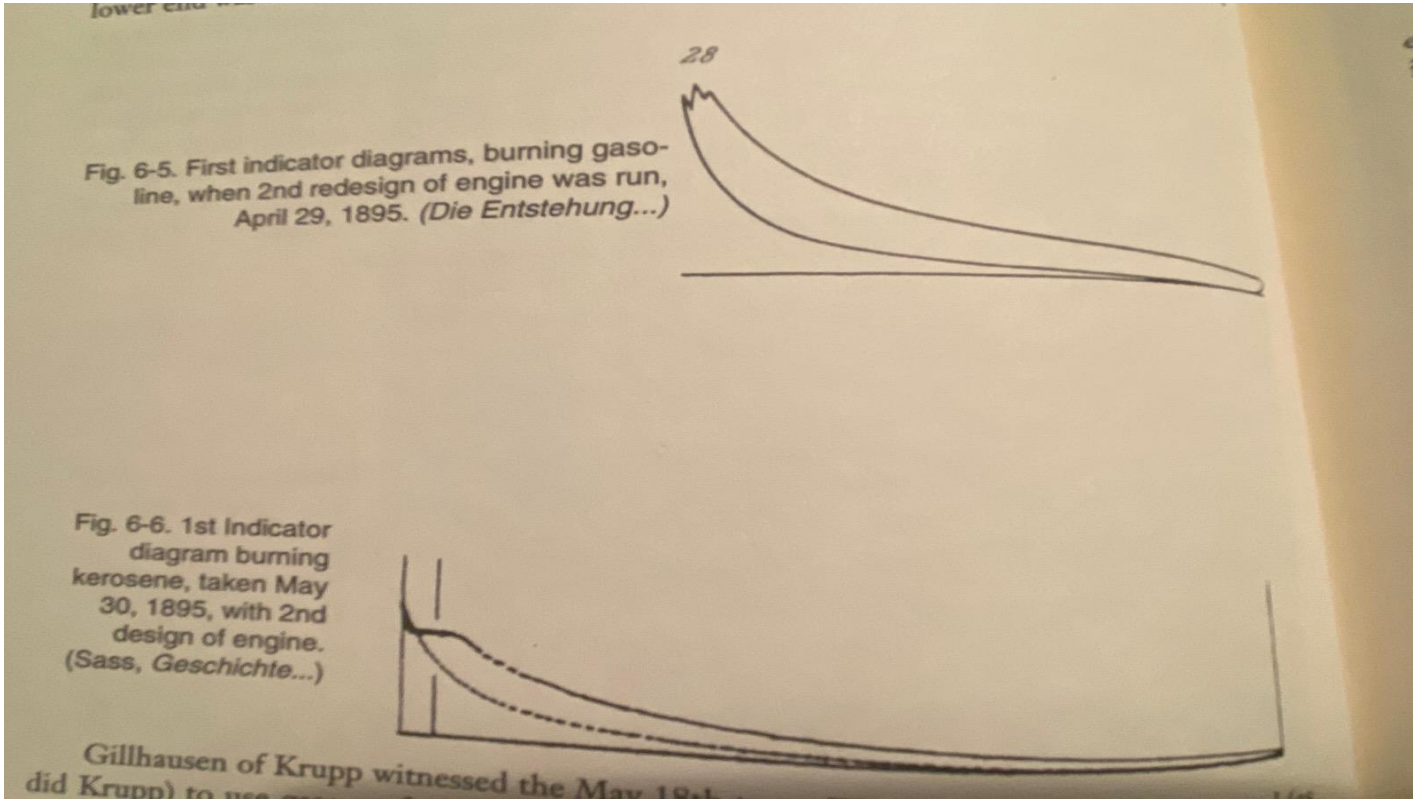



Fig. 3–4. Indicator for making a P–V diagram (indicator card). A pressure trace is made on paper wound on the drum as piston movement turns the drum. This provided a record of the cylinder pressure at each point in the piston stroke. (*Hawkins' Indicator Catechism*, 1903)

worry about how to "fatten" his diagram. But

# The first traces from the device when Rudolf Diesel first ran his engine in1895!!

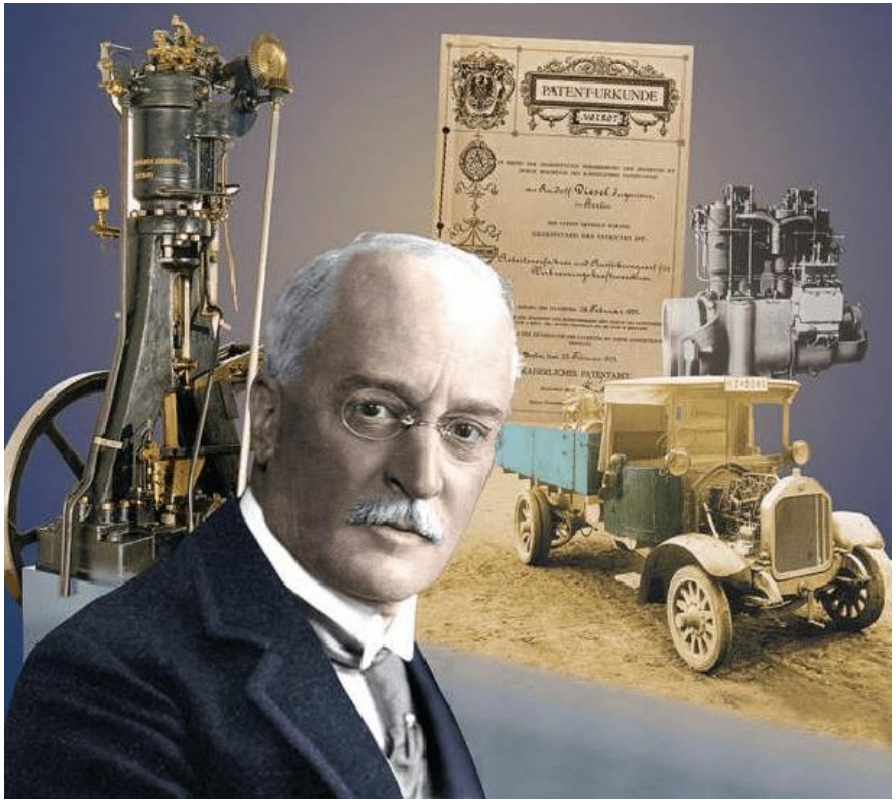


28

Fig. 6-5. First indicator diagrams, burning gasoline, when 2nd redesign of engine was run, April 29, 1895. *(Die Entstehung...)*

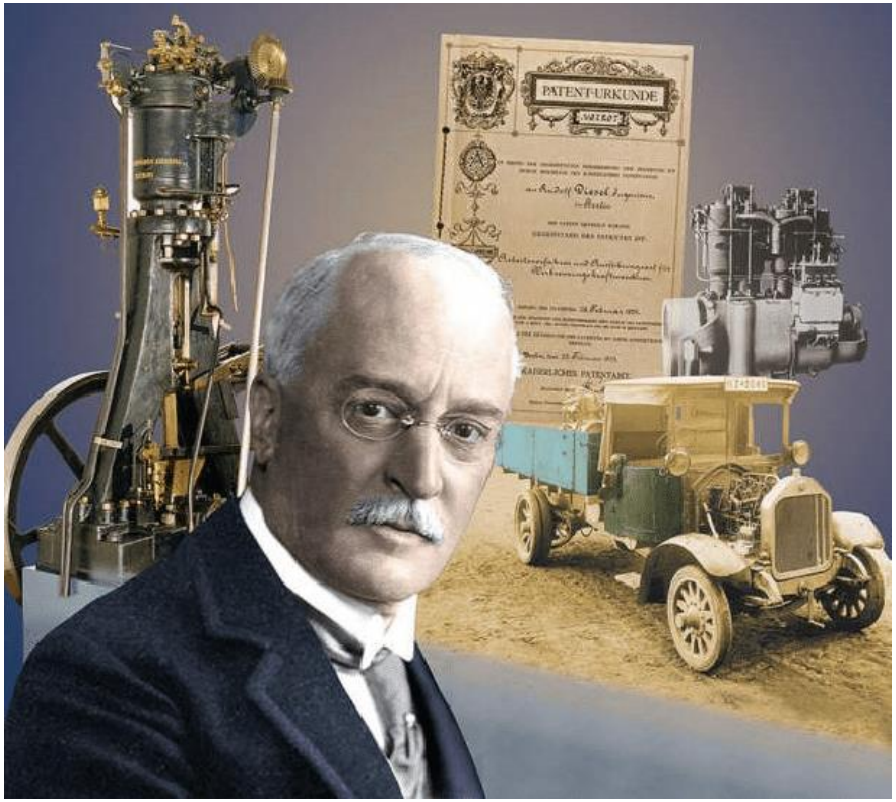
Fig. 6-6. 1st Indicator diagram burning kerosene, taken May 30, 1895, with 2nd design of engine. (Sass, *Geschichte...*)

Gillhausen of Krupp witnessed the May




Rudolph Diesel

- In 1897 demonstrated a 25 HP, 4-stroke, single cylinder engine
- Fueled with peanut or vegetable oil
- By 1912, more than 70,000 diesel engines around the world
- In 1913, he disappeared from the Steamship Dresden while traveling from Antwerp, Belgium to Harwich, England to attend the opening of a new diesel engine factory
- Officially, deemed suicide by drowning

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Conspiracy Theories

- “Inventor thrown into sea to stop sale of patent to British Government”
- “Murdered by agents from big oil trusts”
- “Murdered by coal industrialists”

# Leutert MSI-3 EPPI (Circa 1940)

# Electronics Evolve

Beta-Trap

Windrock 6310 CA

Dynalco 6230

Windrock Autobalance™

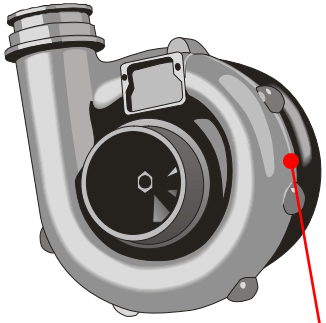
MMS Snapshot® Engine Balancer

Resonance Lenz Engine Kit

Hoerbiger/Cooper Hyperbalance III™

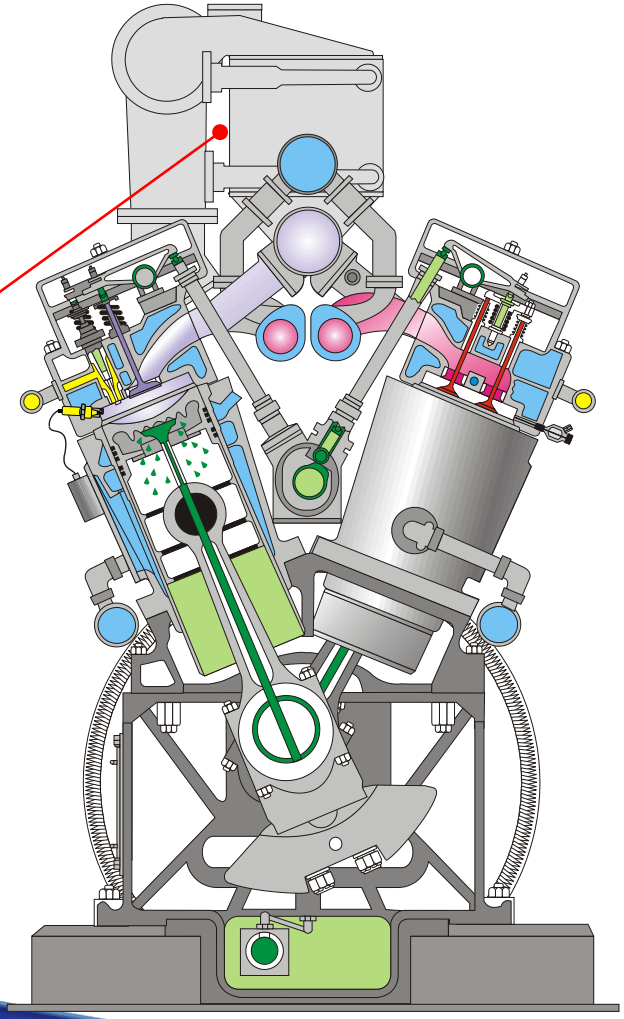
MMS ProBalance® / ProBalance® Plus

# Engine Data Collection



**Turbocharger/blower**

- Accelerometer on bearings and near turbine and compressor wheels
- Frequency domain vibration



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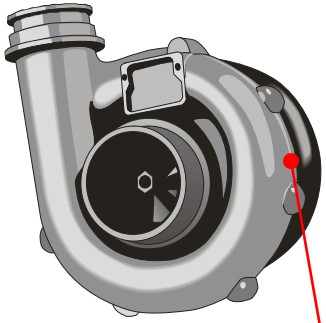

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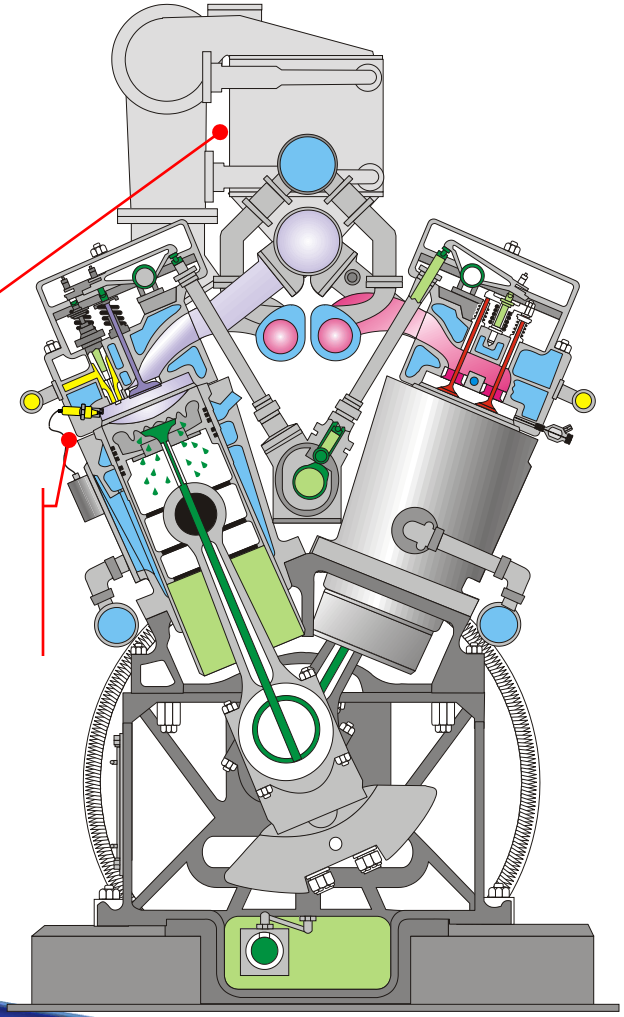
**Ignition secondary**

