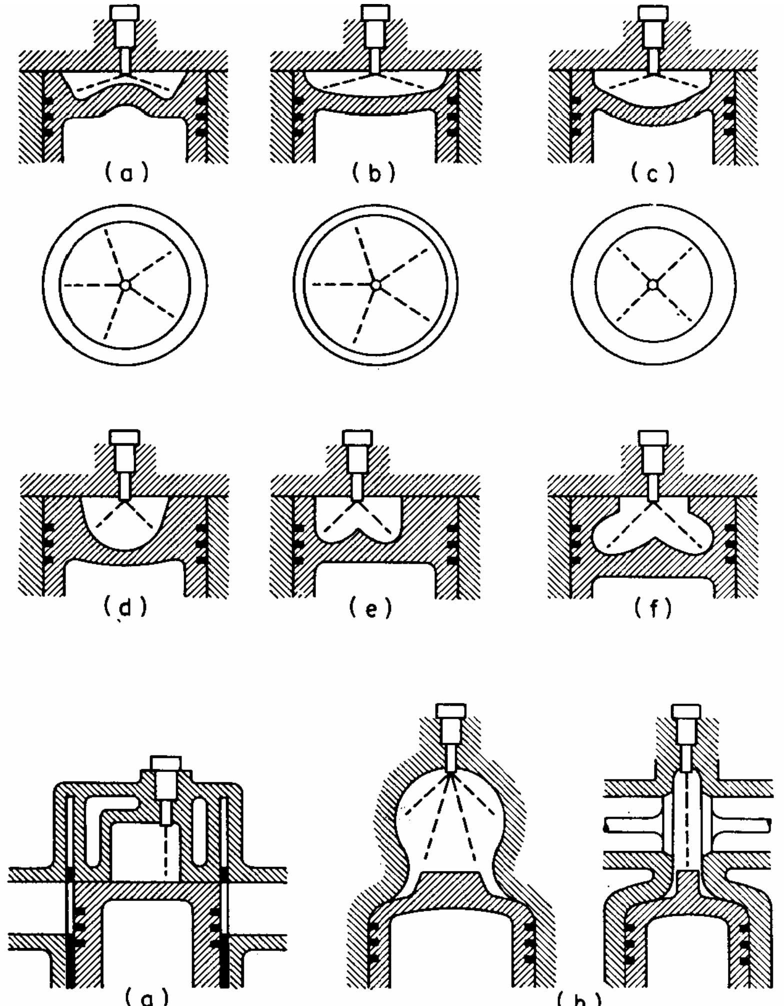
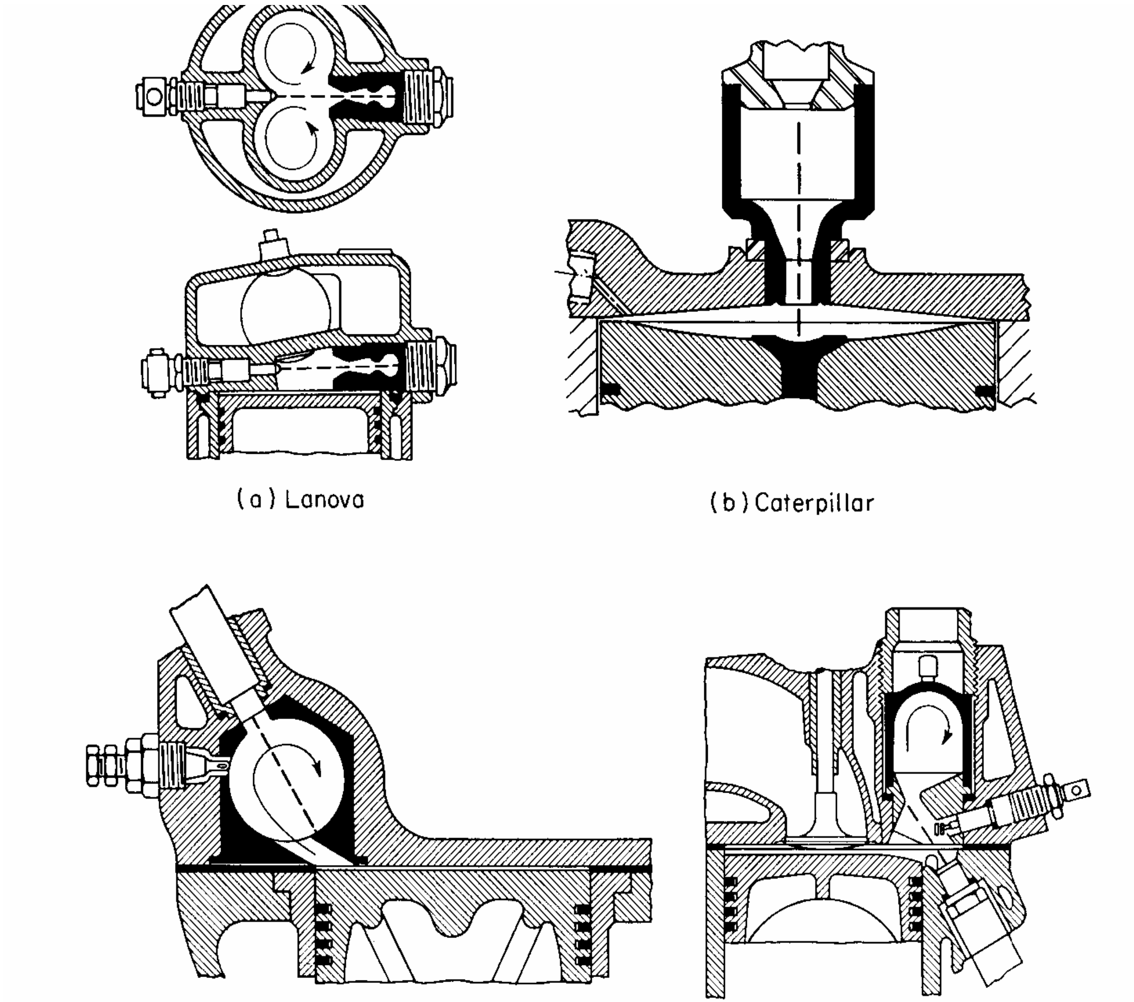
Combustion Quality

