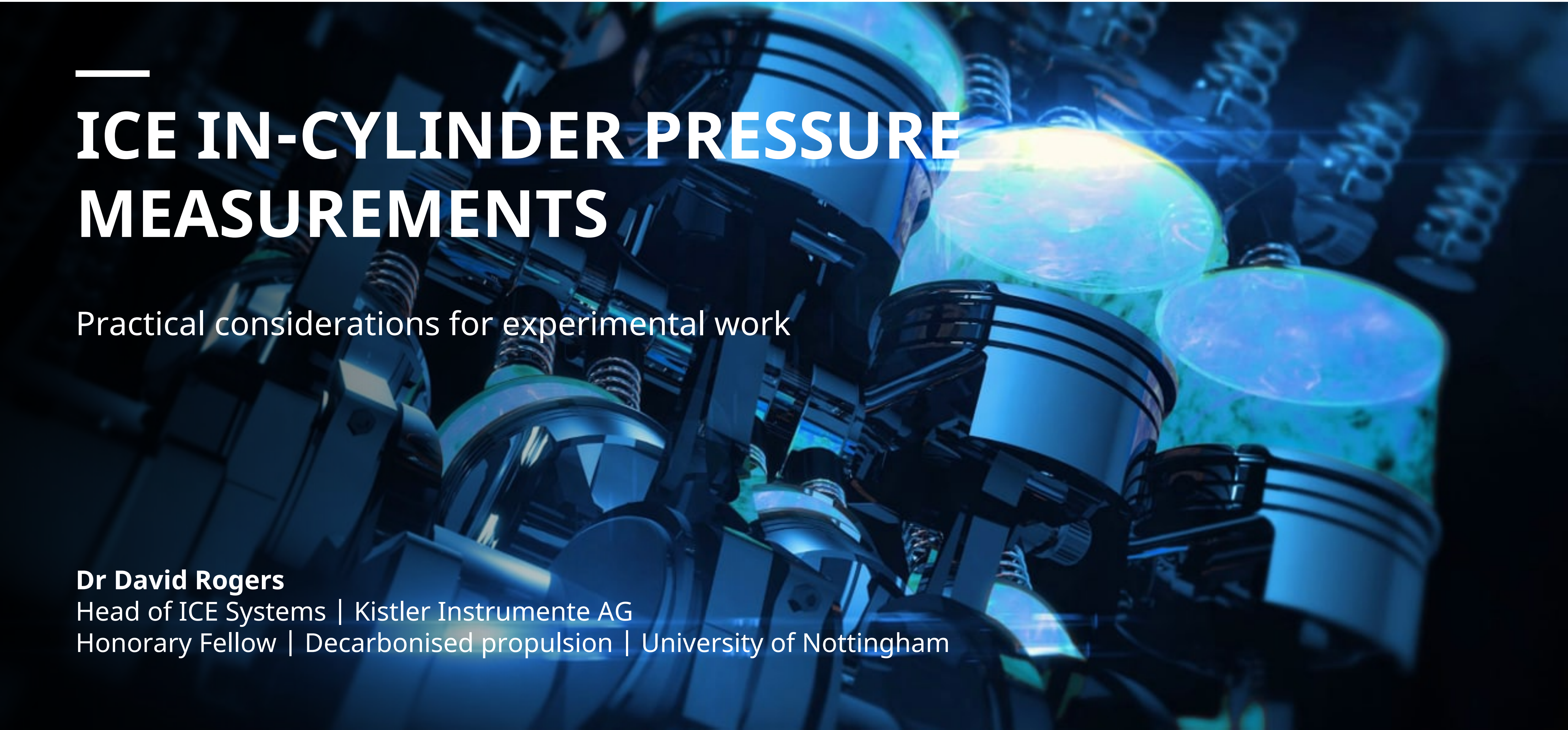
KISTLER

measure. analyze. innovate.



ICE IN-CYLINDER PRESSURE MEASUREMENTS

Practical considerations for experimental work

Dr David Rogers
Head of ICE Systems | Kistler Instrumente AG
Honorary Fellow | Decarbonised propulsion | University of Nottingham

INTRODUCTION

Kistler Instruments | Dave Rogers

About Kistler:

- Global leader in dynamic measurement technology for measuring pressure, force, torque and acceleration
- We support our customers in industry and science to improve their products and make their manufacturing processes more efficient.
- Offering sensors, measurement systems and services that are exactly tailored to needs, we fully focus upon the complex current and future challenges in the areas of automobile development, industrial automation and in fields related to extreme environments

  www.kistler.com

About me:

- Dave Rogers, Business Developer in engine research and development product group, based in Kistler HQ, Winterthur, Switzerland
- Originally from UK, went to live in Switzerland ~8 years ago, to join Kistler
- Commercial Engineer, technical background in Powertrain/Automotive Engineering R&D, various employers in the fields of Instrumentation, Systems, Testing, Software, Services, Consulting

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KISTLER PRESENTATION

Combustion pressure measurement basics, sensors and systems

Pressure data for the gas in the cylinder over the operating cycle can be used to calculate the work transfer from gas to piston.

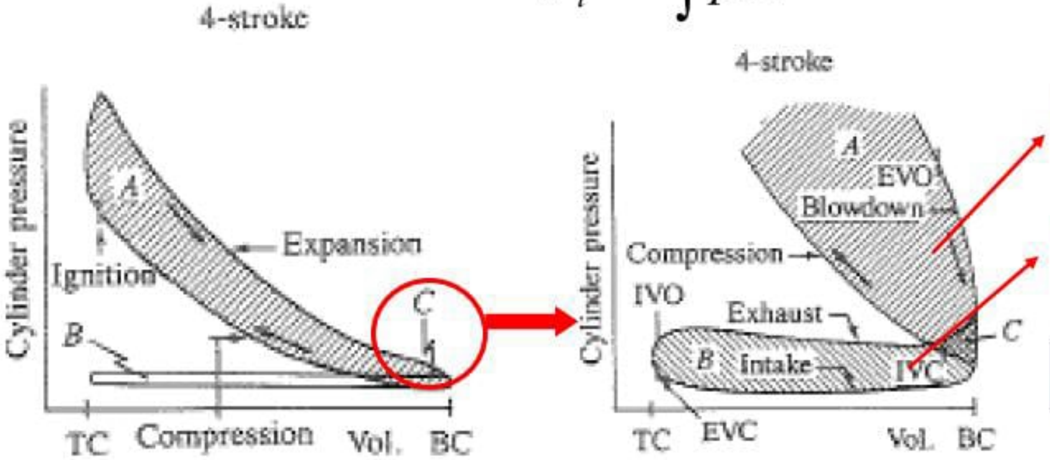
Cylinder Pressure Sensor for Engine Monitoring

Cylinder pressure is measured on real time consecutive cycles and pressure transducer is installed on the cylinder head

A crank angle encoder is also installed on the engine to and provides precise crank-angle position measurements.

This information was then routed to a high speed data acquisition system.

$$W_i = -\oint p dV$$

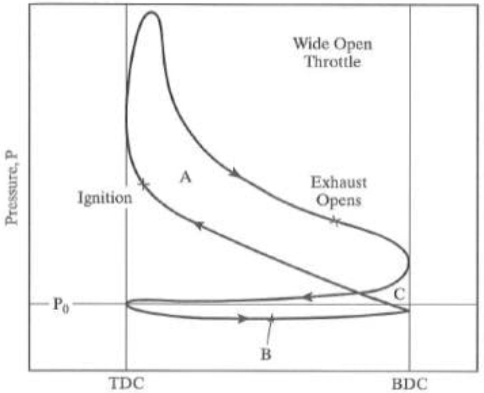


$$W_{i,g} = A + C$$

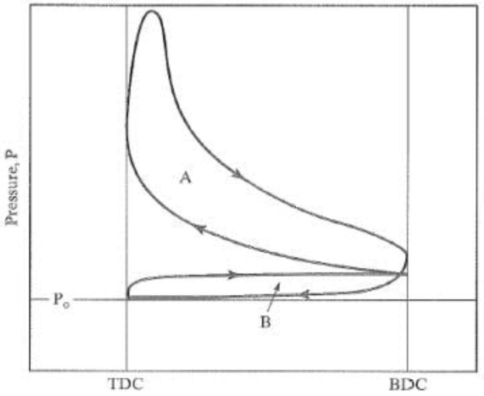
$$W_p = B + C$$

$$W_{c,in} = W_{c,ig} - W_p$$

Naturally aspirated engines



Supercharged/Turbocharged engines



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CONTENTS

AGENDA	
1. Basics	50 mins
2. In-cylinder sensors	
Break (10 mins)	*10 mins*
3. Measuring equipment	50 mins
4. Signal processing	
5. Data quality	
6. Wrap-up	

BASICS

MEASUREMENT AND APPLICATION

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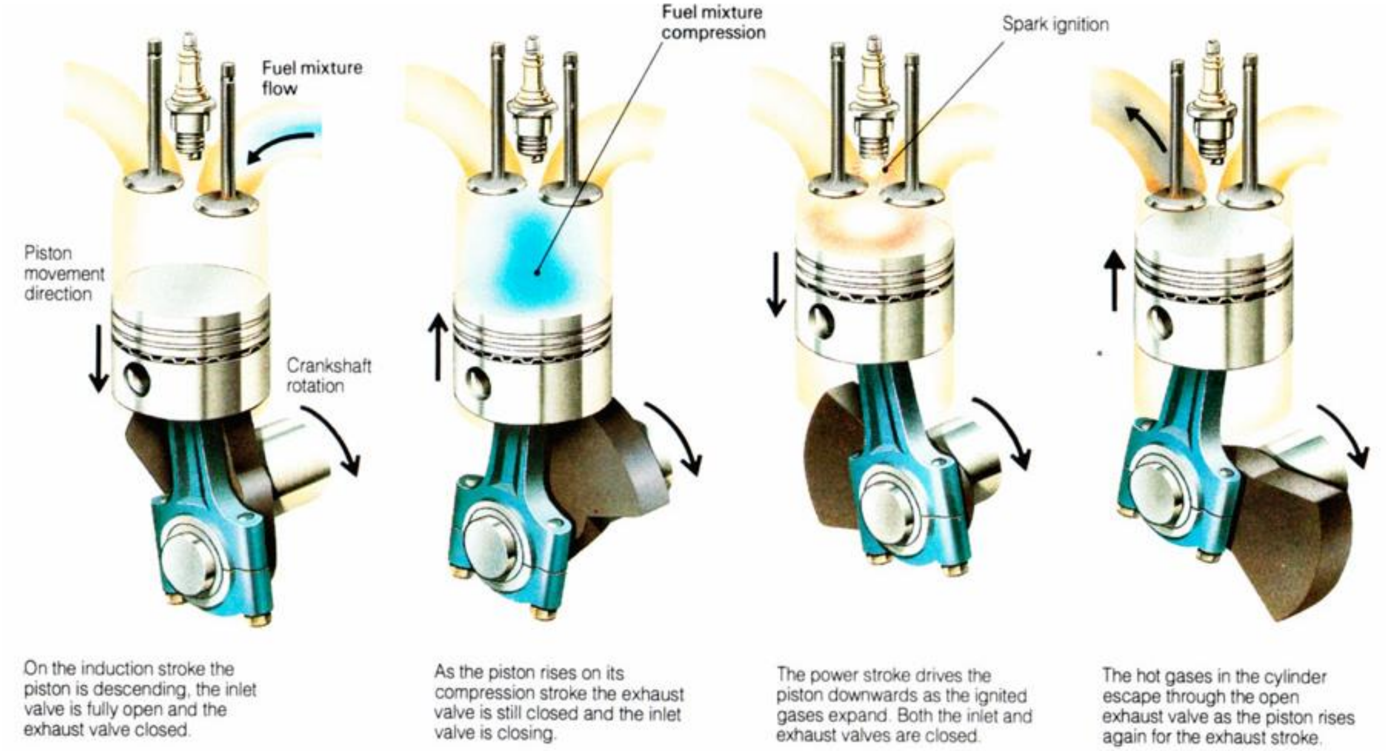
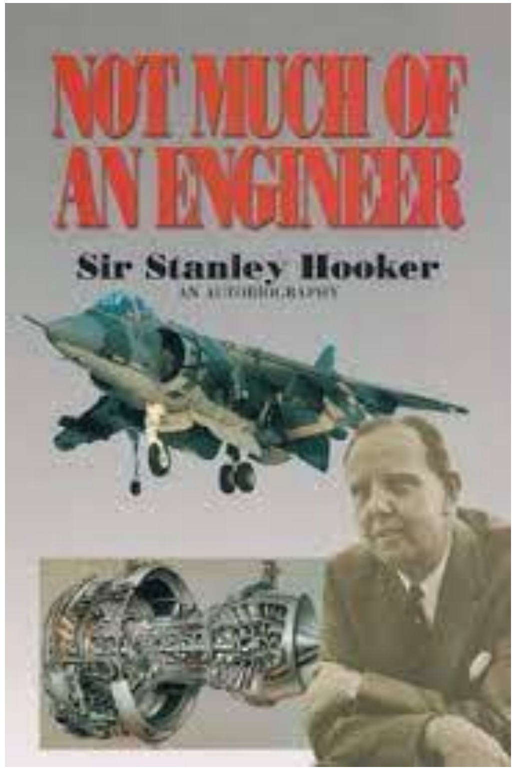
RECIPROCATING ICE

The 4-stroke cycle





"I once facetiously remarked that the four-stroke engine has one stroke for producing power and three for wearing out the engine"

Sir Stanley Hooker, Mathematician, Engineer, Rolls-Royce

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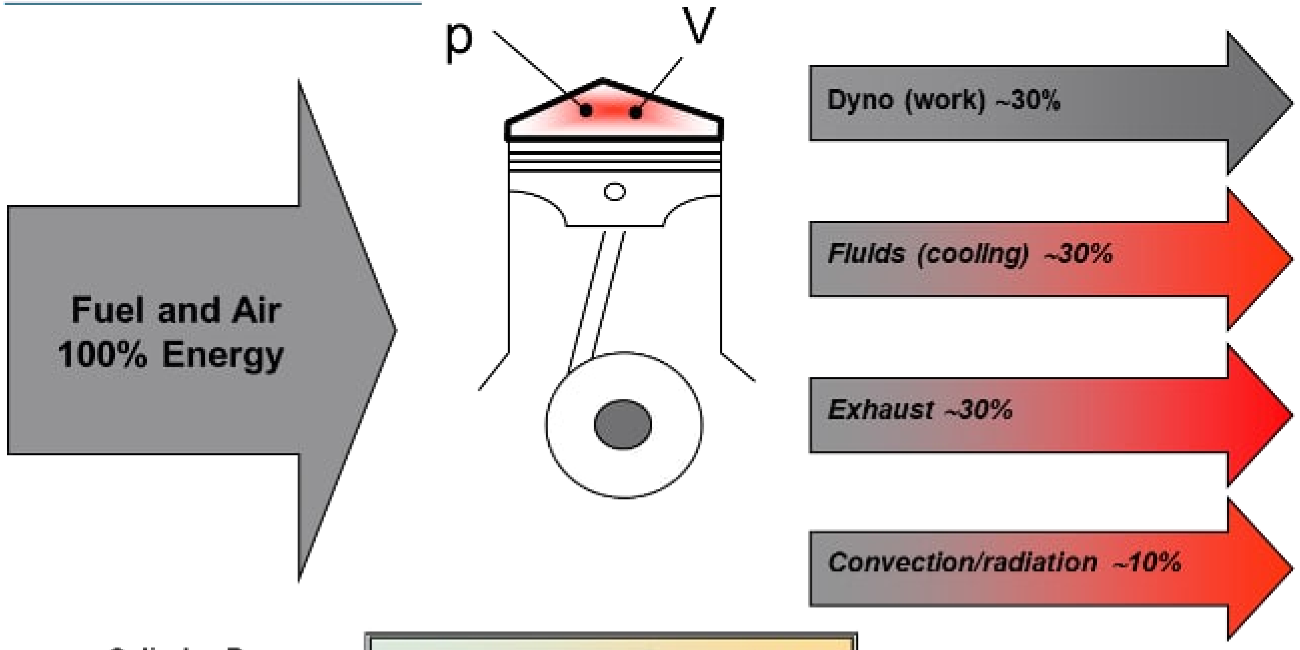
ENERGY CONVERSION PROCESS ICE

Understanding losses, improving efficiency

- Chemical Energy

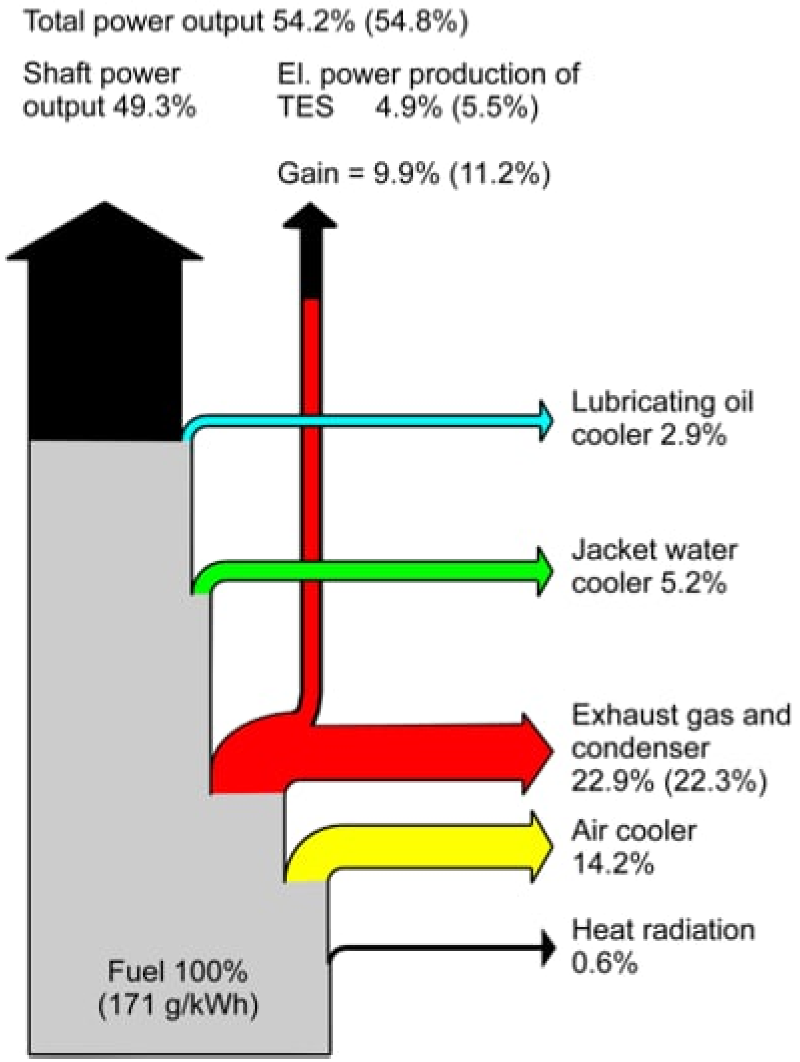
- Mechanical Energy + Heat Energy



p = Cylinder Pressure
V = Volume

$$W_{mech} = \int p \times dV$$

12K98ME/MC with TES
SMCR : 68,640 kW at 94.0 r/min
ISO ambient reference conditions
TES : Single pressure (Dual pressure)



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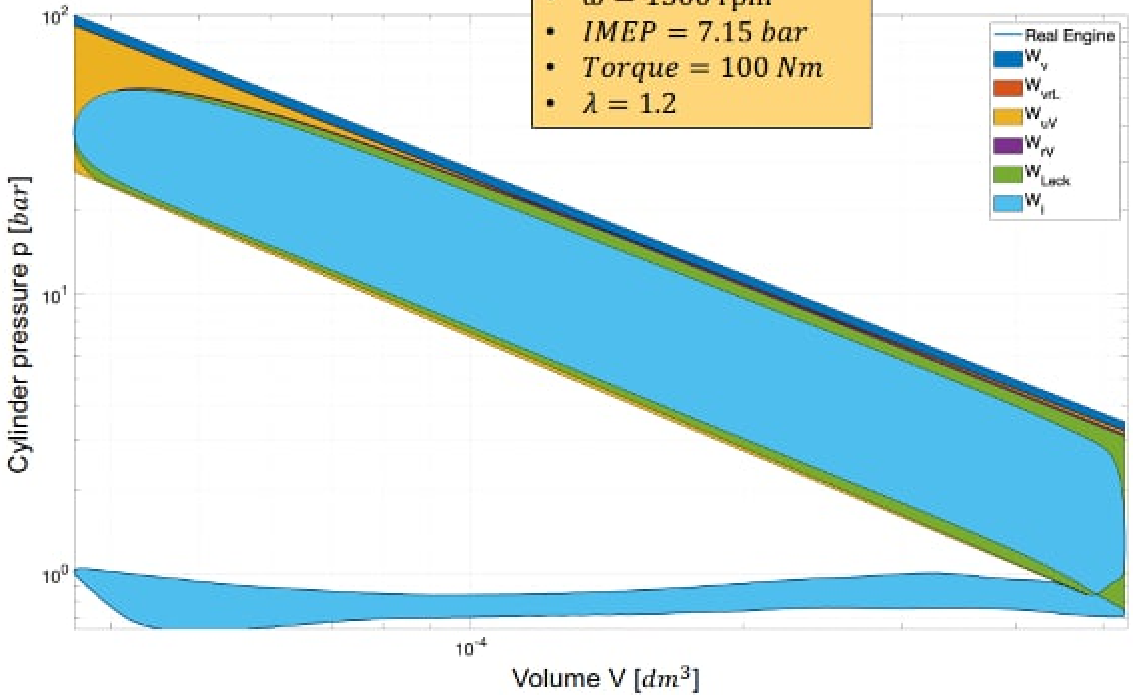
ENERGY CONVERSION PROCESS ICE

Comparing actual and ideal engines allows characterisation of losses

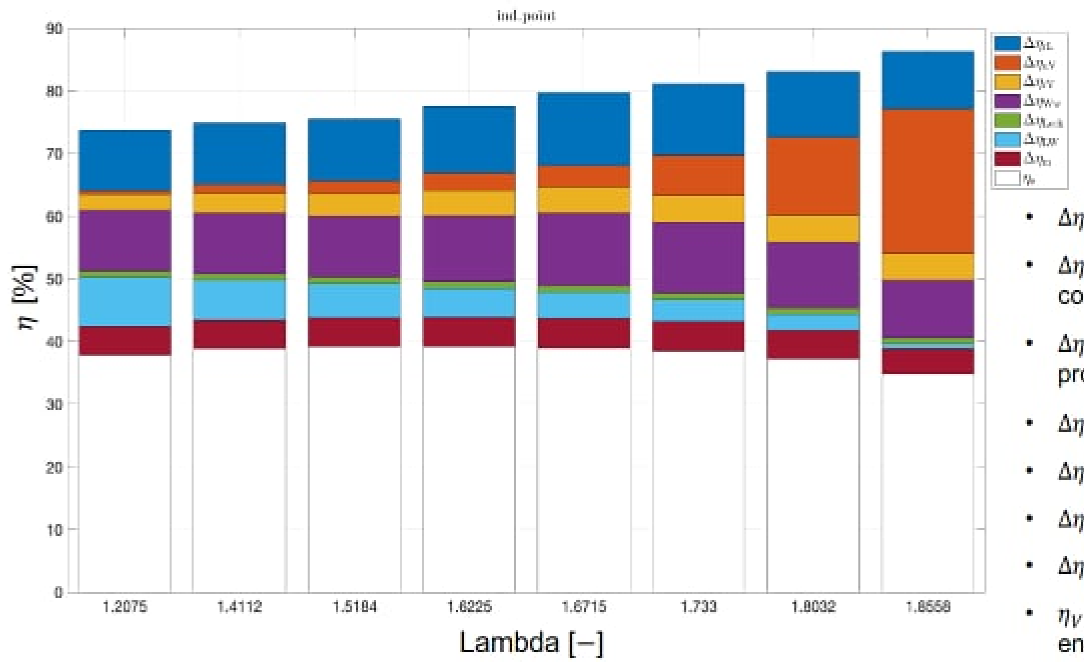
Results – Loss Analysis

Real engine data:

- $\omega = 1500$ rpm
- $IMEP = 7.15\ bar$
- $Torque = 100\ Nm$
- $\lambda = 1.2$



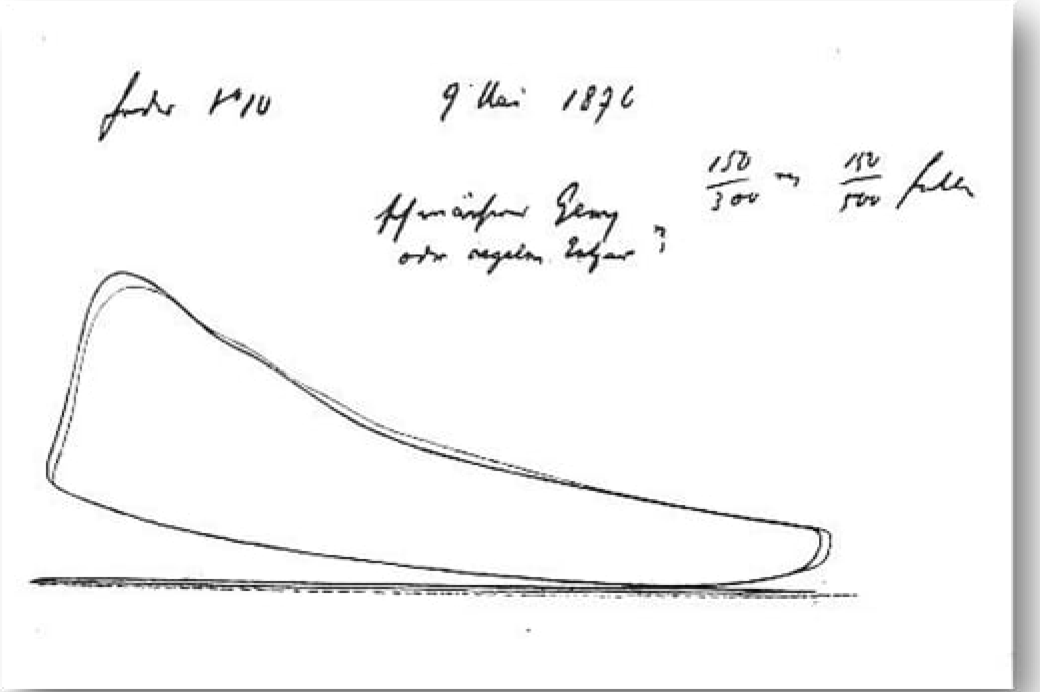
Results – Lambda Variation



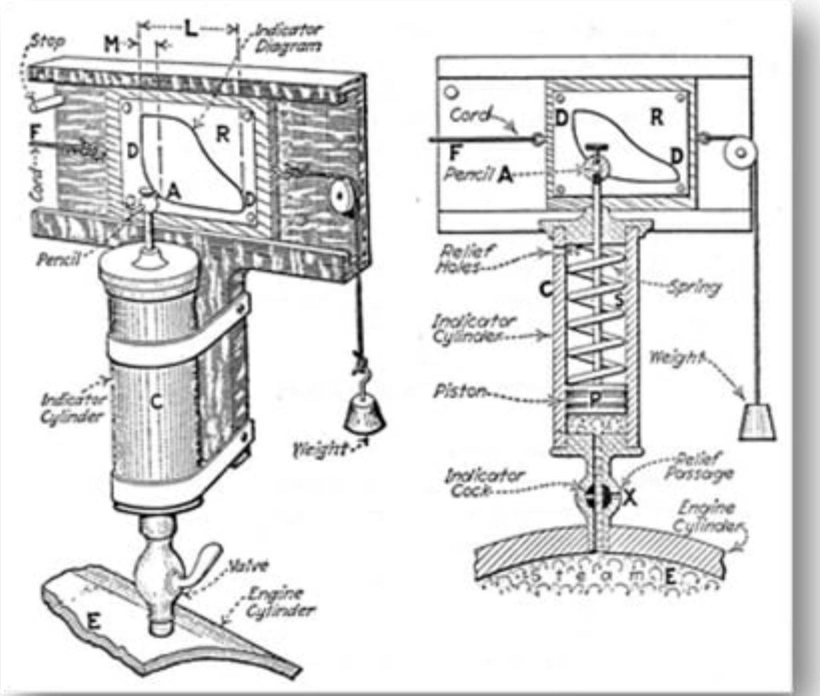
- $\Delta\eta_{rL}$ Effects of real charge
- $\Delta\eta_{uV}$ Incomplete combustion
- $\Delta\eta_{rV}$ Real combustion progression
- $\Delta\eta_{Ww}$ Wall heat losses
- $\Delta\eta_{Leck}$ Leakage/Blow-By
- $\Delta\eta_{LW}$ Pumping losses
- $\Delta\eta_{m}$ Friction Losses
- η_V Efficiency of a perfect engine

RECIPROCATING ICE

History of Cylinder Pressure Measurements



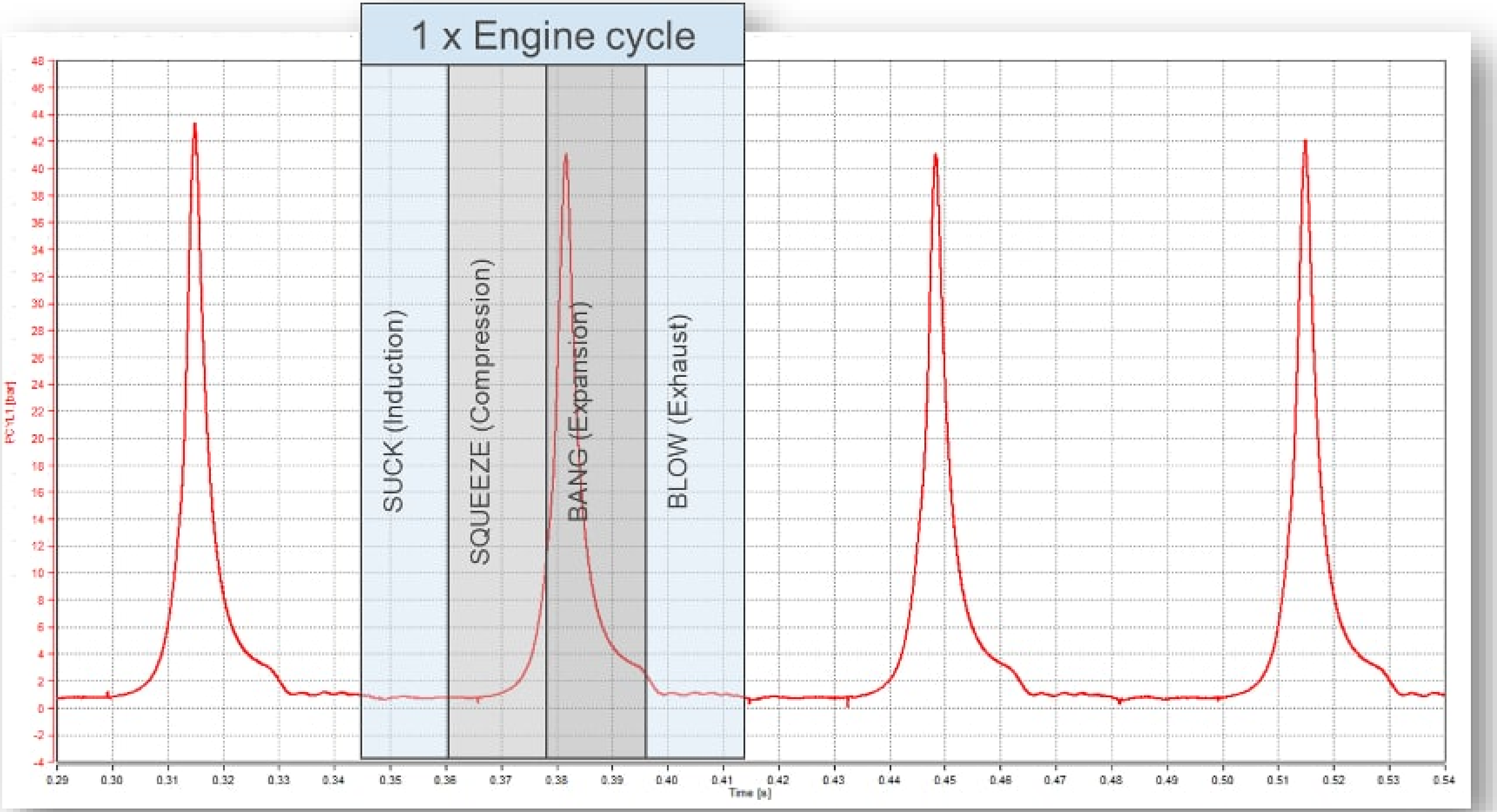
- Indicator diagram plotted by Nikolaus Otto (May 9, 1876)
- Piezoelectric effect of quartz crystals demonstrated by Pierre and Jacques Curie (1880)