- Clip on unshielded spark plug cable
- Multi-cycle sampling statistics
- Ignition secondary patterns



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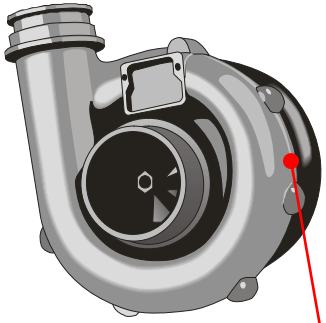

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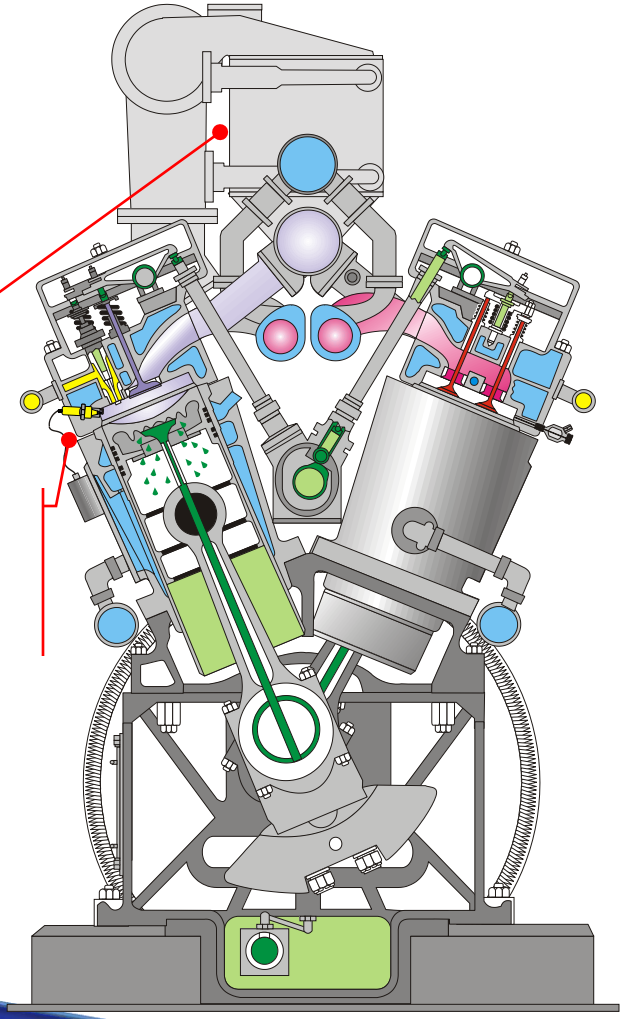

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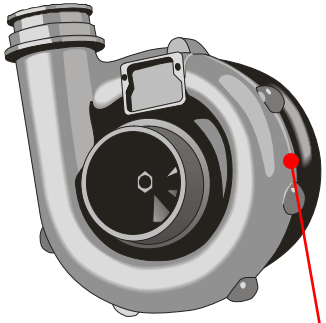

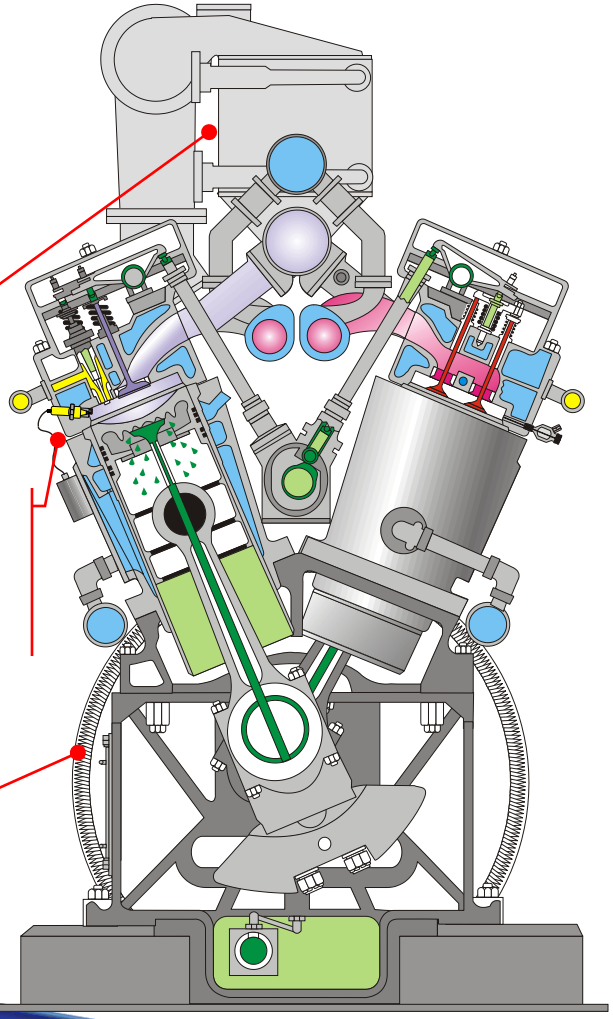

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**TDC Reference**
- Shaft encoder
- Magnetic pickup
- Phased data
- RPM

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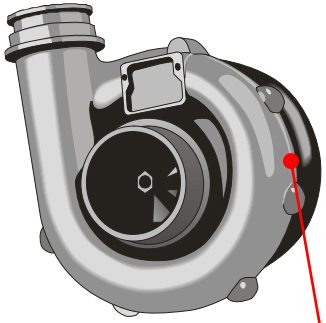

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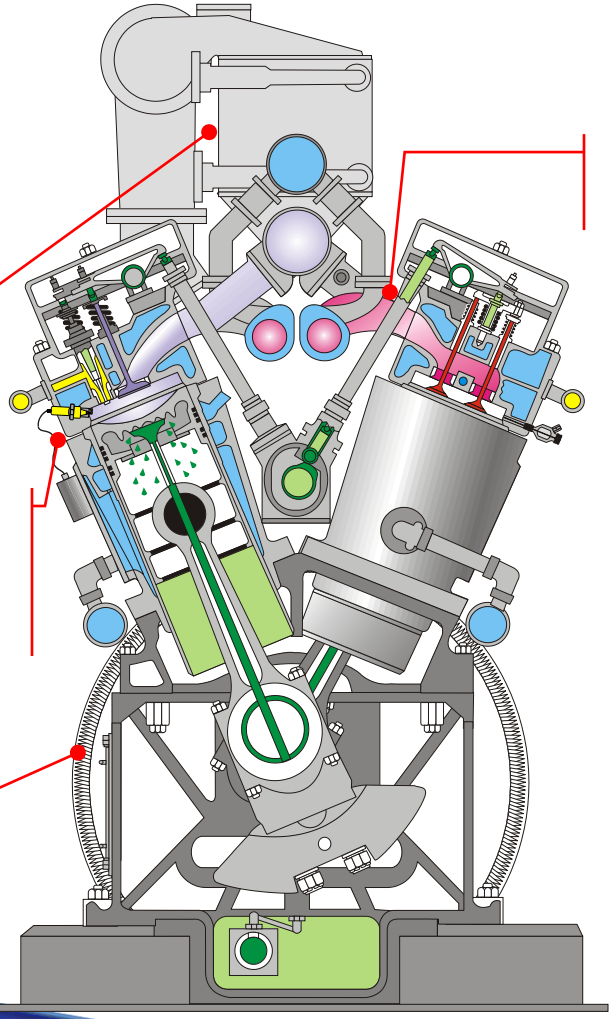

**Cylinder exhaust temperatures**
- Infrared temperature sensor
- Pyrometer
- Panel points

**Ignition secondary**
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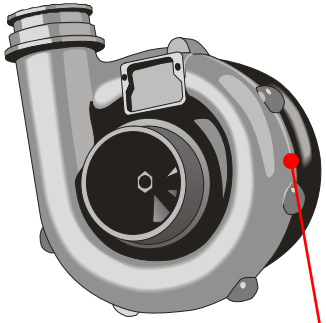

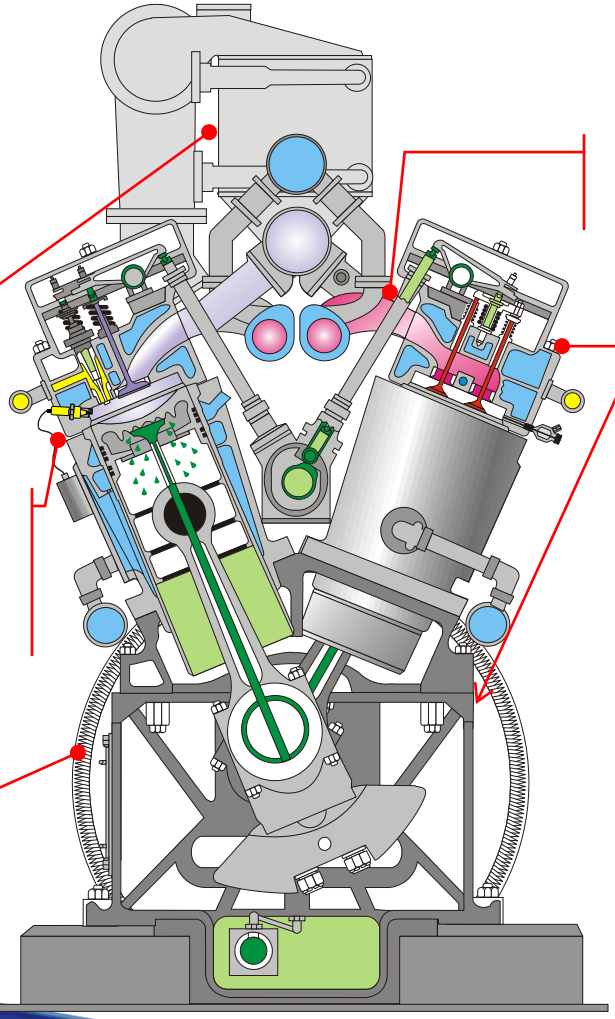

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- Infrared temperature wand
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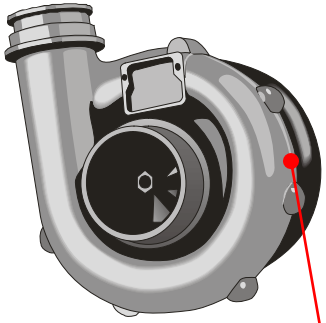
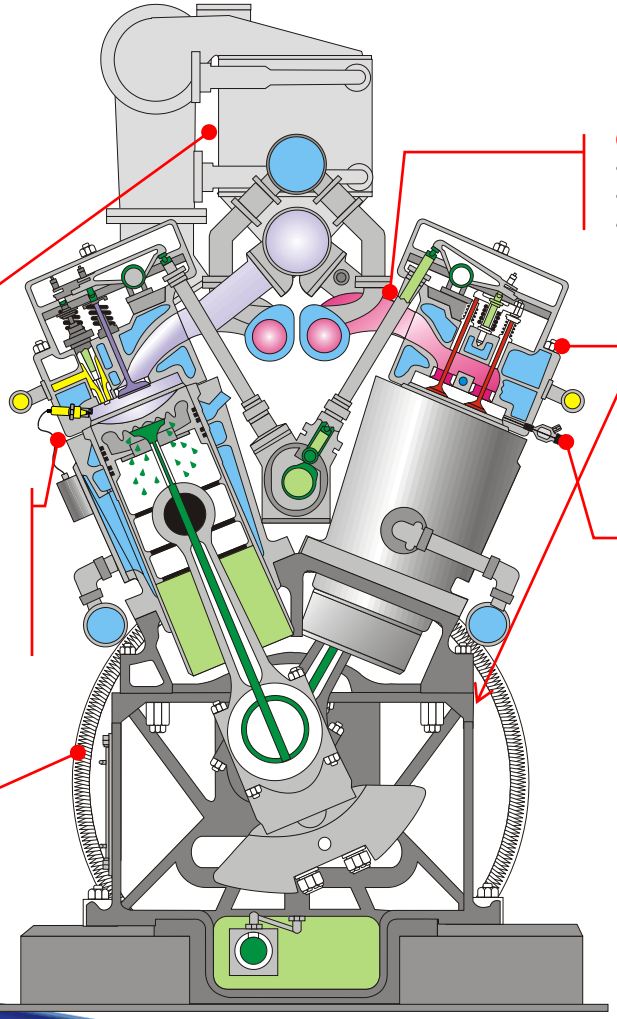
**Cylinder, valve, wrist pin and bearing vibration**
- Ultrasonic
- Accelerometer
- Time domain data phased to crankshaft position

# Engine Data Collection





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- Ultrasonic
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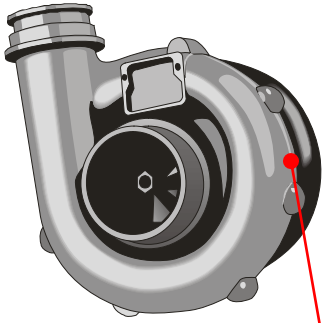
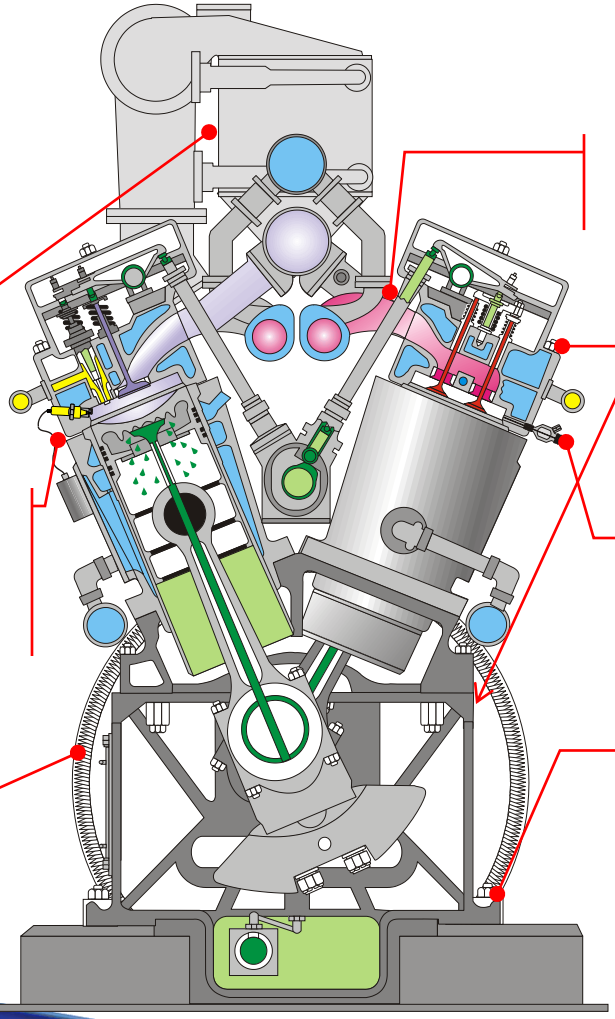
**Cylinder pressure**
- Pressure transducer
- Time domain data phased to crankshaft position
- Peak pressure statistics