Combustion chambers

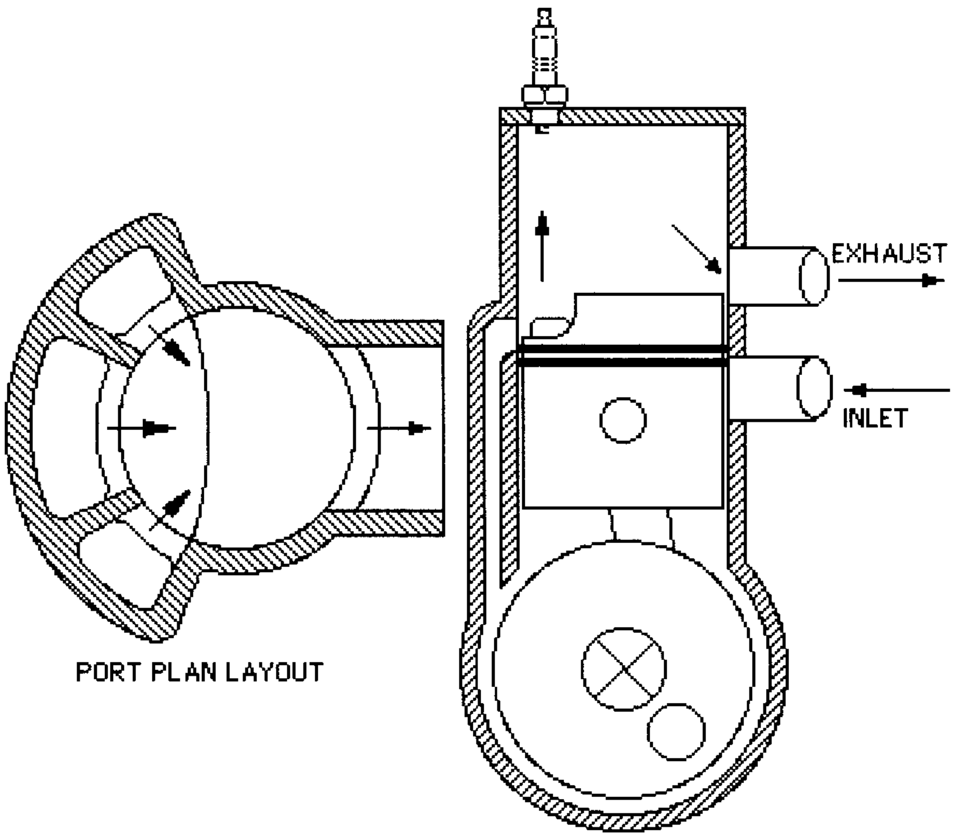


Some classic combustion chambers



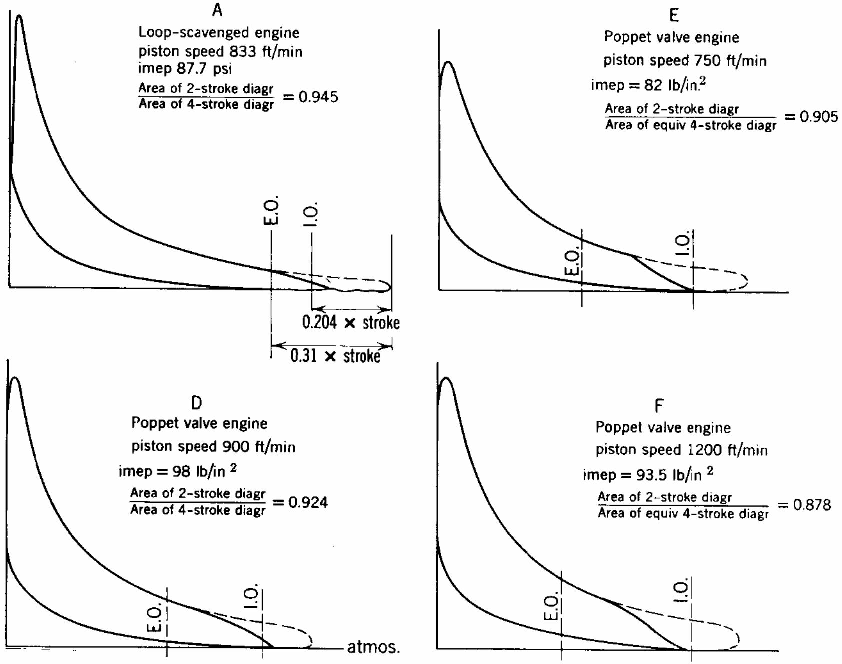
Two stroke diesel

Chapter 1 – Introduction to the Two-Stroke Engine



Pressure/volume indicator diagram for a two stroke engine

Dotted line = four stroke



Indicator diagrams from two-stroke engines: Dotted lines show estimate of corresponding four-stroke diagram.

Configu-ration	Cylinder	Exhaust Lead°	CA_e/CA_i
A	18 x 22 in gas engine loop scav	0	—
D	3¼ x 4½ in poppet valves	7	1.25
E	3¼ x 4½ in poppet valves	14	1.25
F	3¼ x 4½ in poppet valves	21	1.25

Two stroke designs

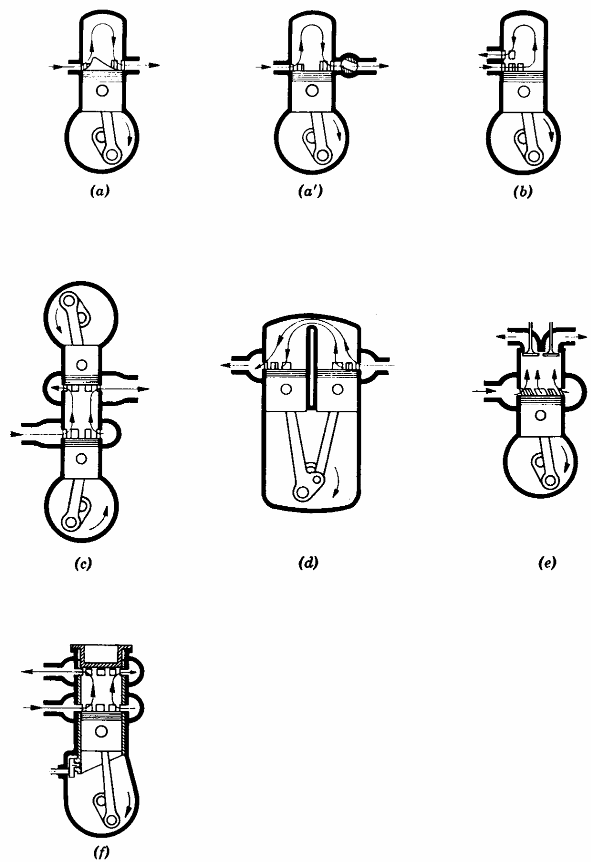


Fig 7-1. Two-stroke cylinder types: (*a*) conventional loop-scavenge; (*a′*) loop-scavenge with rotary exhaust valve; (*b*) reverse-loop scavenge; (*c*) opposed-piston; (*d*) U-cylinder; (*e*) poppet-valve; (*f*) sleeve-valve.