- Moving tablet indicator
- Used by James Watt ~1790

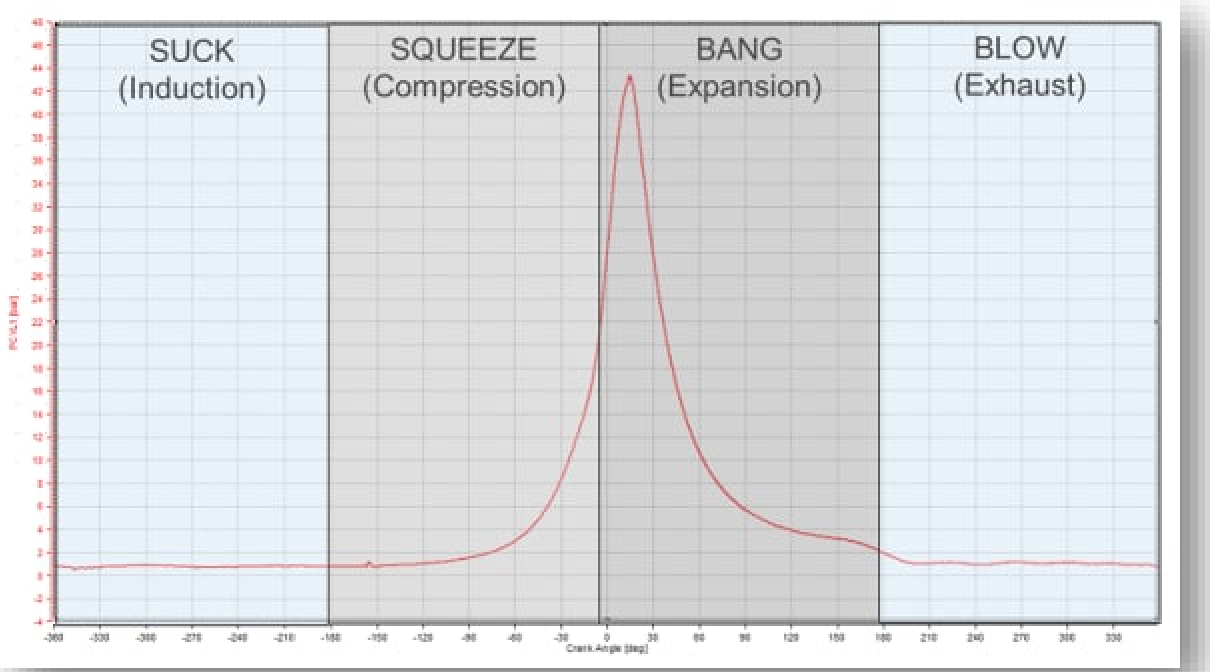
RECIPROCATING ICE

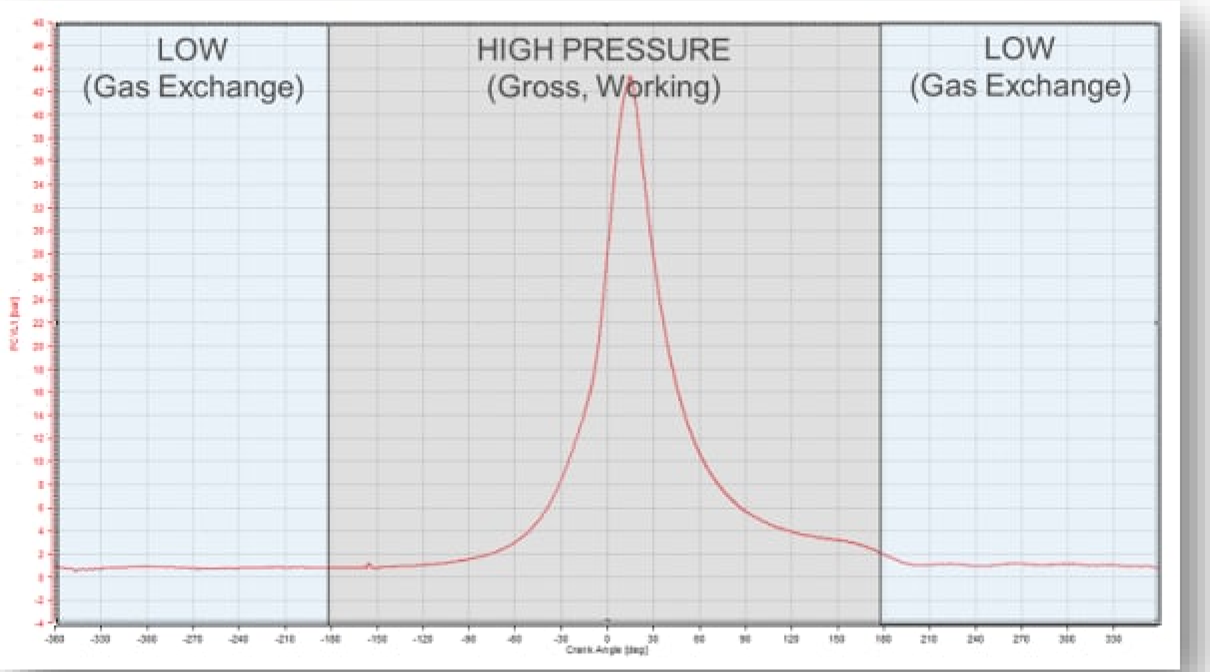
Pressure data in the time domain



RECIPROCATING ICE

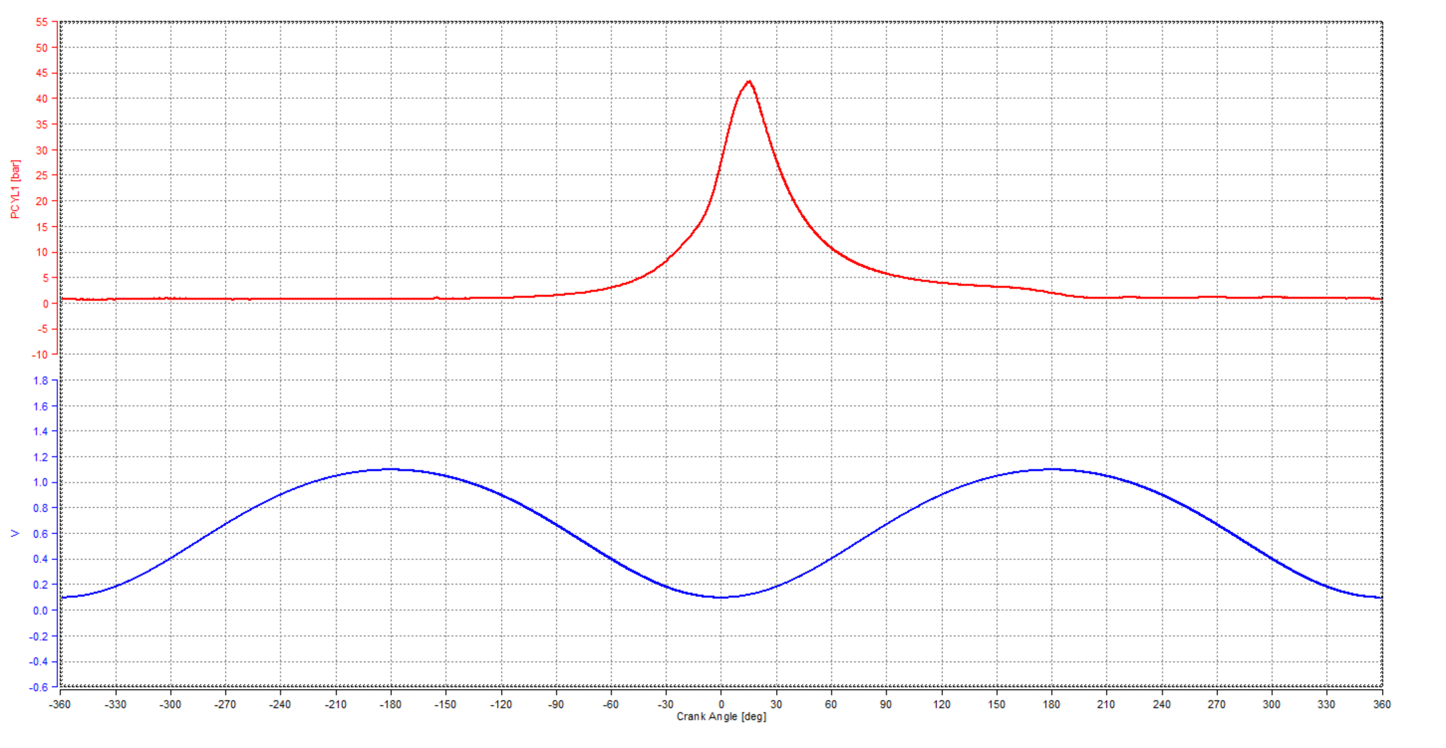
Pressure data in the angle domain





RECIPROCATING ICE

Pressure + Volume | Thermodynamic and cycle analysis



Cylinder volume (*V*) is calculated using for each crank angle division as required according to the measurement table and resolution.

$$V = V_c + \pi \left(\frac{B}{2}\right)^2 (l + a - s)$$

Where s is the distance between the crank axis and the piston pin axis and calculated by

$$s = a\cos\theta + \sqrt{\left(l^2 - a^2 \sin^2\theta\right)}$$

Swept volume (V_s) and clearance volume (V_c) are calculated thus:

$$V_s = 2a\pi\frac{B^2}{4}$$

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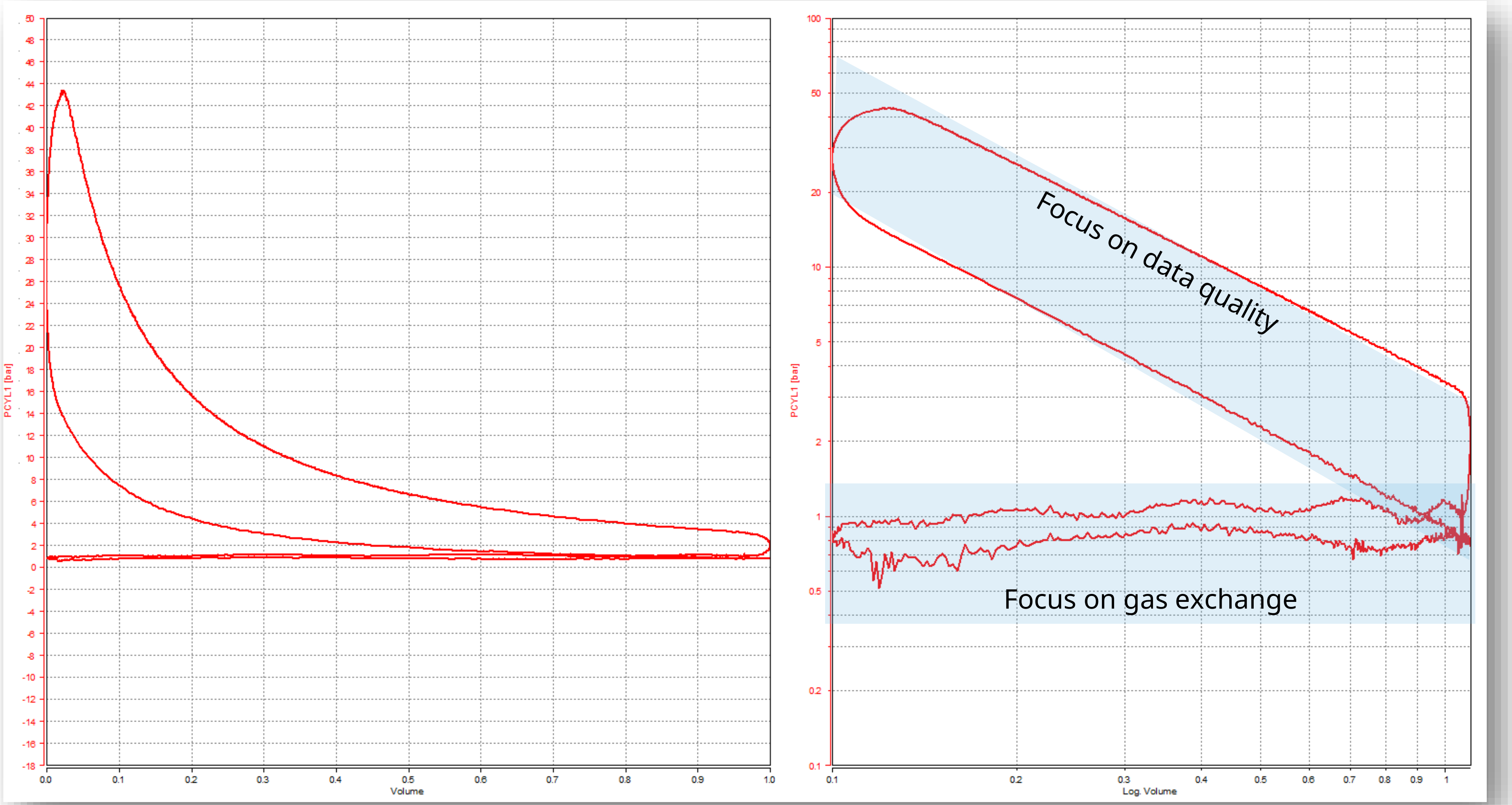
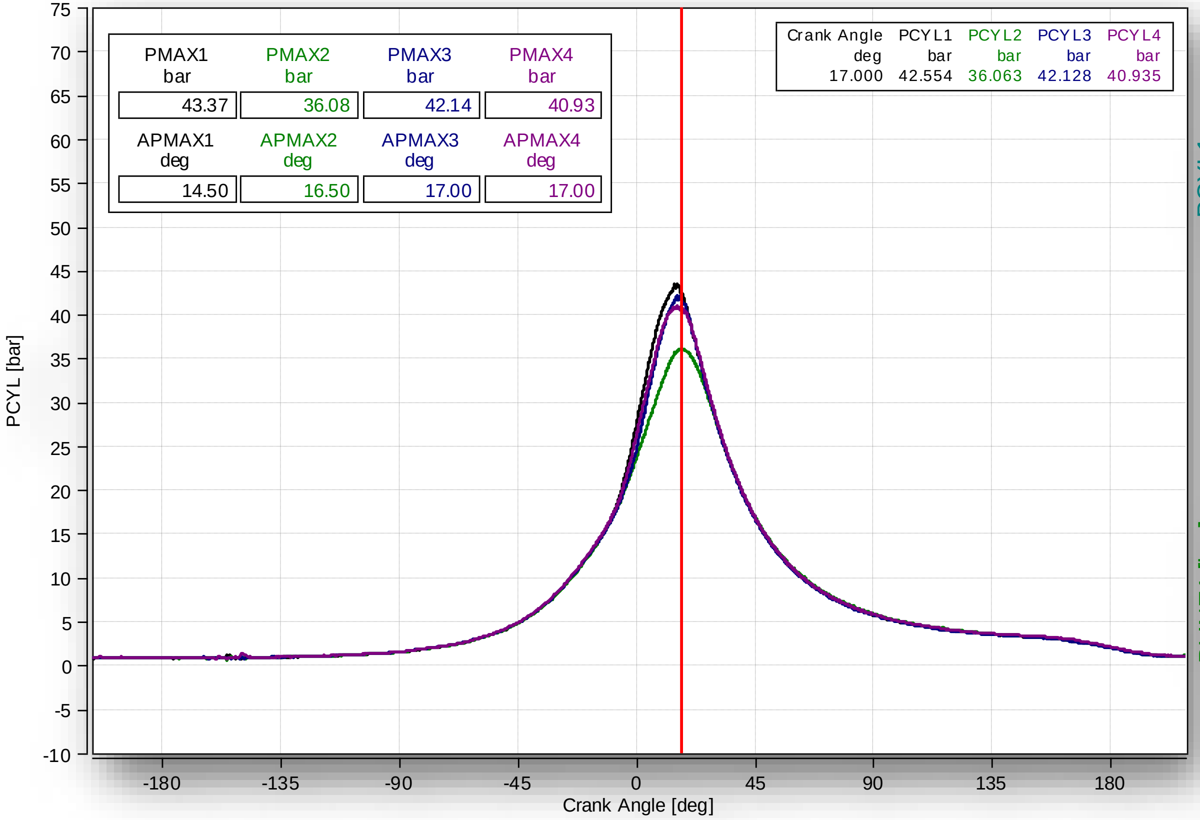
RECIPROCATING ICE

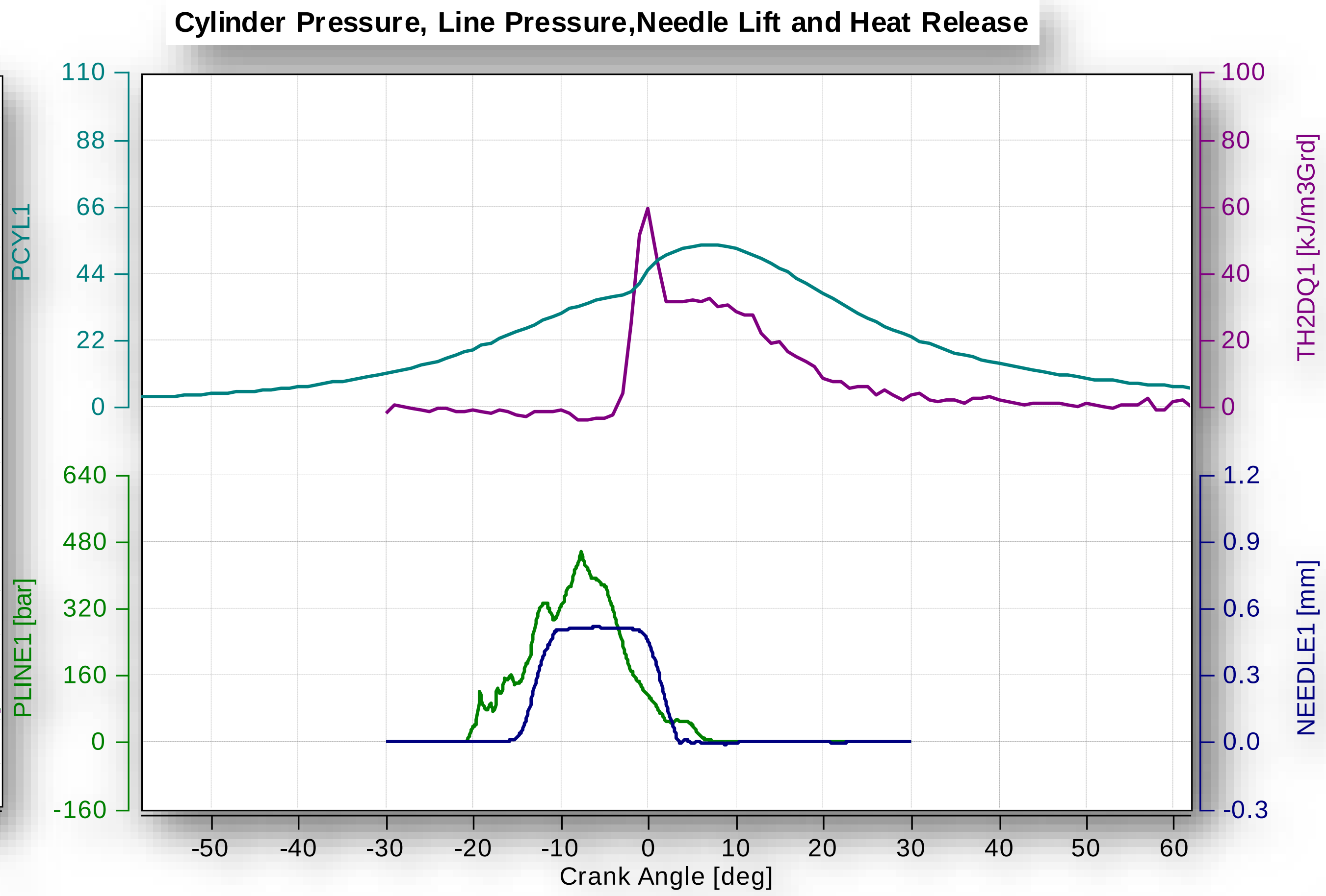
PV diagram | Linear and log scales



DERIVED FROM MEASURED CURVES

Direct results





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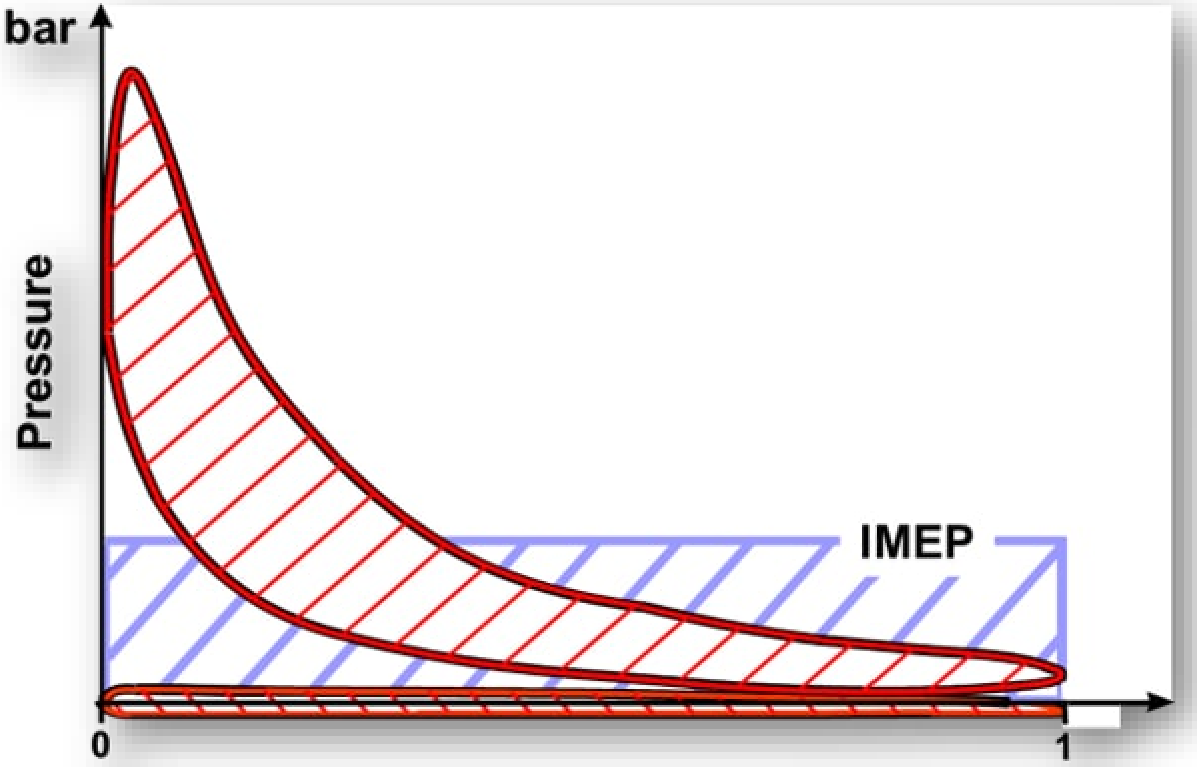
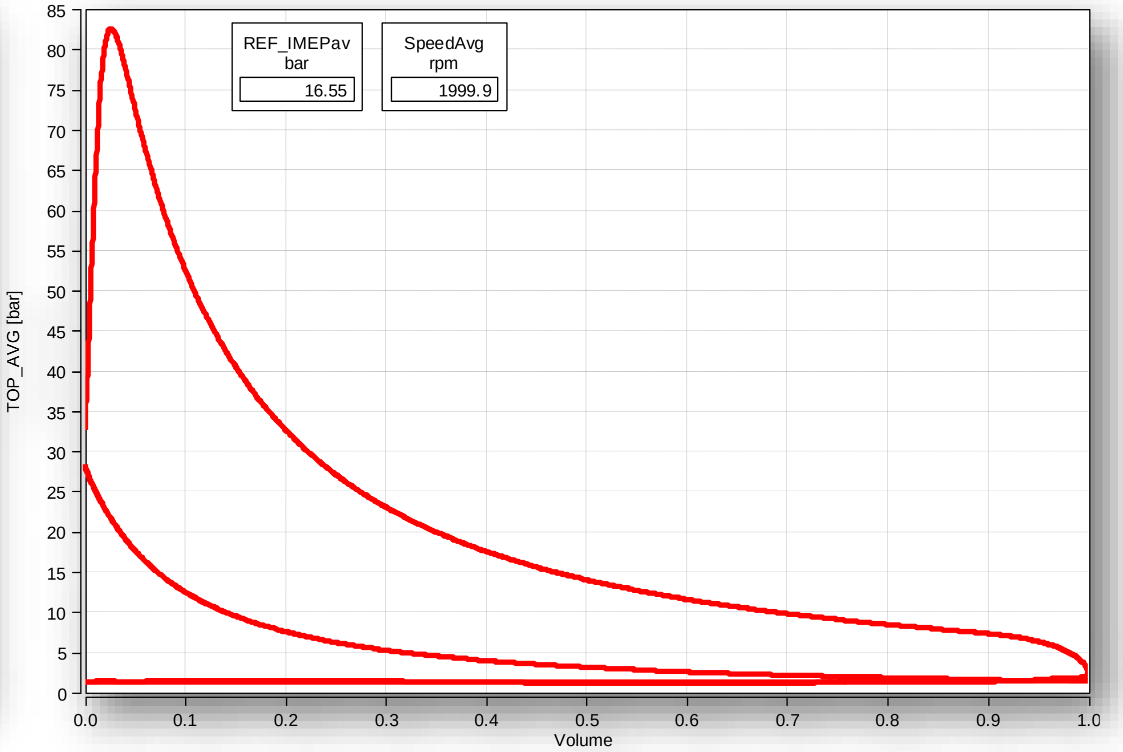
DERIVED FROM MEASURED CURVES

Thermodynamic results | Cyclic work





$$imep(net) = \frac{(area\ of\ \ power\ loop) - (area\ of\ \ pumping\ loop)}{V_s}$$

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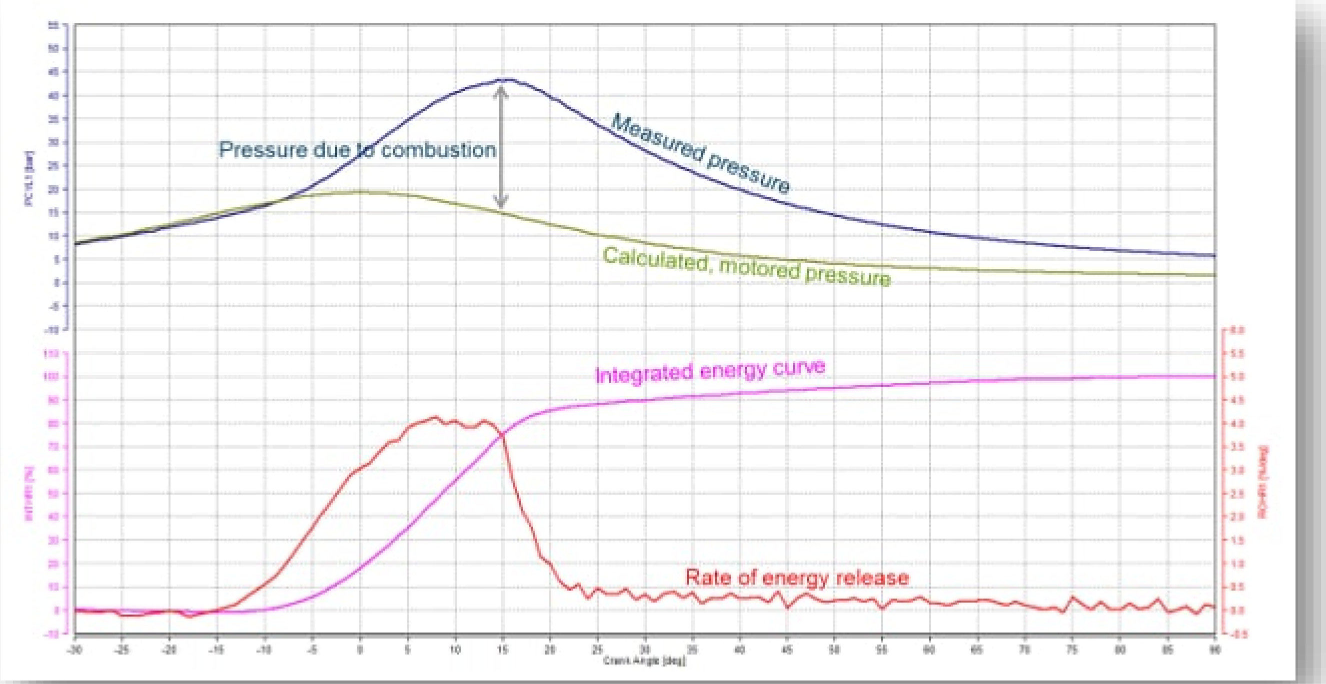
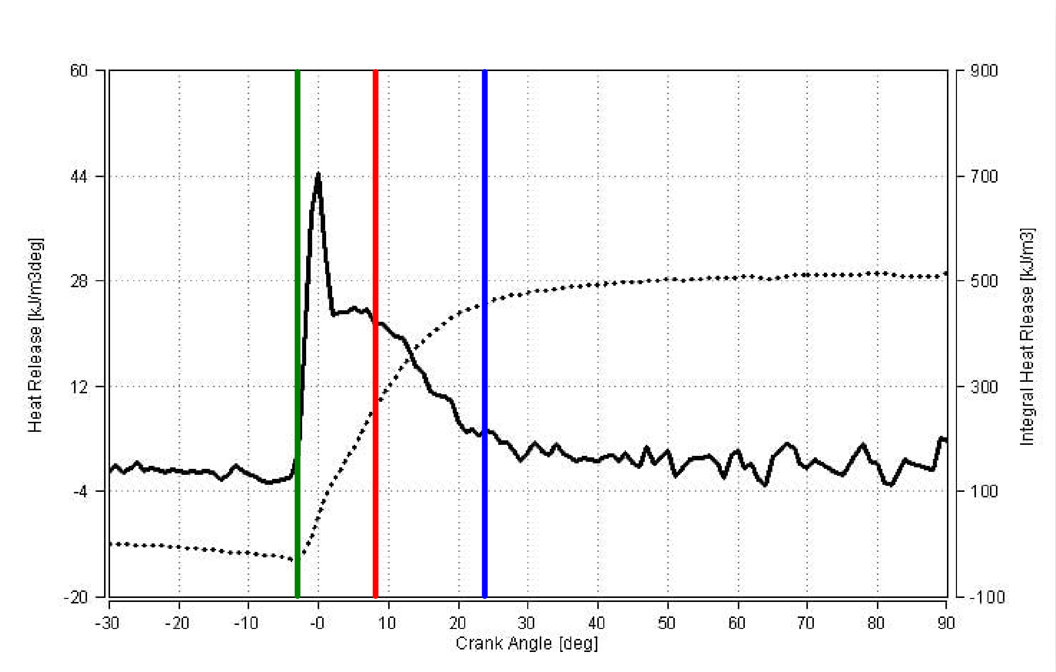
DERIVED FROM MEASURED CURVES

Thermodynamic results | instantaneous energy release





Optimum crucial combustion point at 8-10° CA for SI engine

$$\frac{dQ}{d\theta} = \underbrace{\frac{\gamma}{\gamma - 1} \cdot p \cdot \frac{dV}{d\theta}}_{\text{Volume change}} + \underbrace{\frac{1}{\gamma - 1} V \cdot \frac{dp}{d\theta}}_{\text{Pressure change}}$$

Energy conversion points:

5% , 50% , 90%

Burn duration = 90% - 5% Point

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HEAT RELEASE

from Rassweiler and Withrow original work

Motion Pictures of Engine Flames Correlated with Pressure Cards

By Gerald M. Rassweiler and Lloyd Withrow
Research Laboratories Division, General Motors Corp.

THIS paper represents a continuation of the work with the high-speed motion picture camera described before the Semi-Annual Meeting of the Society, June, 1936.[1]

The experimental observations consist of pictures showing successive positions of the flame at intervals of 2.4 crankshaft deg. during single explosions, and pressure-time records of the same explosions.

A method finally is described for sorting out the pressure changes due to combustion from an observed pressure card. When the pressure changes resulting from combustion are summed and put on a percentage basis, it is found that the per cent of pressure rise due to combustion is approximately equal to the per cent of charge burned (by weight) at the corresponding instants in the combustion period.

highly desirable to interpret the flame pictures in terms of pressure changes produced within the engine. Considerable effort has, therefore, been made to obtain accurate pressure data from the engine cylinder during the photographing of the flame pictures. A description of the methods developed to measure these pressures constitutes the major portion of the experimental work described herein.