# Engine Data Collection





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- Accelerometer
- Time domain data phased to crankshaft position

**Cylinder pressure**
- Pressure transducer
- Time domain data phased to crankshaft position
- Peak pressure statistics

**Frame vibration (displacement)**
- H, V, A taken at various locations on engine frame
- Both Time & Frequency domain data

# Engine Concerns

- Ignition
- Fuel
- Combustion
- Mechanical condition
- Lubrication
- Cooling


MACHINERY MONITORING SYSTEMS, LLC

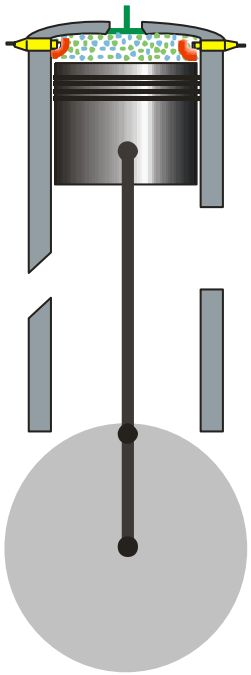
# The Two-Stroke Engine

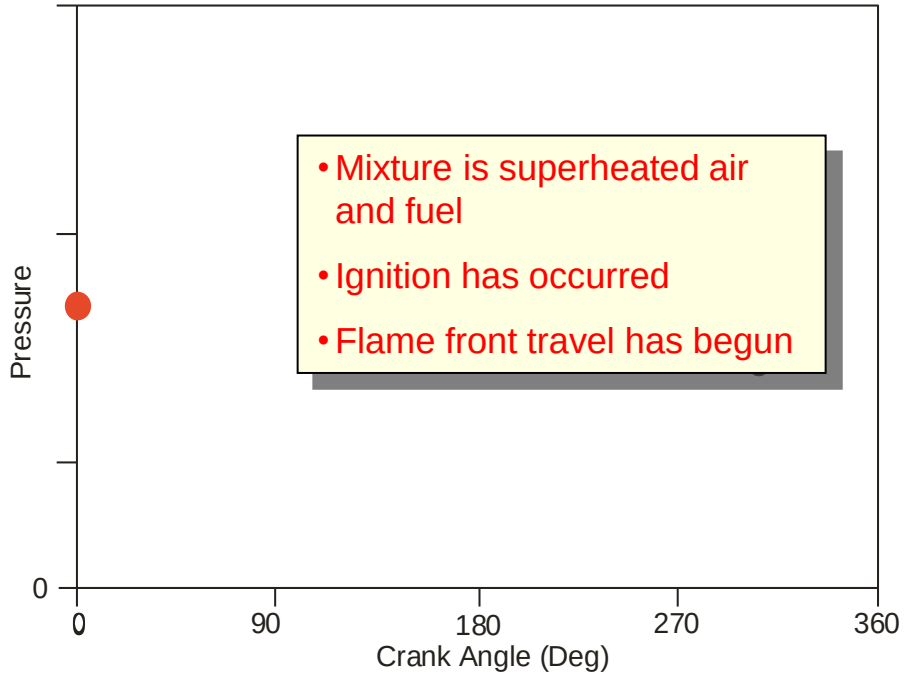
- The complete combustion cycle (compression, power, exhaust and intake) is accomplished in one revolution of the crankshaft
- Portions of both the intake and exhaust processes (scavenging) are accomplished at the end of the power stroke and the beginning of the compression stroke
- The fuel valve cam is driven at engine speed
- Cannot be naturally aspirated

MACHINERY MONITORING SYSTEMS, LLC

# Sequence of events for a 2-stroke engine

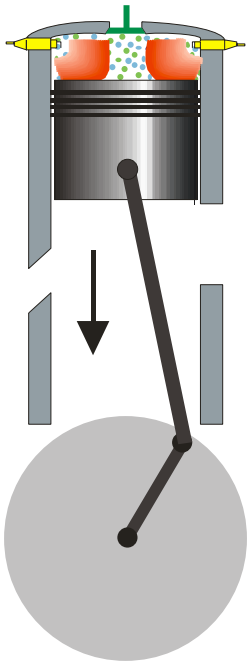
## PT: start of cycle

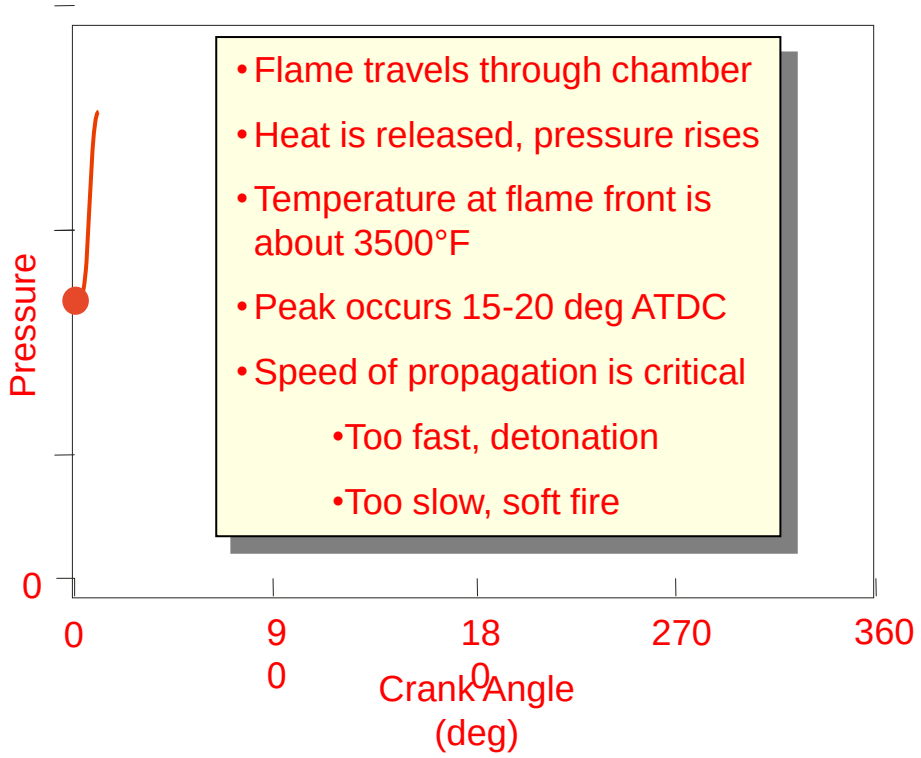




# Sequence of events for a 2-stroke engine

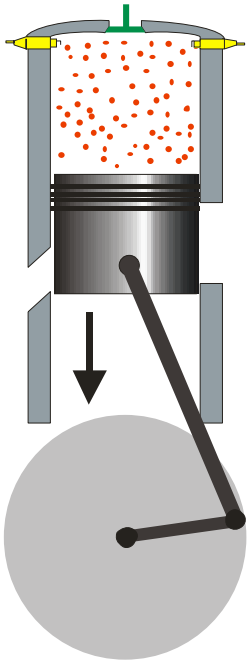
## PT: combustion

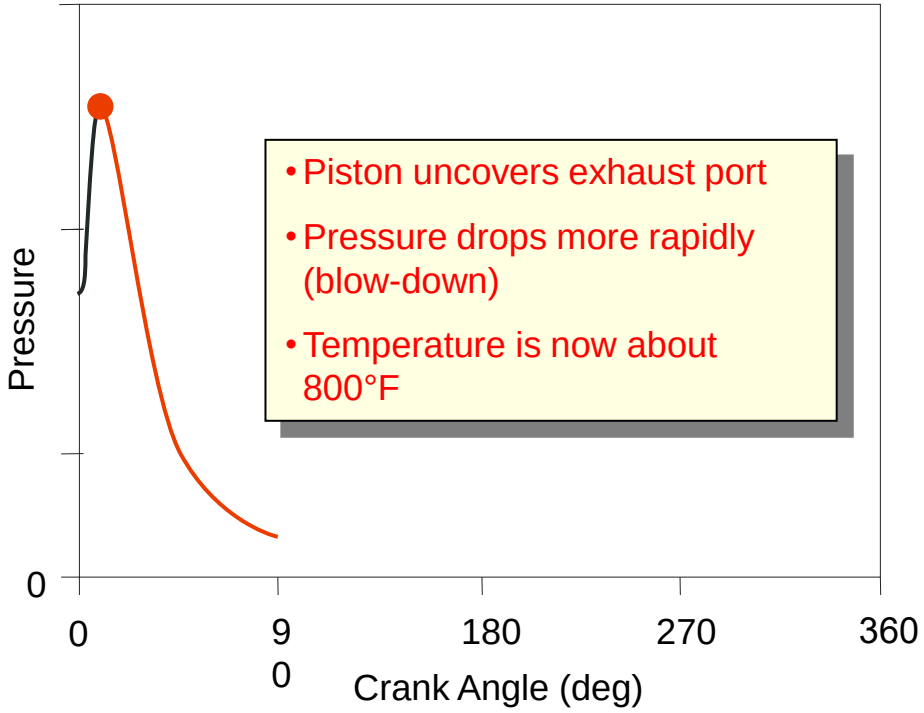




# Sequence of events for a 2-stroke engine

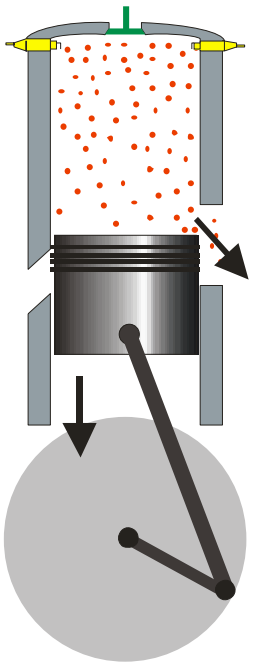
## PT: power

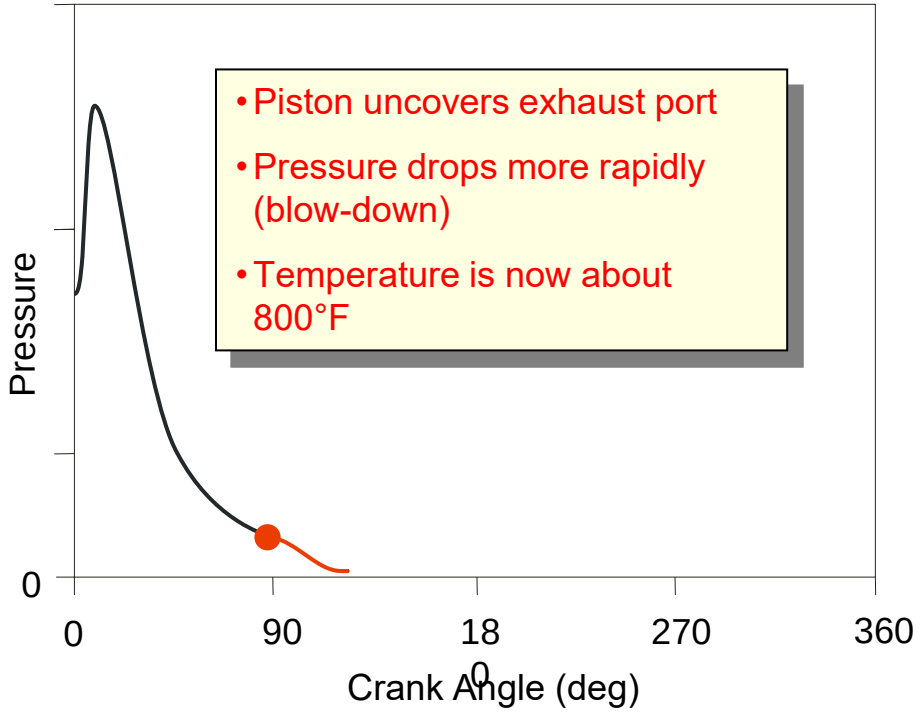




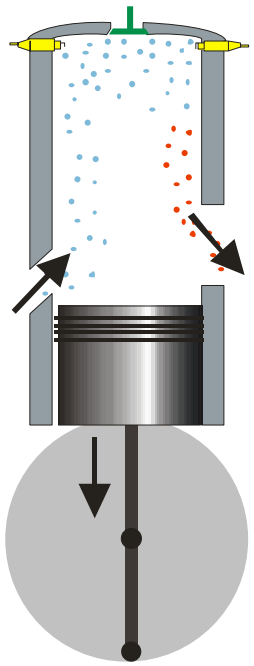
# Sequence of events for a 2-stroke engine

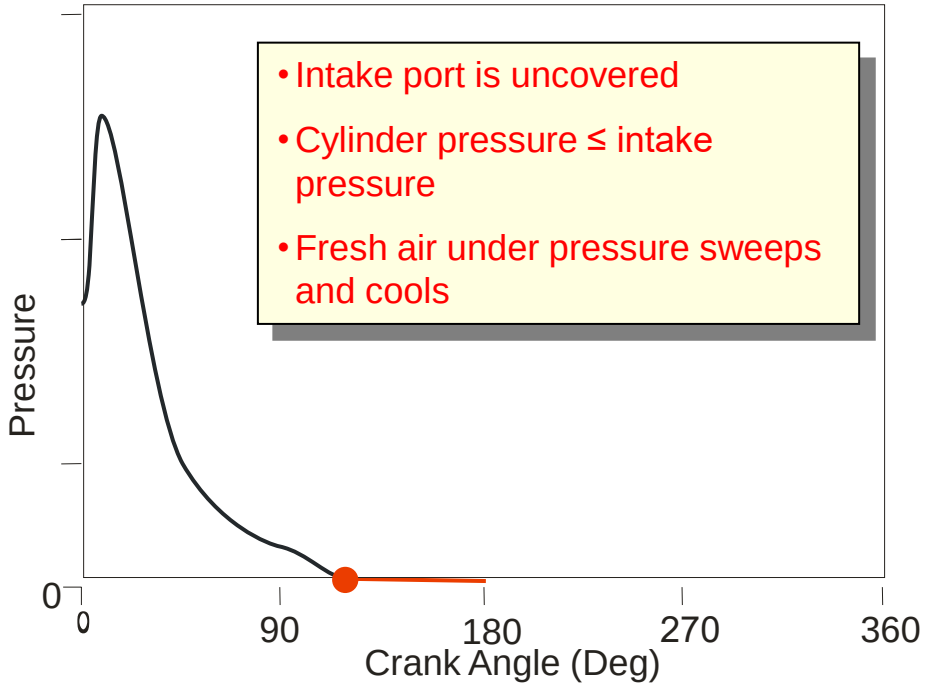
## PT: exhaust blowdown





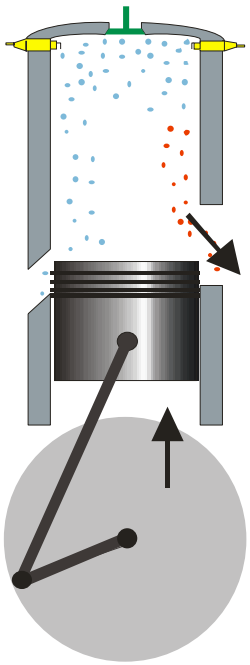
# Sequence of events for a 2-stroke engine
# PT: air intake