a= loop scavenge

a'= rotary valve loop scavenge

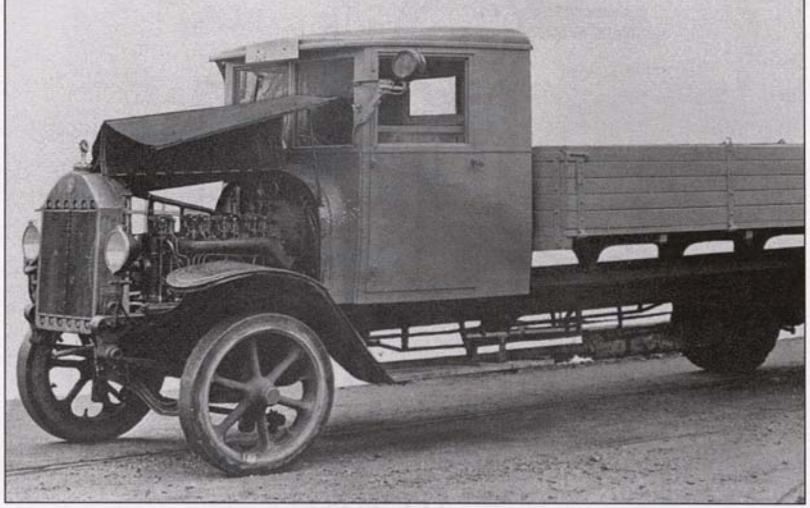
b=reverse loop scavenge

C= opposed piston

d= U-cylinder

e= poppet valve

F = sleeve valve



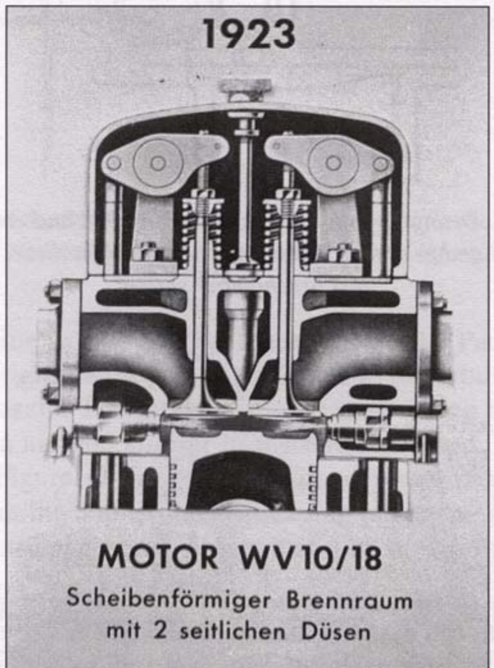
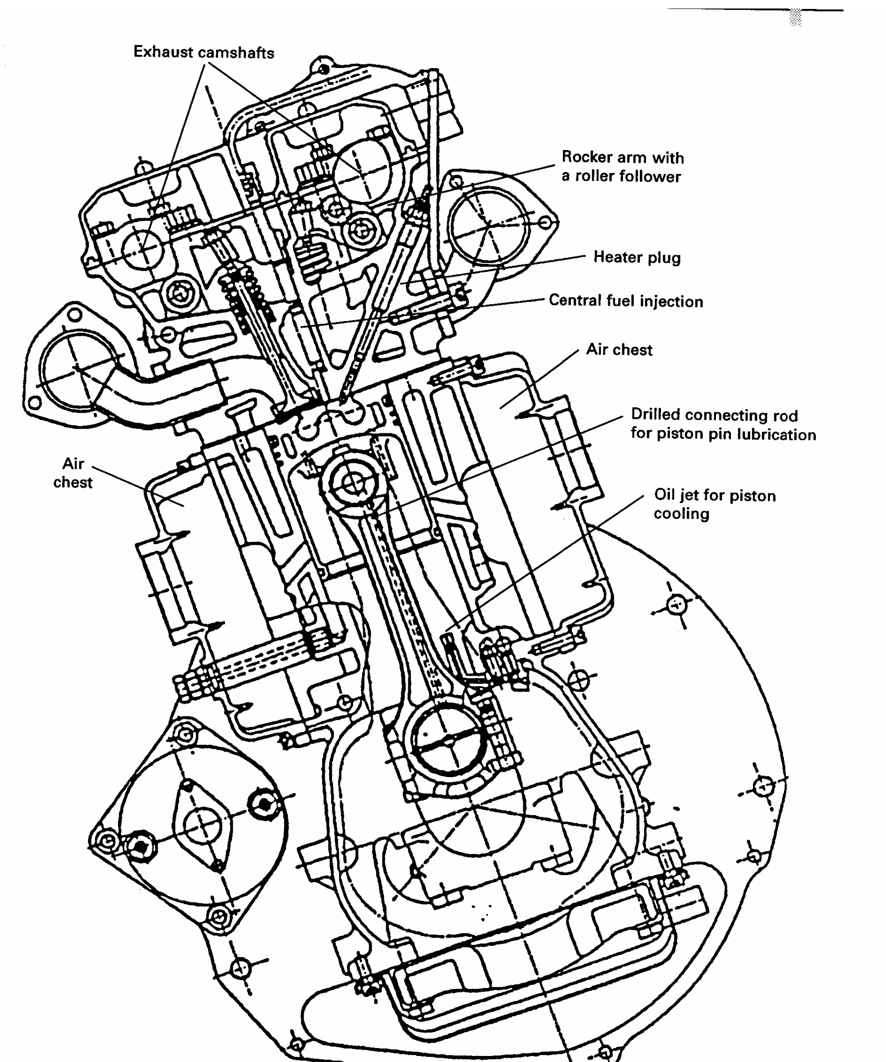
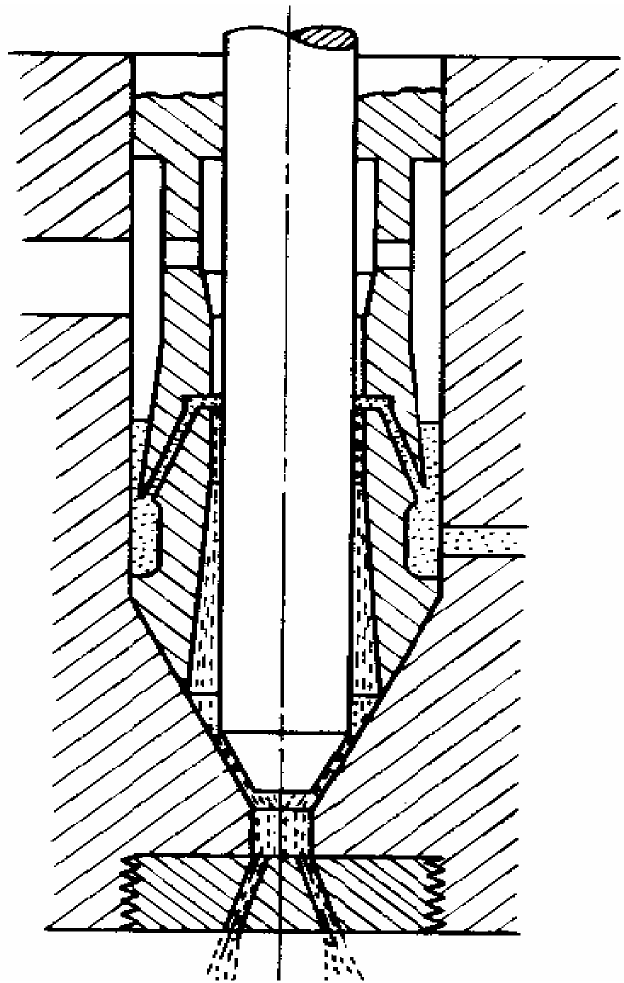


Photo 32-6 First diesel truck (1924): The MAN four-ton truck and its combustion chamber. Six months earlier in the same year, Benz completed a truck based on the prechamber system (MAN Museum).

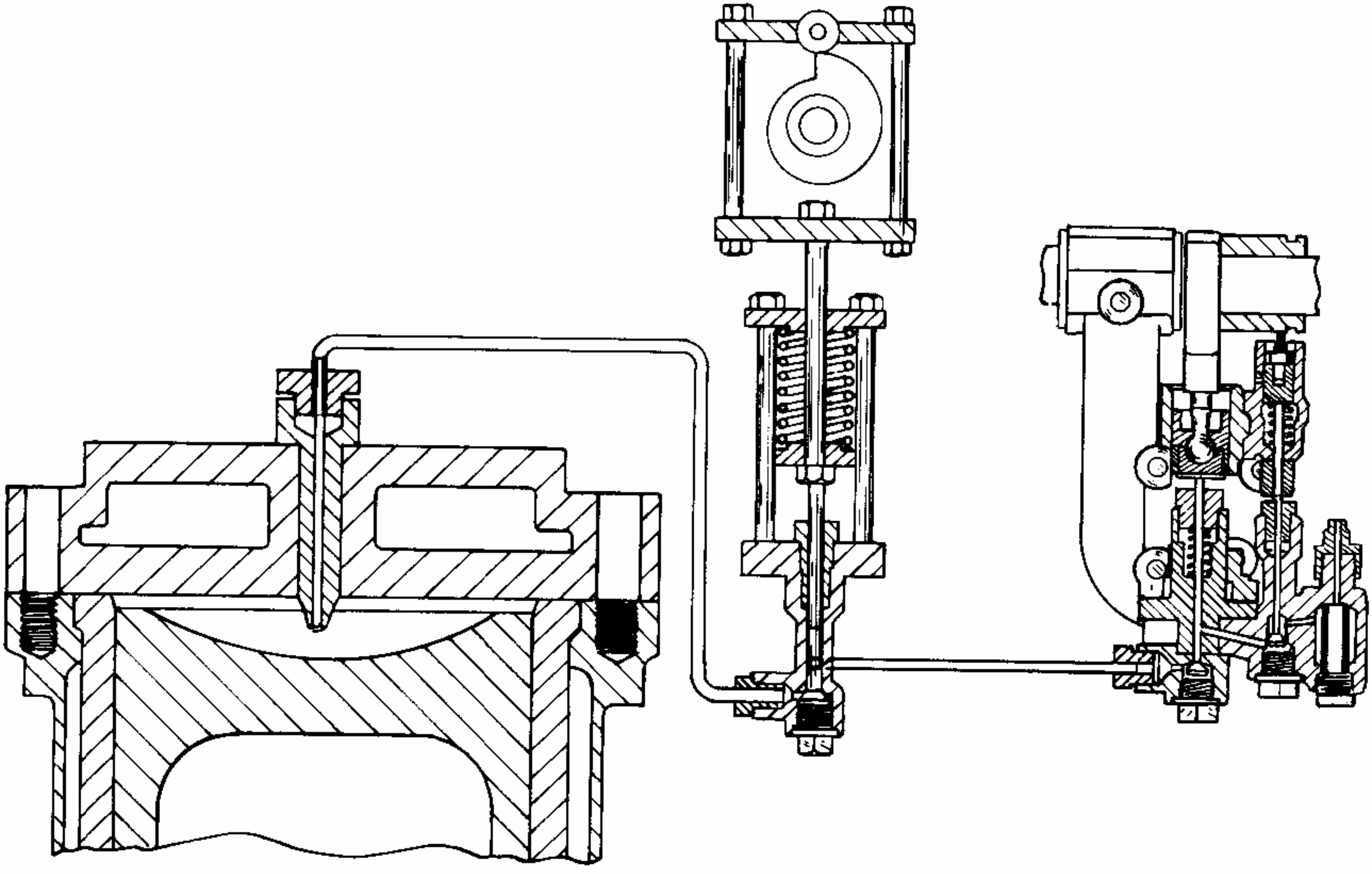
AVL advanced 2 stroke automotive concept 1996