In the analysis of the data it has been found convenient to express the progress of combustion both in terms of inflamed volume of charge and in terms of burned fraction of the weight (or mass) of charge. Although the latter quantity cannot be obtained directly from the flame pictures, its use aids materially in understanding the significance of the relationships. In studying the relationships between inflamed volume, inflamed fraction of the mass, and pressure, an effort has been made to keep the analysis direct and straightforward, to avoid introducing assumptions which have not been tested experimentally, and to determine experimentally the constants used in the equations.

Engine Conditions

All of the data in this paper were obtained under one set of

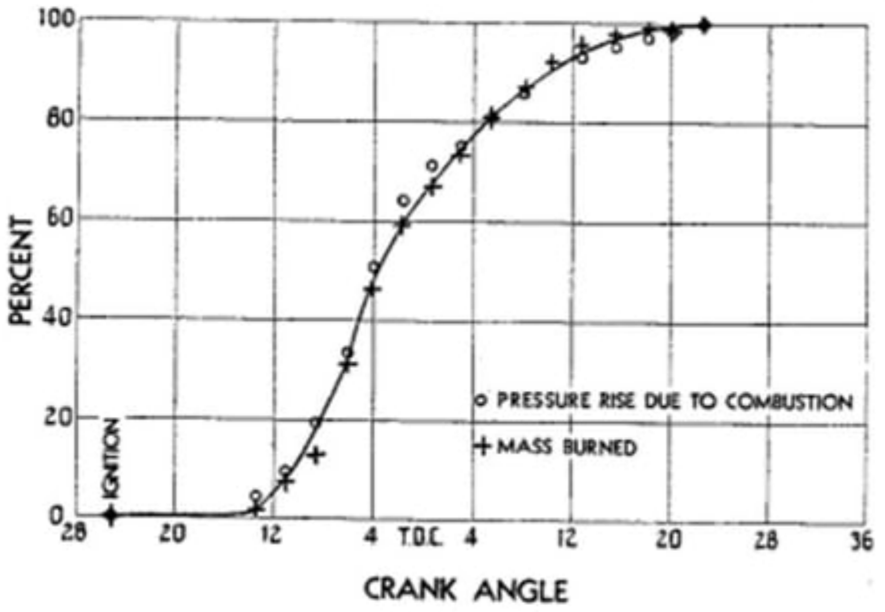


Fig. 17 – Per Cent Pressure Rise Due to Combustion Compared with Per Cent Mass Burned in Each Frame of Fig. 1

$$\Delta Q = \frac{\gamma}{\gamma - 1}\left(p - p_{\text{poly}}\right)\Delta V \qquad p_{\text{poly}} = p_0 \left(\frac{V_0}{V}\right)^n$$

HEAT RELEASE

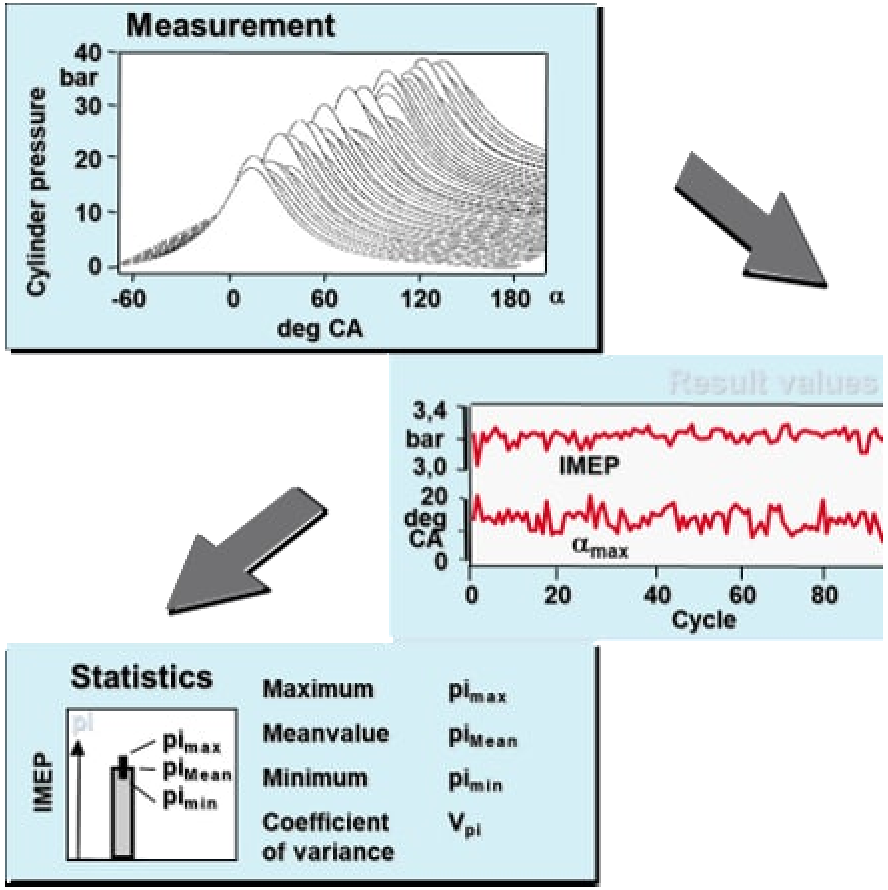
Feature	First-Law Method	Rassweiler–Withrow Method
Basis	Thermodynamics (energy balance)	Polytropic approximation + pressure integration
Discrete form	$dQ/d\theta = (\gamma/(\gamma-1)) \cdot p \cdot dV/d\theta + (1/(\gamma-1)) \cdot V \cdot dp/d\theta$	$\Delta Q = (\gamma/(\gamma-1)) \cdot (p - p\_poly) \cdot \Delta V$ where $p\_poly = p_0 \cdot (V_0/V)^n$
Input data	Pressure, volume, gas properties (gamma)	Pressure, volume, estimated polytropic exponents
Assumptions	Ideal gas, constant gamma, small heat transfer ignored	Compression/expansion approximated as polytropic, empirical corrections
Accuracy	High if gamma known and measurements precise	Moderate; depends on polytropic exponent choice
Sensitivity	Sensitive to measurement noise	Less sensitive to pressure noise
Use	Detailed research / engine modelling	Practical engine testing, quick analysis

Key takeaway:

- First-law method = more rigorous, physically grounded. Best for detailed analysis where gas properties are well known.
- Rassweiler–Withrow = practical, semi-empirical. Easier for experimental engine tests, but less accurate if polytropic assumptions are off.

CURVES | RESULTS | STATISTICS

Data reduction for intelligent data analysis, transfer to host systems



Result	Relevance
IMEP,PMEP	Friction & Mechanical Losses, indicated torque
CoV IMEP	Stability indicator
0-5% MBF	Early flame growth (SI)
50% MBF	Calibration strategy target (Gasoline)
10-90% MBF	Turbulent flame growth (SI)
Pmax/APmax	Component loading
Rmax/ARmax	Noise metric
Knock peak	Gasoline abnormal combustion
Noise/Ignition delay	Diesel abnormal combustion

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ENGINE DEVELOPMENT V CYCLE

with combustion pressure measurement context

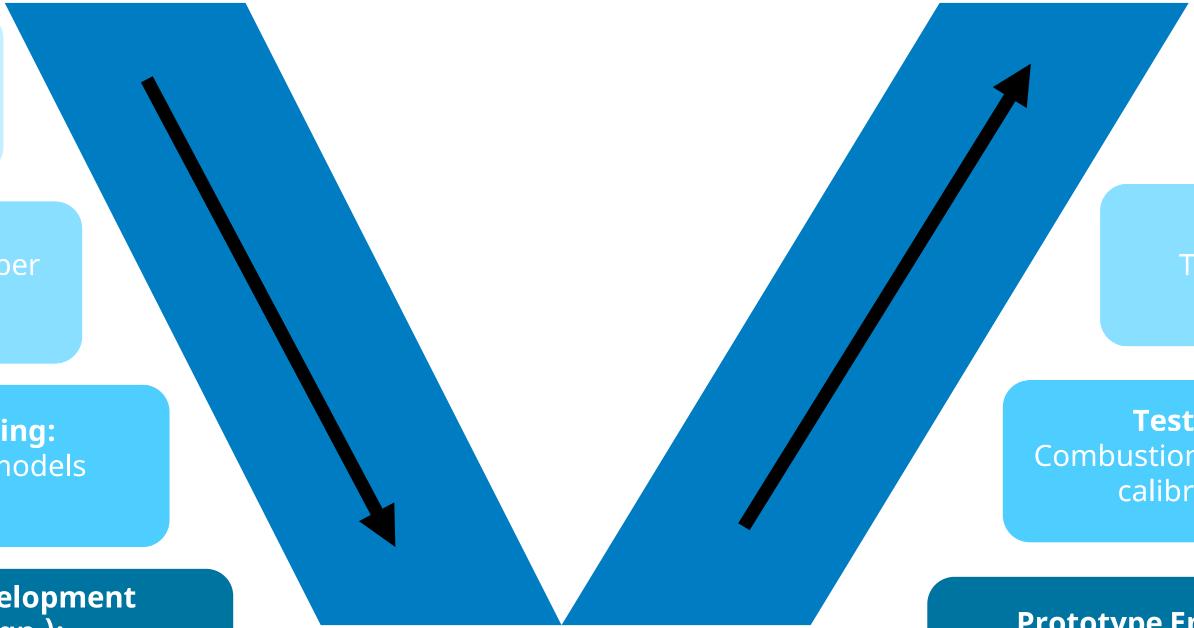
Development & Design

Requirements Definition:
Define combustion metrics, knock limits, and phasing targets

System Design :
Design combustion system (chamber shape, injector placement, swirl/tumble characteristics)

Simulation/modelling:
Validate combustion models (1D/3D)

Subsystem Development (Injector/Ign.):
Evaluate ignition, heat release, PMax limits



Prototype Engine Build:
First full engine prototypes equipped with instrumented cylinders
Combustion pressure sensors are used for baseline performance and design correlation

Integration & Testing

Prototype Engine Testing:
Full thermodynamic combustion analysis

Testbed Calibration:
Combustion phasing, knock control, calibration optimization

Vehicle Development:
Transient analysis, emissions correlation

Validation & Verification:
Final safety/durability checks, control validation

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WHY MEASURE?

In-cylinder pressure

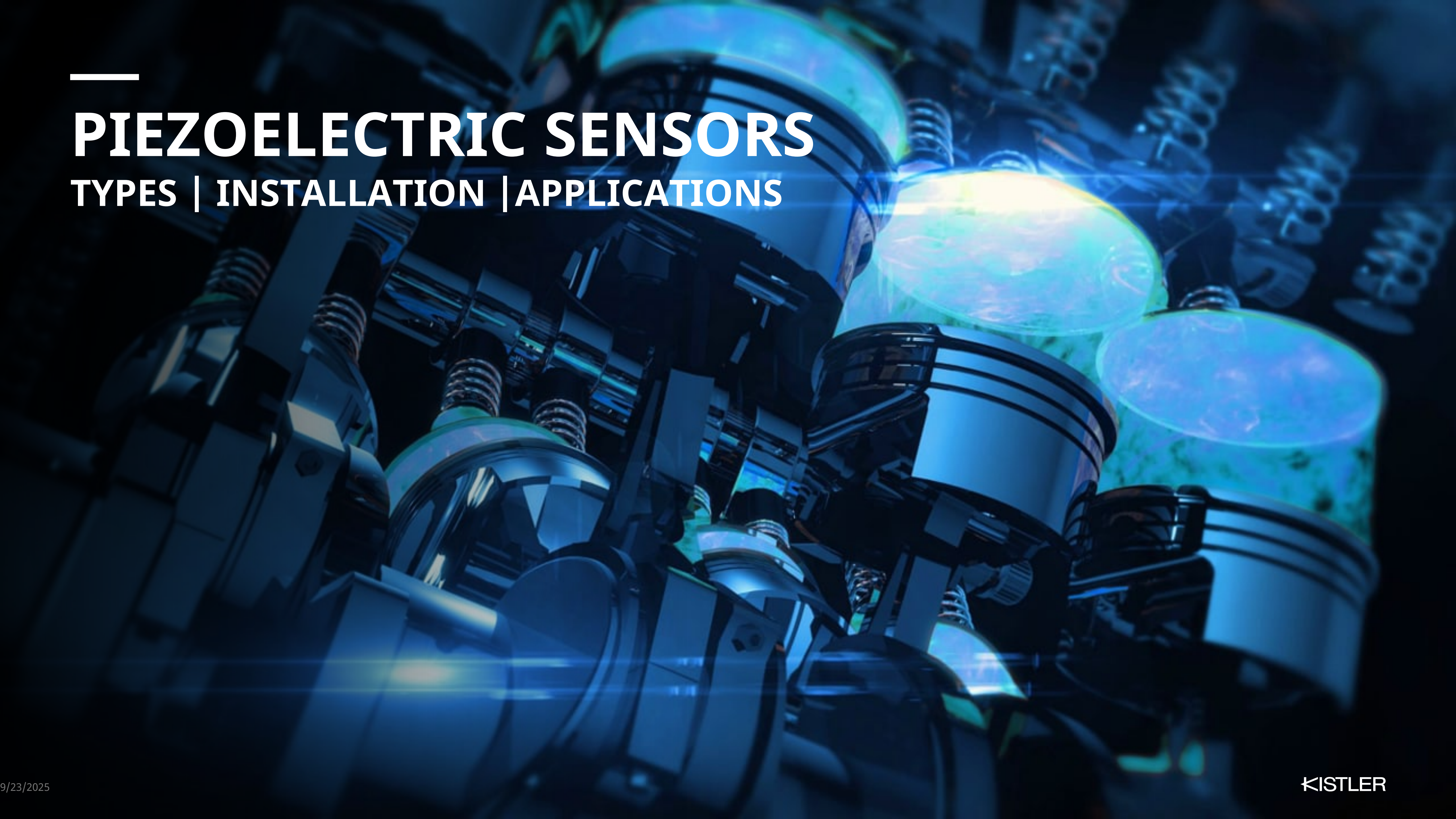
In-cylinder pressure measurement is one of the most important diagnostic and development tools in engine research, testing, and control. Here's why it matters:

- **Combustion Insight** – Direct view of ignition, burn rate, knock, and stability
- **Performance & Efficiency** – Enables IMEP, heat release, and indicated efficiency evaluation
- **Emissions & Control** – Supports clean combustion and advanced closed-loop engine control
- **Durability & Safety** – Prevents excessive pressure rise and mechanical overstress

👉 In short: **in-cylinder pressure is the most direct window into** combustion—without it, you rely only on indirect signals (e.g., torque, exhaust emissions) that don't capture the full picture.

PIEZOELECTRIC SENSORS

TYPES | INSTALLATION |APPLICATIONS

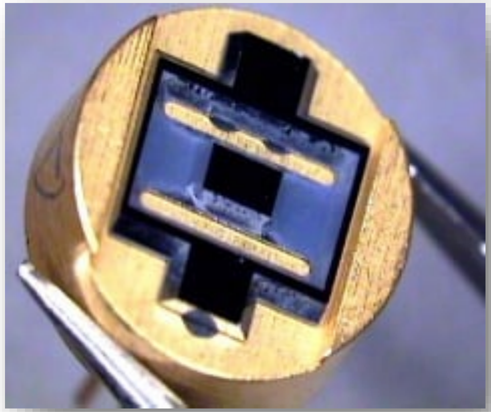


BASIC SENSOR TECHNOLOGIES

Piezoelectric | Piezoresistive

Piezoelectric Technology

- Linear output charge / pressure
- High electrical insulation $>10^{13}\ \Omega$
- High temperatures up to 350 °C
- Quasi-static / dynamic measurements
- Active sensing principle
- Suitable for Cylinder pressure measurements



Piezoresistive Technology

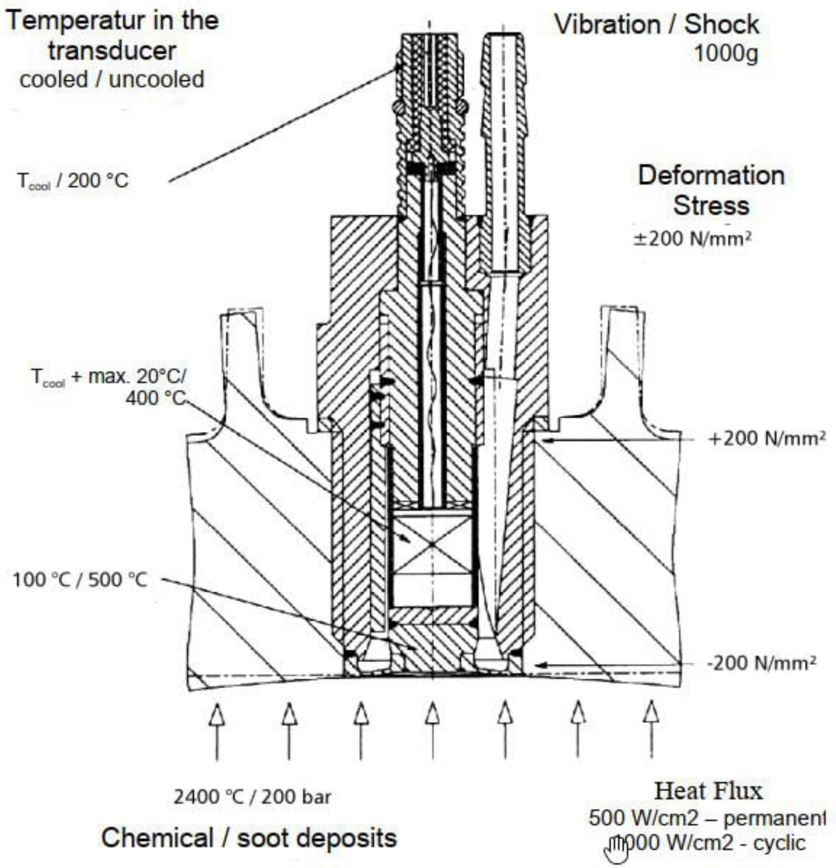
- Linear output voltage / pressure
- Temperatures $\leq$ 200 °C
- Static / absolute measurements
- Passive sensing principle
- Suitable for inlet and exhaust gas pressure measurements as well for hydraulics

IN-CYLINDER INSTALLATIONS

Boundary conditions

- Short term thermal shock
- Long term thermal drift
- Electrical noise and interference
- Structural vibrations and noise
- Extreme pressures (short term overloads)
- Mechanical deformation/strain
- Contamination externally/internally

- **Sensor design, optimisation and production is a challenging exercise!**
- **The sensor is a sensitive, micro-mechanical, precision measuring device - if handled well, will give many years of good service!**



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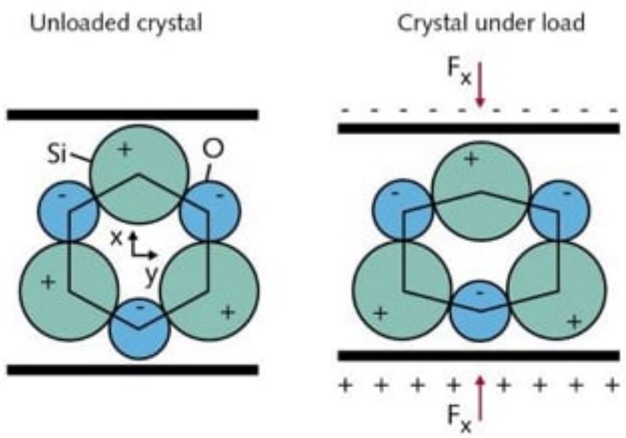
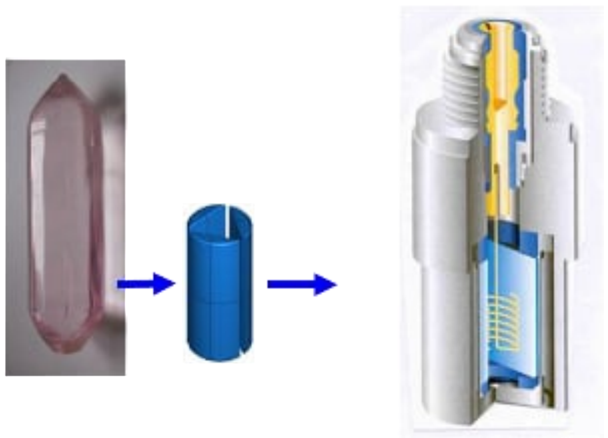
WORKING PRINCIPLE

Piezoelectric sensor





Overview:

- PE crystals generate an electric charge when exposed to mechanical stress
- Signal is proportional to the force applied
- The charge amplifier converts the charge signal into a voltage signal

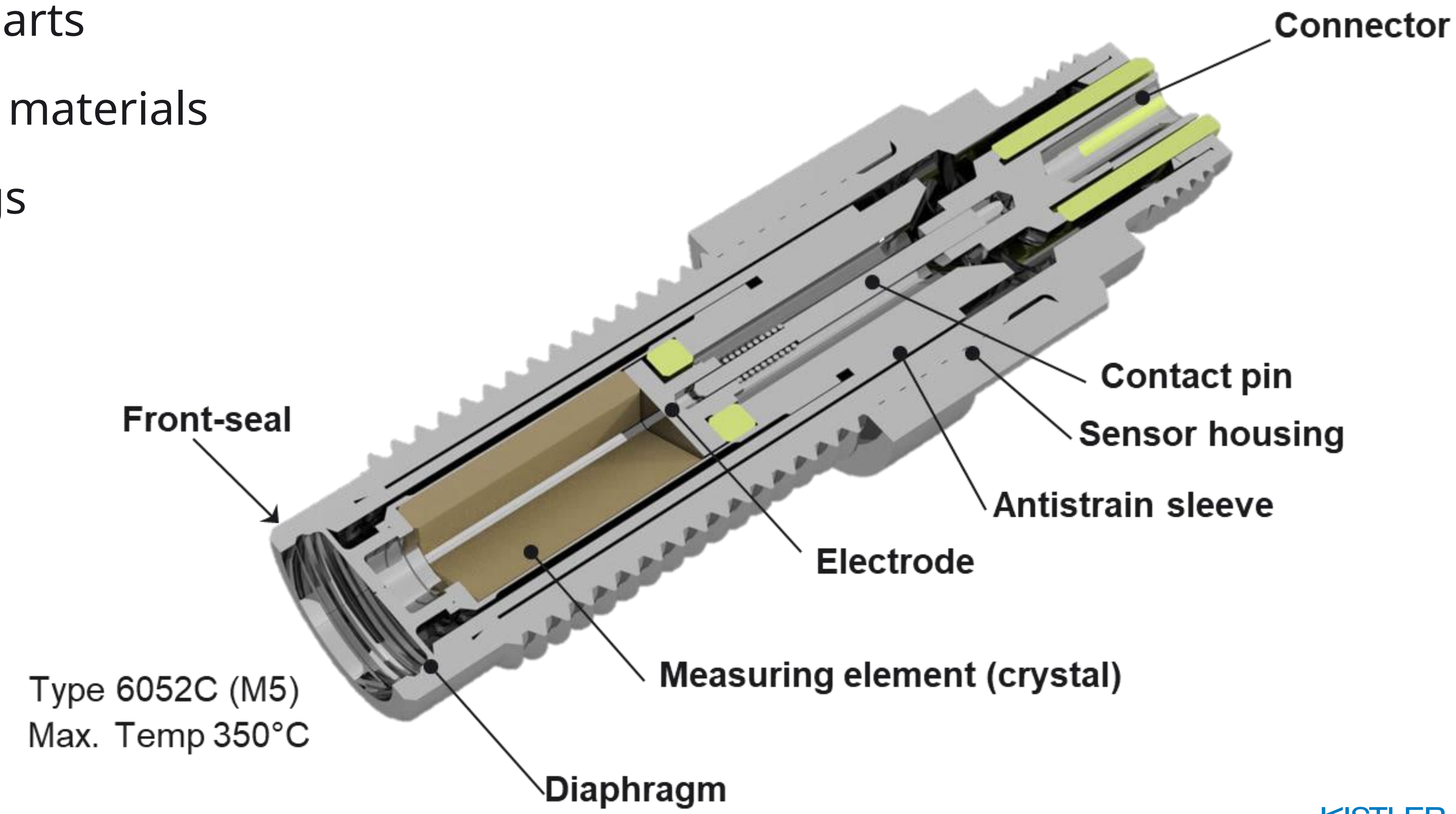
Advantages:

- Wide measuring range (up to six decades)
- Compact design, high rigidity
- Wide temperature range, long-term stability

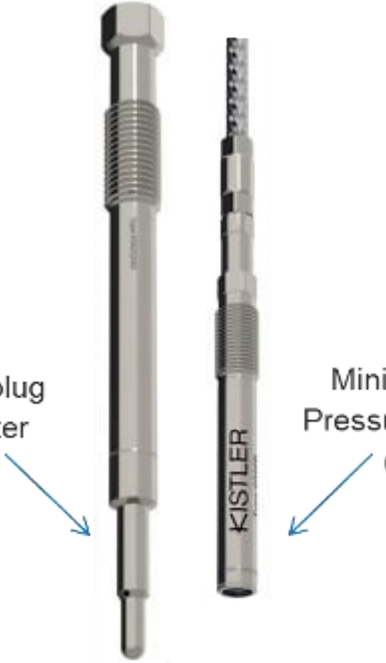
HIGH-END MEASUREMENT TECHNOLOGY

Precision micro-mechanical measuring device

- 17 single parts
- 9 different materials
- 11 weldings



SENSORS FOR CYLINDER PRESSURE ANALYSIS

Not integrated	System Gasoline	System Diesel
		
Type 6054C, 6044A, 6041C	Type 6113C, 6115C, 6118C	6542Q with sensor type 6056B 6544Q with sensor type 6058A

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SENSORS FOR CYLINDER PRESSURE ANALYSIS

Main portfolio

6054C (M5)
6052C (M5)
6056B (M5)
6044A (M8)
6045B (M8)
6124A (D6.2)
6125C (D6.2)

Non-Cooled

6041C (M8)
6061C (M10)
6067D (D9.9)
7061C (M14)

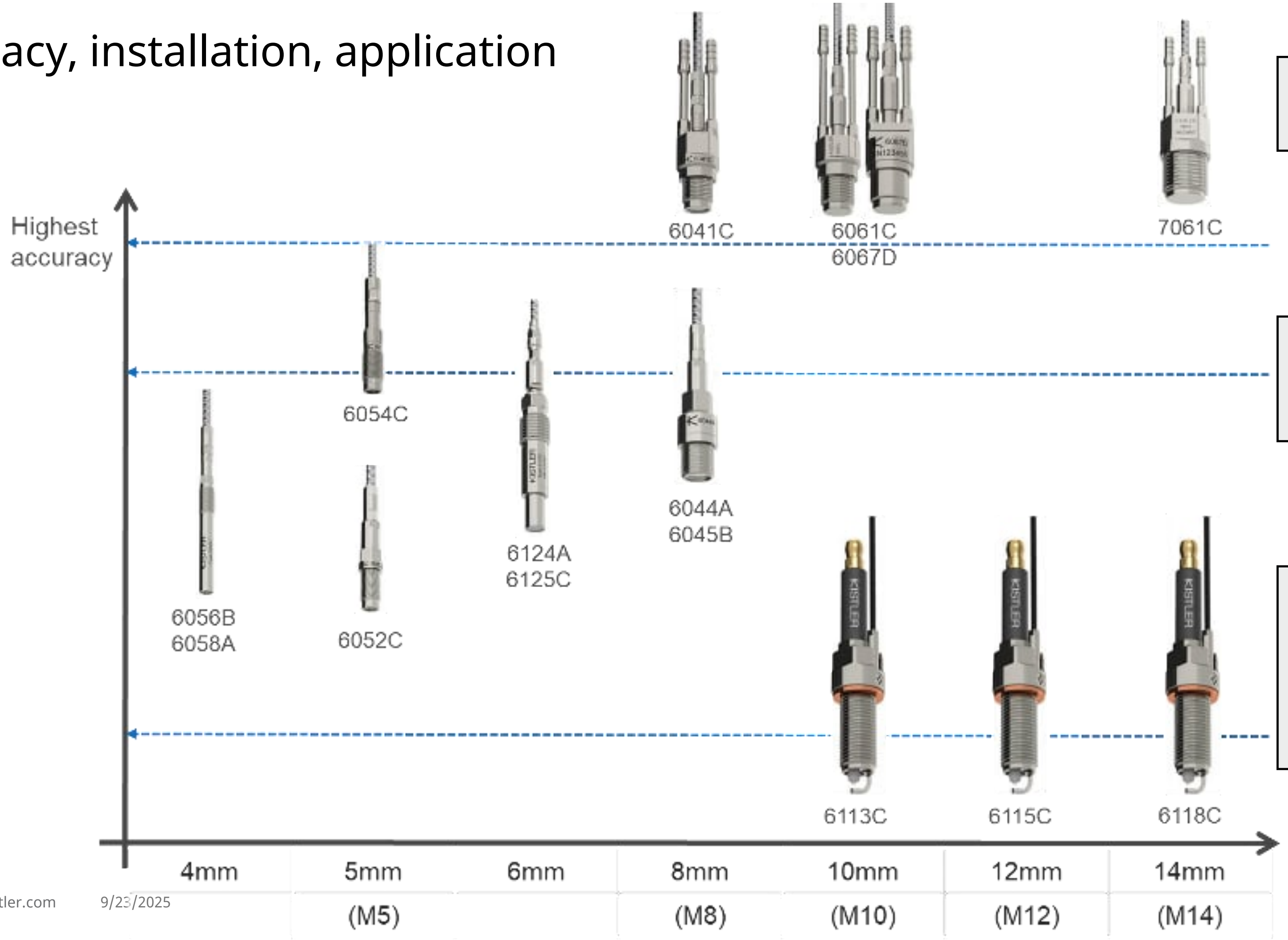
Water-Cooled

MSP
GPA

Systems

SENSORS FOR CYLINDER PRESSURE ANALYSIS

Accuracy, installation, application



- friction and loss-analysis
- IMEP

- general thermodynamic analysis, gas-exchange
- IMEP, pmax, heat-release

- general ECU mapping, trouble shooting
- start/ center/ duration of combustion
- knocking

DIRECT SENSOR INSTALLATIONS

Direct mounted sensors

Direct mounted

Direct mounted sensors in cylinder head or via mounting sleeve

Advantage

Best possible sensor integration in a reworked cylinder head for highest accuracy and best measurement results.