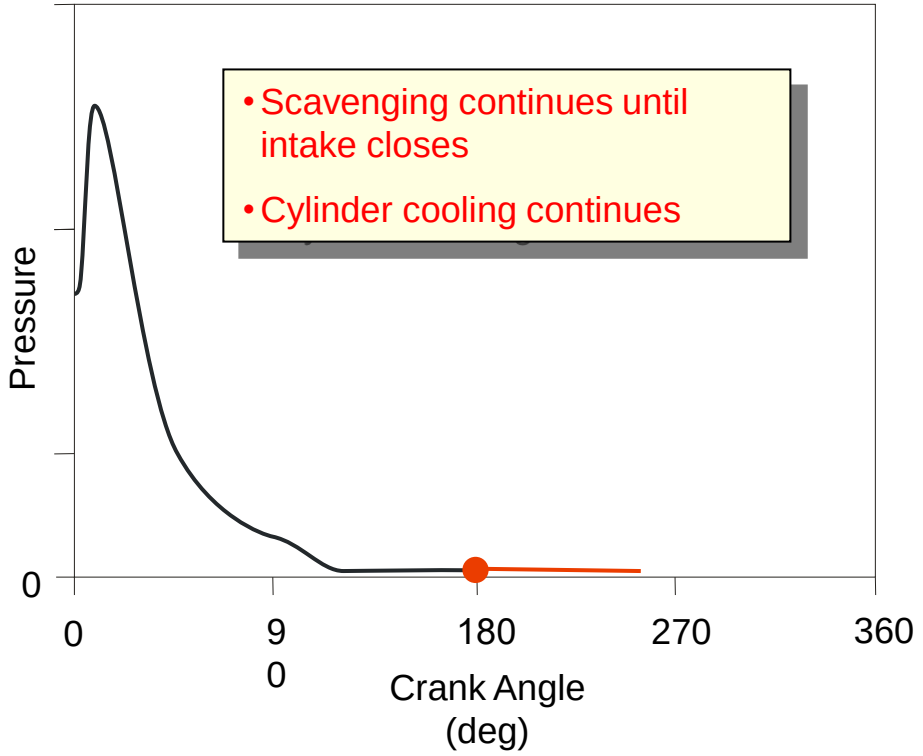




# Sequence of events for a 2-stroke engine

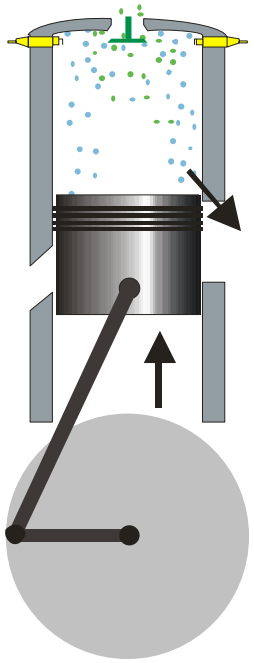
## PT: scavenging

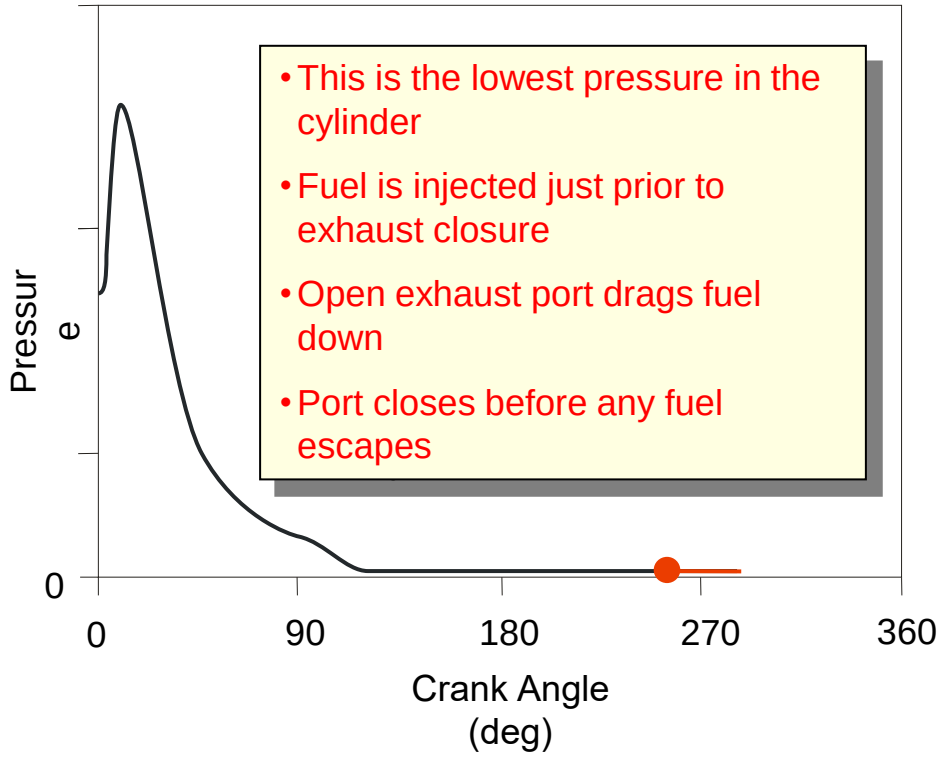




# Sequence of events for a 2-stroke engine

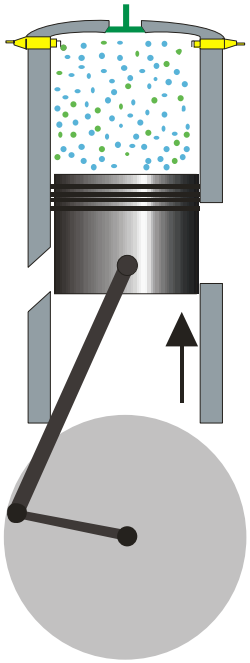
## PT: fuel intake

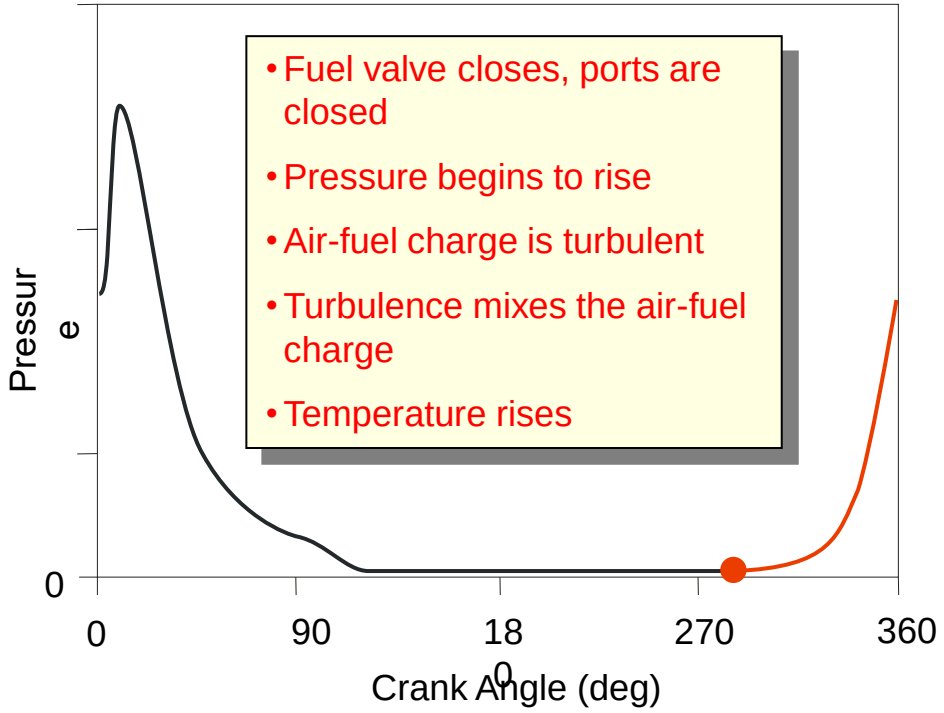




# Sequence of events for a 2-stroke engine

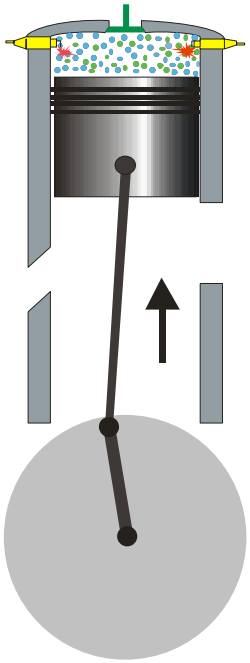
## PT: compression

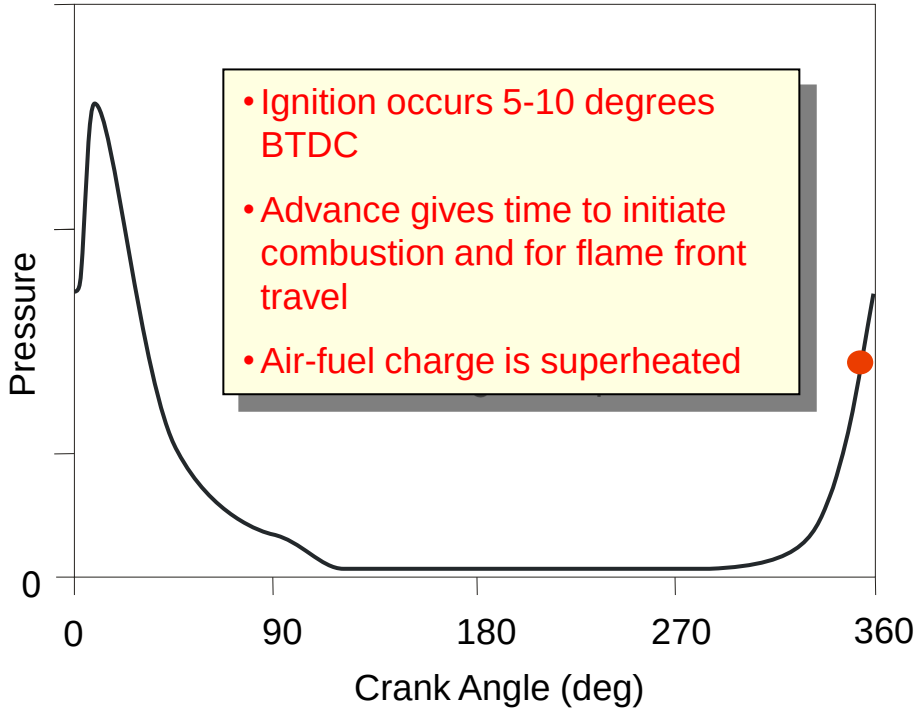




# Sequence of events for a 2-stroke engine

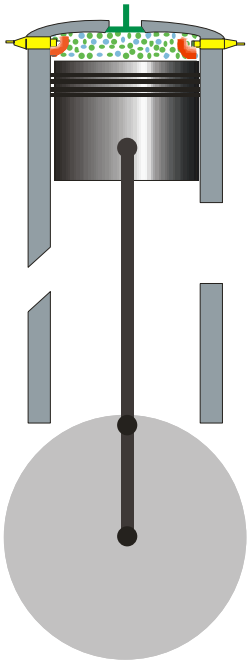
## PT: ignition

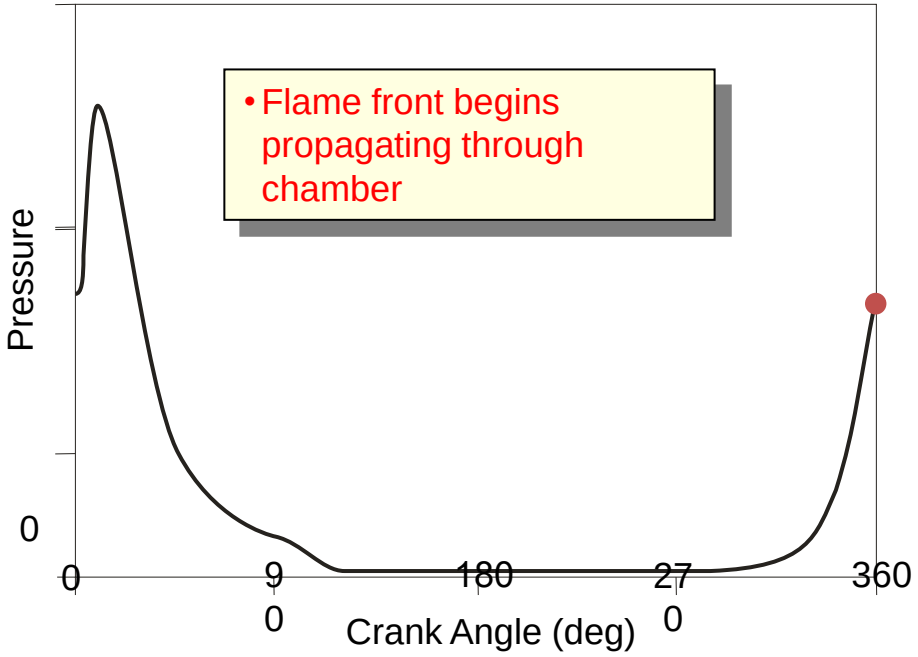




# Sequence of events for a 2-stroke engine

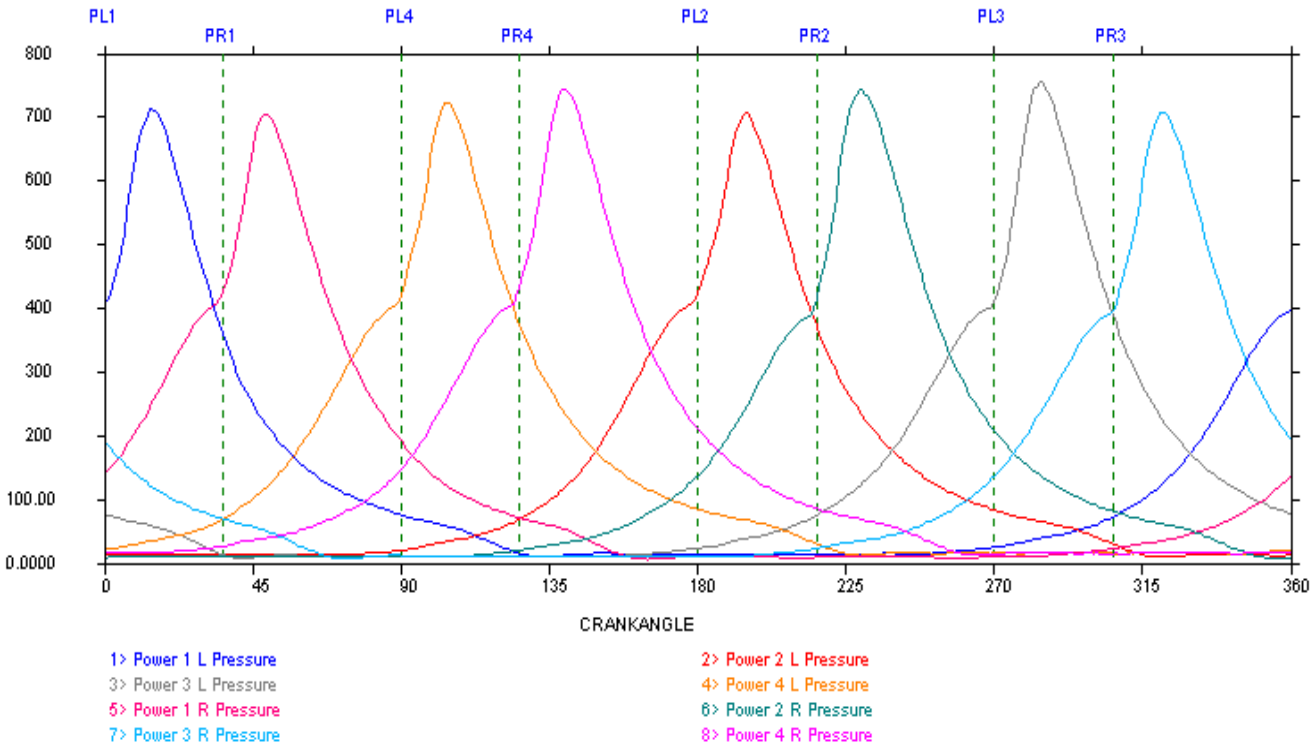
## PT: end of cycle



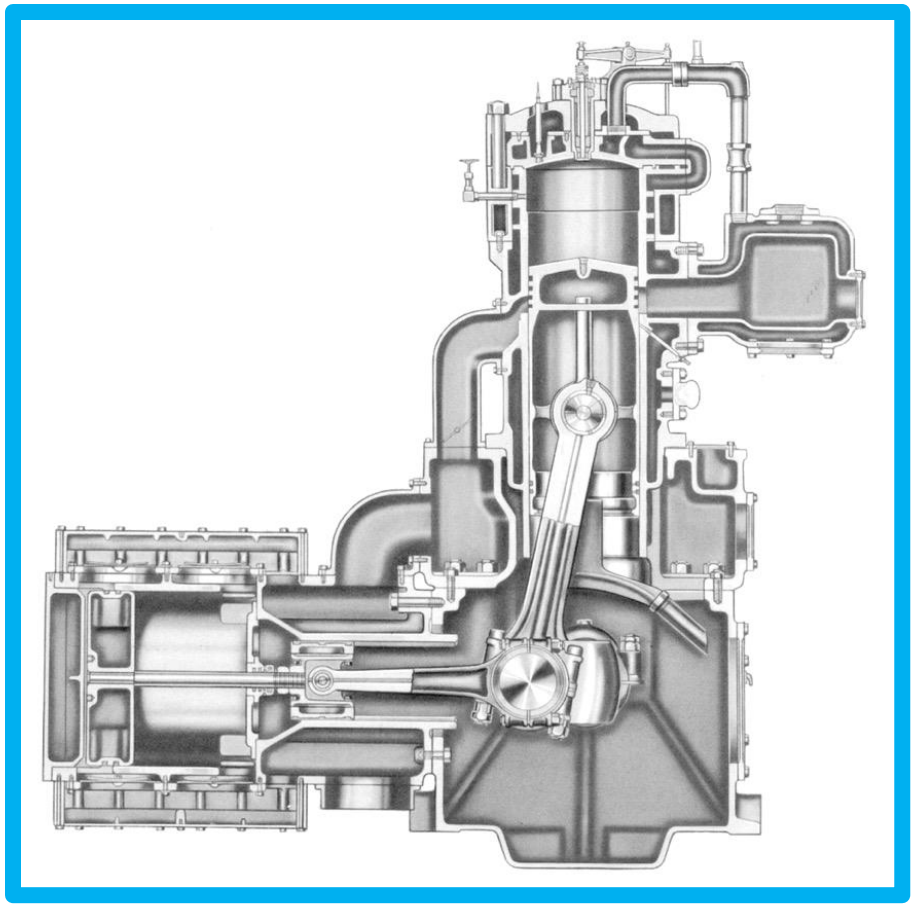


# 2-Stroke Pressure Parade

Averaged Pressure Trace