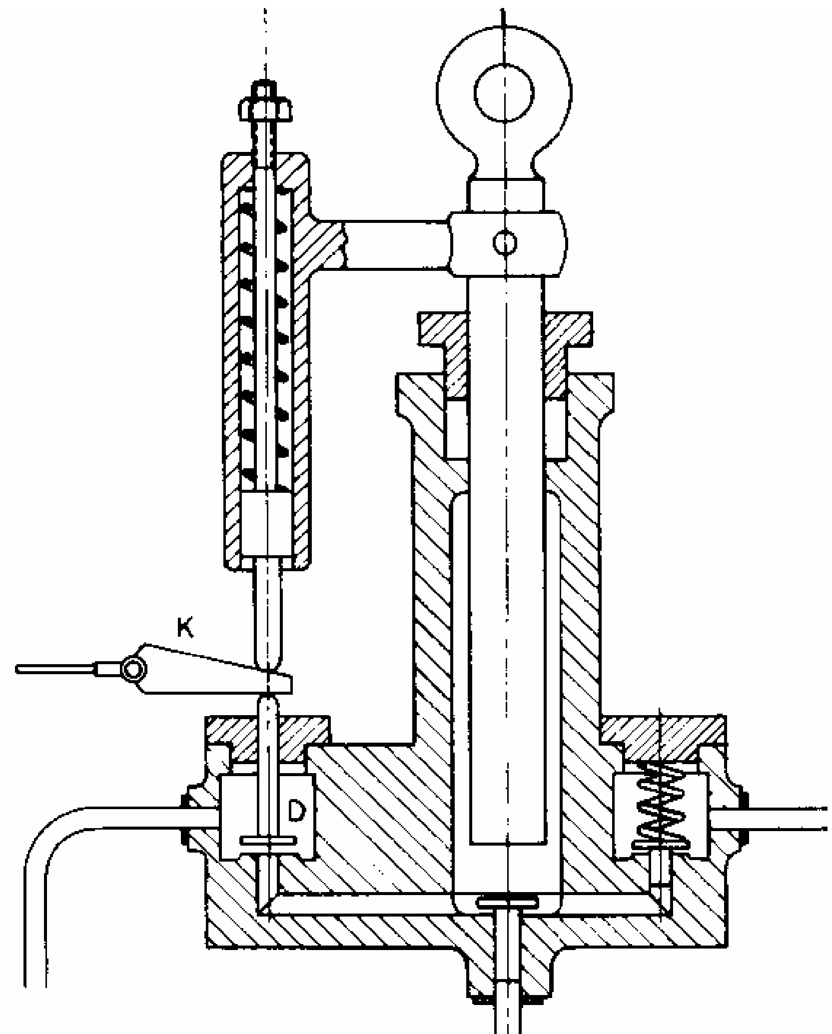
Hesselman injector 1908



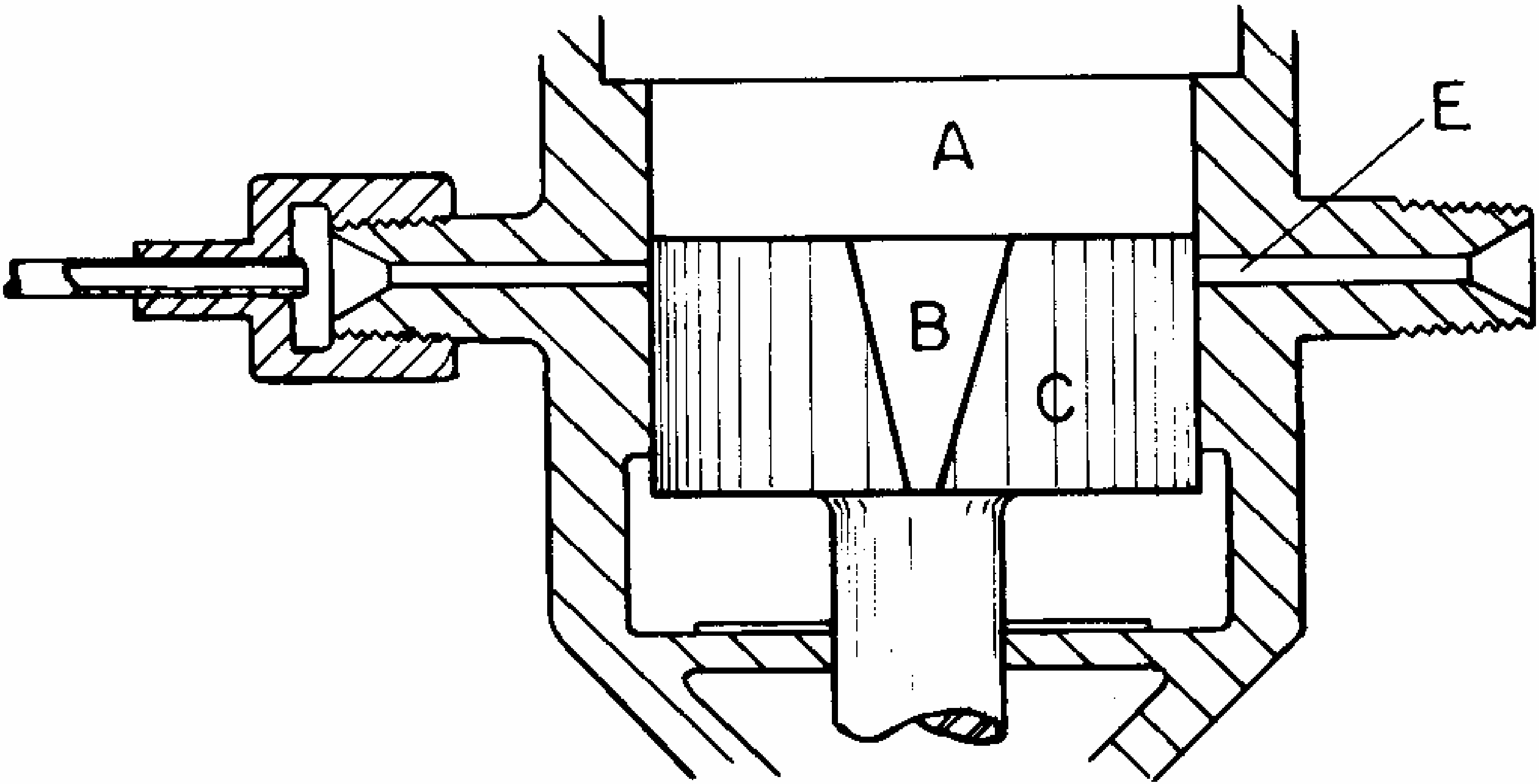
1910 McKechnie of Vicars



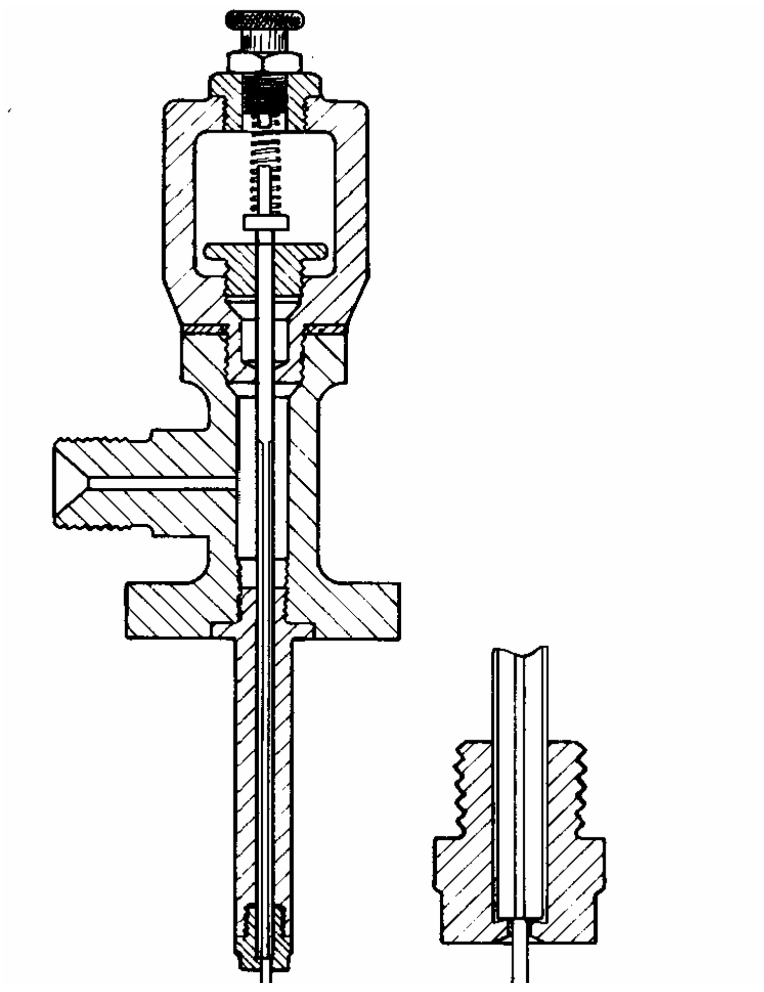