Applications

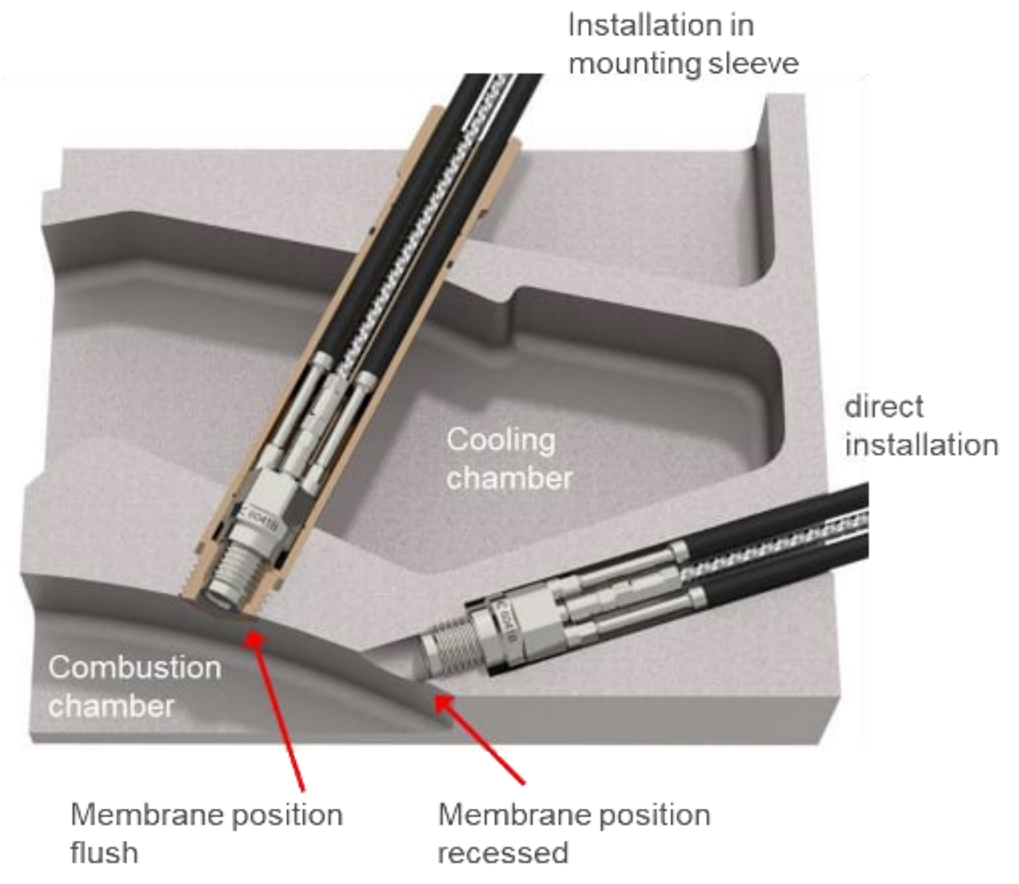
- Gas exchange analysis
- Friction loss
- Thermodynamic Analysis
- Cold start analysis
- Knocking analysis
- Engine calibration
- Monitoring, cylinder balancing

Use cases

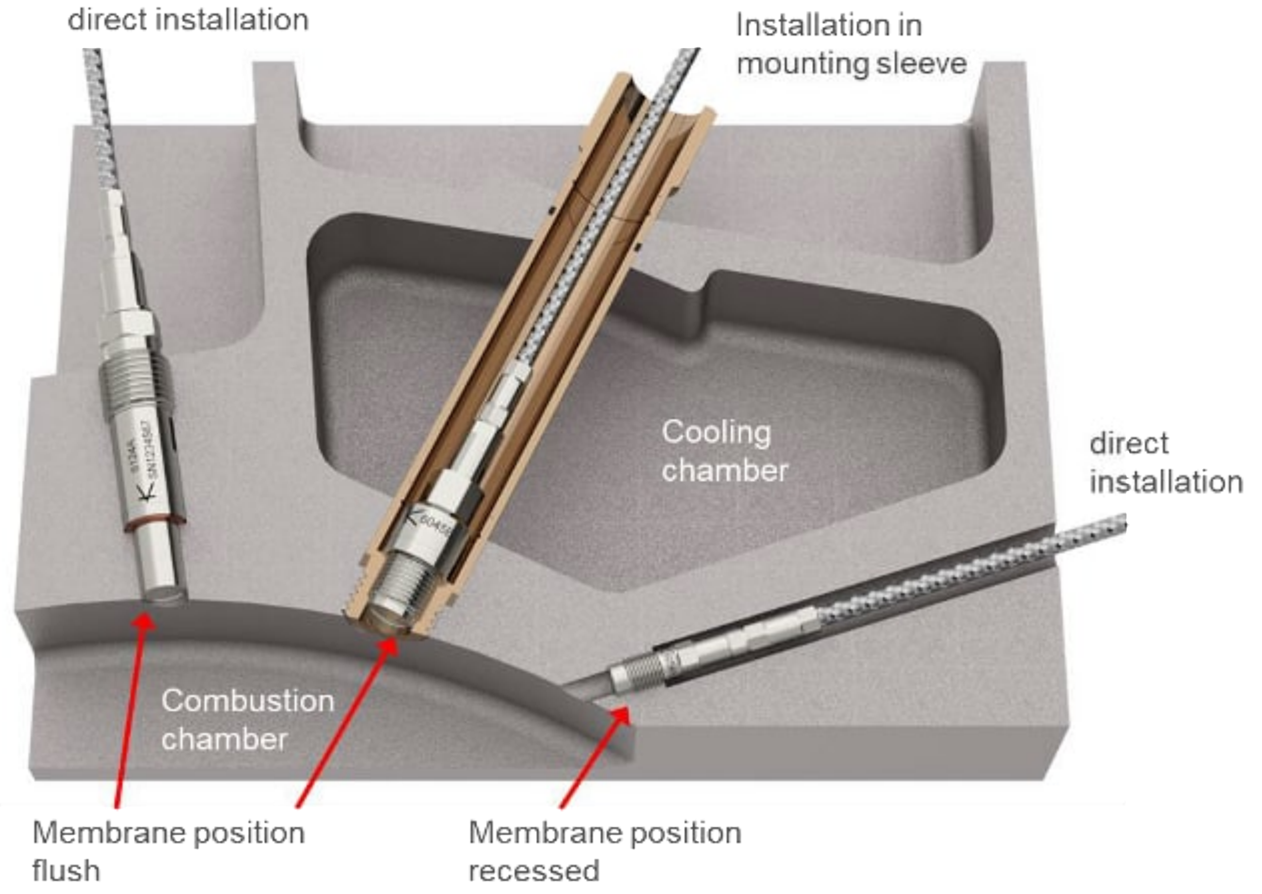
Suitable for all Research and Development activities.
Direct mounted sensors provide the best possible measurement data for every task.

INSTALLATION OPTIONS

Cooled M8

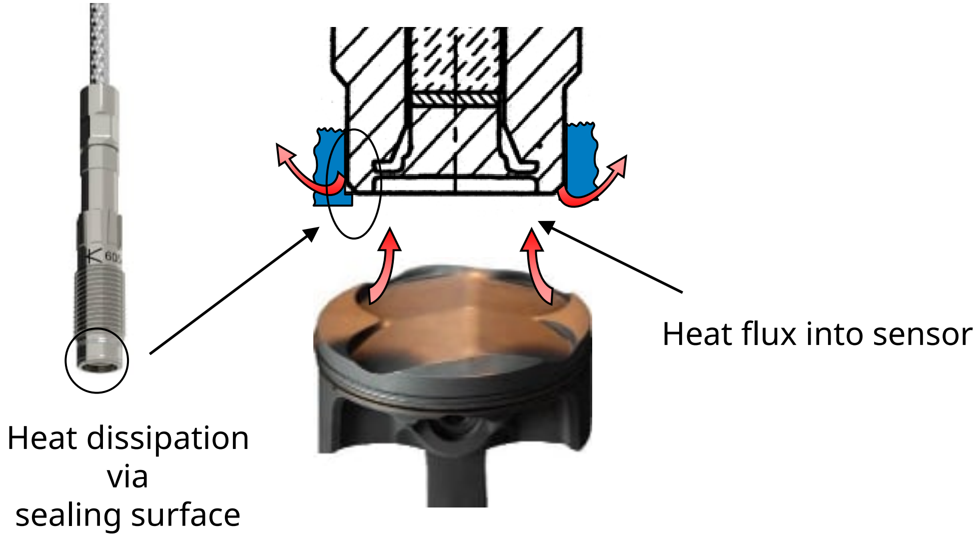


Non-cooled 6.2mm / M8 / M5



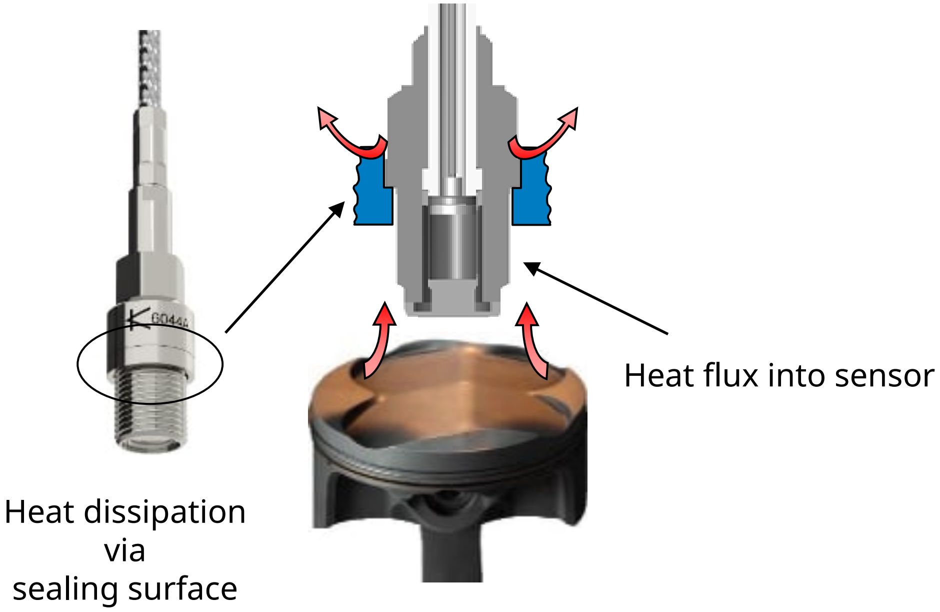
SEALING OPTIONS

Front sealing / recessed mounted



- sealing surface on the front
- direct heat dissipation via diaphragm
- 'high quality' sealing surface necessary
- no flush mounting
- special design for minimized cavities

Shoulder sealing / flush mounted



- sealing surface recessed
- 'classical' design
- for flush mounting of sensor possible
- easy handling and bore preparation
- heat dissipation 'through' the sensor

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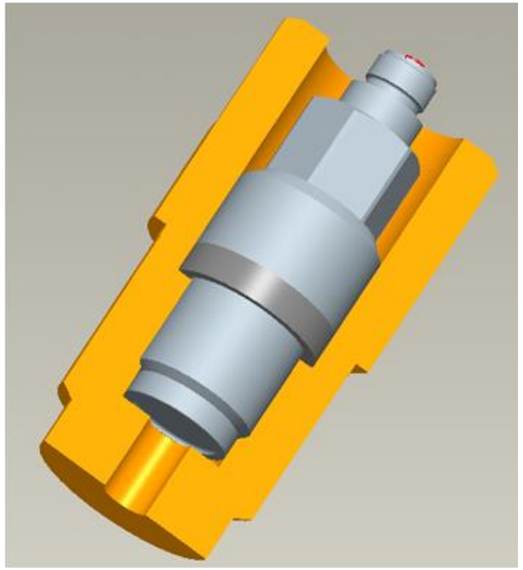
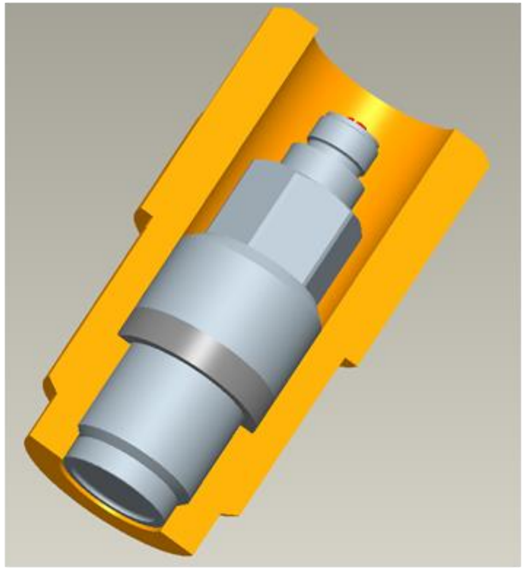
SEALING OPTIONS

Front sealing / recessed mounted



n [min-1]	6125T
1500 VL 8° v. OTP [°C]	271 / 259
1000 VL 3° v. OTP [°C]	248 / 237

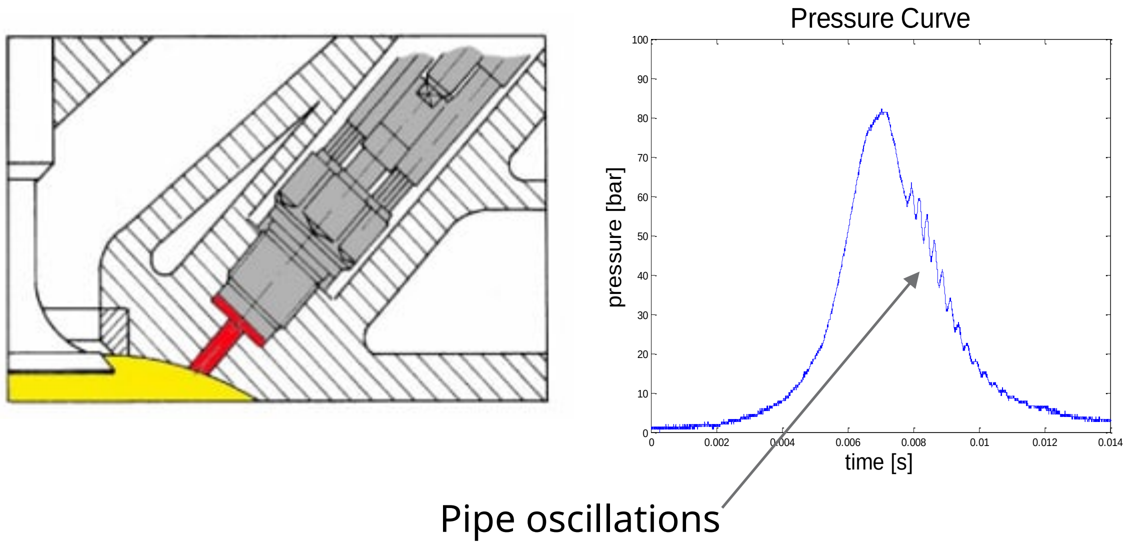
Shoulder sealing / flush mounted

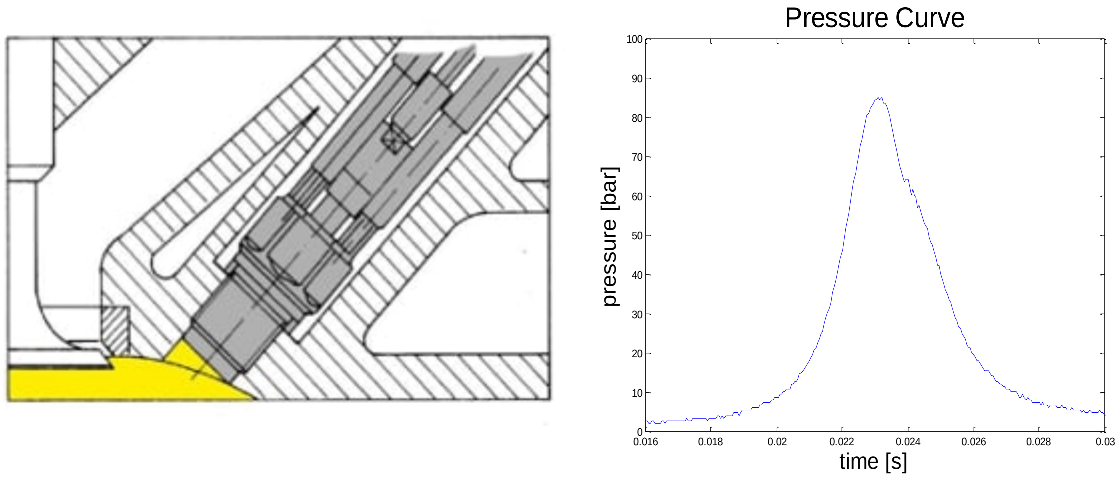


n [min-1]	6125T
1500 VL 8° v. OTP [°C]	339 / 314
1000 VL 3° v. OTP [°C]	300 / 281

- Temperature difference in recessed mounting up to >60°C lower compared to flush mounting
- Impact on Thermoshock, Sensitivity shift and durability

SEALING OPTIONS

Front sealing / recessed mounted	Shoulder sealing / flush mounted




- Indicator passages exhibit acoustic resonance which is superimposed on the combustion pressure and distorts the signal
- The acoustic oscillations in the cavities are initiated by the strong pressure gradient at start of combustion
- Important information becomes difficult to extract, e.g., peak pressure, knock intensities, mass fraction burned, …

- ➢ The higher the pipe natural frequency the lower the pressure amplitude of the gas oscillation
- ➢ If possible, keep condition for passage design: Ø ≥ L
- ➢ Keep cavity volume Vk as small as possible with a flat washer thickness not more than 0.5 mm

SENSOR PORTFOLIO | GENERAL INFORMATION

Pro’s & Con’s of watercooled sensors

Pro:

- Exceptional thermal stability across all engine operating points
- Enhanced long-term reliability and endurance due to cooled diaphragm design
- Seamless integration into high-temperature settings through flush mounting
- Precise measurement accuracy, maintained even under rapidly changing operating conditions

Con:

- Minor thermal shock error from diaphragm temperature gradient (short-term drift)
- Cooling may cause minor sensor signal disturbances
- More complex than uncooled sensors due to cooling systems, tubing, manifolds, and maintenance needs

Important / Advice:

- Adhere to cooling fluid specs for sensor performance, stability, and longevity.
- Consistent checks and maintenance ensure stable, accurate measurements over time.
- Kistler temperature control system is recommended for integration with test setups; includes preventive alarms and warnings

Type 6041C

INSTALLATION OPTIONS

System Gasoline

Measuring spark plug with flush mounted 3mm pressure sensor

Advantage

Replacement of the original spark plug to allow a cylinder pressure measurement without the need to mechanically modify the cylinder head

Applications

General ECU mapping, trouble shooting
Start/ center/ duration of combustion
Knocking

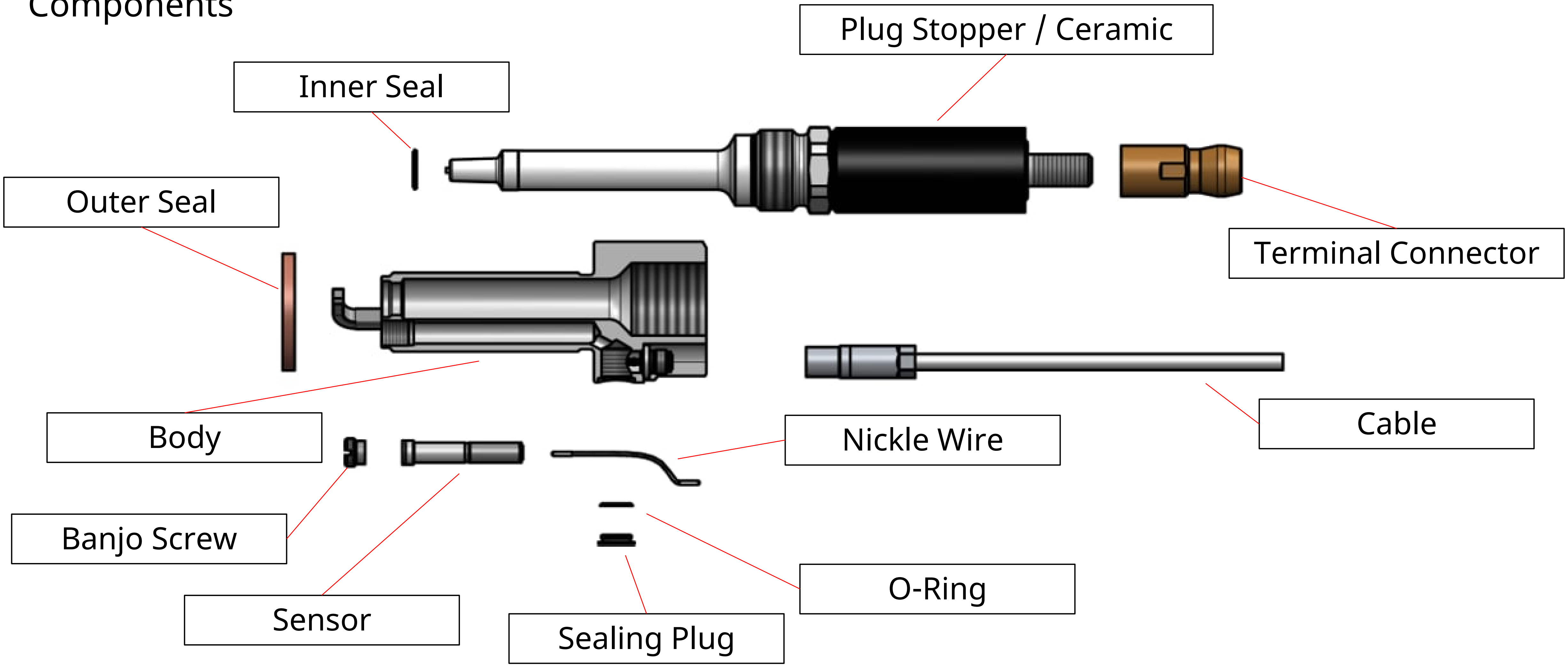
Use cases

In-vehicle engine calibration, Troubleshooting
Validation of engine performance + emissions in real driving situations (Synchronized in combination with a PEMS)
Benchmarking, Competitor analysis

Important:
For Engine Development activities, directly mounted cylinder pressure sensors with high accuracy should be used

MEASURING SPARK PLUG (MSP)

Components



INSTALLATION OPTIONS

System Diesel

Glow plug adapter

Miniaturized Pressure sensor (M5)

Glow plug adapter with M5x0,5 pressure sensor

Advantage

Replacement of the original glow plug to allow a cylinder pressure measurement without the need to mechanically modify the cylinder head

Applications

General ECU mapping, trouble shooting

Start/ center/ duration of combustion

Knocking

Use cases

In-vehicle engine calibration, Troubleshooting

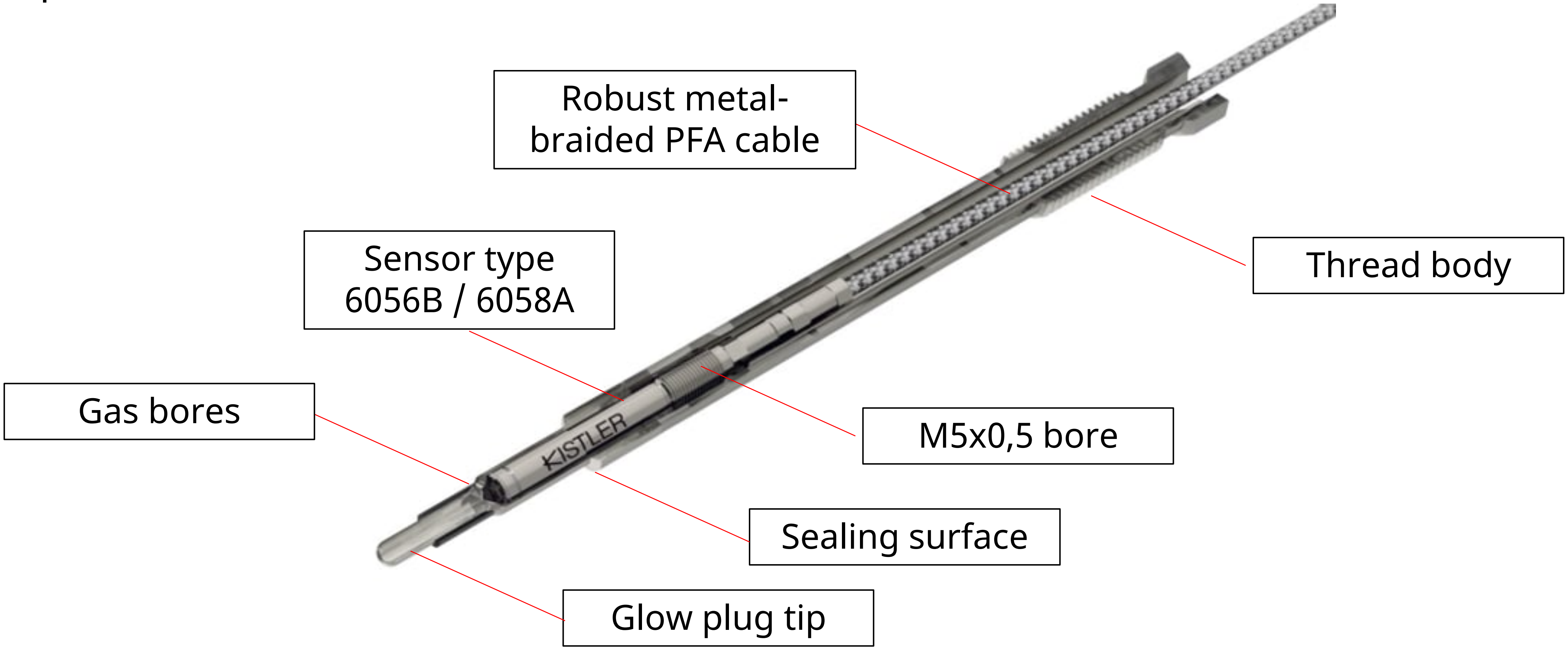
Validation of engine performance + emissions in real driving situations (Synchronized in combination with a PEMS)

Benchmarking, Competitor analysis

Important:
For Engine Development activities, directly mounted cylinder pressure sensors with high accuracy should be used

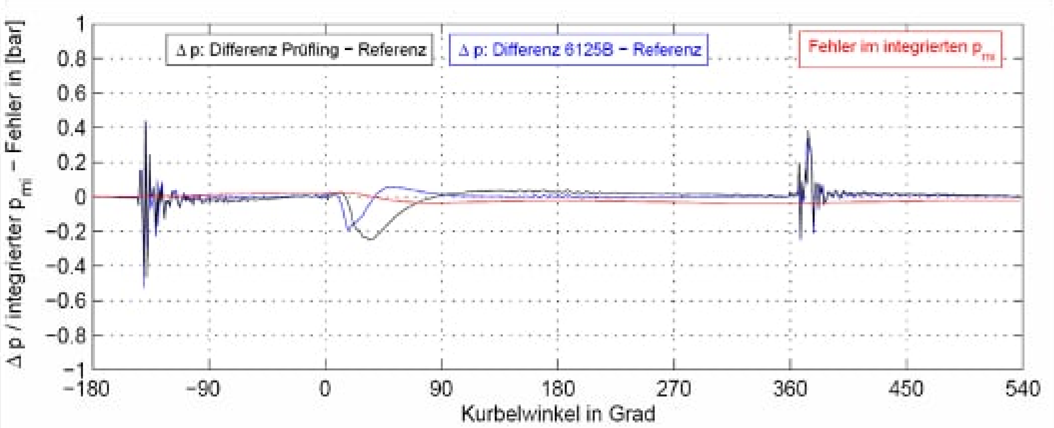
GLOW PLUG ADAPTOR (GPA)

Components

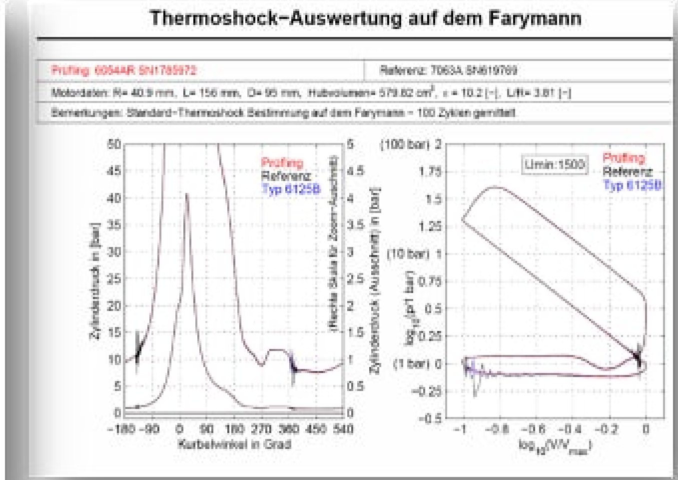


PROPERTIES OF PIEZOELECTRIC SENSORS

Thermal Shock Measurement (Intra-cycle drift)

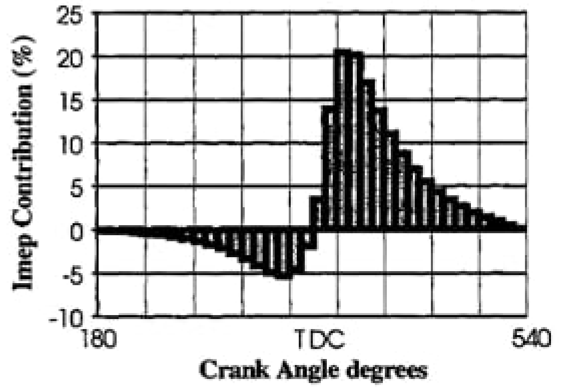


	$p_{mi,ND}$	$p_{mi,HD}$	$p_{mi,Netto}$	p_{max}
Typ 6125B	−0.28 bar	9.56 bar	9.28 bar	40.7 bar
Referenz	−0.29 bar	9.55 bar	9.26 bar	40.84 bar
Prüfling	−0.29 bar	9.52 bar	9.23 bar	40.66 bar
Δ (Prüf−Ref)	0.01 bar	−0.03 bar	−0.02 bar	−0.18bar
Δ %	-2.2%	-0.3%	-0.2%	-0.5%



Thermal shock error		
(at 1 500 1/min, p_{mi} = 9 bar)		
Δp (short time drift)	bar	≤±0,5
Δp_{mi}	%	≤±2
Δp_{max}	%	≤±1,0

The contribution to the imep is thus small near to TDC and reaches a maximum typically 40 degrees ATDC (after TDC) when the maximum combination of pressure and volume change rate occur together. This is illustrated in figure 4 which reveals the percentage contribution over 10 degree steps to the final gross imep for a typical full load gasoline case. The plot illustrates that the peak negative contribution occurs at about 20 degrees BTDC (before TDC) whilst the peak expansion stroke work occurs at about 35 degrees. It is also interesting to note that the peak rate of contribution is about 20% over the 10 degree interval or 2% per crank angle degree.



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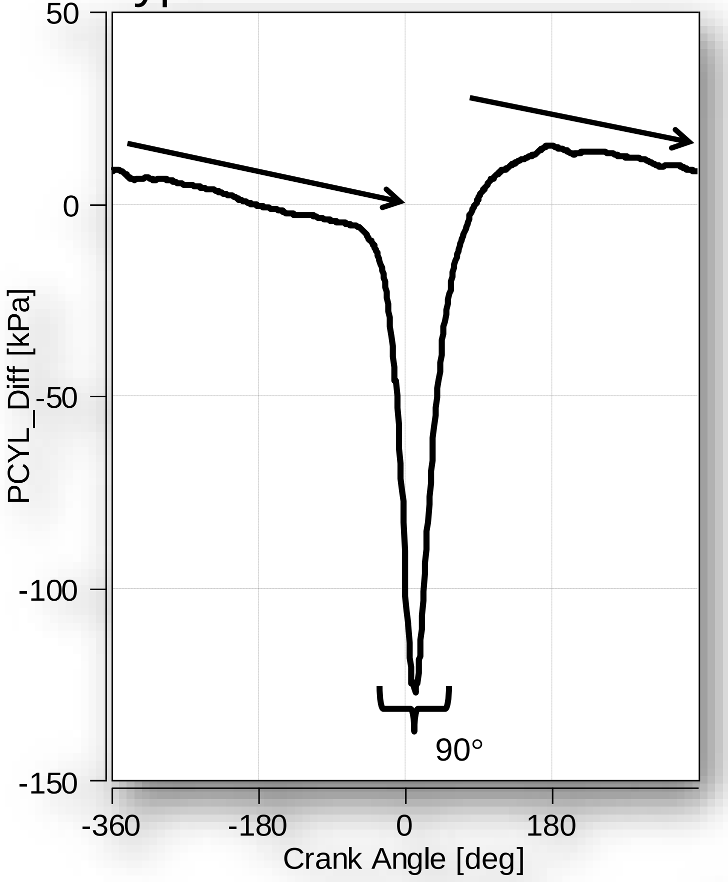
THERMODYNAMIC SPECIFICATIONS

Compare to a reference sensor

Typical



Actual

Datasheet

Technical data		
Measuring range	bar	0 ... 300
Calibrated ranges (23°C, 200°C, 350°C)	bar	0 ... 100, 0 ... 150, 0 ... 200, 0 ... 300
Overload	bar	350
Sensitivity (at 23°C)	pC/bar	–17
Natural frequency (measuring element)	kHz	≈185
Linearity (at 23°C)	%FSO	±0.3
Tightening torque, greased	N·m	1.5
Shock resistance (half sinus 0.2 ms)	g	≥2,000
Acceleration sensitivity		
axial	mbar/g	0.8
radial	mbar/g	0.2
Sensitivity shift		
23°C ... 350°C	%	±1.0
200 ± 50°C	%	±0.4
Operating temperature range	°C	–20 ... 350
Temperature, min./max.	°C	–40 ... 400
Thermal shock error (at 1,500 1/min, IMEP = 9 bar)		
Δp (short-term drift)	bar	±0.25
ΔIMEP	%	±1.5
Δp_{max}	%	±1.0
Insulation resistance (at 23°C)	Ω	$\geq 10^{13}$
Capacitance sensor	pF	8
Connector, sapphire insulator		M3x0.35
Protection rating, with cable Type 7 (IEC 60529)	IP	65
Weight sensor	g	1.5

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THERMODYNAMIC SPECIFICATIONS

Accuracy: overview on a sensor's datasheet

Main parameters to assess the operating conditions

Main parameters to assess the sensor's intrinsic accuracy

Technical data

Measuring range	bar	0 ... 300
Calibrated partial ranges RT, 250, 350 °C	bar	0 ... 100, 0 ... 150, 0 ... 200, 0 ... 300
Overload	bar	350
Sensitivity	pC/bar	≈–30
Natural frequency	kHz	≥100
Linearity, all ranges (at 23 °C)	%/FSO	≤±0.3
Acceleration sensitivity		
axial	bar/g	≤0.002
radial	bar/g	≤0.0002
Operating temperature range	°C	–20 ... 350
Temperature, min./max.	°C	–40 ... 400
Sensitivity shift		
RT ... 350 °C	%	≤±1
250 °C ±100 °C	%	≤±0.5
Thermal shock error (at 1 500 1/min, IMEP = 9 bar)		
Δp (short-term drift)	bar	≤±0.2
ΔIMEP	%	≤±1
Δp_{max}	%	≤±1
Insulation resistance at 20 °C	Ω	≥10^{13}
Tightening torque, greased	N·m	6
Capacitance, without cable	pF	10
Weight sensor	g	8
Connector, sapphire	–	M4x0.35

Description of Icons

H2 tested: Suitable for the use in hydrogen combustion engines	Anti Strain Design: Insensitive to mechanical strain effects
Ready to Use: Easy installation - minimal modifications	High Thermal Stability: Temperature stable over measuring range
Closed Loop Combustion Control: Suitable for closed loop control applications	High Robustness: High durability with good thermodynamic performance

Illustration: Abstract datasheet 6044A_003-399e

SUMMARY

What general statements/conclusions can be drawn?