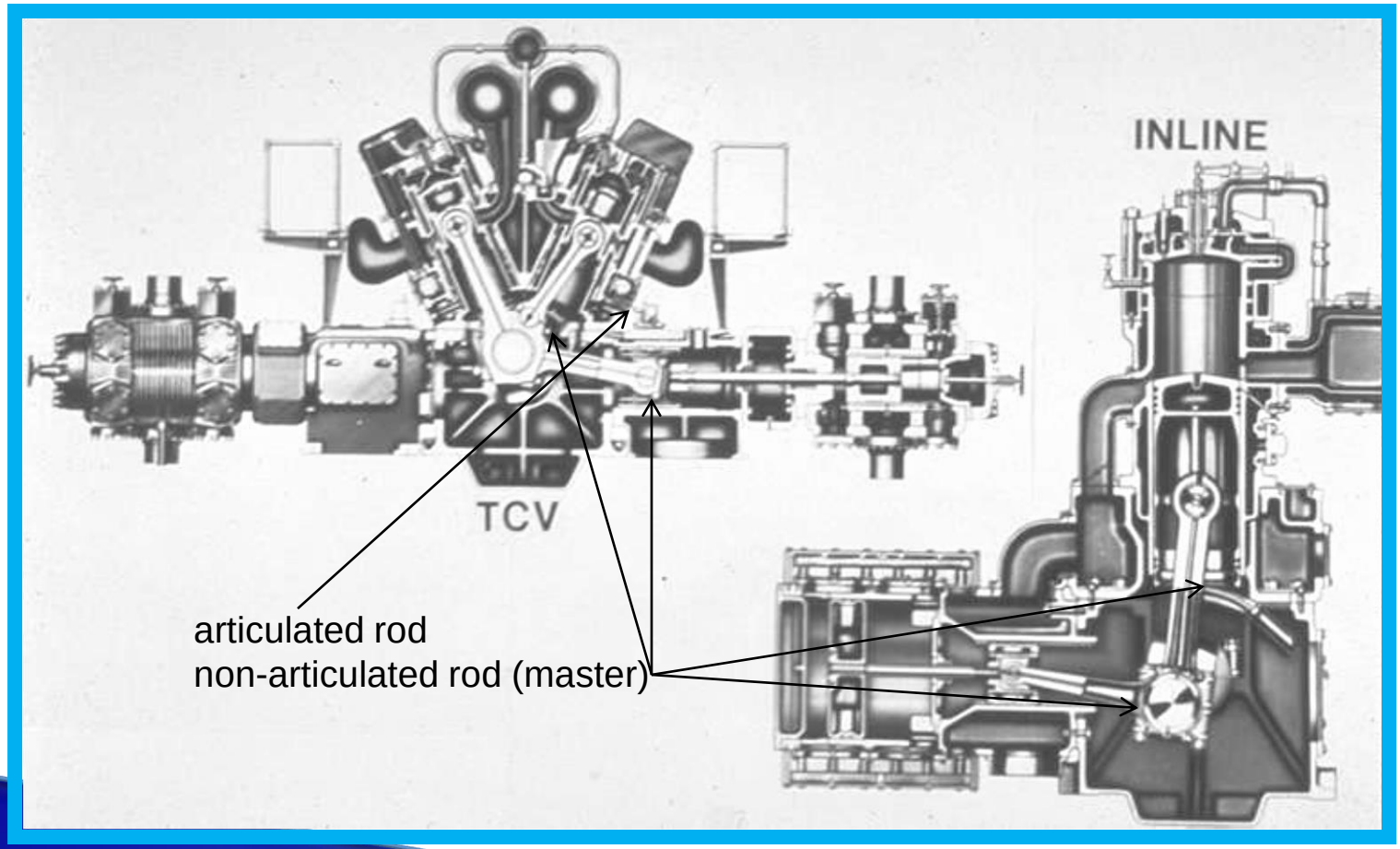
# 2 Stroke Scavenged Engine



Integral types have a common crankshaft shared between the power cylinders and compressor cylinders.

Dresser-Rand (Clark) RA, 2-stroke integral gas engine & compressor with non-articulated power connecting rods

# 2 Stroke Integral (Vee & Inline)



# Combustion Types
(2 & 4 Stroke)

- Normal ✓
- No Ignition *X*
- Early Ignition *X*
- Late Ignition *X*
- Detonation *X*
- Pre-ignition *X*
- Intermittent Firing *X*

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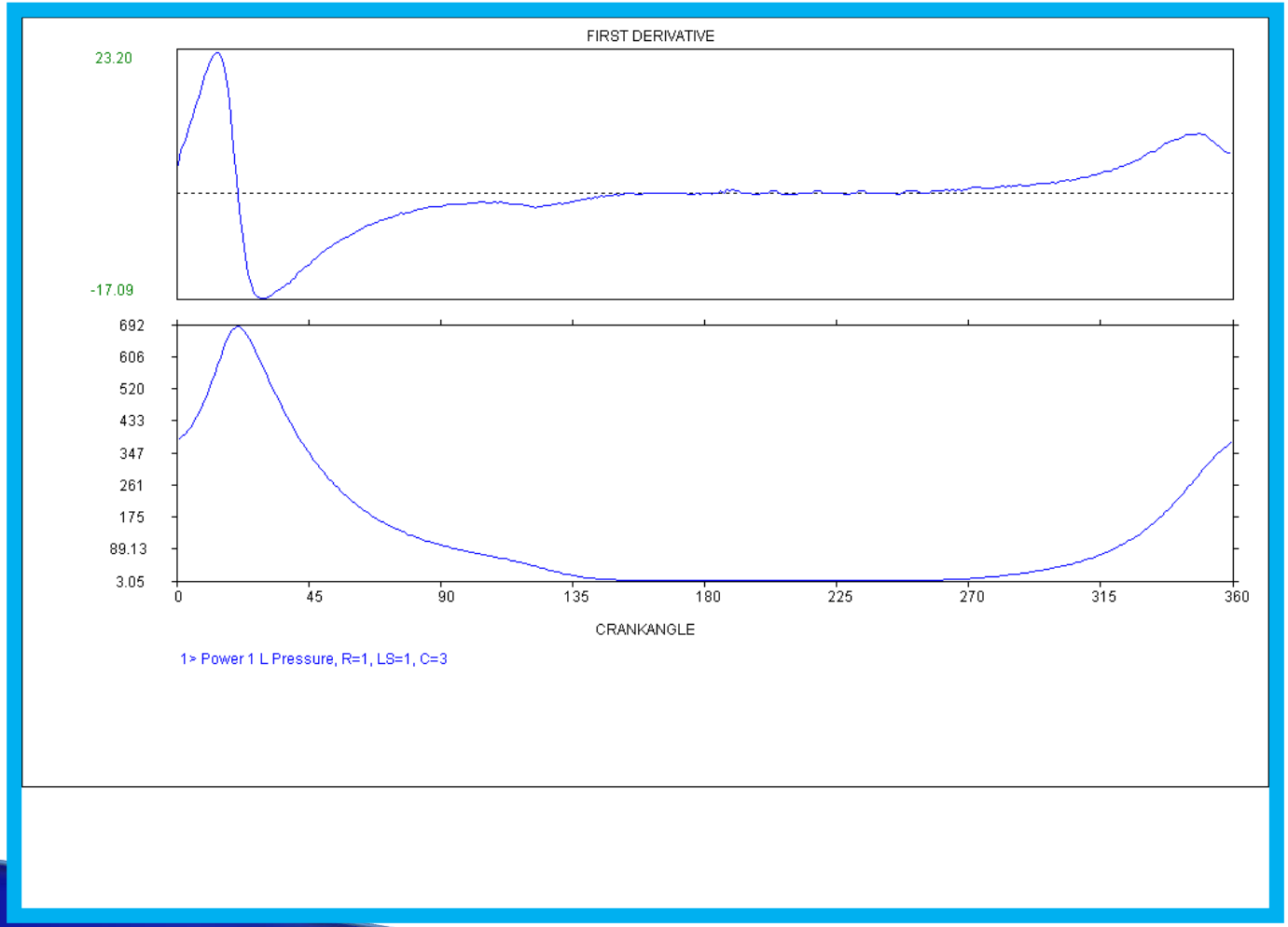
# Normal Combustion Requirements

- Correct amount of fuel with the proper BTU
- The right amount of air at the right pressure and temperature to control the combustion rate
- Proper amount of ignition energy at the right degree of crankshaft rotation