Diesel's pump with spill valve wedge control



1914 Rotary valve
Francois Feyens of Belgium



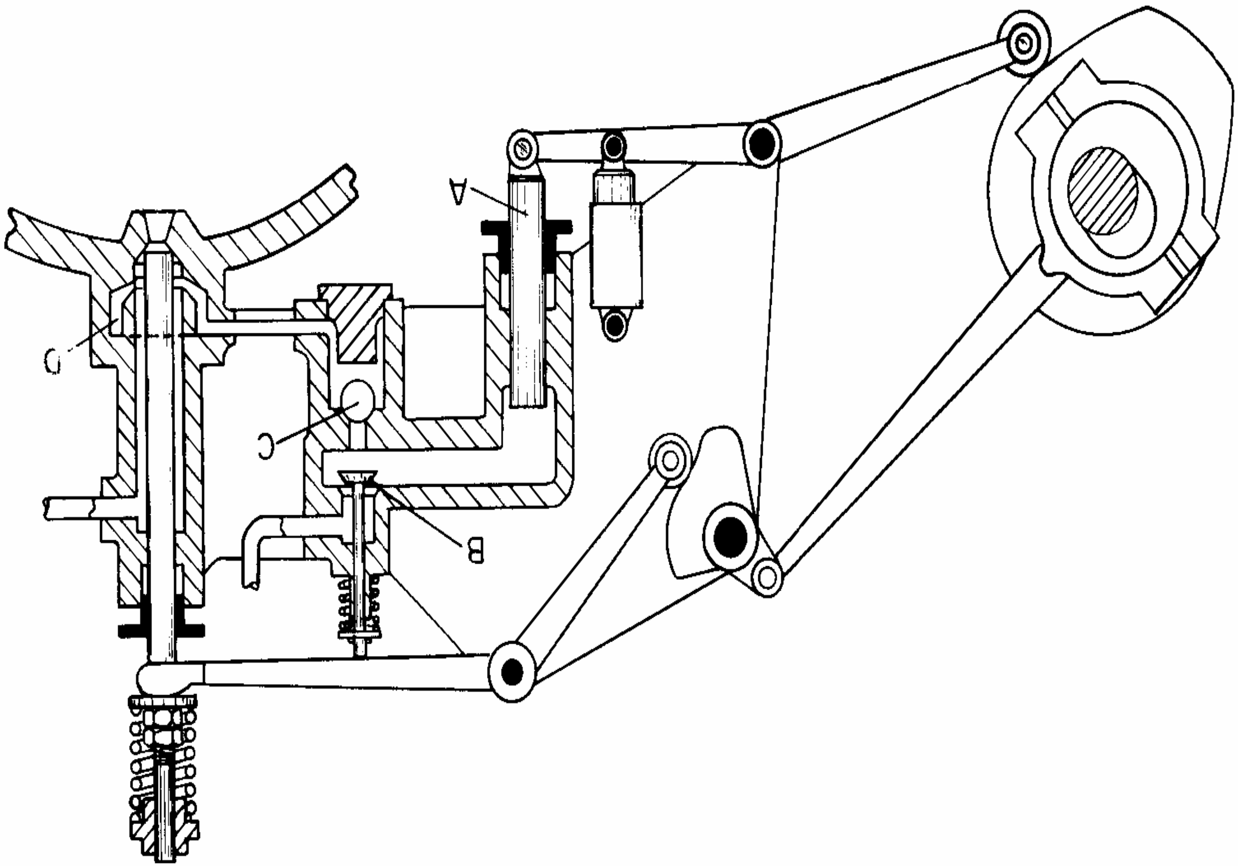
1910 Peter Bowman Denmark
Pintle valve. Bosch took on patent in 1935