Sensor Selection & Setup – Key Takeaways

- No "one size fits all" → use any sensor that fits the job, as long as it stays in its limits.
- Even the best sensor gives bad data if installed or handled poorly.
- The whole measurement setup matters as much as the sensor itself.

Sensor Types

- 8 mm sensors → gold standard, work for most applications; cooling is personal preference.
- 5 mm sensors → easier to fit, great all-rounders, but not ideal for ultra-detailed studies.
- MSP/GPA → easy to use, perfect for development tasks like torque/knock calibration or cold-start studies.

👉 **Remember:** Know the thermodynamic specs if you want to pick or compare sensors properly!

measure. analyze. innovate.

QUESTIONS?
DISCUSSION?

Dr David Rogers
Kistler Instrumente AG
Business Unit Engines

CONTENTS

AGENDA	
~~1. Basics~~	50 mins
~~2. In-cylinder sensors~~	
Break (10 mins)	*10 mins*
3. Measuring equipment	50 mins
4. Signal processing	
5. Data quality	
6. Wrap-up	

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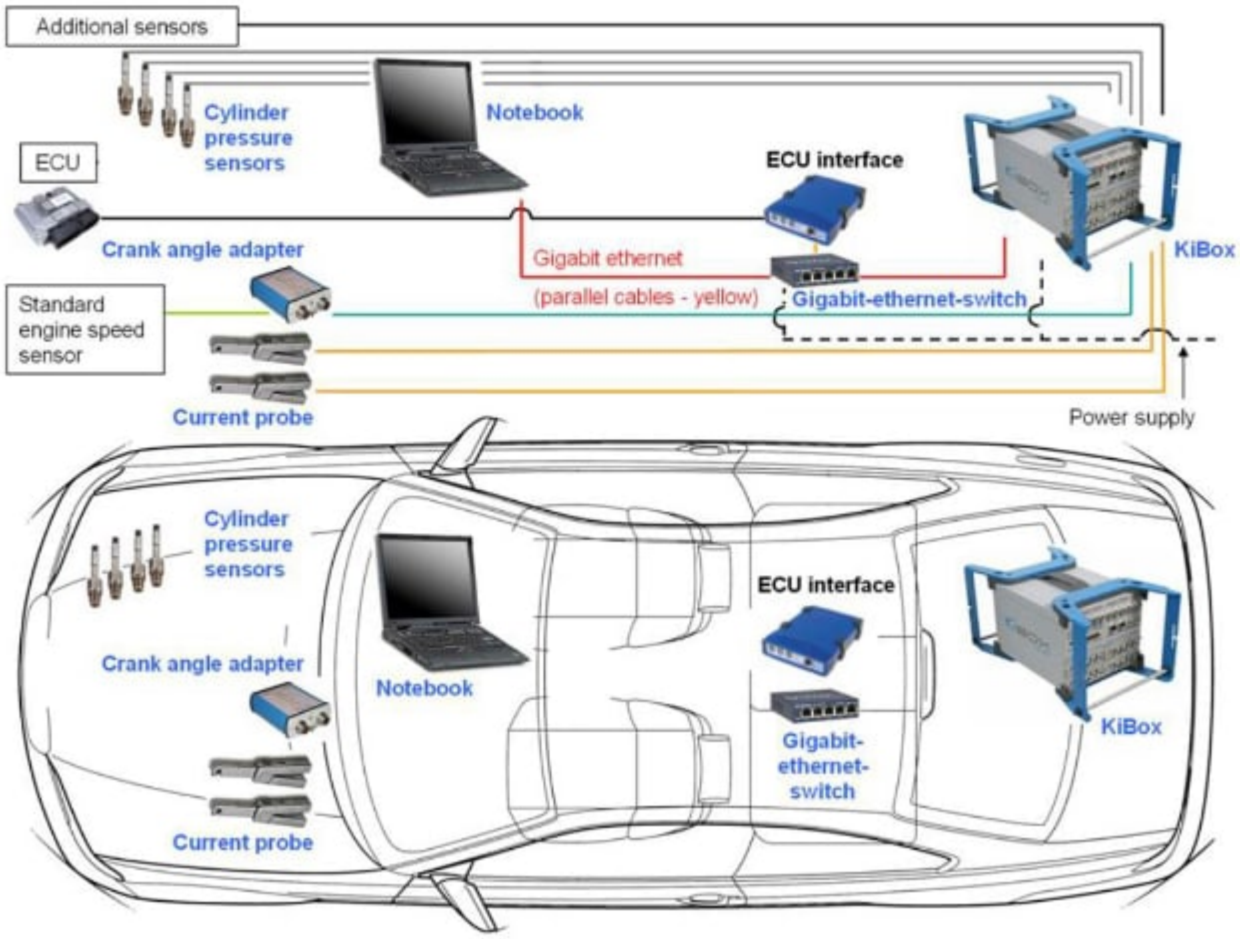
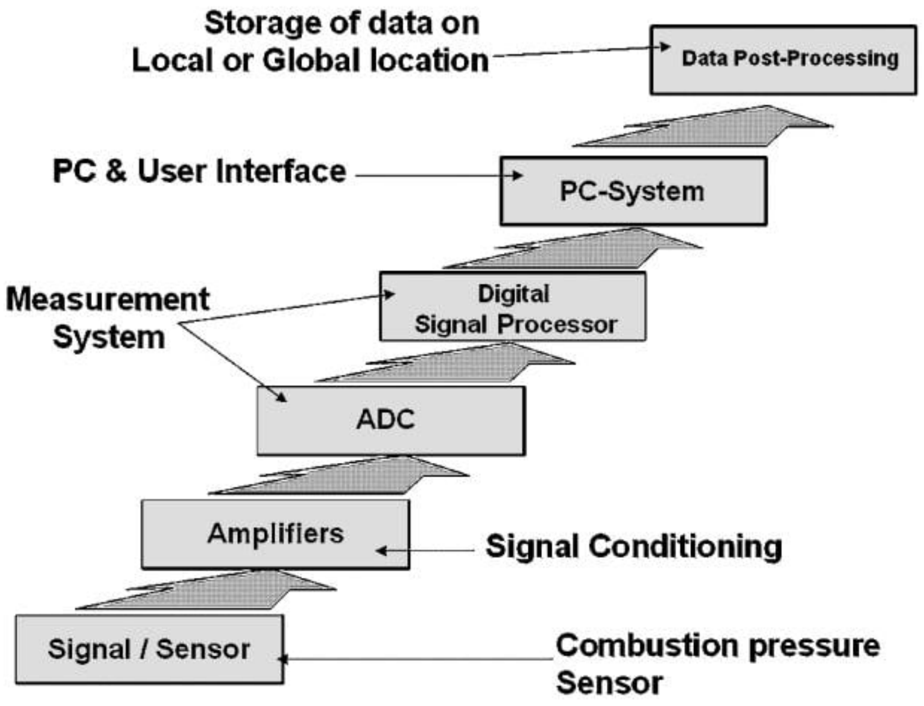
MEASUREMENT EQUIPMENT

MEASURING CHAIN AND ACCESSORIES

MEASUREMENT SYSTEM OVERVIEW

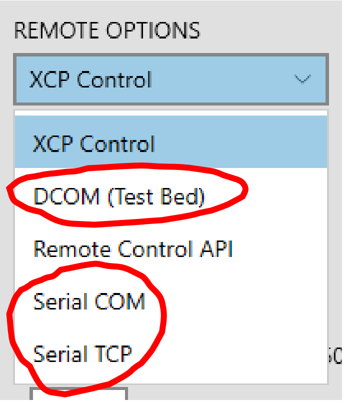
Components and functions

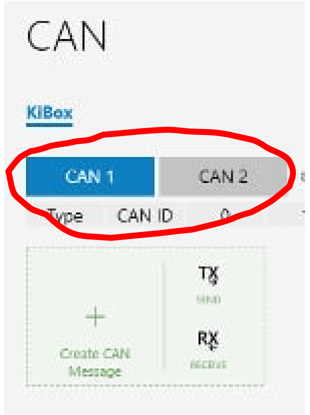


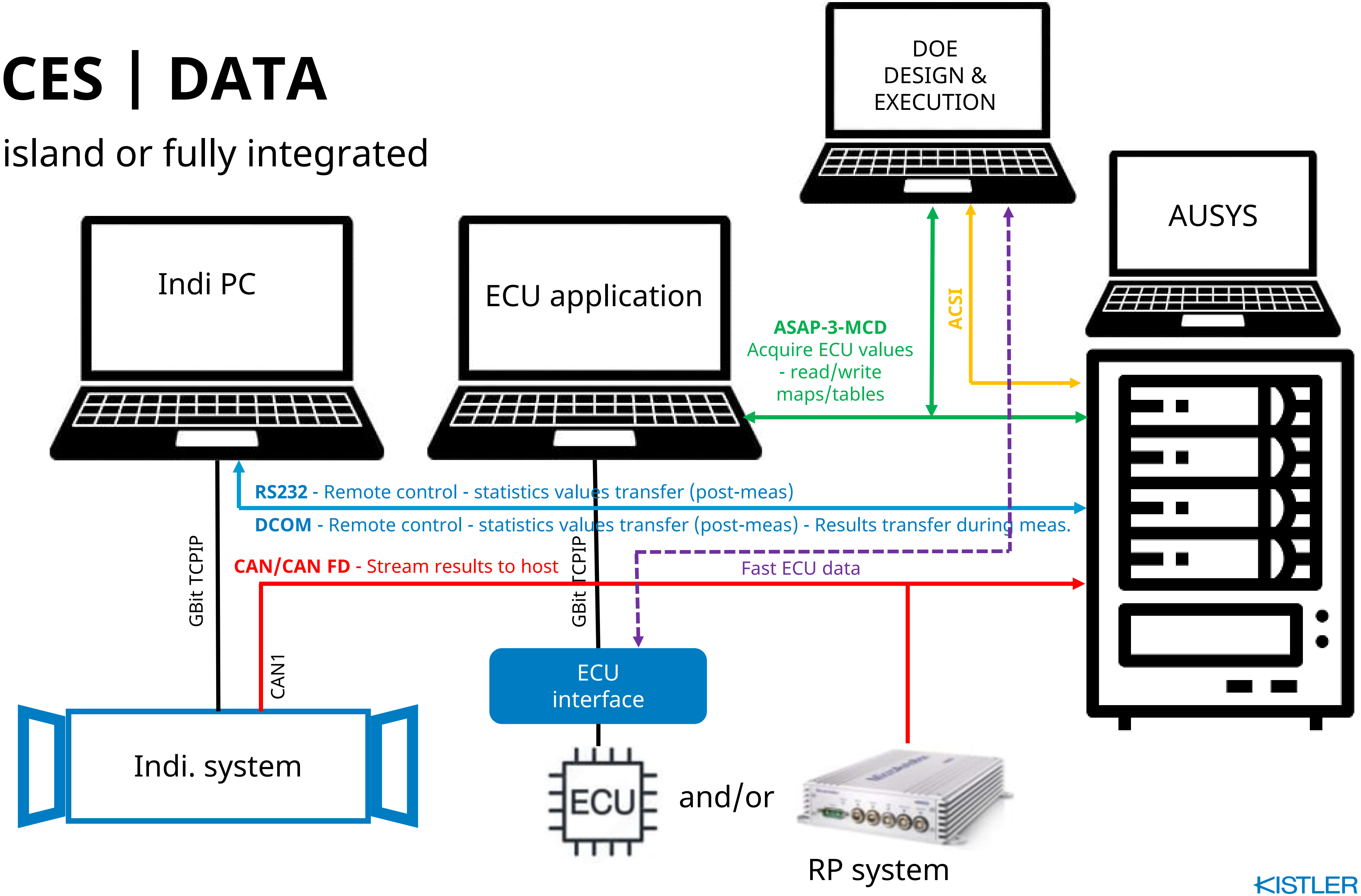


INTERFACES | DATA

Measurement island or fully integrated







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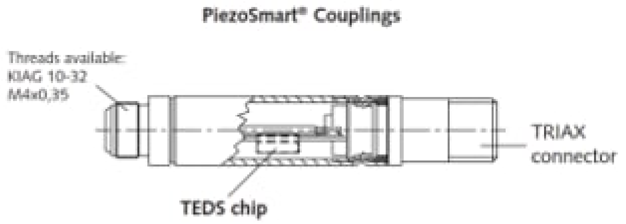
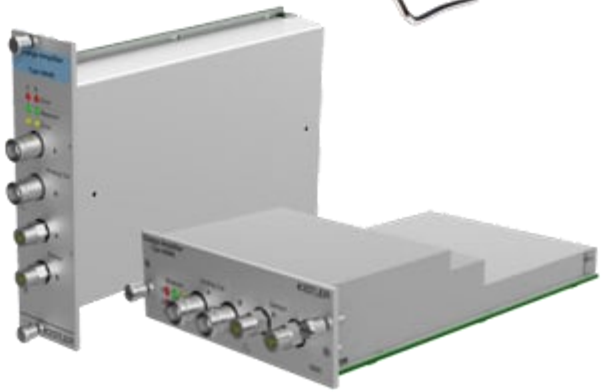
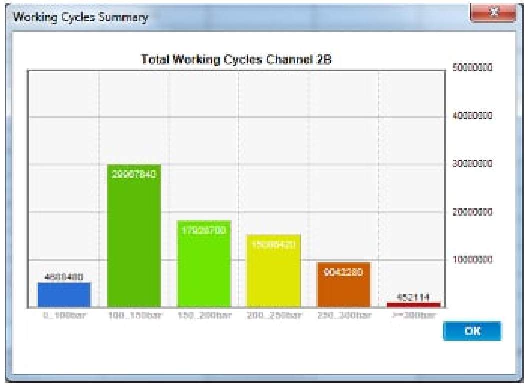
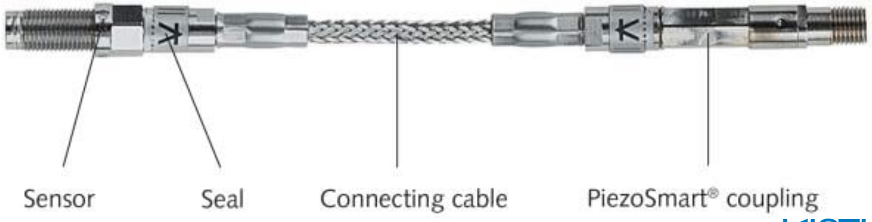
AMPLIFIERS

The sensor interface



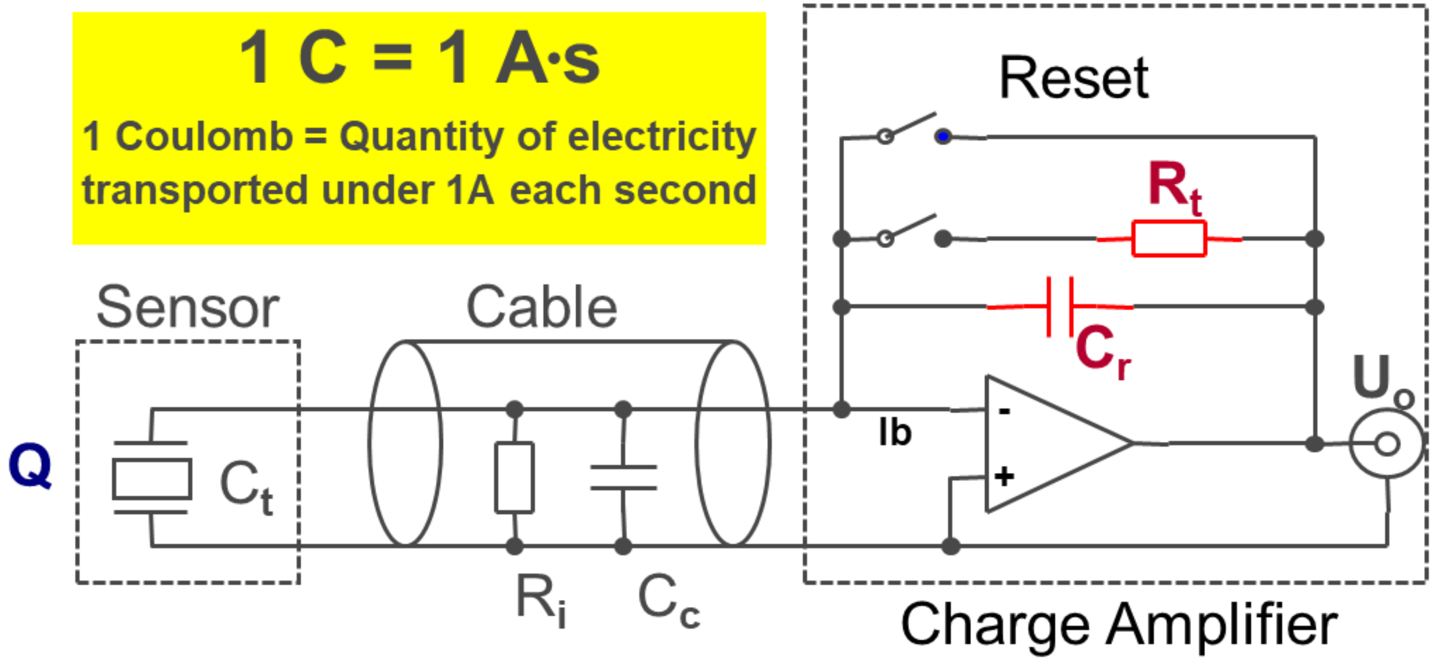






WORKING PRINCIPLE

Charge amplifier

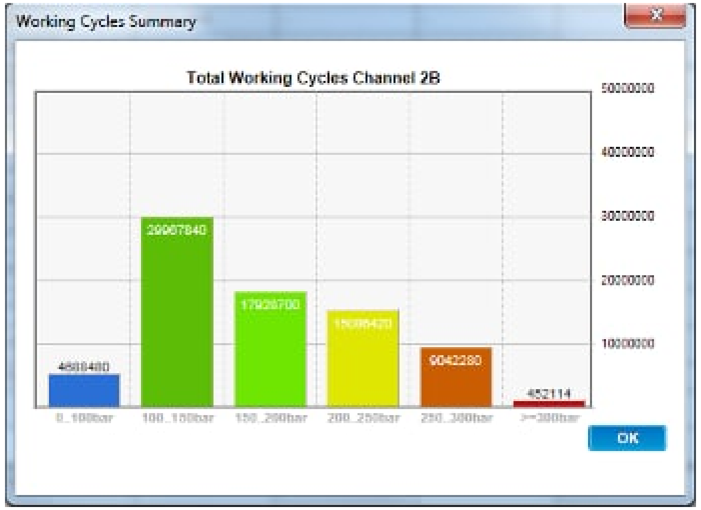


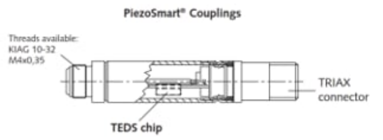
- **Conversion of charge to voltage**: It takes the tiny charge signal from a sensor (like a piezoelectric transducer) and converts it into a proportional voltage using a feedback capacitor in an op-amp circuit.
- **Stability and independence from cable effects**: Because the output depends on the feedback capacitor, not the sensor or cable capacitance, the measurement remains stable even with long cables.
- **Integration and amplification**: The amplifier integrates the input current over time, producing a usable, amplified voltage output that can be read by standard instruments.

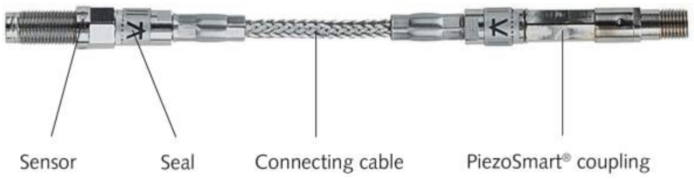
SIGNAL CONDITIONING FOR PE SENSORS

The charge amplifier - Engine pressure measurement specifics

How does a charge amplifier work?
Cyclic drift compensation: Prevents signal drifting too far from the zero line such the that output voltage could saturate the ADC inputs of the measuring device. Specific drift compensation modes for engine slow-speed
Voltage offset: A -8 volt offset is possible for predominantly +ve signals (i.e. cylinder pressure curves) - this allows full optimisation of the input range of the ACD on the measuring device
TEDS: Standard templates are supported for sensor recognition, sensor runtime (cycles and time) and calibration information
PMax detection: The amplifier separately calculates PMax for every cycle and stores this in a classification matrix that defines the duty cycle of the sensor, this can be used to assess the sensor life cycle and failure risk, data is stored on the TEDS connector. This data can also be used for engine monitoring/protection (output via CAN)
System overview/monitoring: System monitoring and notification for sensor and amplifier pending calibration/maintenance



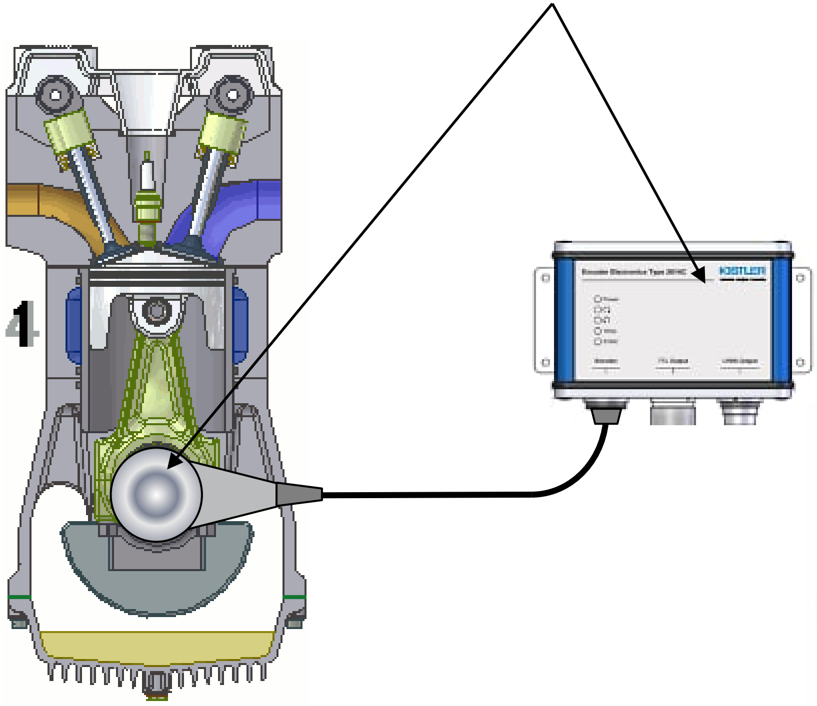


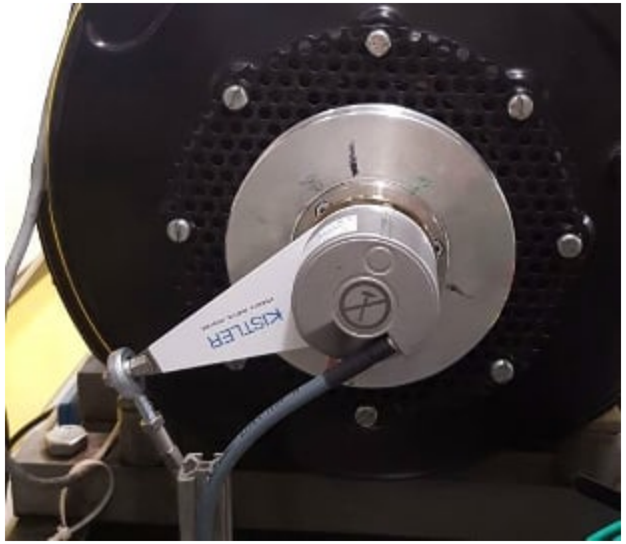


ANGLE ENCODER

To derive volume table

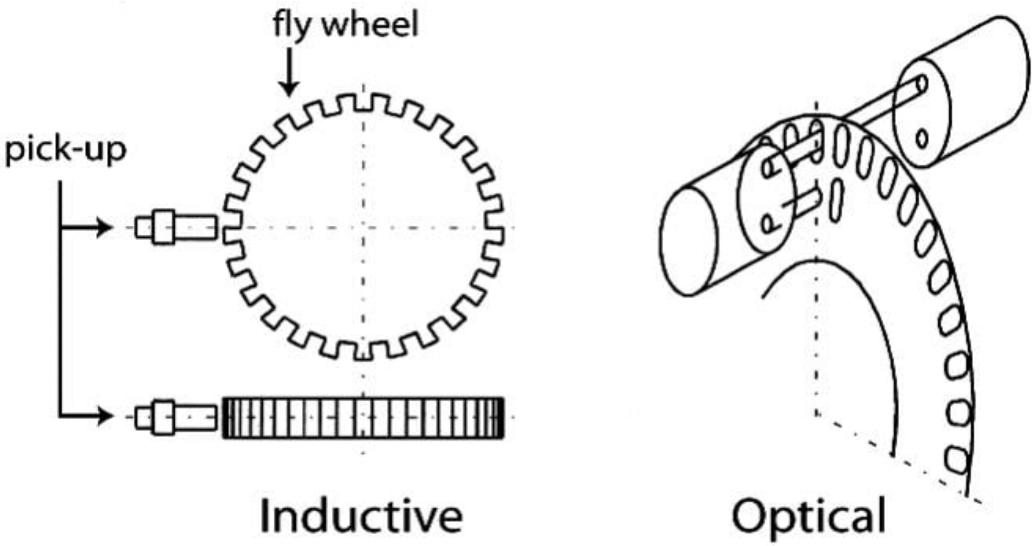
Crank-Angle
Encoder Set
2614DK1

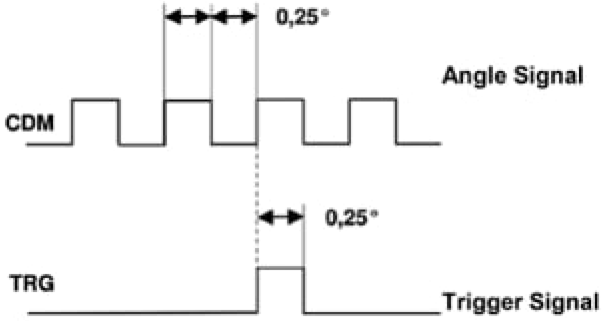


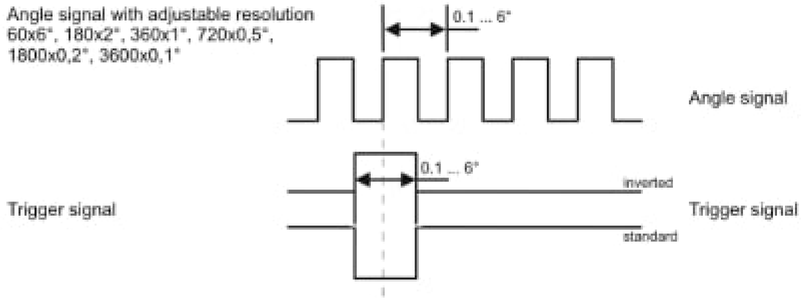


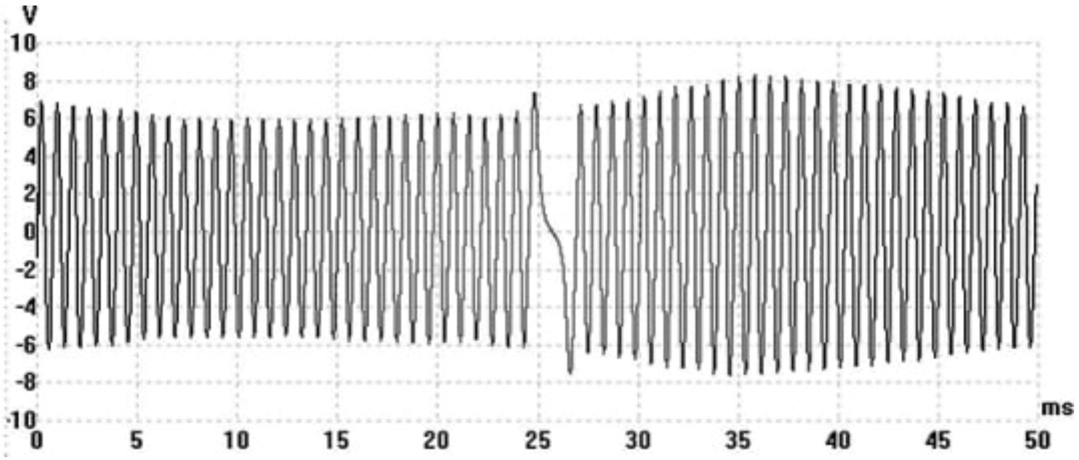
CRANKSHAFT ENCODER

Signal types









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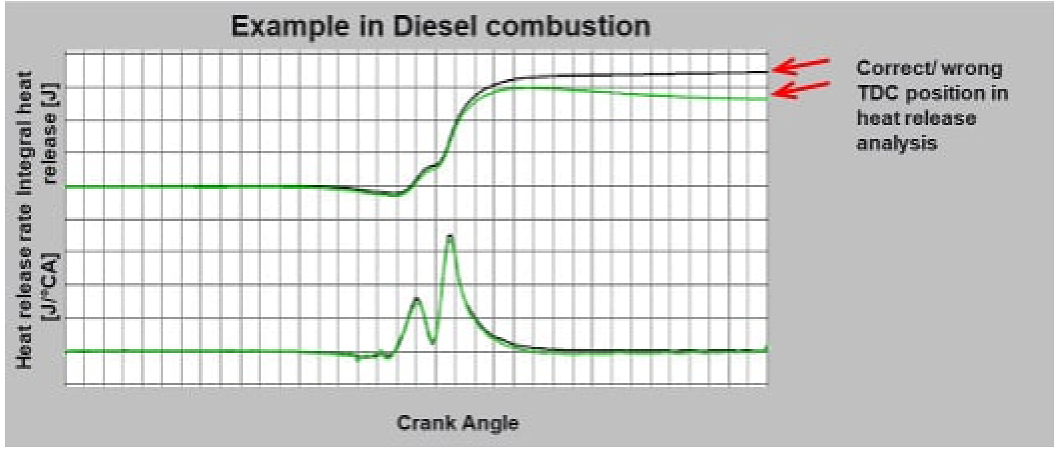
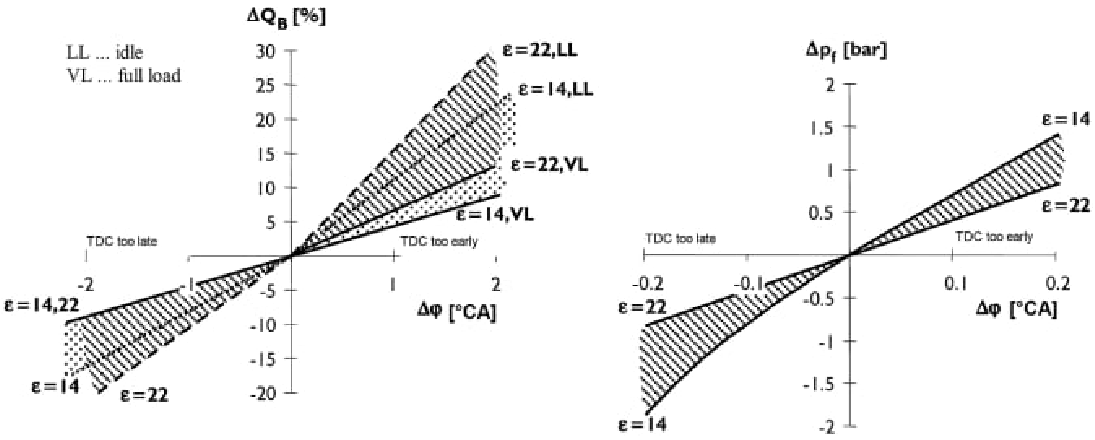
TDC SENSOR

Problem statement

- An error of TDC determination leads to **major errors in IMEP calculation and heat release curve**
- TDC inaccuracy can lead to reduced application quality; **error in CA50**
- The same is valid for thermodynamic loss angle
- **When the engine/encoder is installed - TDC calibration must be done!**
- **TDC should be check regularly during a test series**
- There are 2 main methods…