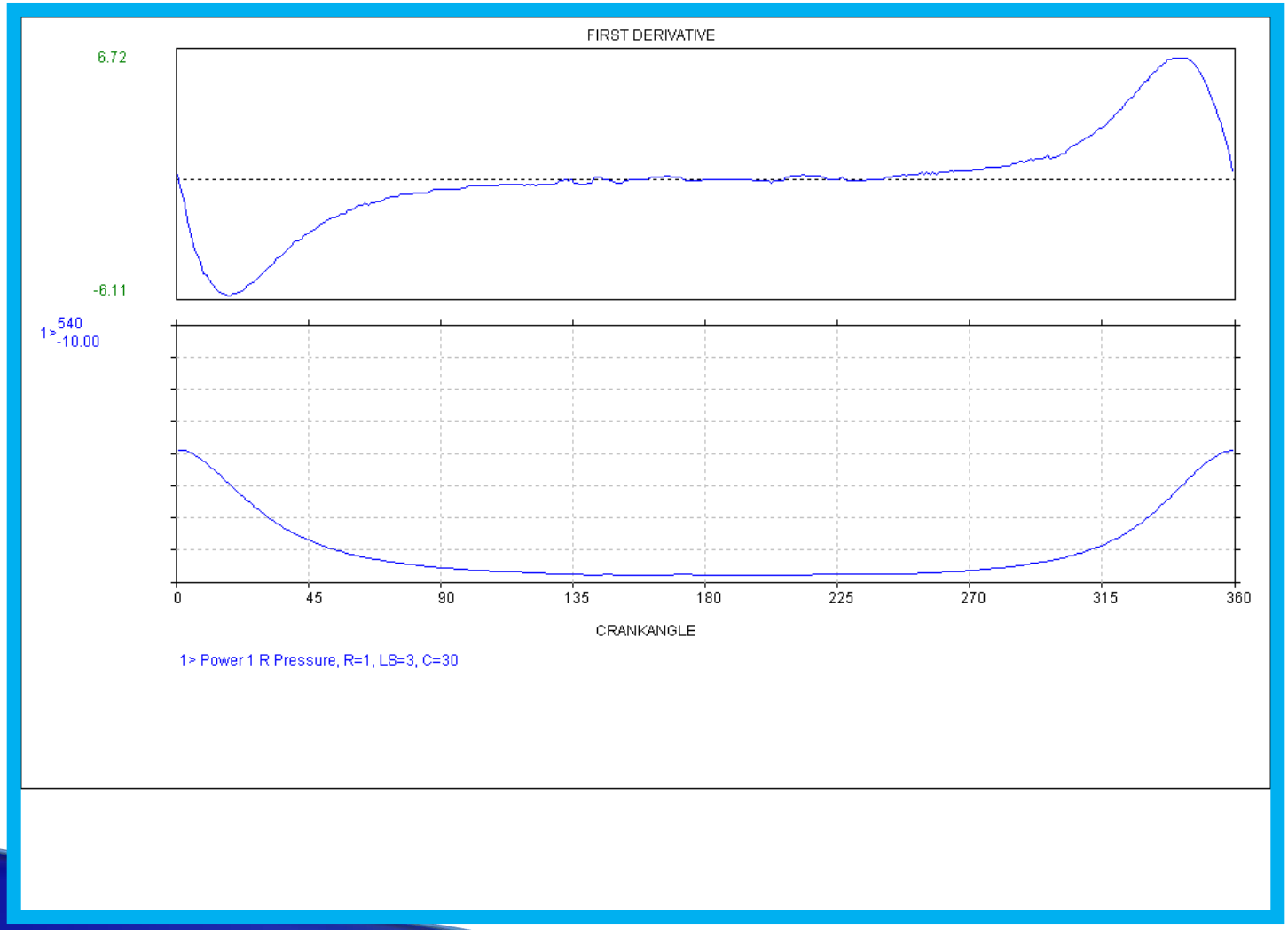
# Normal Combustion



# No Combustion

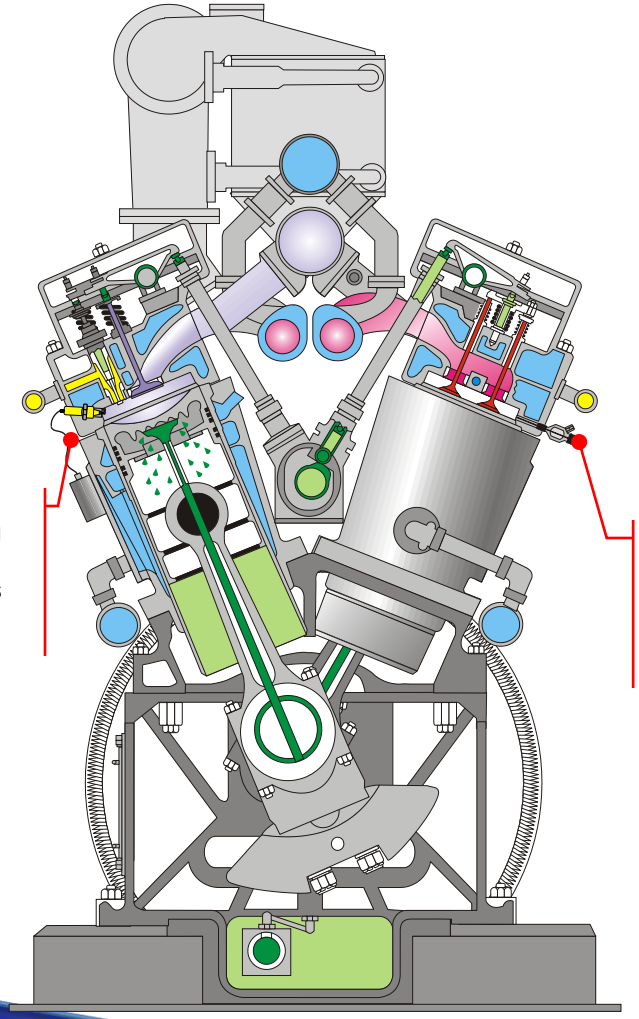
- The air/fuel charge does not ignite and there is no pressure rise except from the compression process
- Negative horsepower results due to pumping losses
- Caused by problems with air, fuel, foreign material or defective ignition

# No Combustion



# Routine Engine Balancing

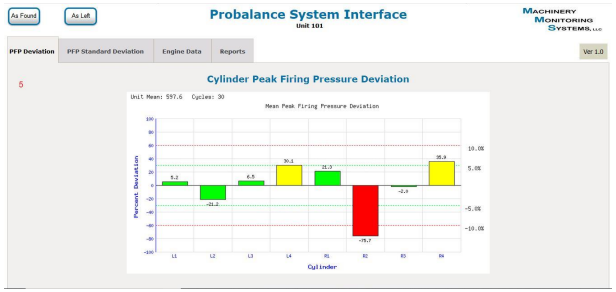
**Ignition secondary**
- Clip on unshielded spark plug cable
- Multi-cycle sampling statistics
- Ignition secondary patterns



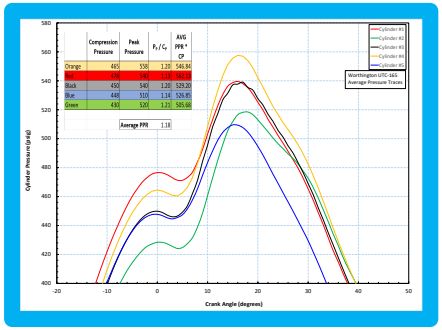
**Cylinder pressure**
- Pressure transducer
- Time domain data phased to crankshaft position
- Peak pressure statistics

# Engine Balance Methods

- **Peak Firing Pressure (PFP)**




- **Peak Pressure Ratio (PPR)**

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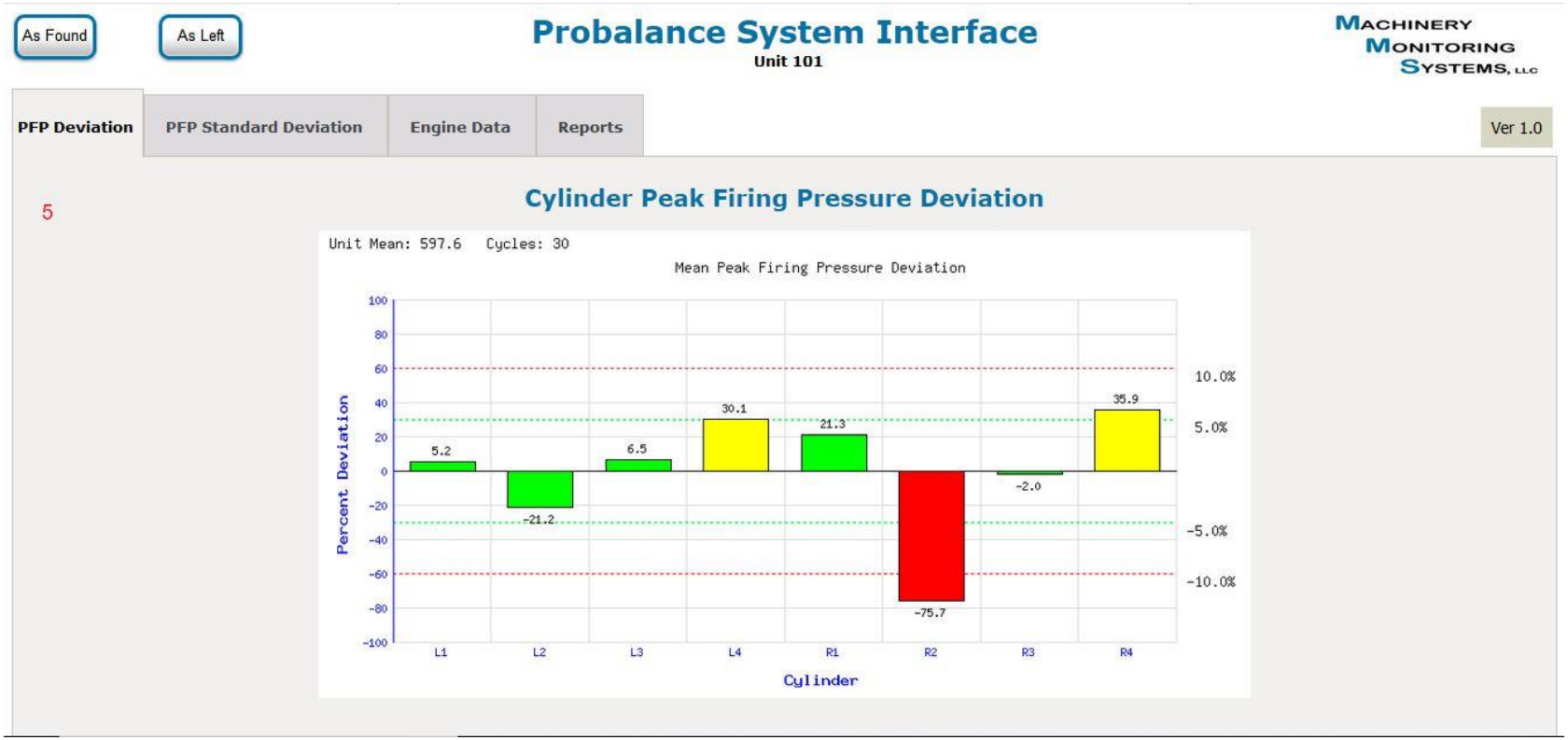
# Peak Firing Pressure Balancing

- **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 PFP for the engine, and adjusting the cylinder firing pressures as close to that mean pressure as possible.

# PFP Balancing

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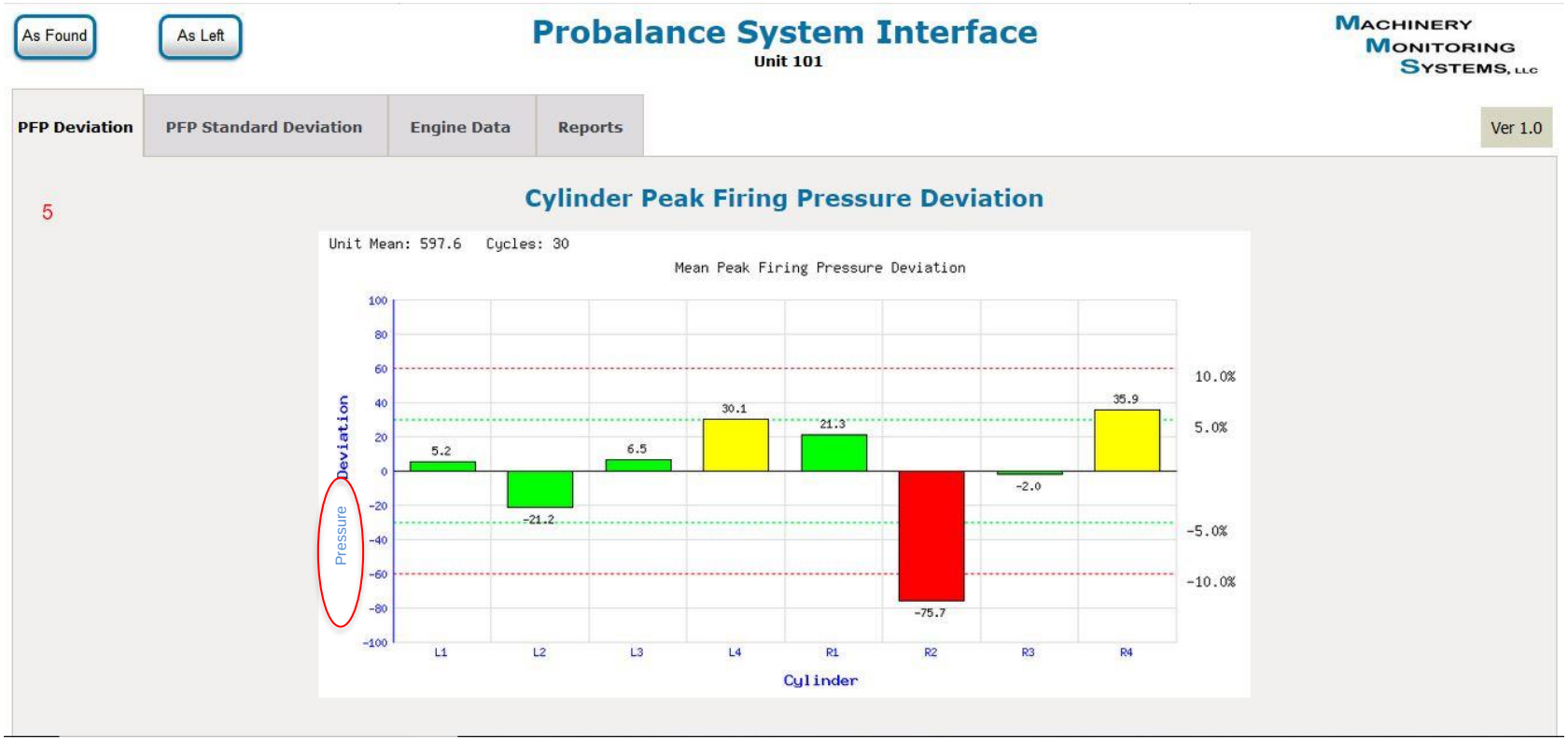
# PFP Balancing