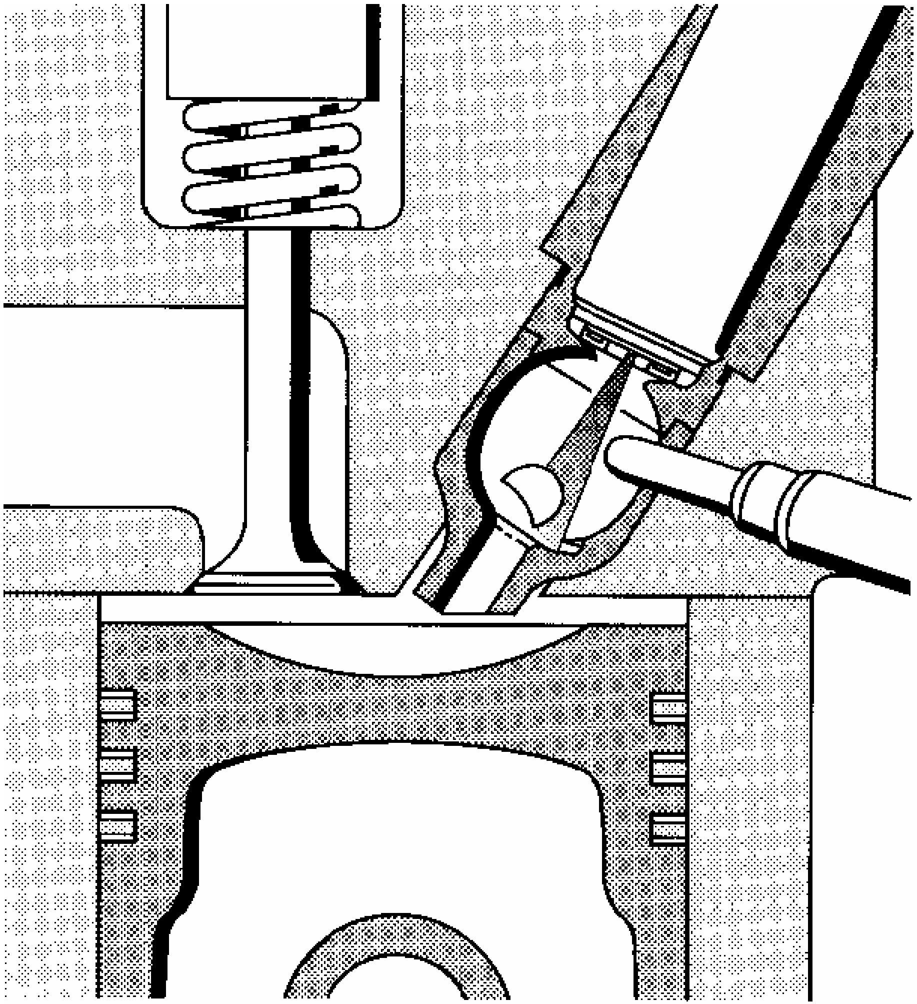
Electro magnetic injector

- **This was patented by Thomas T Gaff in the USA 1913**

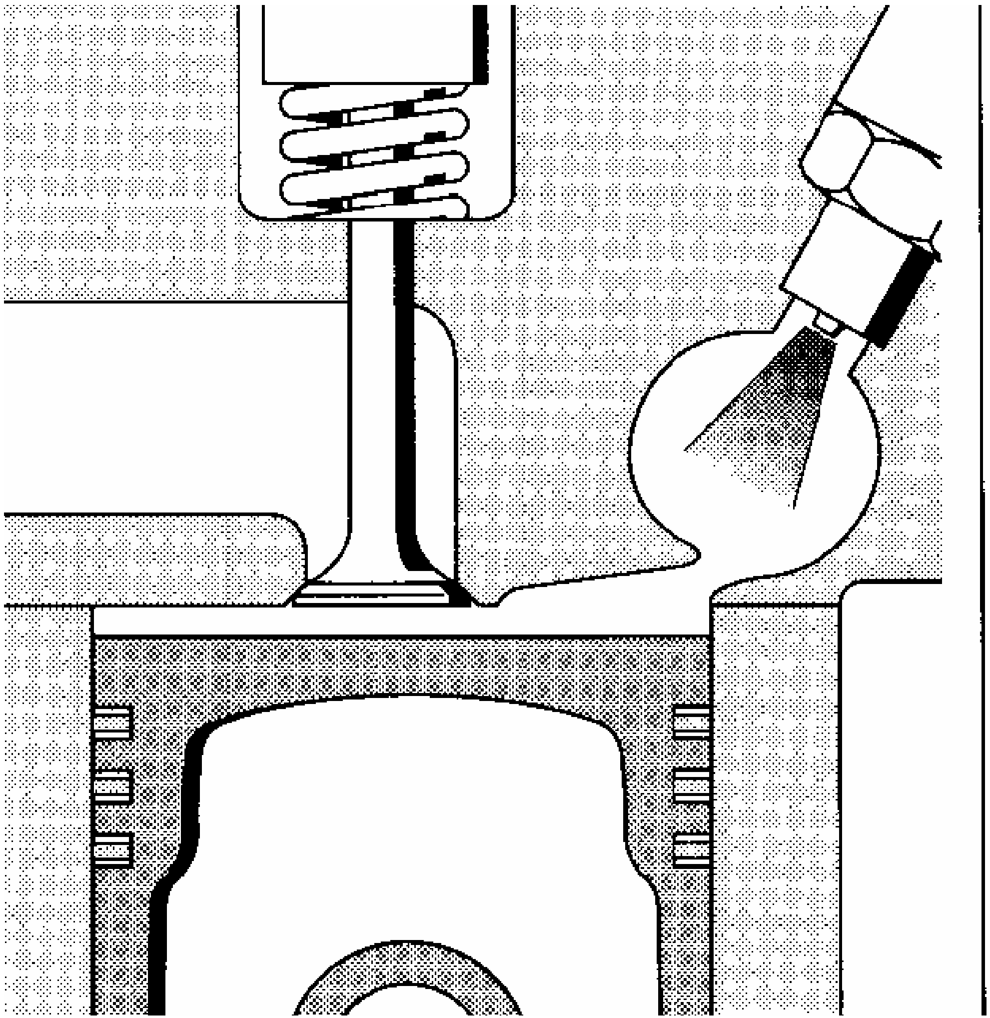
1905 Unit injector
combined nozzle and pump