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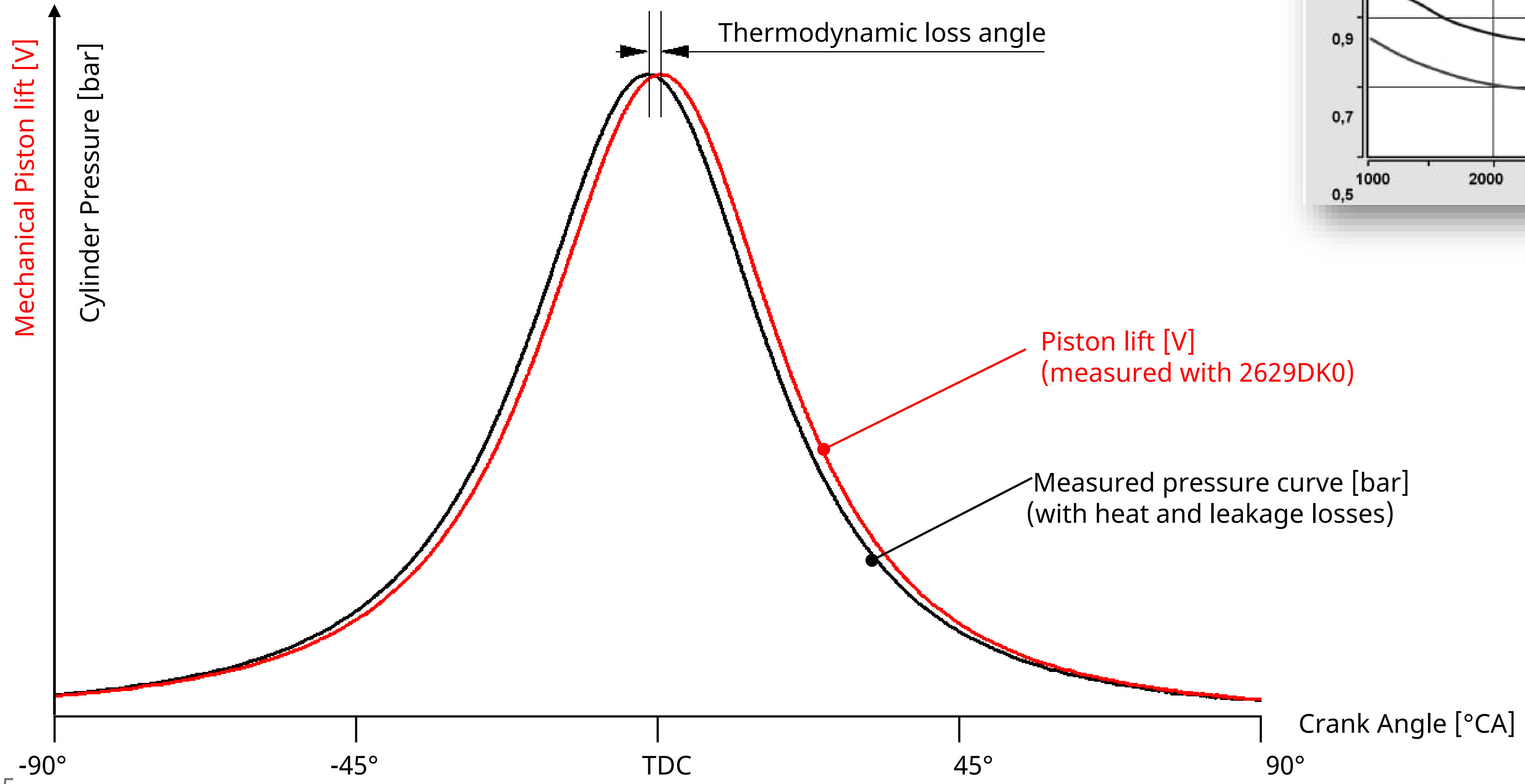
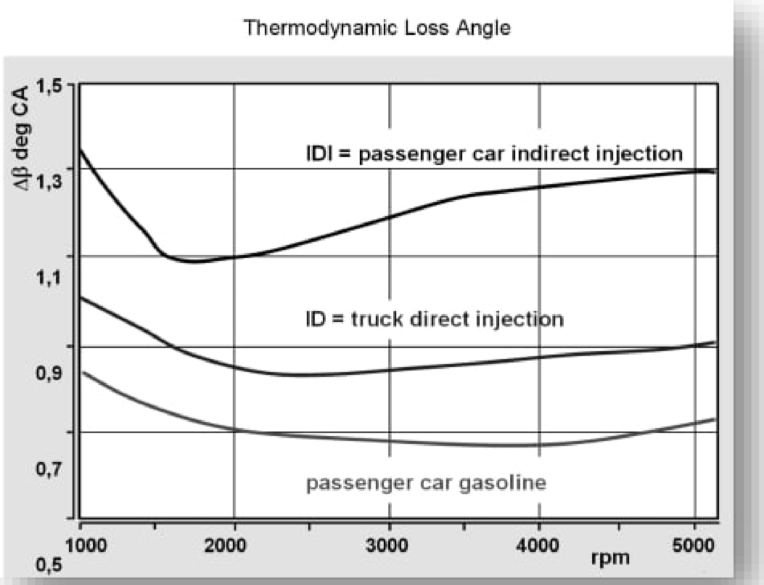
TDC DETERMINATION

Dependence on thermodynamic loss angle





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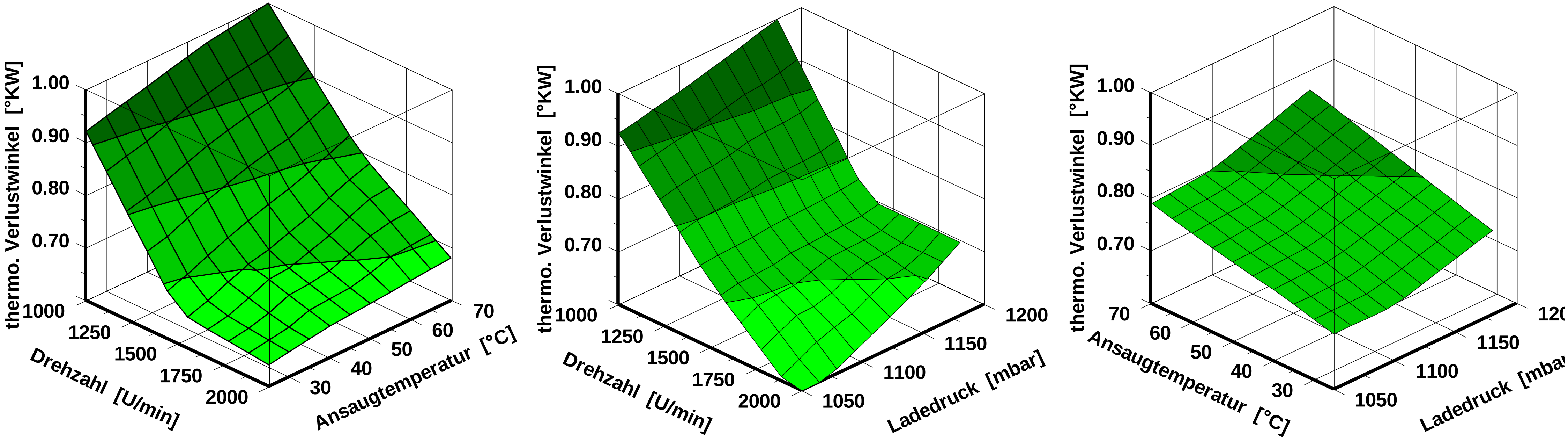
TDC SENSOR

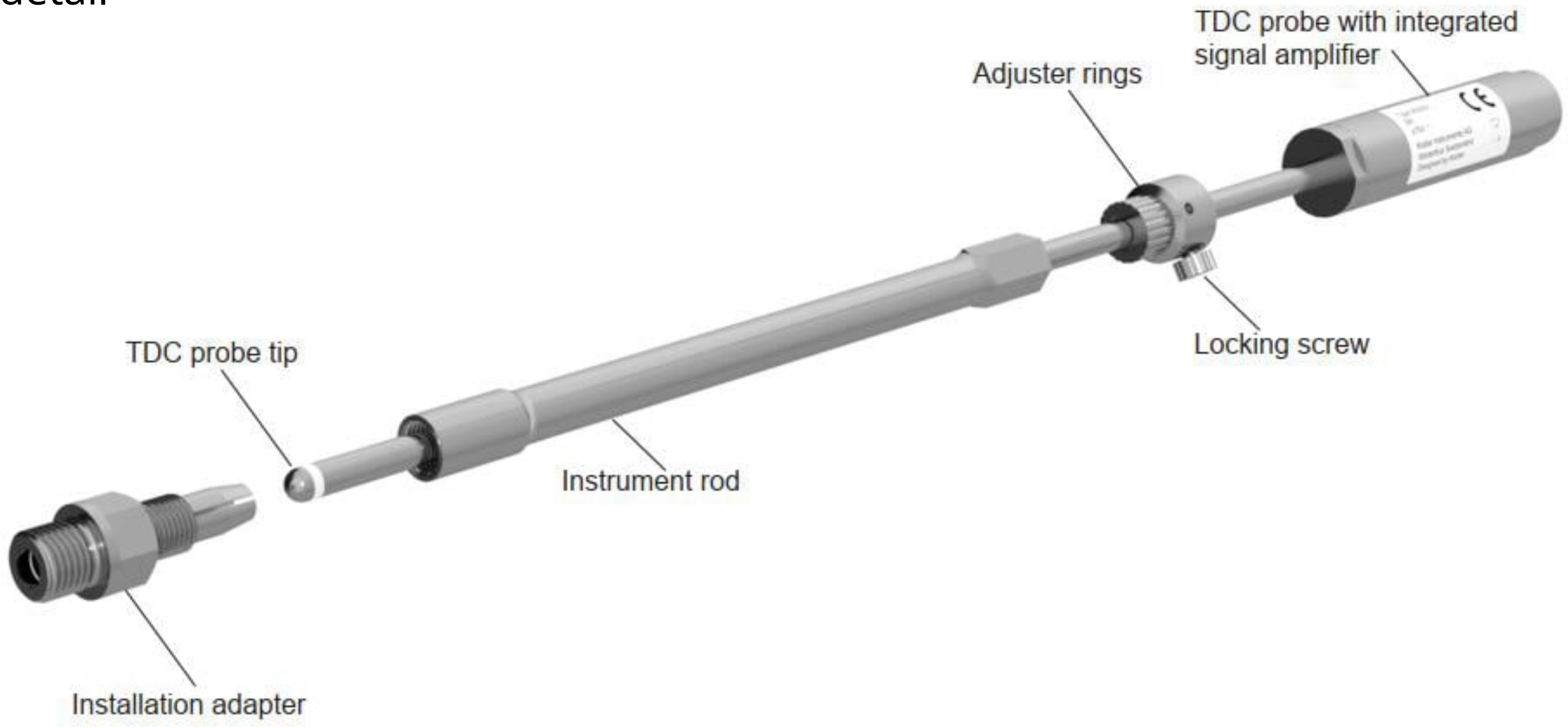
Loss angle is sensitive to boundary conditions



- Conditioning of engine is from high importance
- Strong influence of engine speed and cylinder wall temperature
- Minor influence of boost pressure and intake air temperature

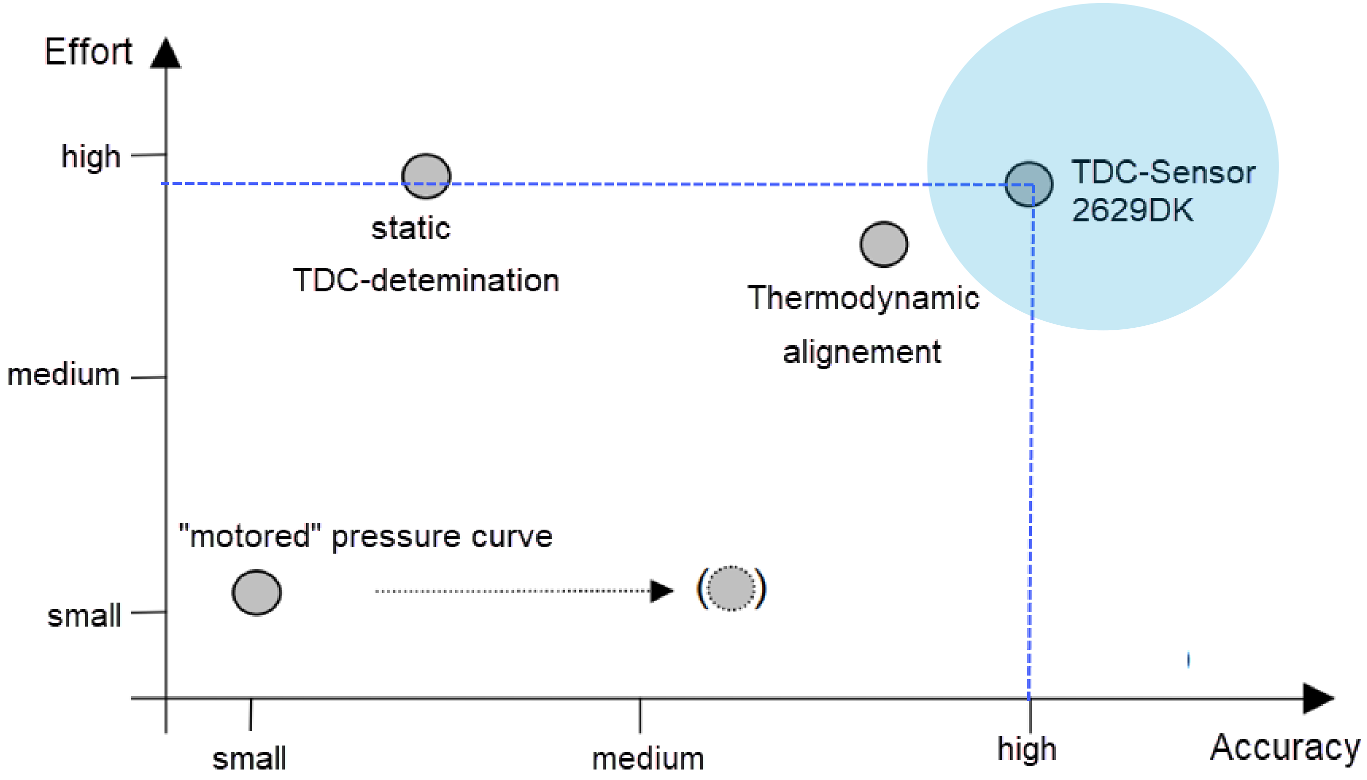
TDC SENSOR OVERVIEW

Probe detail



TDC SENSOR OVERVIEW

Comparison of TDC determination methods



- Most precise TDC determination with TDC sensor set

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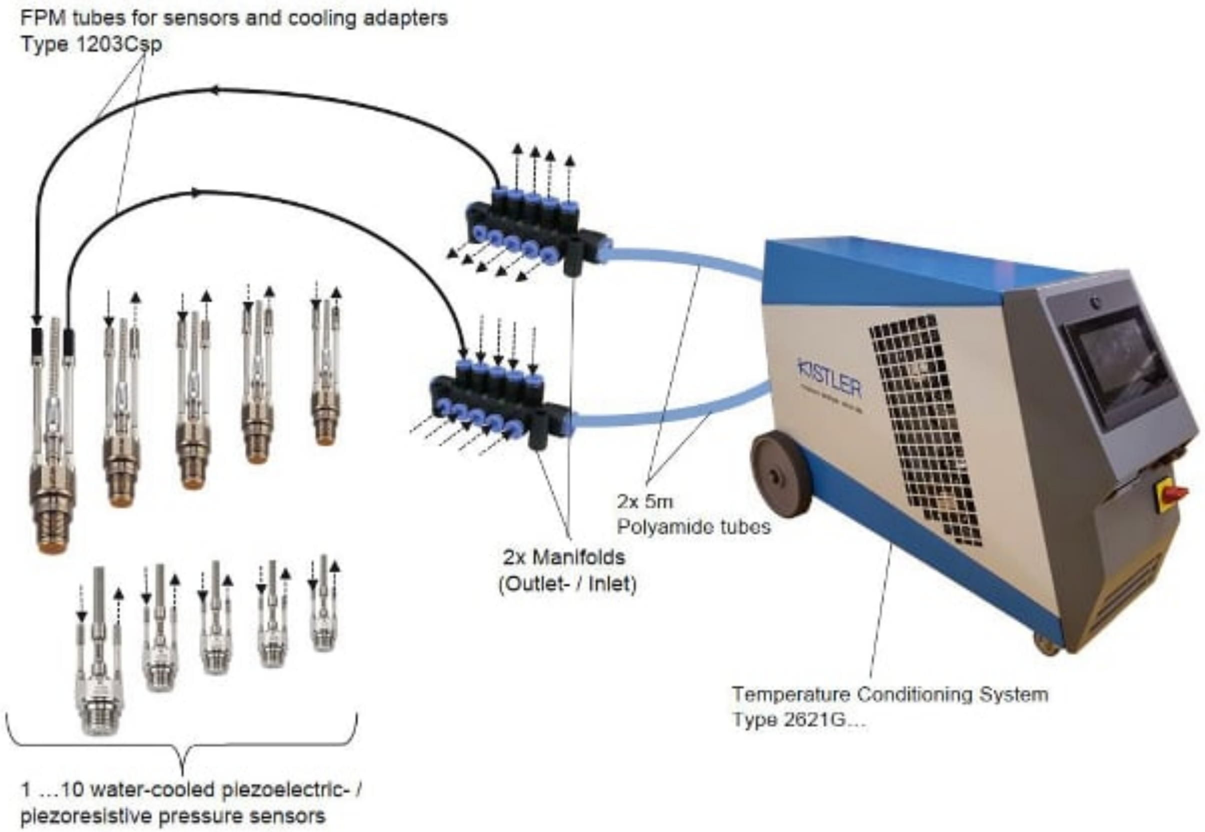
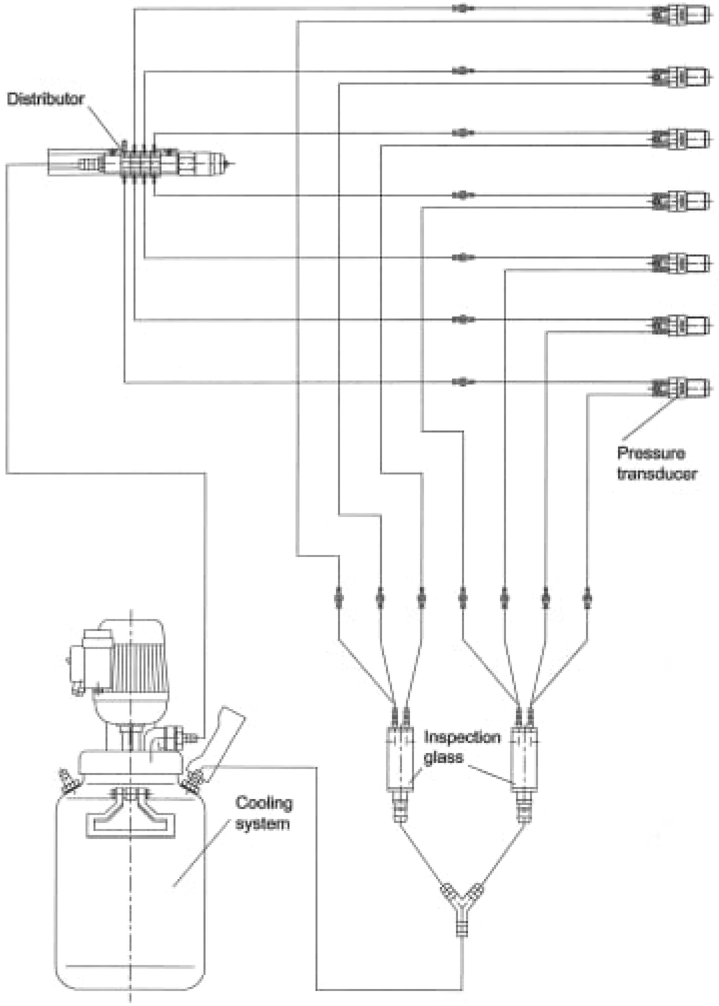
SENSOR COOLING SYSTEM

Kistler system is unique on the market



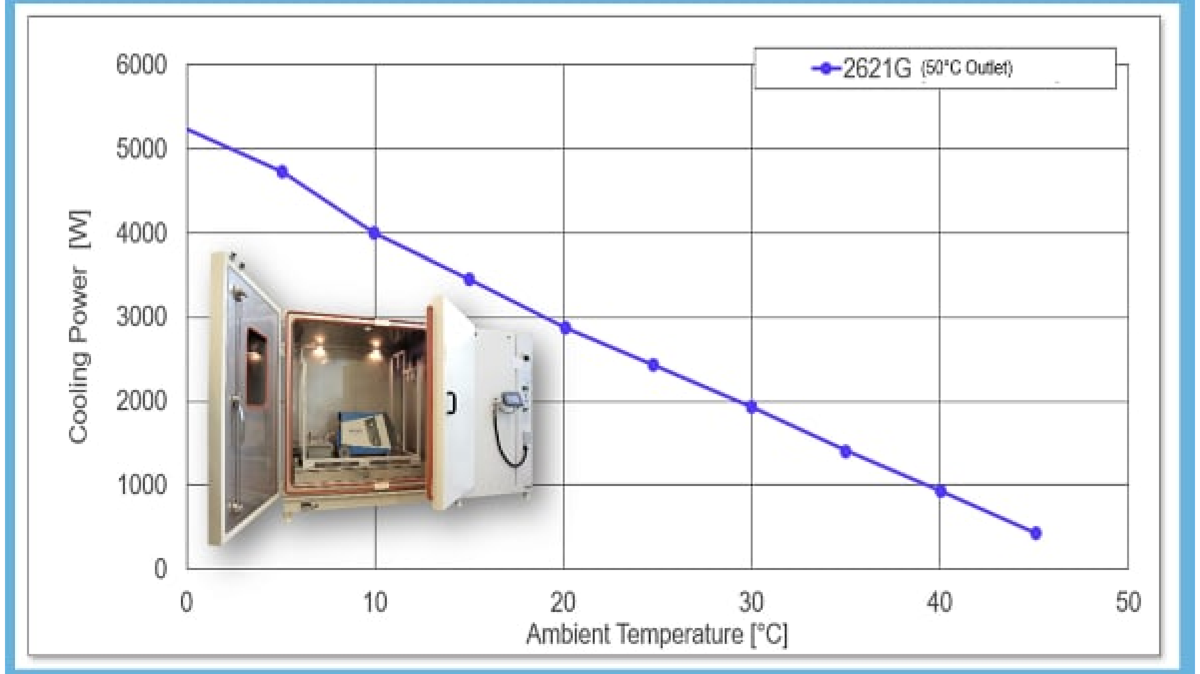


Other system:

SENSOR COOLING SYSTEM

Why do you need one?

Cooling Power of Type 2621G
(ambient temperature range form 0 … 45°C)



Typical Thermal Output of a water-cooled PE- and PR-Sensor

160 … 200 W

220 … 250 W

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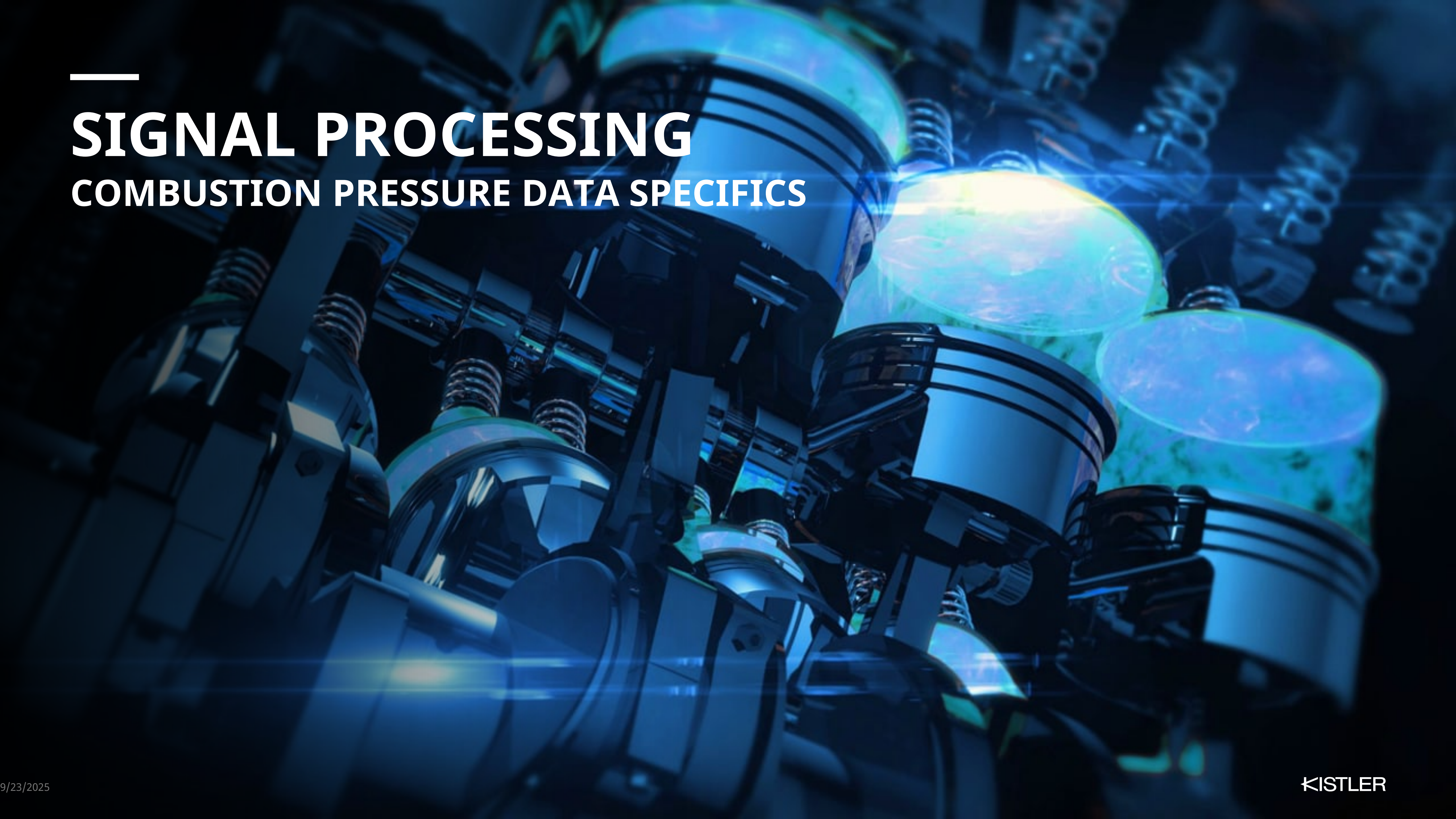
SIGNAL PROCESSING

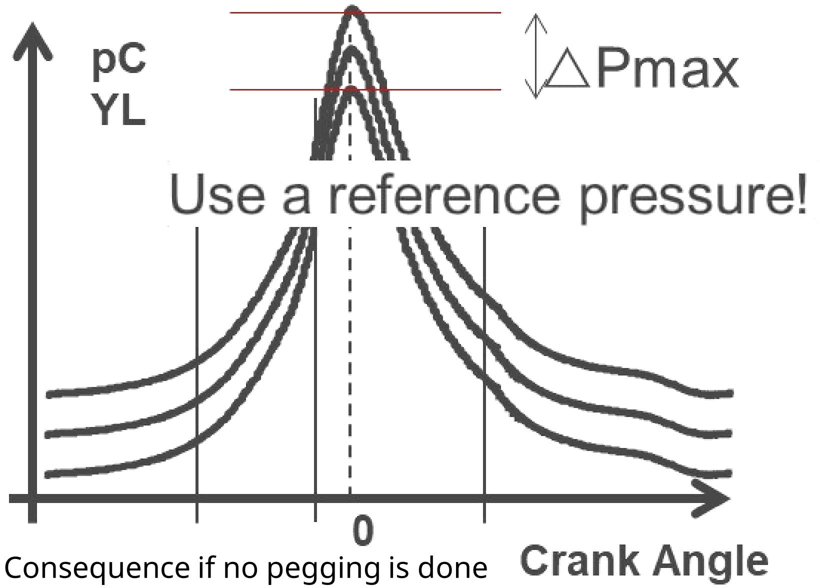
COMBUSTION PRESSURE DATA SPECIFICS



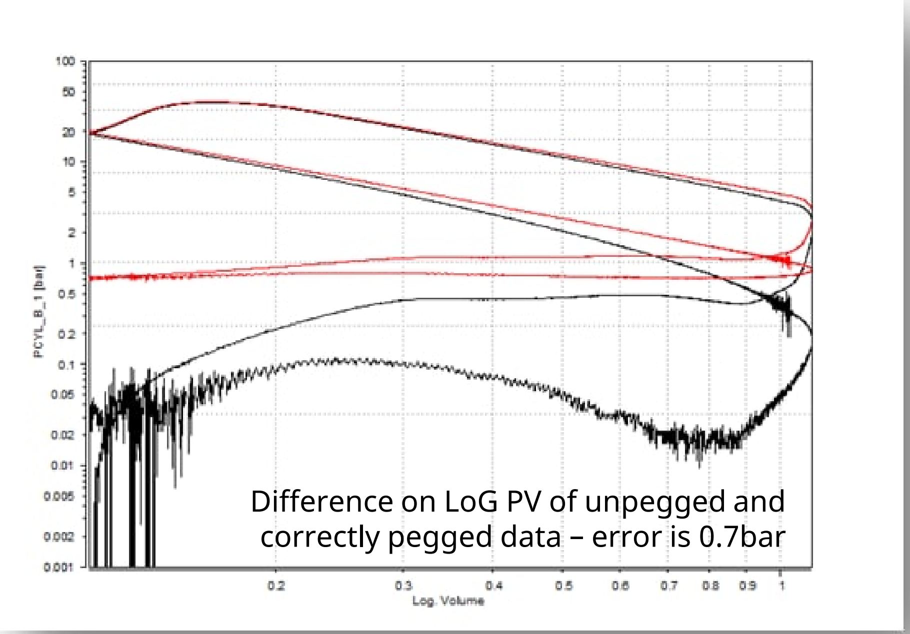
ZERO LEVEL CORRECTION/PEGGING

Why do we need it?

- Piezoelectric pressure sensors can measure only changes, for this reason we have to calculate the absolute pressure
- PE measurement chain is never ideal and a slight leakage always occurs. Therefore Pcyl traces shhift imperceptibly cycle after cycle.
- Dynamic pressure measurement with PE sensors needs to use a reference absolute pressure



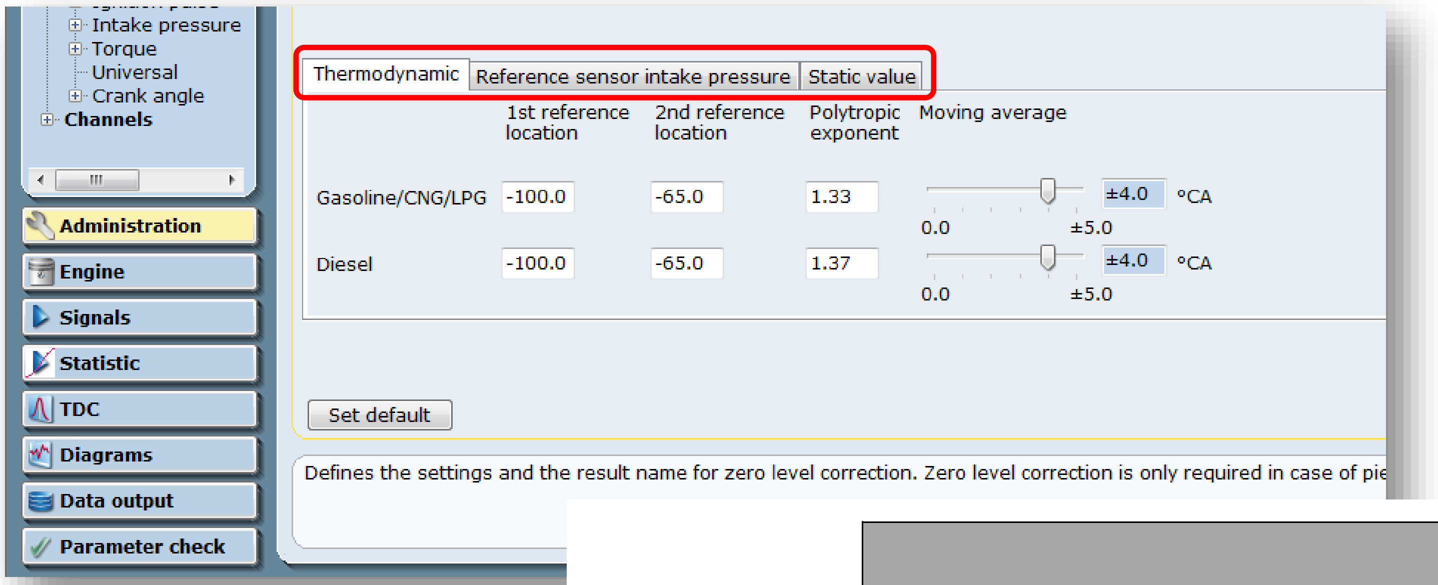
Consequence if no pegging is done



Difference on LoG PV of unpegged and correctly pegged data – error is 0.7bar

ZERO LEVEL CORRECTION/PEGGING

How is it implemented? methods?