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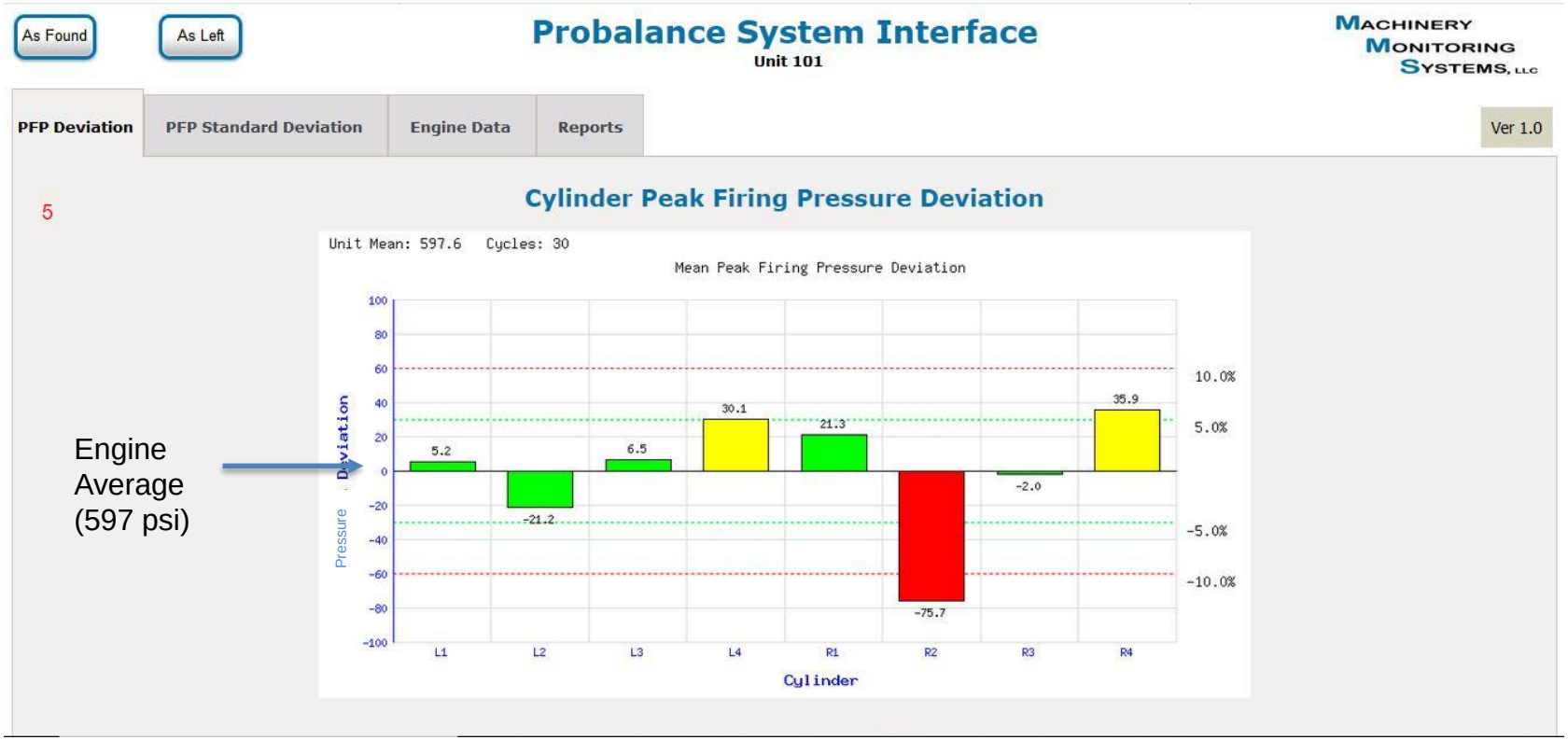
# PFP Balancing

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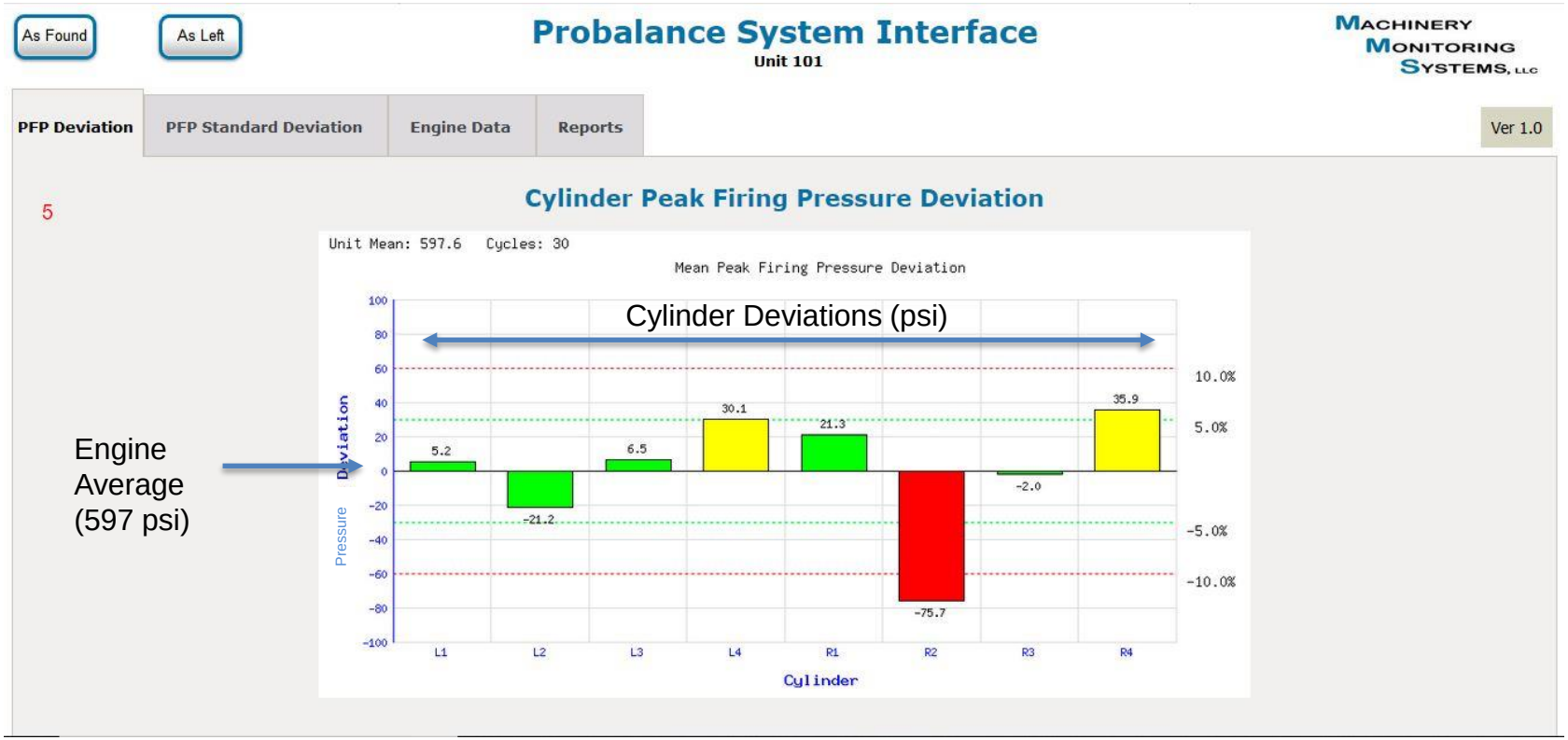
# PFP Balancing

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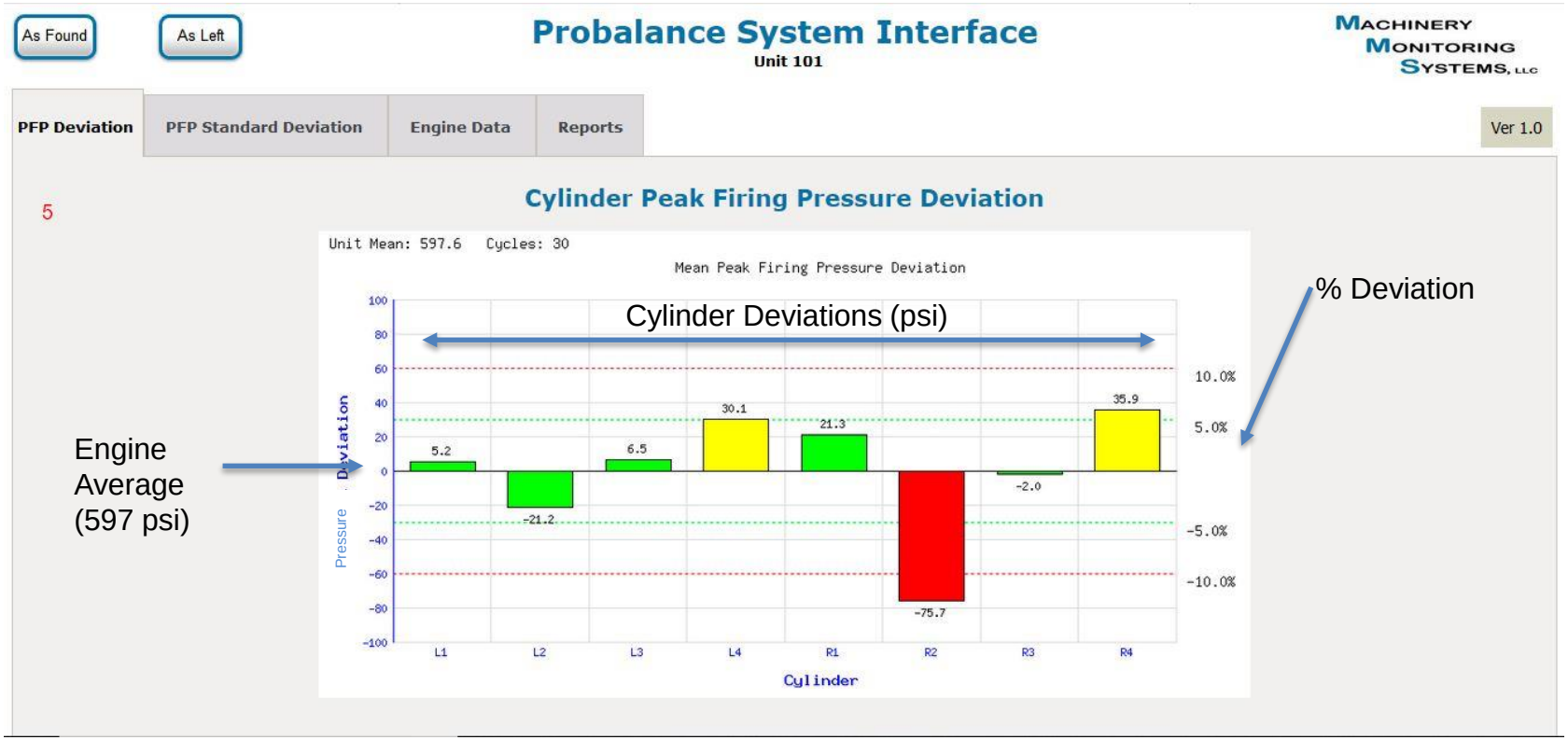
# PFP Balancing

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# PFP Balance Procedure

- Measure PFP for each cylinder
- Calculate mean PFP for the engine & deviations of each cylinder from the engine mean (As-Found)
- Identify which fuel modulators need to be increased/decreased
- Make adjustments
- Re-measure each cylinder's PFP (As-Left…hopefully!)

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# Peak Pressure Ratio Balancing

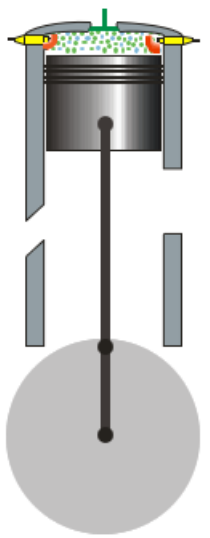
- **Peak Pressure Ratio (PPR)** is a method suggested in EPPL / SWRI / DOE study in 2008. In this method, the PFP and the running Compression Pressure (Cp) of each cylinder is measured.

- 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 influences the combustion process.