The pre-combustion chamber

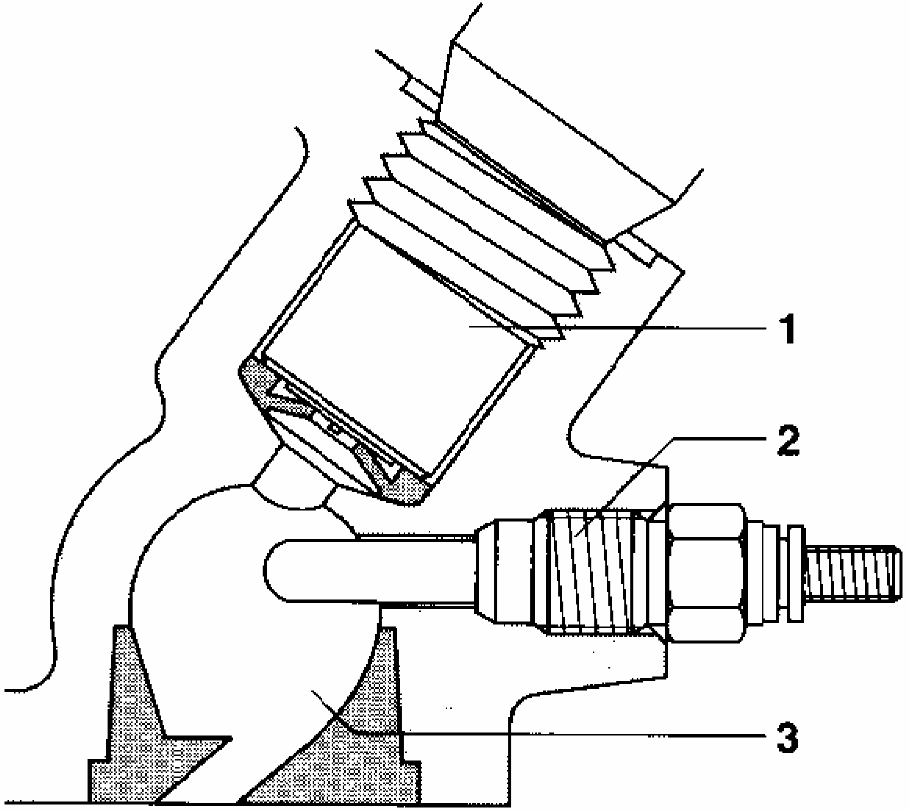


The Wirl-chamber process

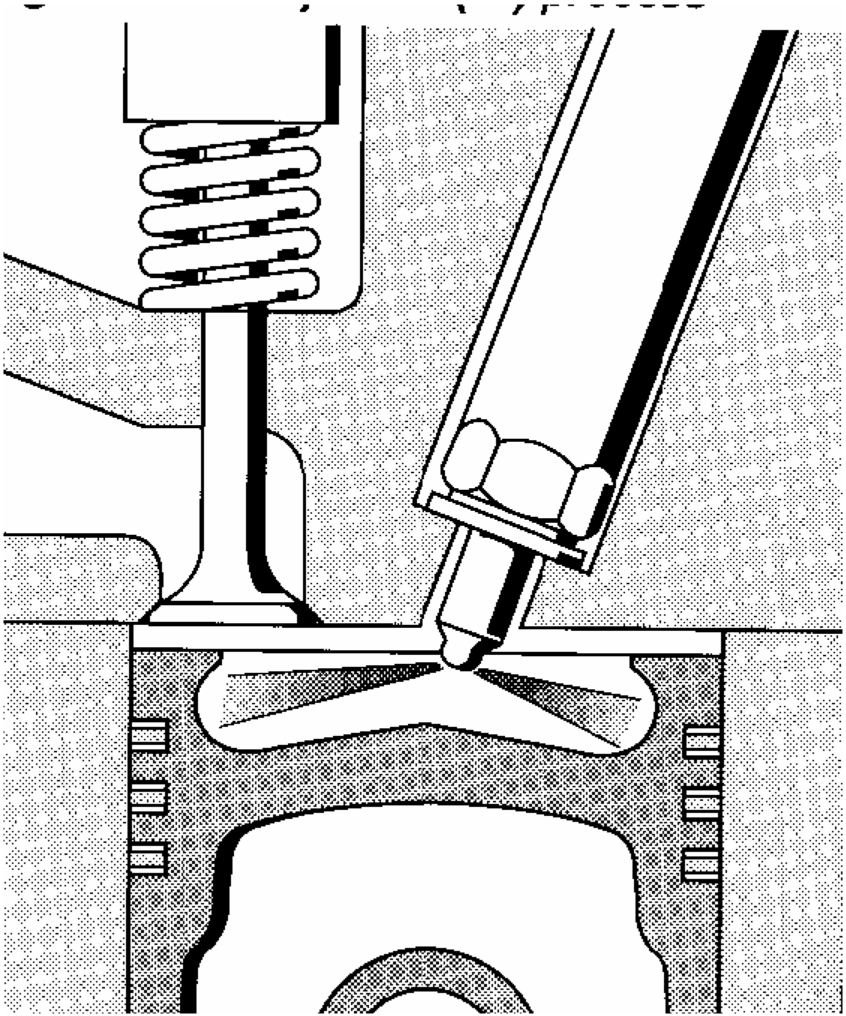


Sheathed element glow plug

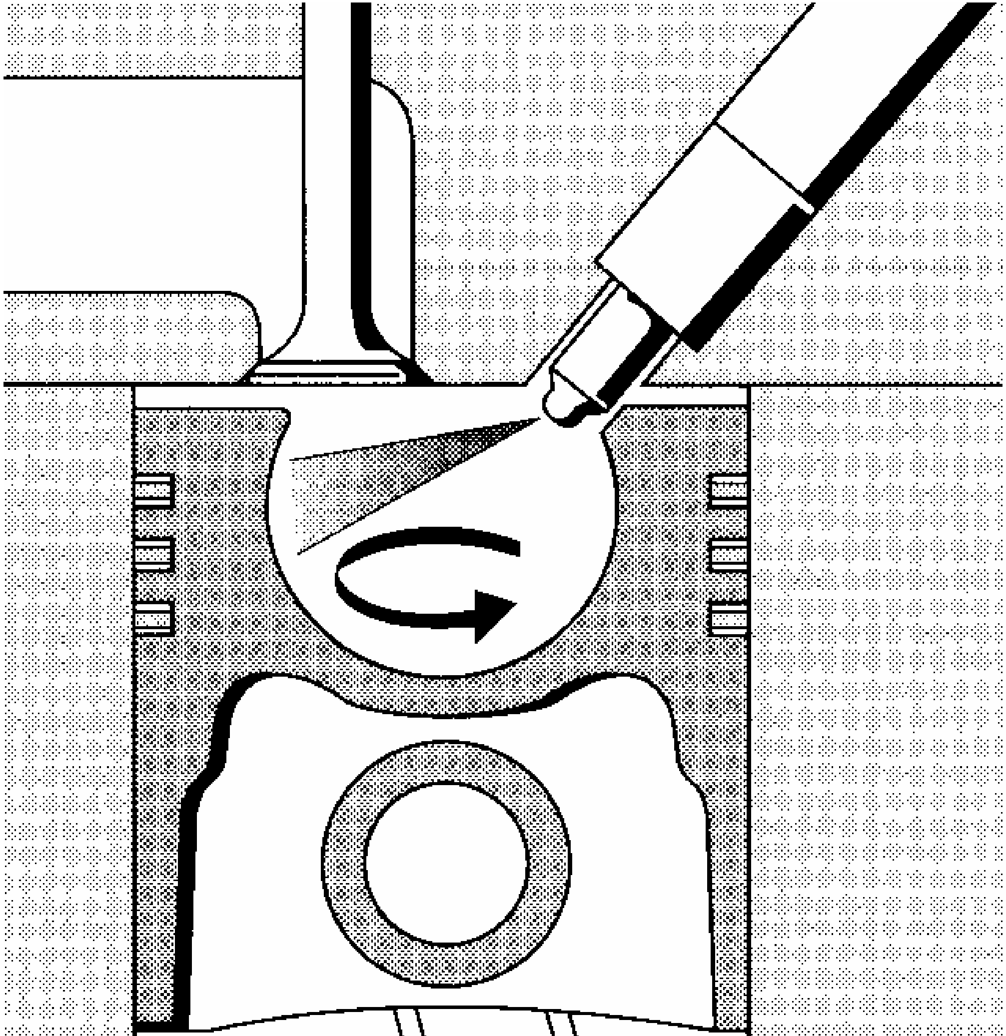
Configuration in the turbulence chamber.
1 Injection nozzle, 2 Sheathed-element glow plug,
3 Turbulence chamber.