- Fixed reference value
- Thermodynamic zero line detection (polytropic exponent = const.)
- Crank angle-based intake air pressure (dynamic piezoresistive sensor)
- (as low end alternative: Mean intake air pressure)

	Task							
	peak pressure	IMEP	burn duration	ignition delay	50% HR	energy balance	accuracy	real time
1-Fixed value	-	o	--	--	--	--	-	yes
2-Thermodynamic zero line	+	o	-	+	+	-	+	yes
3-Crank angle-based intake air pressure	+	o	+	+	+	+	++	yes
Mean intake air pressure	-	o	-	-	-	--	-	yes

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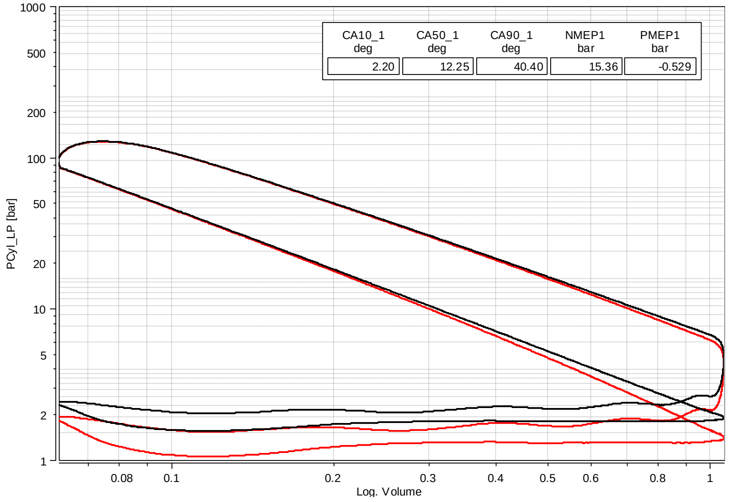
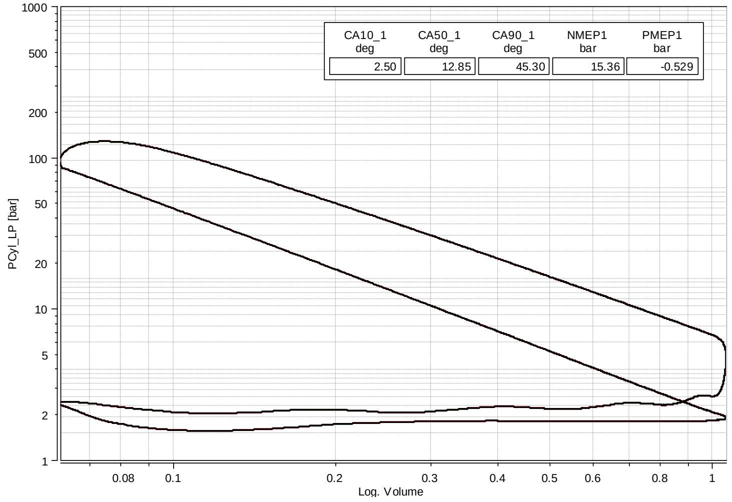
ZERO LEVEL CORRECTION/PEGGING

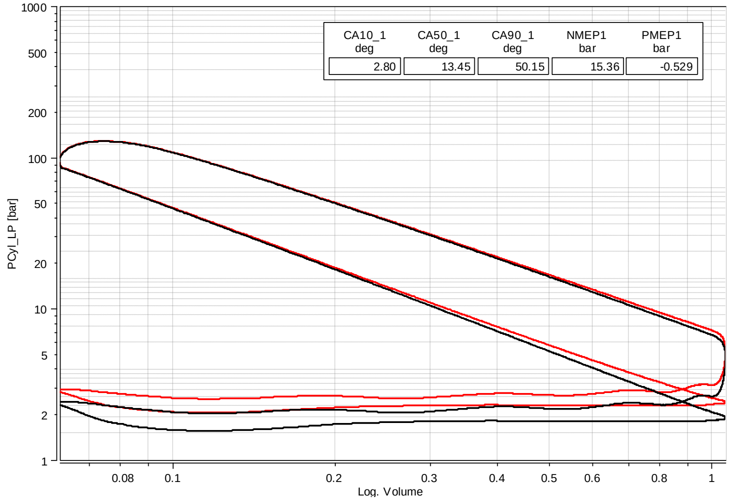
Example data

-ve 0.5 Bar ZLC error



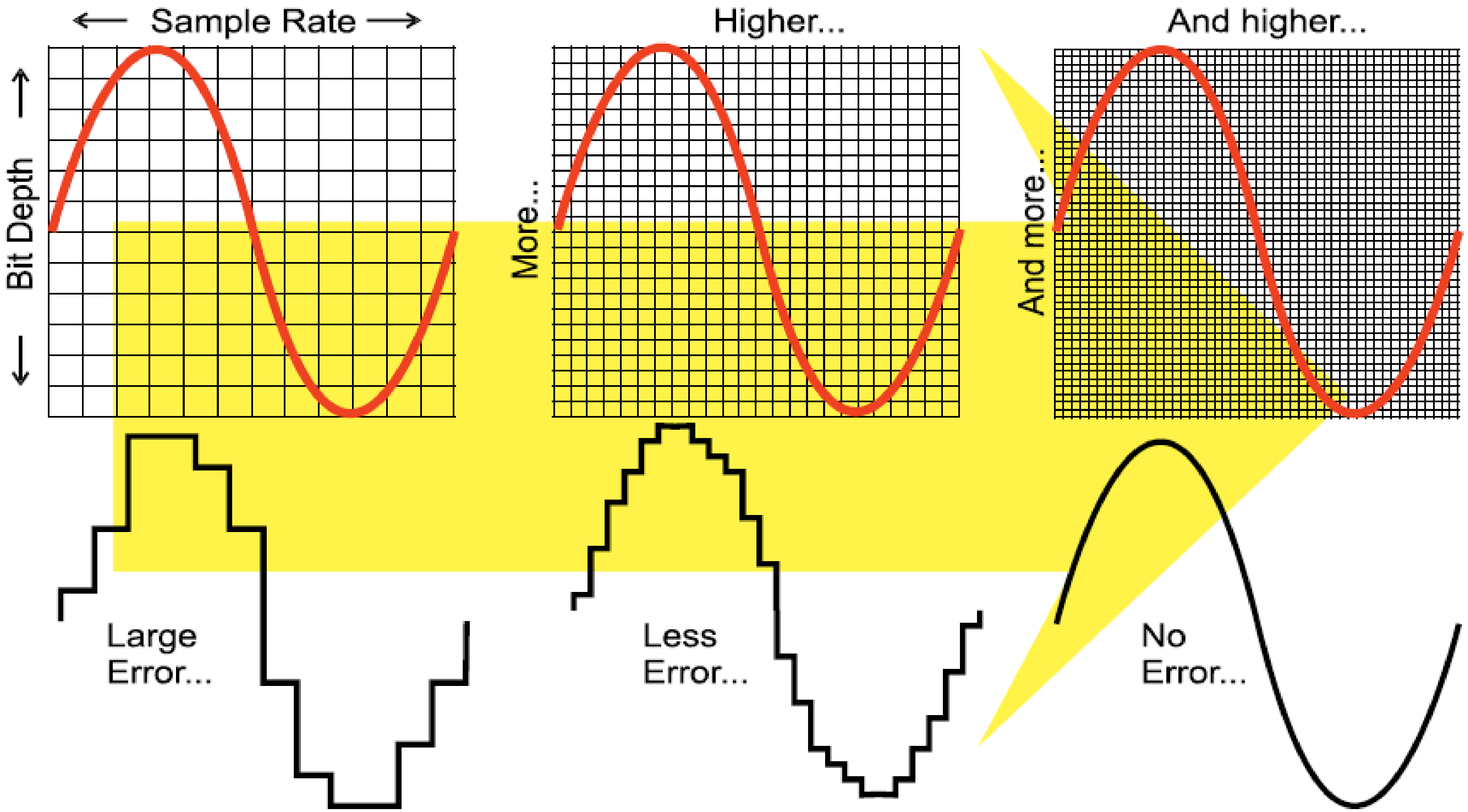


+ve 0.5 Bar ZLC error



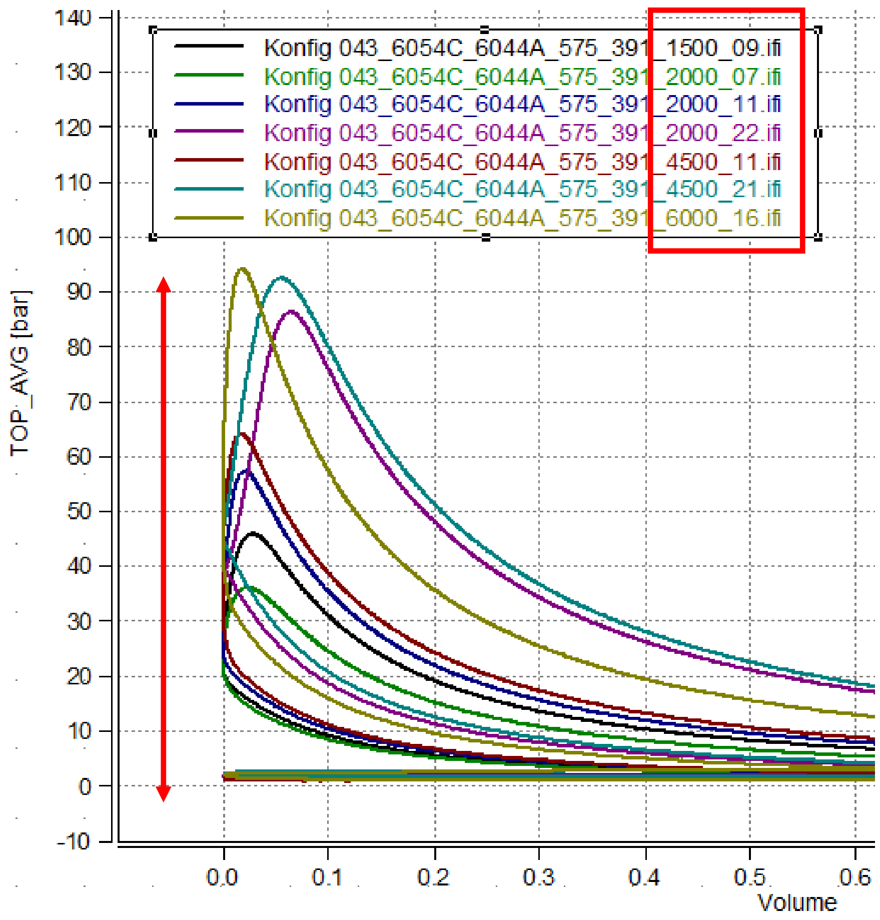
SAMPLING

Acquisition frequency and vertical resolution

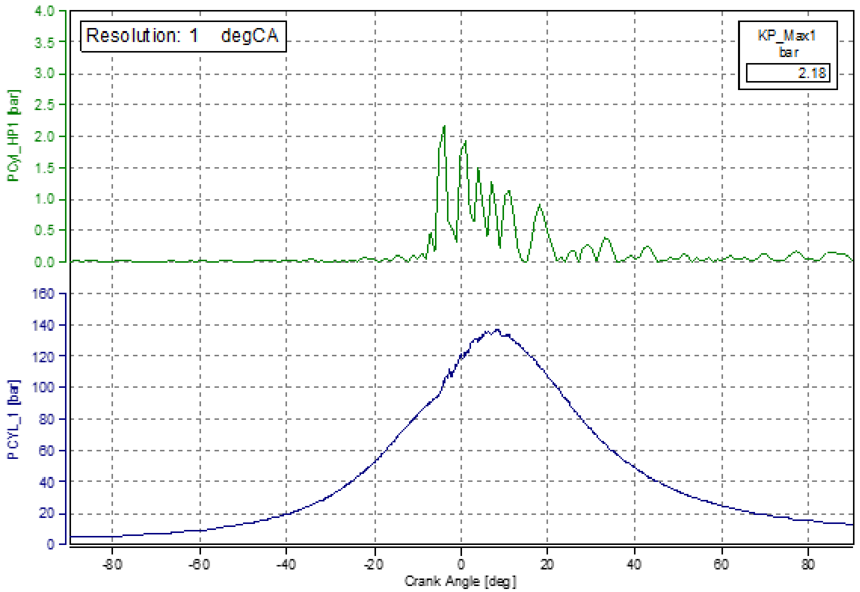


SAMPLING

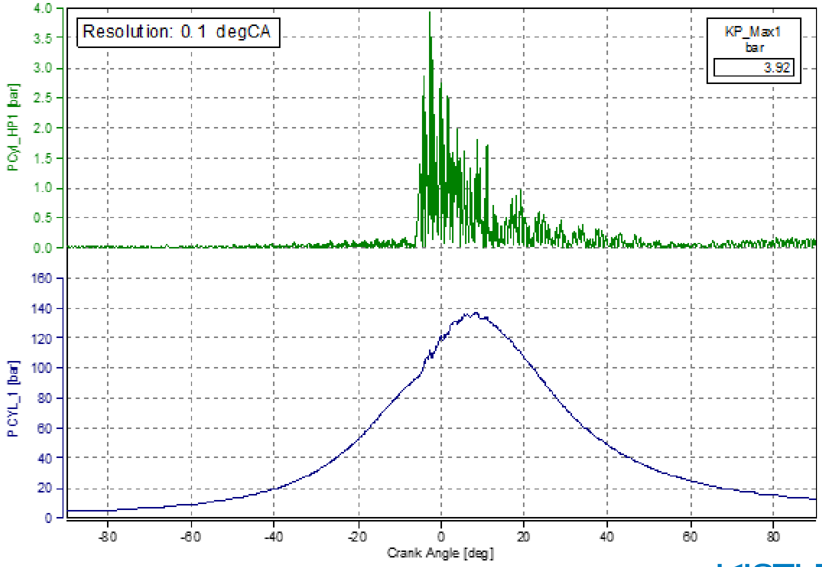
Acquisition frequency and vertical resolution



1.0 degCA



0.1 degCA



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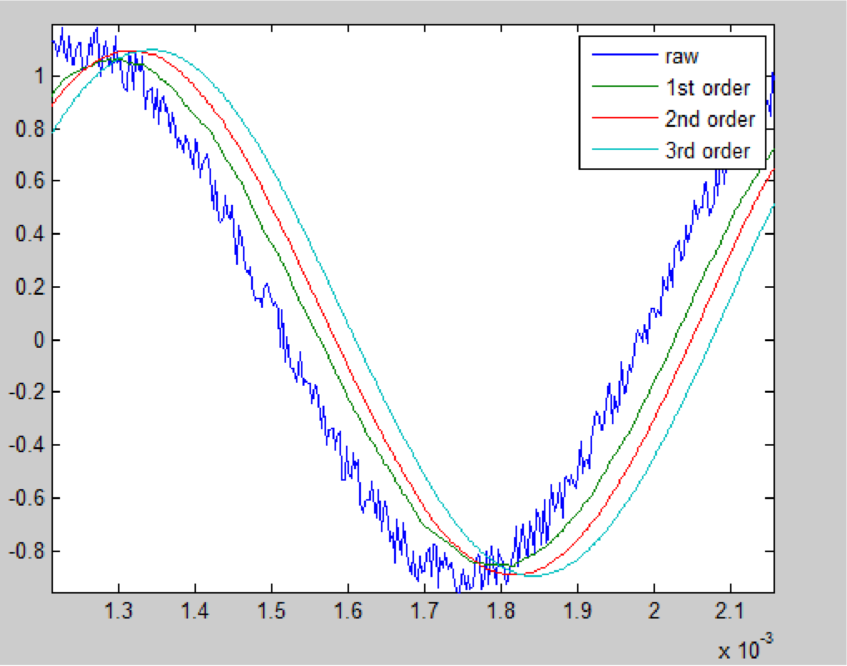
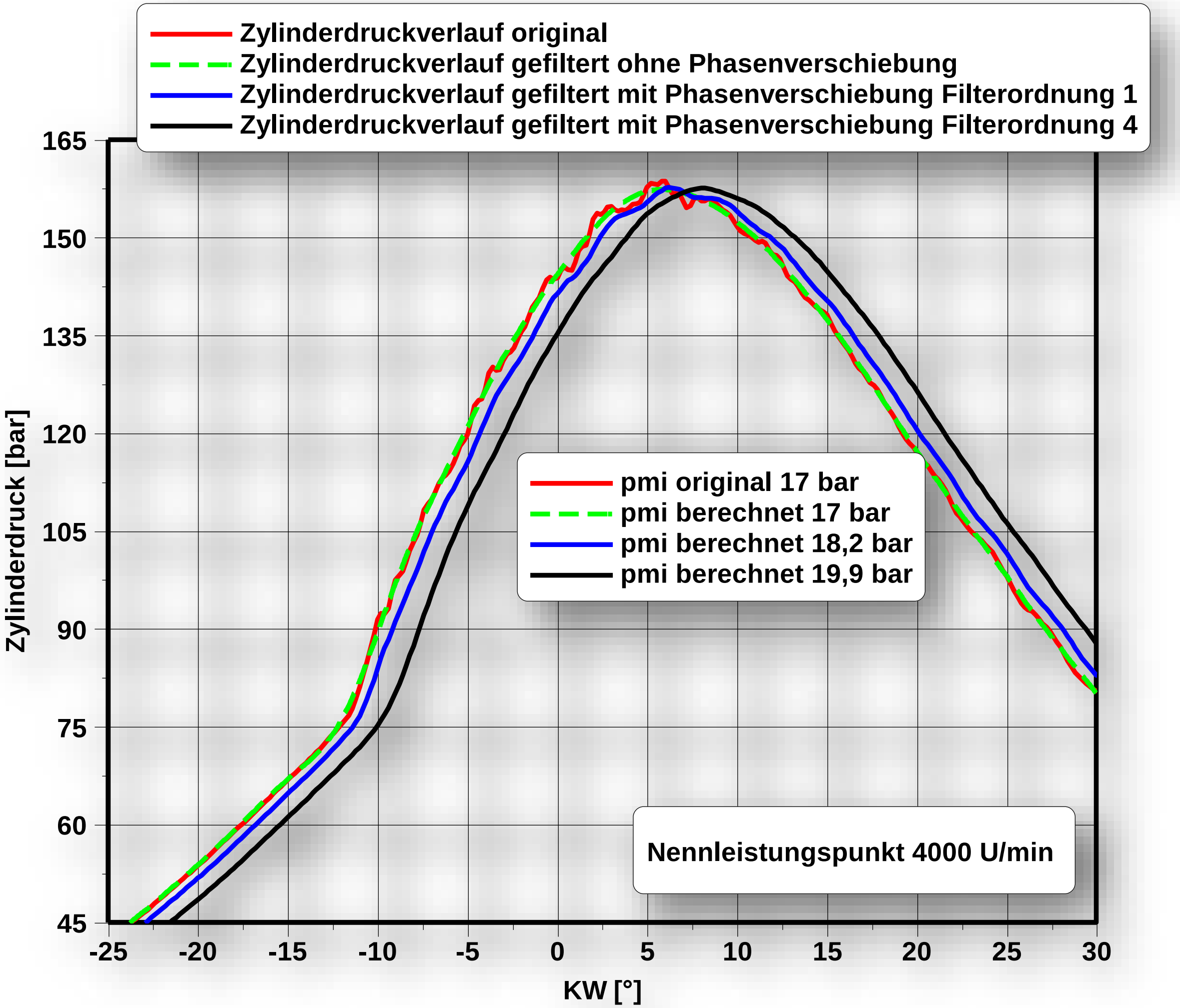
FILTERING OF CYLINDER PRESSURE

Filters always cause phase shift!





Further influence on pressure - volume assignment

- Too strong filtering of cylinder pressure signal → **phase shift**
- Same influence as TDC shift!

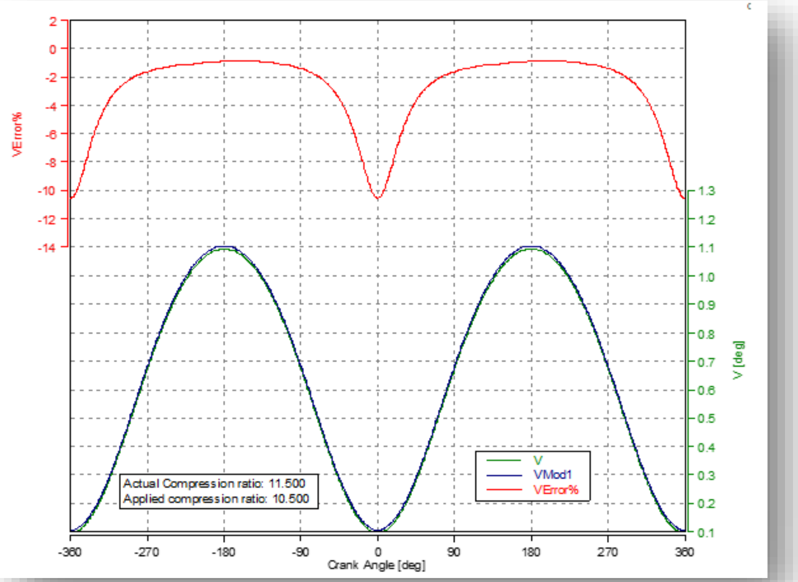
STATIC PARAMETER BASED ERRORS

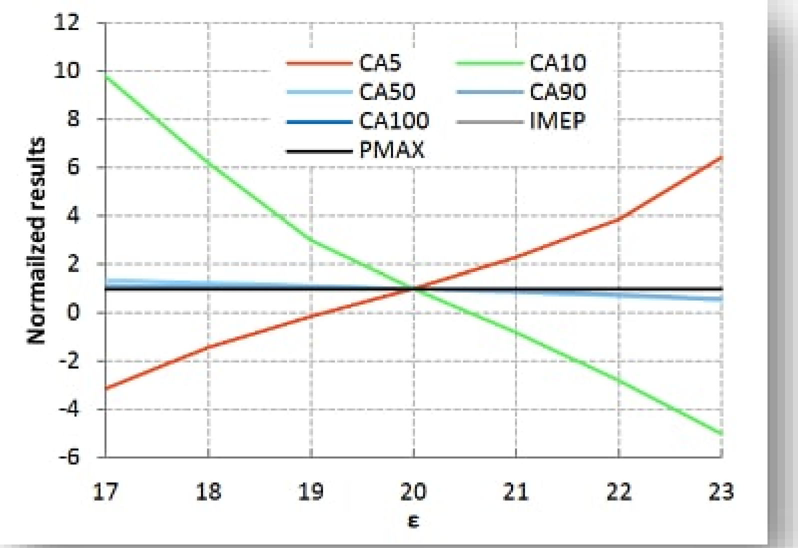
Compression ratio, Engine geometry, Polytropics

From literature:

- **Karim et al.:** 2% error in compression ratio → up to 40% error in gross heat release; precise CR definition is critical.
- **Brunt et al.:** CR errors cause cylinder volume, polytropic index, and MBF discrepancies.
- **Lancaster & Amann:** Use liquid displacement for high-CR engines; dynamic inaccuracies remain due to mechanical/thermal deformations.
- **Kuratle et al.:** Accuracy depends on correct definition of all static parameters: crank geometry, CR, and TDC.

Nahkle, M., Rogers, D., Meier, J., Fusshoeller, H. et al., "A Method for Improvement in Data Quality of Heat Release Metrics Utilizing Dynamic Calculation of Cylinder Compression Ratio," SAE Int. J. Engines 13(2):135-142, 2020, https://doi.org/10.4271/03-13-02-0010.





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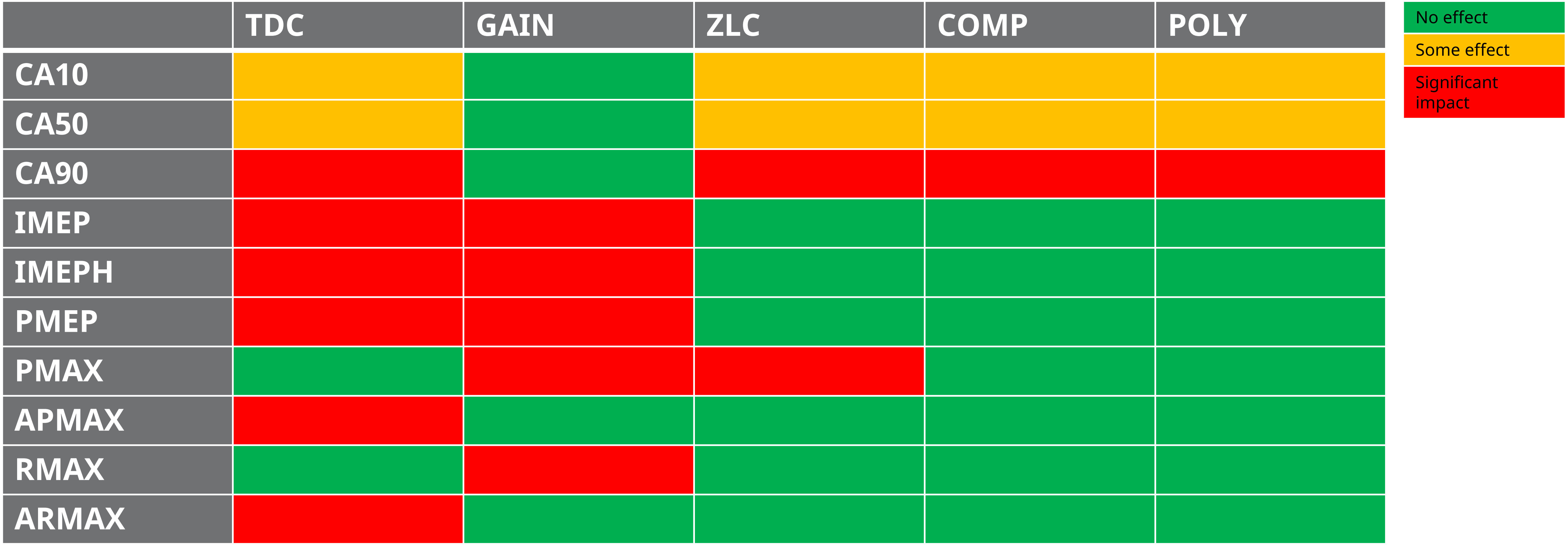
SENSITIVITY ANALYSIS

Static errors heat map



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DATA QUALITY ASSESSMENT

WHAT IS DATA QUALITY?

Generally

- Fit for its intended purpose in operations, decision making and planning
- Correctly represents the real-world construct to which it refers

Combustion data (Raw):

- Correctly scaled
- Correctly phased
- Correct parameters/volume definition
- Noise free

Combustion Results:

- Correctly parameterized
- Known or robust parameter values

→ Compared to a test bed, channel count is lower but **sensitivity to parameterisation errors** is much higher

HOW CAN DATA QUALITY BE COMPROMISED?

Instrumentation error effect

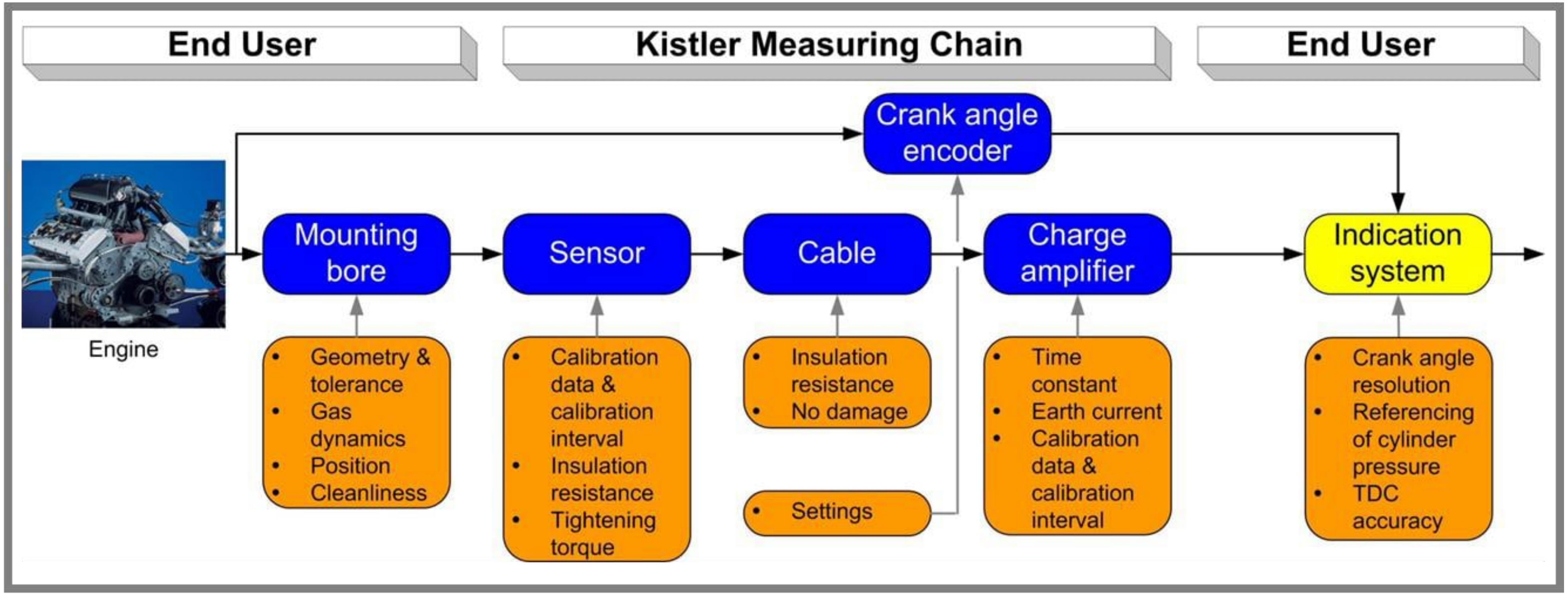
	Transducer and cabling	Amplifier	Encoder	Measurement device
Drift	Significant	Significant	None	None
Linearity	Significant	Some	None	Some
Stability	Significant	Significant	Some	Some

Sensitivity to external interference

	Transducer and cabling	Amplifier	Encoder	Measurement device
Electrical noise	Significant	Significant	Significant	Significant
Vibration	Significant	None	None	Significant
Temperature	Significant	Some	Some	Some

Reproduced from Rogers D.R. "Engine Combustion: Pressure measurement and analysis, 2nd Edition", published by SAE International, 2020

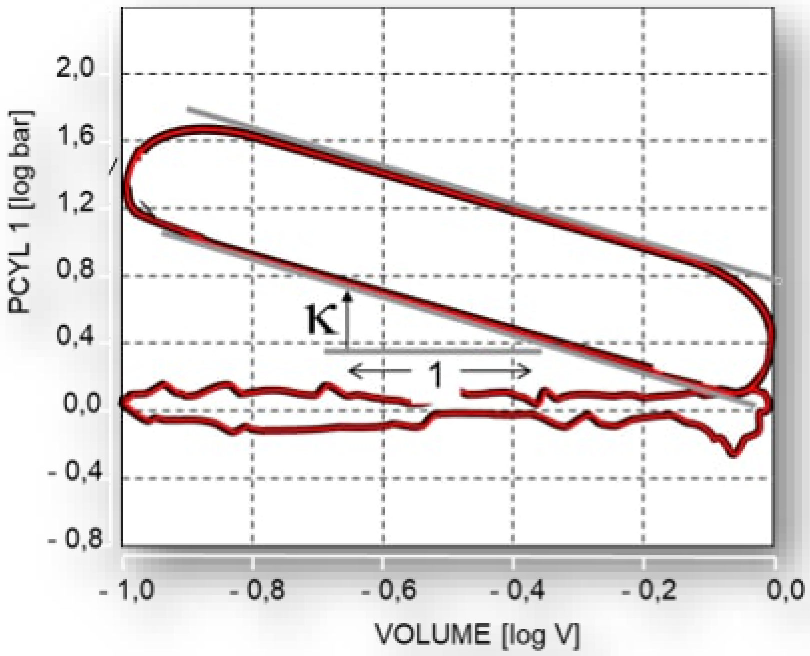
MEASURING CHAIN - SOURCES OF ERROR



- The **correct application and maintenance** of all measuring chain components is of primary importance