# Peak Pressure Ratio Balancing

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

$$PPR = PFP \,/\, Cp$$



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

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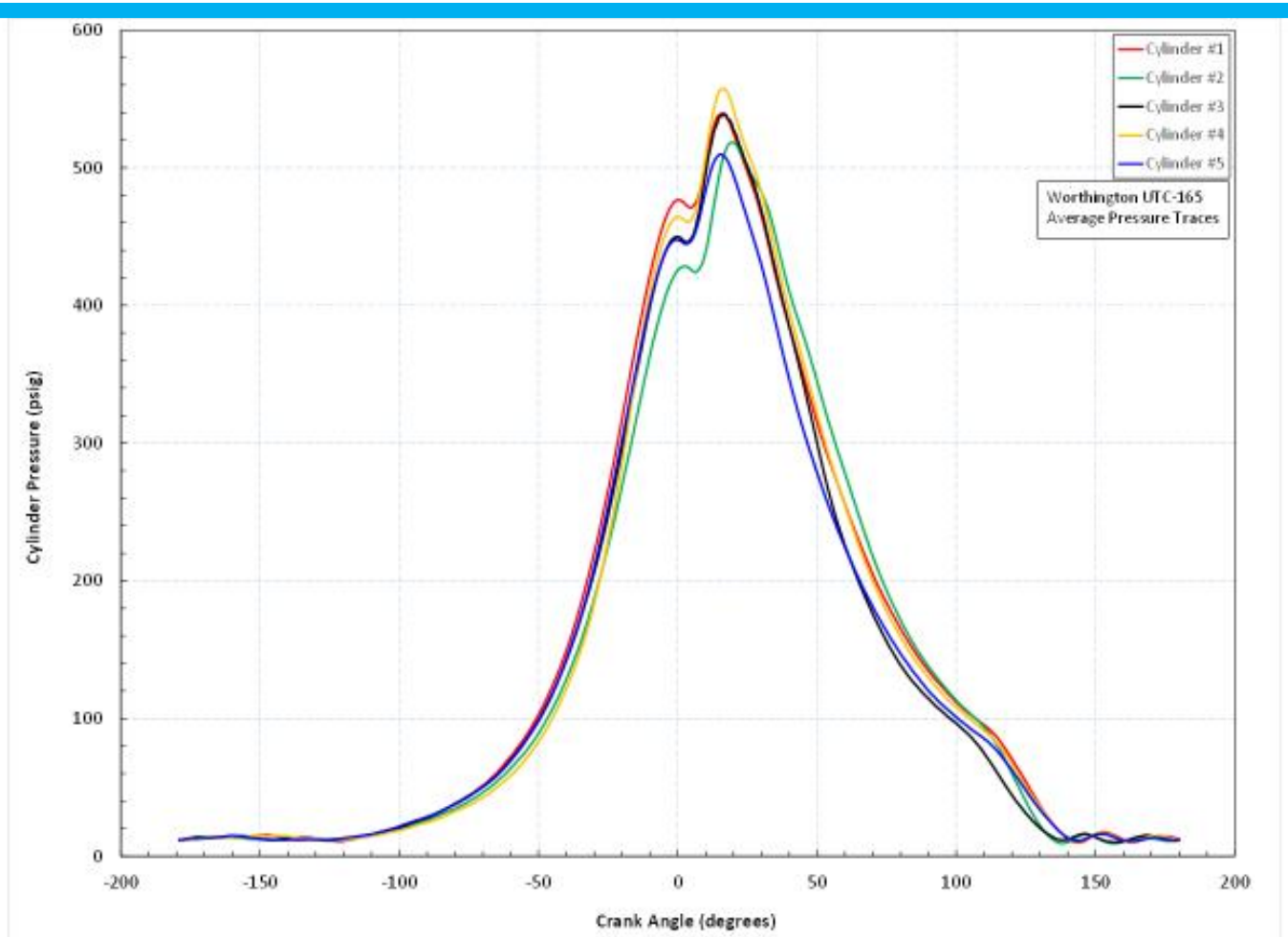
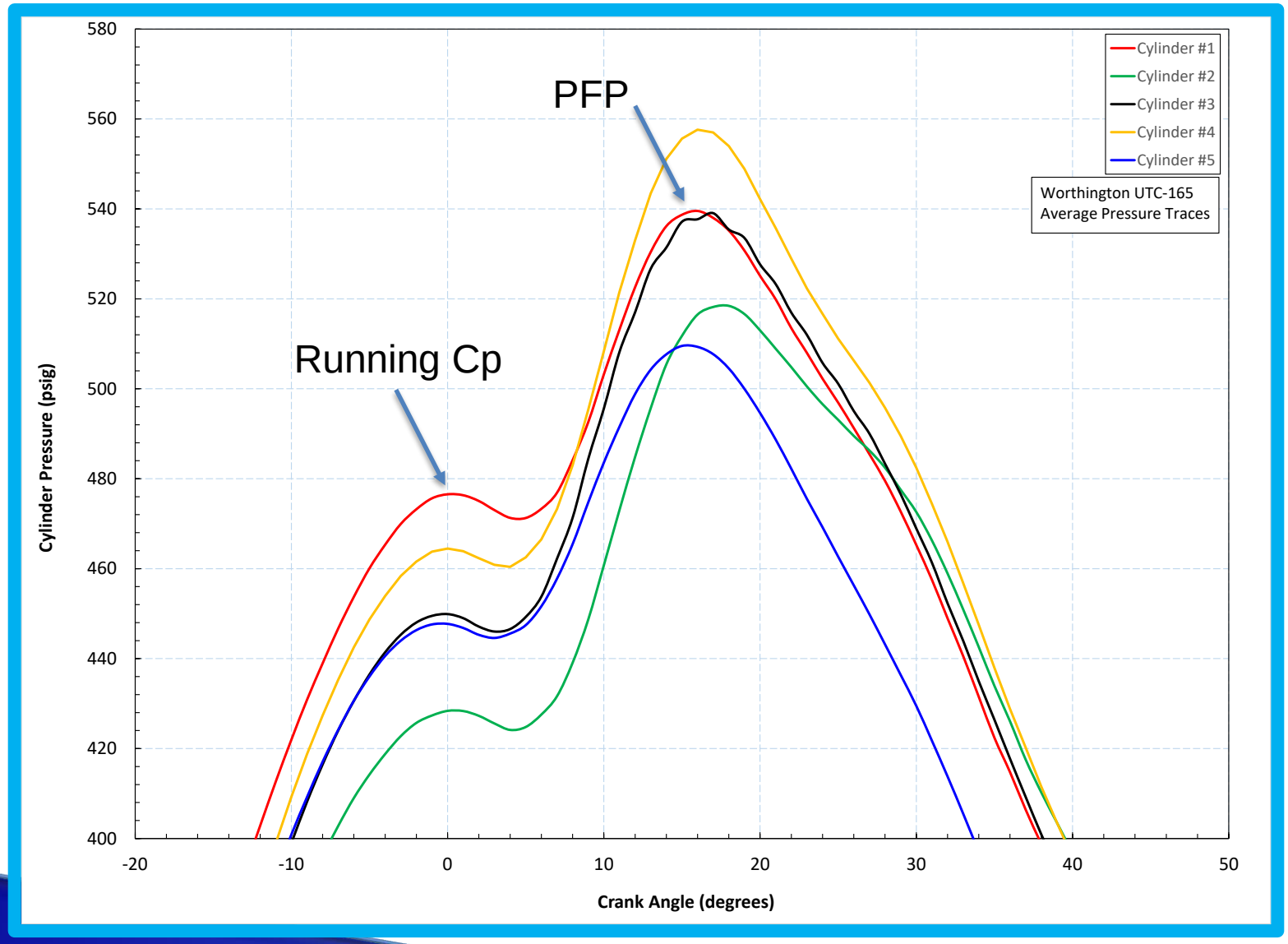
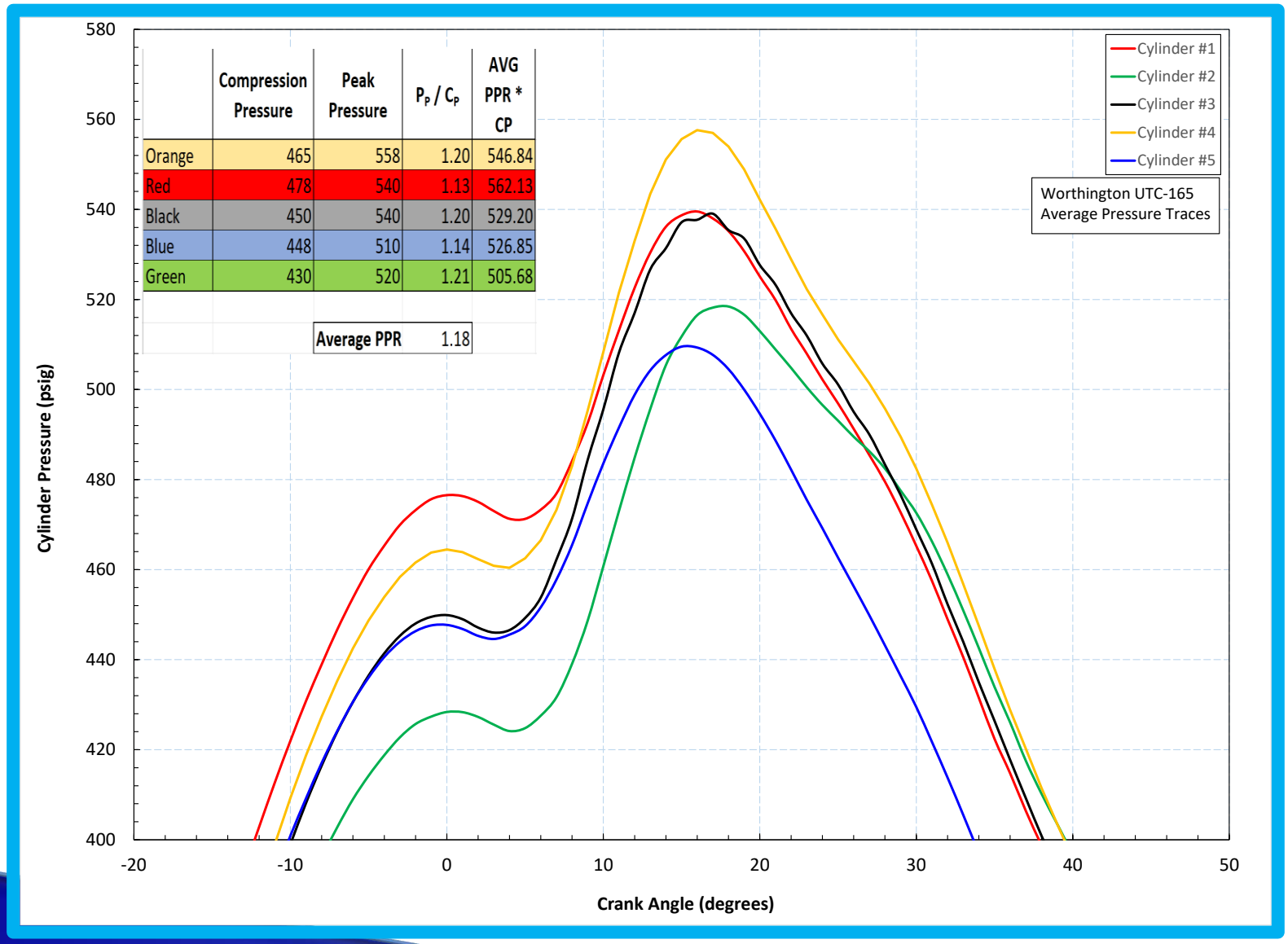

Cylinder #1
Cylinder #2
Cylinder #3
Cylinder #4
Cylinder #5
Worthington UTC-165
Average Pressure Traces
Cylinder Pressure (psig)
600
500
400
300
200
100
0
-200
-150
-100
-50
0
50
100
150
200
Crank Angle (degrees)


PFP
Running Cp
Cylinder #1
Cylinder #2
Cylinder #3
Cylinder #4
Cylinder #5
Worthington UTC-165
Average Pressure Traces
Cylinder Pressure (psig)
Crank Angle (degrees)
580
560
540
520
500
480
460
440
420
400
-20
-10
0
10
20
30
40
50


Compression Pressure
Peak Pressure
$P_P / C_P$
AVG PPR * CP
Orange 465 558 1.20 546.84
Red 478 540 1.13 562.13
Black 450 540 1.20 529.20
Blue 448 510 1.14 526.85
Green 430 520 1.21 505.68
Average PPR 1.18
Cylinder #1
Cylinder #2
Cylinder #3
Cylinder #4
Cylinder #5
Worthington UTC-165
Average Pressure Traces
Cylinder Pressure (psig)
580
560
540
520
500
480
460
440
420
400
-20
-10
0
10
20
30
40
50
Crank Angle (degrees)

# PPR Balance Procedure

- Measure PFP for each cylinder
- Calculate each cylinder's PPR (PFP / Cp) and then engine's average $PPR_{avg}$
- Use the Engine Average PPR to calculate each cylinder's target PFP

  Target PFP = Cyl Cp x $PPR_{avg}$

- Bar chart the cylinder's differences between the as-found PFPs and their target PFPs (As-Found Balance)
- Identify which fuel modulators need to be increased/decreased (e.g +/- 5% from their target PFP)
- Make adjustments
- Re-measure each cylinder's PFP, plot differences between measured PFP & Target PFP (As-Left…hopefully!)

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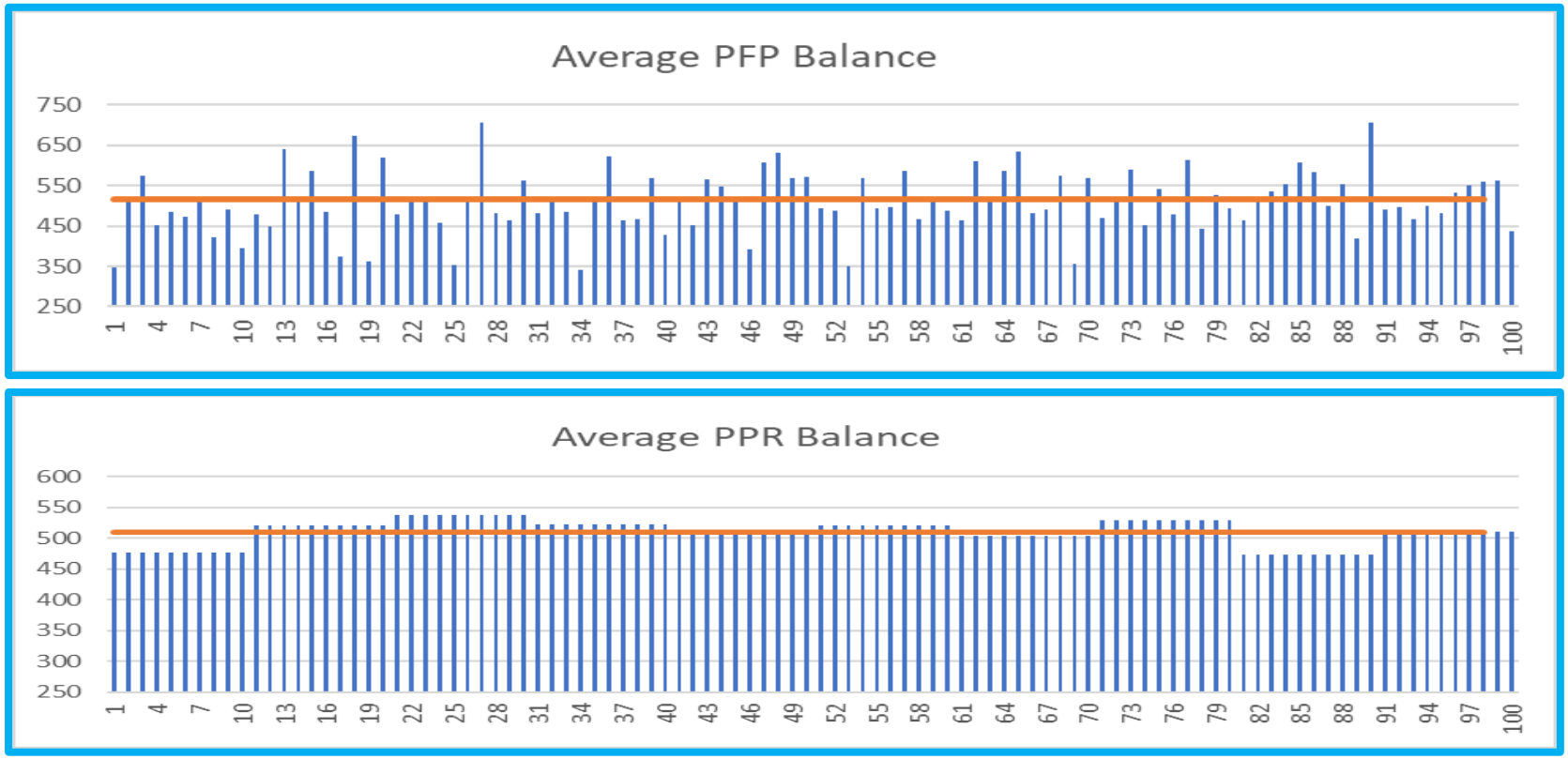
# PFP to PPR Comparison

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# Bottom Line


My Awesome Company
PROFIT AND LOSS
January - December 2018

| | TOTAL |
|---|---|
| Income | $87,763.99 |
| Cost of Goods Sold | $9,328.00 |
| GROSS PROFIT | $78,435.99 |
| Expenses | $5,707.06 |
| NET OPERATING INCOME | $72,728.93 |
| Other Income | $43.12 |
| Other Expenses | $10,721.88 |
| NET OTHER INCOME | $ -10,678.76 |
| NET INCOME | $62,050.17 |

- Research has shown 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

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# Next Steps

- **Education** – End users need to understand the benefits of PPR. How do you explain it to your Ops Supervisors!

- **Implementation** – MMS is working to incorporate the PPR method (as an option) in our portable balancer (Snapshot Engine Balancer) as well as our online products (ProBalance & ProBalance Plus).

Thank you

Questions?

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