LOG PV DIAGRAM

Data quality analysis (fired)

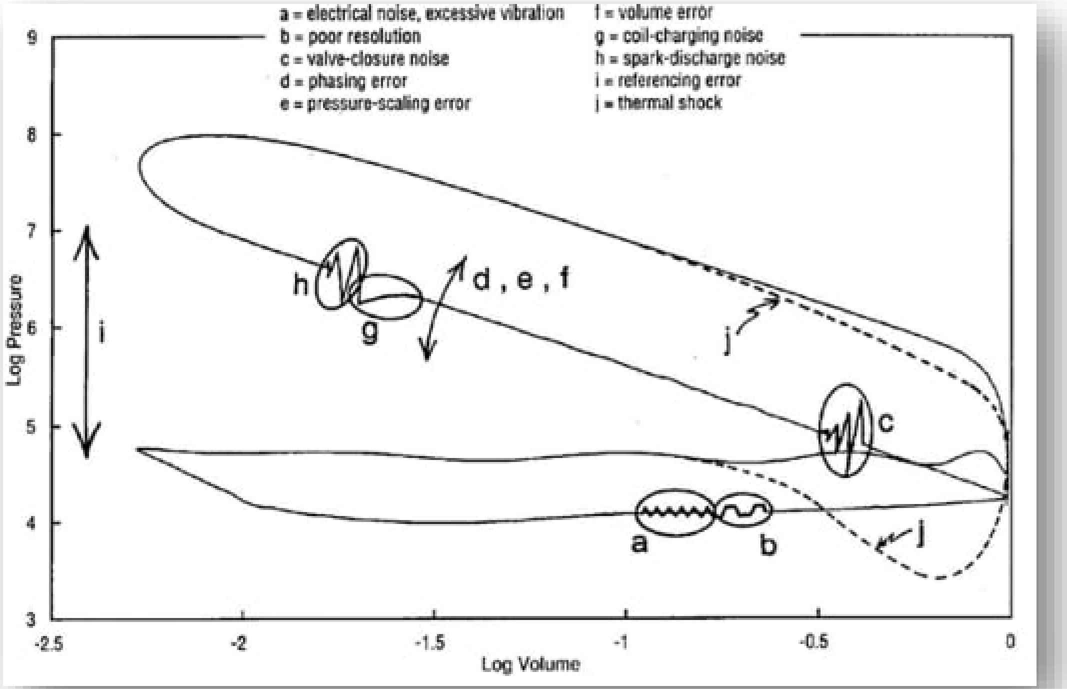


Error Causes:

Zero Level
- Too High:
- Too Low:

TDC
- Too Early: κ too low
- Too Late: κ too high

Compression Ratio
- ε too High: κ too low
- ε too Low: κ too high



κ....Polytropic Coefficient of Gas in the Combustion Chamber

κ ~ 1,32 Gasoline κ ~ 1,37 Diesel

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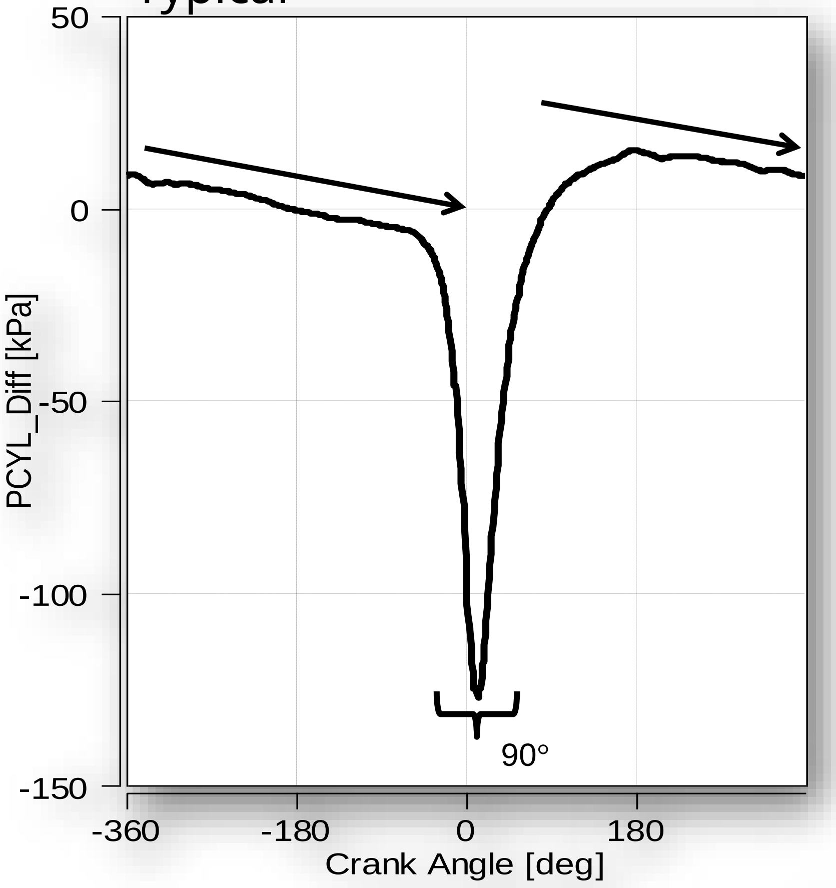
SENSOR PERFORMANCE CHARACTERISATION

For thermoshock

Typical



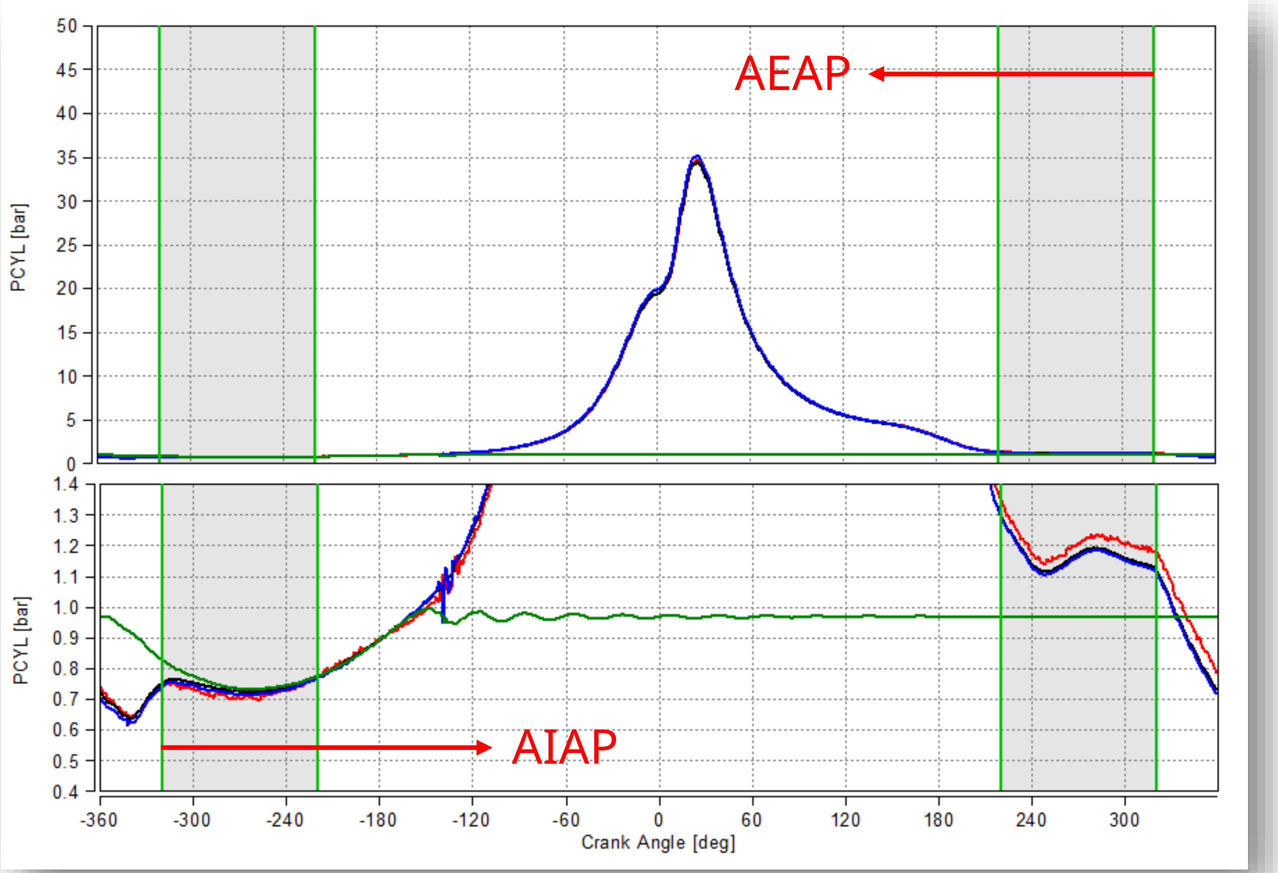
Actual

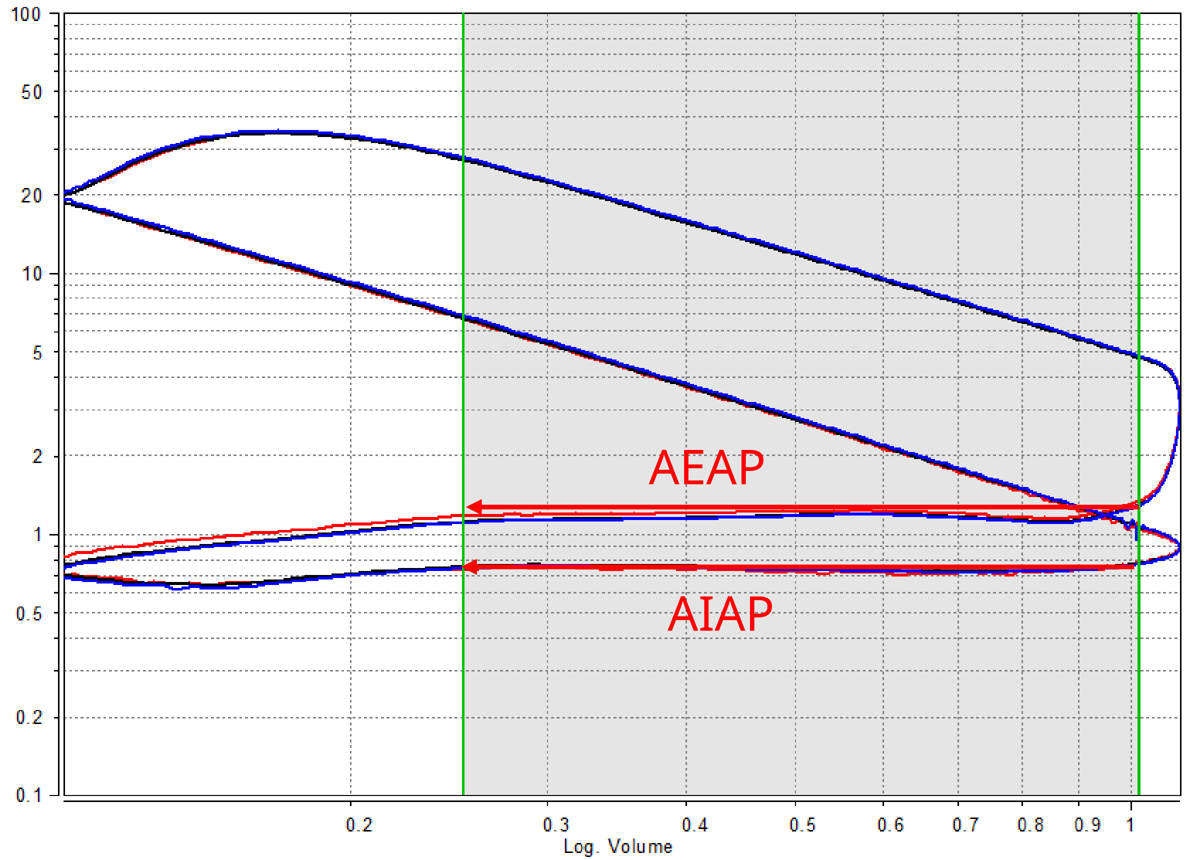
Datasheet

Technical data		
Measuring range	bar	0 ... 300
Calibrated ranges (23°C, 200°C, 350°C)	bar	0 ... 100, 0 ... 150, 0 ... 200, 0 ... 300
Overload	bar	350
Sensitivity (at 23°C)	pC/bar	–17
Natural frequency (measuring element)	kHz	≈185
Linearity (at 23°C)	%FSO	±0.3
Tightening torque, greased	N·m	1.5
Shock resistance (half sinus 0.2 ms)	g	≥2,000
Acceleration sensitivity		
axial	mbar/g	0.8
radial	mbar/g	0.2
Sensitivity shift		
23°C ... 350°C	%	±1.0
200 ± 50°C	%	±0.4
Operating temperature range	°C	–20 ... 350
Temperature, min./max.	°C	–40 ... 400
Thermal shock error (at 1,500 1/min, IMEP = 9 bar)		
Δp (short-term drift)	bar	±0.25
ΔIMEP	%	±1.5
Δp_{max}	%	±1.0
Insulation resistance (at 23°C)	Ω	$\geq 10^{13}$
Capacitance sensor	pF	8
Connector, sapphire insulator		M3x0.35
Protection rating, with cable Type 7 (IEC 60529)	IP	65
Weight sensor	g	1.5

SENSOR PERFORMANCE CHARACTERISATION

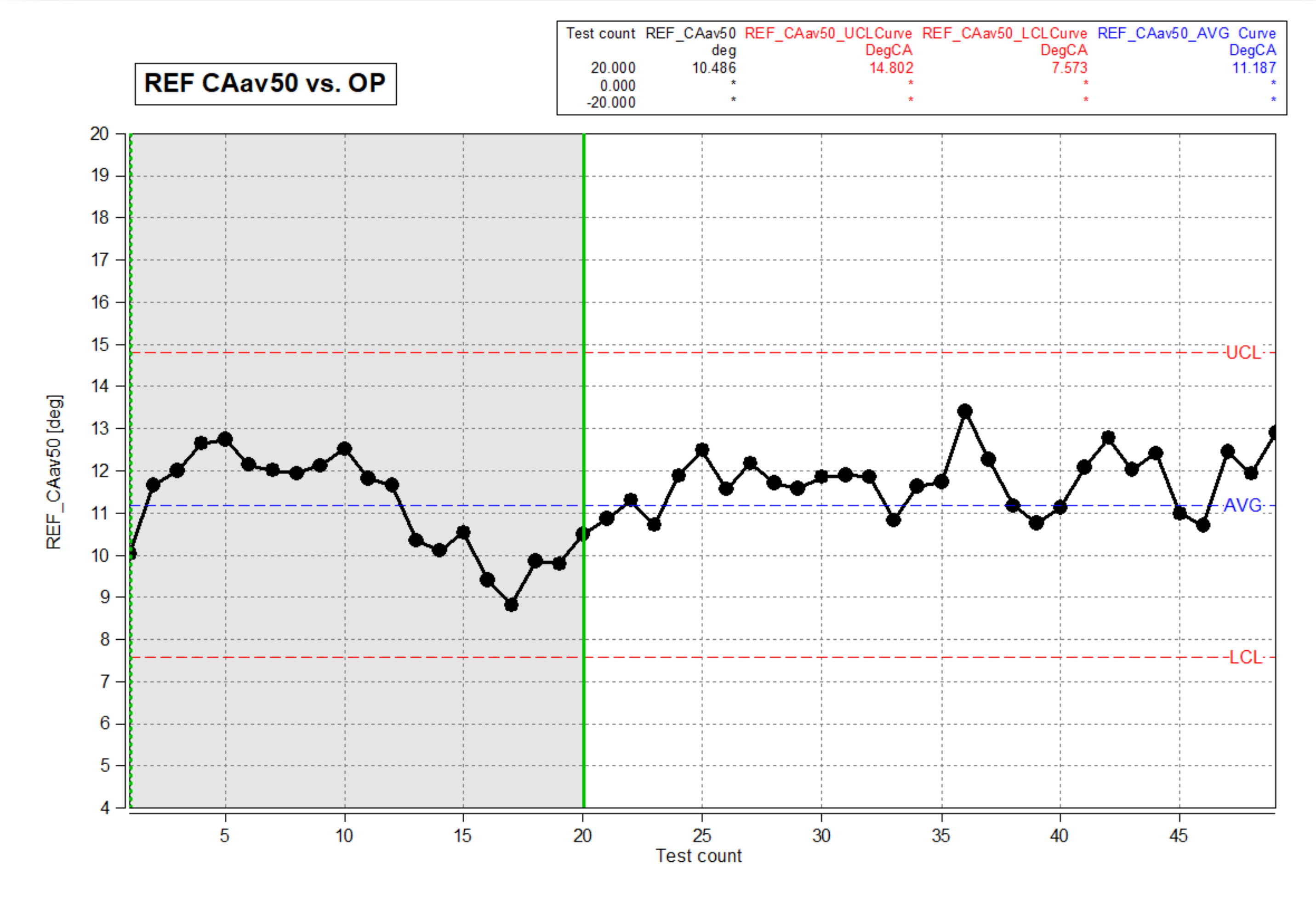
AEAP and AIAP

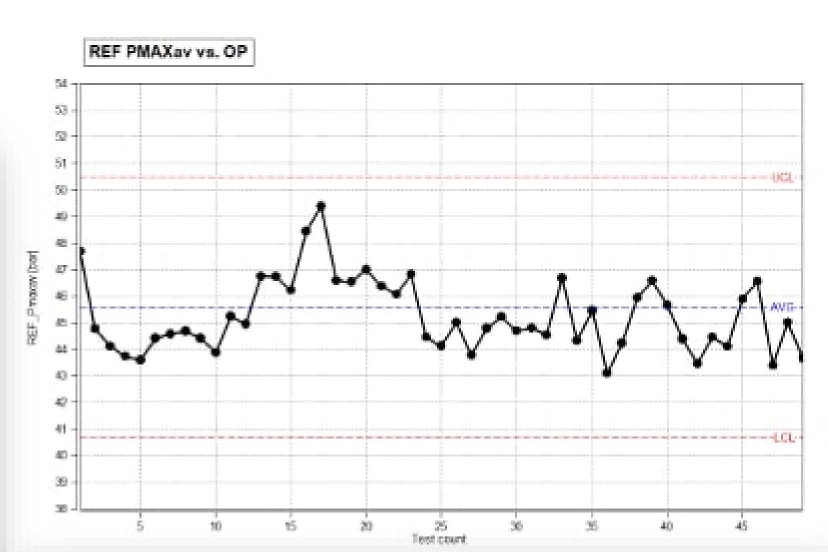


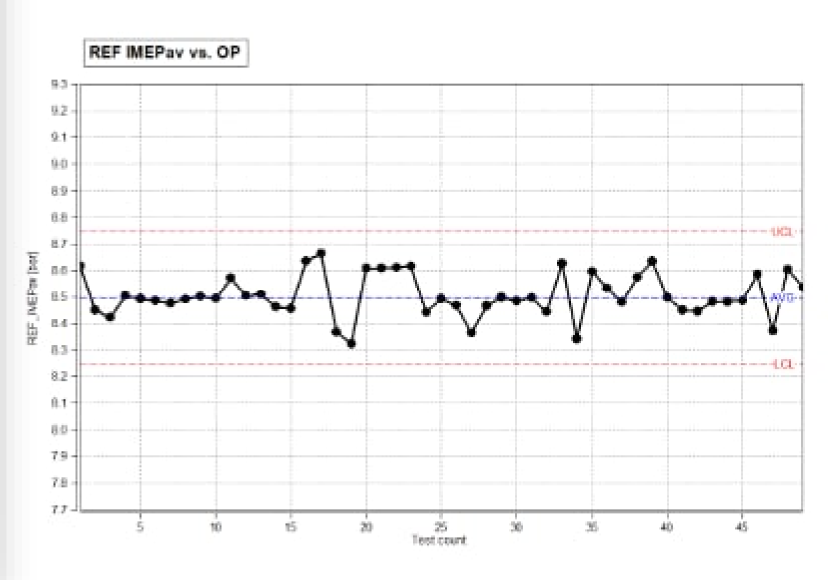


DATA QUALITY ASSESSMENT

Control charts







SENSOR PERFORMANCE CHARACTERISATION

Metrics for Evaluating Sensor Performance (no reference sensor needed)

1. AEAP & AIAP StdDev

- *What it is:* Average Exhaust and Inlet Pressure variation.
- *What it tells us:* How well the sensor diaphragm handles heating and cooling each cycle.
- *Key point:* Shouldn't depend on combustion timing. Helps separate **thermal shock effects** from the normal combustion cycle variability.

2. PMEP CoV (Coefficient of Variation)

- *What it is:* Cycle-to-cycle variation of the pumping loop work.
- *What it tells us:* How stable the sensor is under thermal stress.
- *Note:* Also influenced by natural combustion cycle differences.

3. NMEP Norm

- *What it is:* A comparison of Net IMEP values across sensors.
- *What it tells us:* Sensor health and consistency.
- *Key point:* All sensors should match within **±1% tolerance**.

👉 Think of it like this:
•**AEAP/AIAP** = "How the sensor feels the heat."
•**PMEP CoV** = "How steady the sensor is under stress."
•**NMEP Norm** = "Are all the sensors telling the same story?"

QUICK SYSTEM CHECKS

Simple plausibility screening

👉 Think of it like a checklist:

- Curve shape: clean + symmetric.
- Reference: manifold or compression curve, double-check at 180° BTDC.
- Efficiency check: NMEP beats BMEP, and IMEPH beats IMEPL.

Motored Pressure Curves

- Should look **smooth and symmetrical** around TDC.
- Always check after TDC calibration → use **log(p–V) plot**.
- The **peak point** should rise cleanly – no kink or dip before the maximum.

Pressure Referencing

- Use a **manifold pressure sensor** as reference, or calculate reference pressure from the **compression curve** (thermodynamic method).

Quick check: At **180° BTDC**, cylinder pressure = manifold pressure.

- **IMEP vs BMEP**
- **NMEP > BMEP** (net indicated > brake).
- **IMEPH > IMEPL** (high-pressure part > low-pressure part).

SUMMARY

Sensor Errors & Data Quality

Why it matters:

- Sensor-related errors are the **biggest threat** to keeping accurate combustion pressure data.
- A motoring curve check shows if the **setup is OK**, but not the sensor’s dynamic performance.

Key Metrics:

- **PMEP CoV / NMEP Norm** → “MEP-based checks” (statistical consistency).
- **AEAP / AIAP** → “Thermal shock checks” (heat effects on sensor).

Extra Checks:

- Look at **raw PV data** → can reveal hidden sensor/engine/setup issues.
- Track metrics **over time** → helps spot sensor drift or degradation.

👉 Think of it as:
Errors → Metrics → Checks → Trends = Confidence in your data

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QUIZ

QUESTIONS…

Easy, basics…

Question 1:
👉 *"Where is the piston when the cylinder volume is smallest?"*

A) TDC
B) BDC
C) Halfway in between

Question 2:
👉 *"Which stroke of a 4-stroke engine does the combustion pressure peak normally occur in?"*

A) Intake
B) Compression
C) Power (Expansion)
D) Exhaust

QUESTIONS...

Medium

Question 3:
👉 *"Why do we 'peg' or correct the zero level in cylinder pressure traces?"*

A) To make the graphs look nicer
B) To remove drift and ensure absolute pressure accuracy
C) To match the sensor to engine speed

Question 4:
👉 *"If you sample pressure data too slowly, what happens?"*

A) Nothing – the trend looks the same
B) You get aliasing and lose critical detail in the pressure trace
C) The sensor overheats

QUESTIONS...

Final

Question 5:
👉 *"Imagine your pressure trace is shifted because TDC was defined incorrectly. What is the biggest consequence?"*

A) The curve looks strange, but calculations are still fine
B) Heat release and efficiency calculations become meaningless
C) It only affects idle operation

QUESTIONS…

Final

Bonus question 1/2:
👉 *"If you had only one minute to explain why in-cylinder pressure measurement is useful for engine development, what would you say?"*

Bonus question 2/2:
👉 *"You measure the heat release in a cylinder and see that shifting combustion slightly changes both the peak pressure and overall efficiency. Why might an engineer choose a timing that isn't the most efficient, and what trade-offs are they considering?"*

CONTENTS

AGENDA	
~~1. Basics~~	50 mins
~~2. In-cylinder sensors~~	
Break (10 mins)	*10 mins*
~~3. Measuring equipment~~	50 mins
~~4. Signal processing~~	
~~5. Data quality~~	
6. Wrap-up	

WRAP-UP

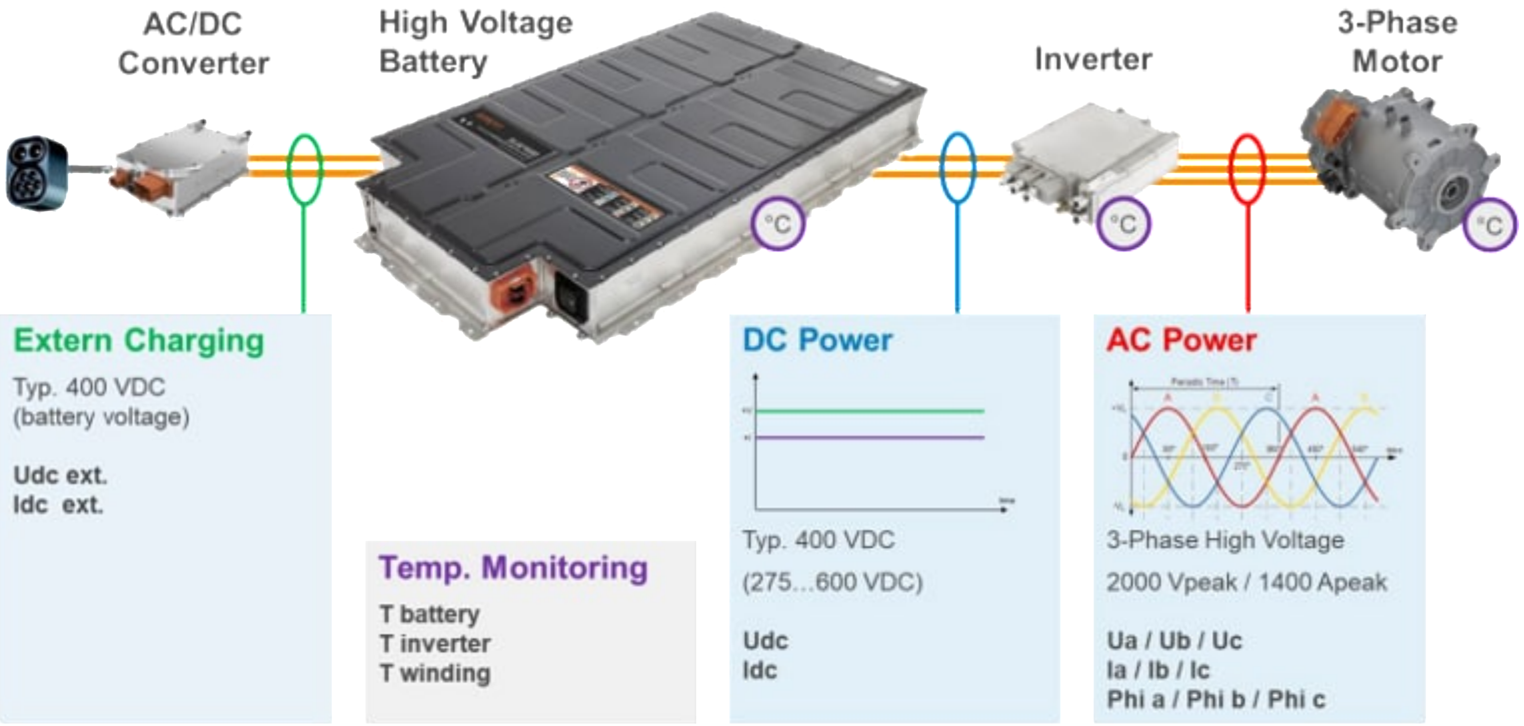
FINAL THOUGHTS

Takeaways

- **In-cylinder measurement isn't difficult** – with the right tools and know-how, you can get excellent results.
- **It all starts at the sensor** – mount it wrong, handle it poorly, and the whole measurement is lost. You can't fix bad data later!
- **Nail the basics** – rules of data acquisition and signal processing always apply. Respect them.
- **Don't forget the engine-specifics** – TDC phasing, pegging, and parameter definitions make or break combustion analysis.
- **Look after your kit** – these are precision instruments. Treat them like a high-performance car: care for them, and they'll give you years of reliable service.

FINAL THOUGHTS

Engines vs. Electric Motors: A System-Level Analogy



- **Cylinders ↔ Phases**: Each must be balanced for smooth, efficient operation.
- **Combustion / Current Phasing**: Timing matters — misalignment reduces performance.
- **Efficiency ≠ Always the Goal**: Smart trade-offs often matter more than peak efficiency.

👉 **Key Takeaway:** Skills in system-level analysis, phasing, and trade-offs transfer directly between engines and electric motors — only the “instruments” differ.

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FURTHER READING

- Brown, W.L., “Methods for evaluating requirements and errors in cylinder pressure measurements”, SAE Paper No. 670008, Society of Automotive Engineers, 1967
- Brunt, M.F., Emtage, A.L, “Evaluation of IMEP Routines and Analysis Errors”, SAE Paper No. 960609, Society of Automotive Engineers, Warrendale, Pa., 1996
- Davis, R.S. and Patterson, G.J., “Cylinder pressure data quality checks and procedures to maximize data accuracy”, SAE Paper No. 2006-01-1346, Society of Automotive Engineers, Warrendale, Pa., 2006
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- Soltis, D., "Evaluation of Cylinder Pressure Transducer Accuracy based upon Mounting Style, Heat Shields, and Water cooling," SAE Technical Paper 2005-01-3750, 2005
- Rogers, David R., "Engine Combustion: Pressure Measurement and Analysis 2E” SAE International, Warrendale PA, USA, 2021

GLOSSARY OF TERMS

LABEL	MEANING
MEP	MEP Effective pressure - The average pressure per cycle that would do the same amount of work as the pressure variations in that cycle, normally stated with respect to the location from where it is derived (e.g. High or low pressure part of the cycle)
GMEP	Gross Mean Effective Pressure – Also known as IMEPH, The average pressure (as above) but for the high pressure part of the cycle only (-180 to +180 degCA)
PMEP	Pumping Mean Effective Pressure – Also known as IMEPL (Low), The average pressure (as defined above) but for the low pressure (Gas exchange) part of the cycle
IMEP	Indicated Mean Effective Pressure – Also known as NMEP (NetMEP) The average pressure per whole cycle (as described above) derived from the area of the Indicator diagram. Note that IMEP/NMEP = GMEP-PMEP (Note: PMEP is –ve work)
BMEP	Brake Mean Effective Pressure – A MEP value derived from the measured torque of the engine at the dynamomenter (also know as a “brake”)
FMEP	Friction Mean Effective Pressure – An MEP value that represents friction and parasitic losses based on... NMEP (In-cylinder net work) minus BMEP (measured work output).
CA10	Angle of 10% Energy conversion – Also known as MBF10, or MFB10 (Mass Burn Fraction). 5% and 10% metrics are used as an indicator of start of combustion
CA50	Angle of 50% Energy conversion – Also known as MBF50, or MFB50 (Mass Burn Fraction). The 50% metric is important for gasoline engine combustion phasing optimisation, the optimum is 8-10 degCA
CA90	Angle of 90% Energy conversion – Also known as MBF90, or MFB90 (Mass Burn Fraction). 90% metric is used as an indicator of end of combustion

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GLOSSARY OF TERMS

LABEL	MEANING
PMAX	Maximum/Peak pressure per cycle
APMAX	The angle position of PMAX
RMAX	The maximum pressure rise
ARMAX	The angle of maximum pressure rise
ROHR	Rate of instantaneous heat release – also known as Q or dQ
INTHR	Integral of the ROHR – Also know as I, from this curve energy conversion points are derived (CA10, CA50 etc. etc.)
KPEAK	Knock pressure peak – Peak pressure amplitude due to uncontrolled combustion alone (Gasoline only)
CNL	Combustion Noise Level – Noise metric derived from the combustion event alone (Diesel only)
SOC	Start of Combustion
SOI/EOI/DOI	Start of injection/End of Injection/Injection duration

ICE IN-CYLINDER PRESSURE MEASUREMENTS

Thanks for listening

Any questions, please feel free to contact me...

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measure. analyze. innovate.

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