DI Configuration



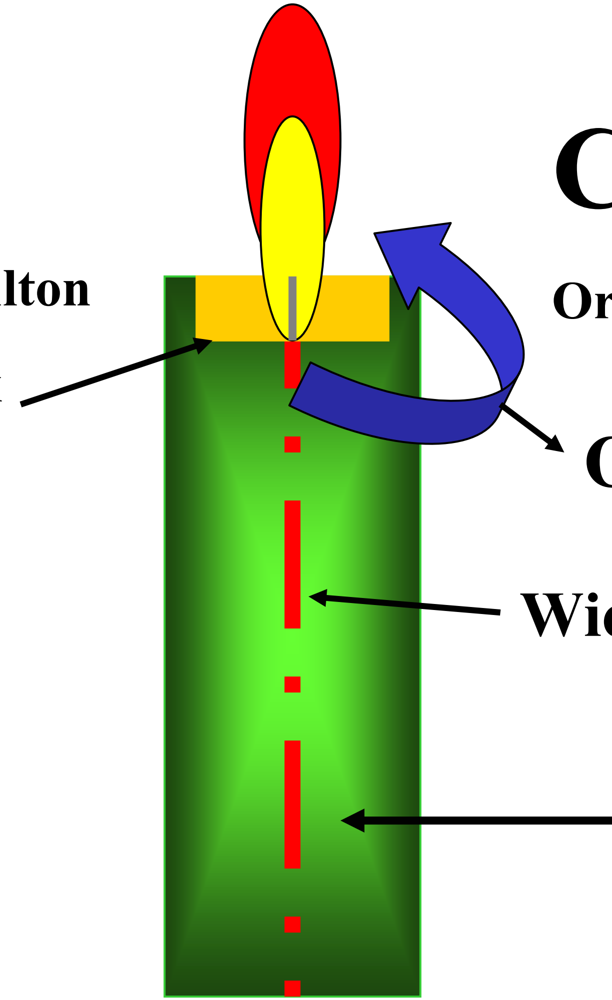
DI with wall distribution



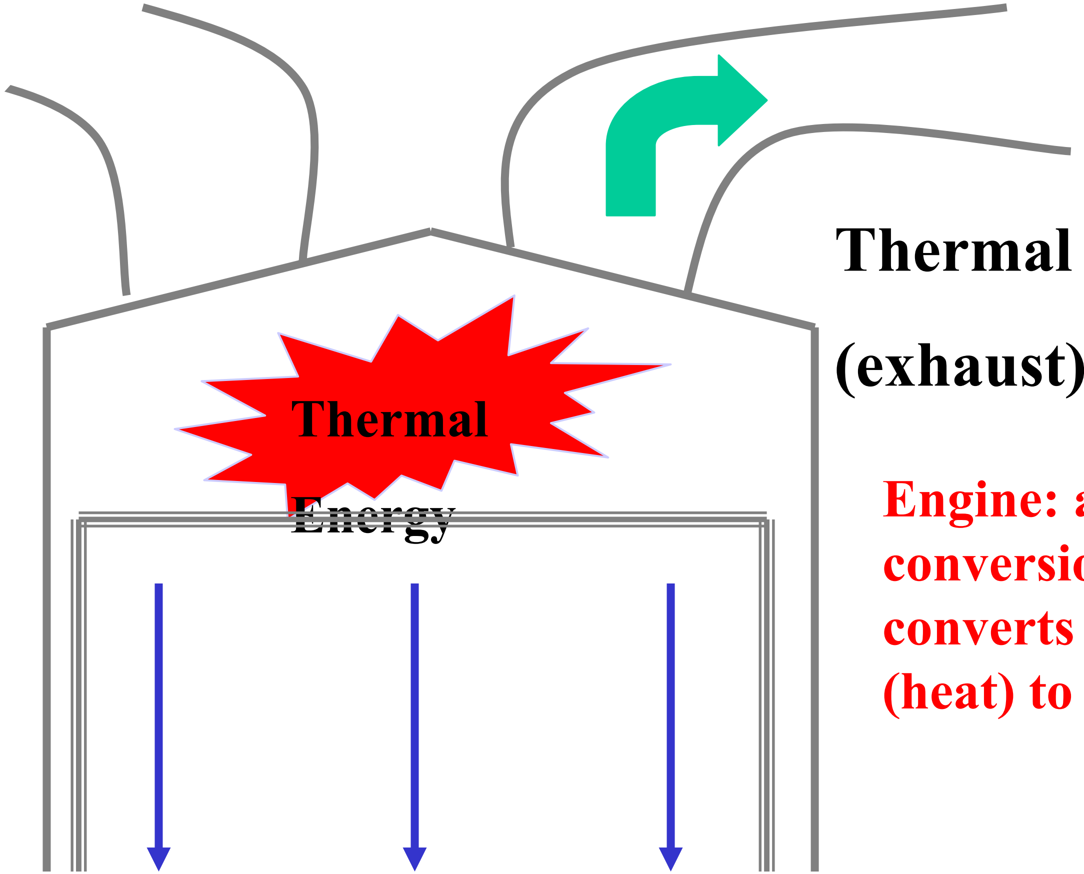
Silent External Combustion

Combustion

Organic Compound+O_2>CO_2+H_20+Heat



Chemical Energy (fuel,air)

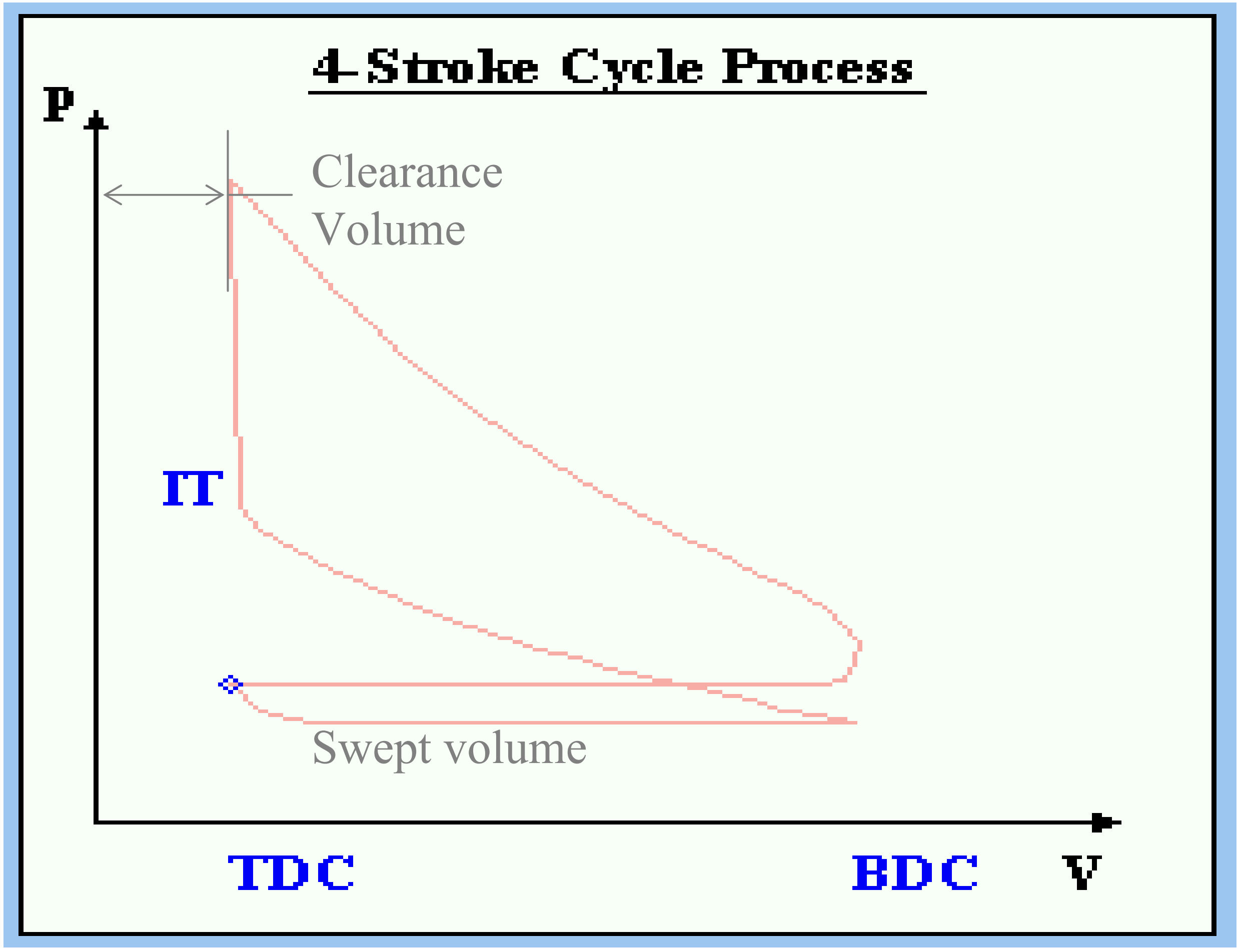


Thermal Energy (exhaust)

Engine: an energy conversion device that converts thermal energy (heat) to mechanical energy

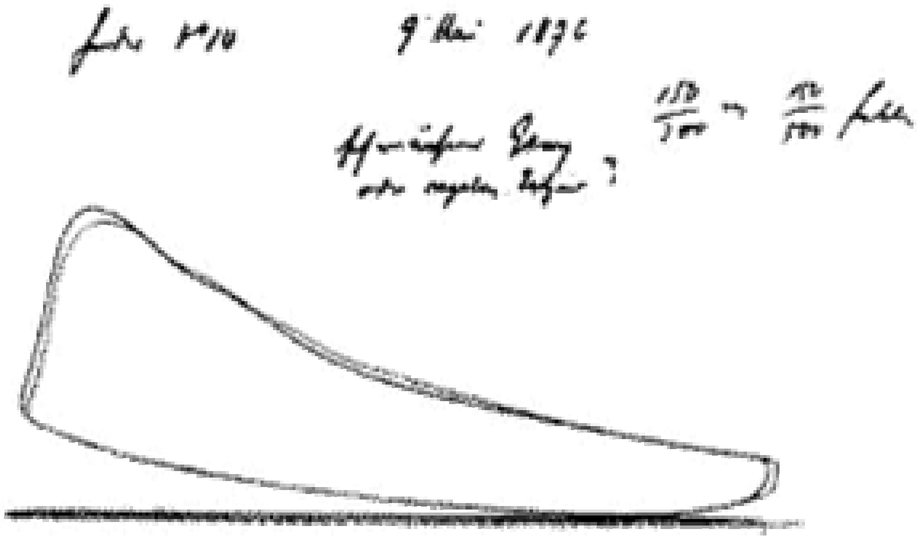
Mechanical Energy

PV Diagram

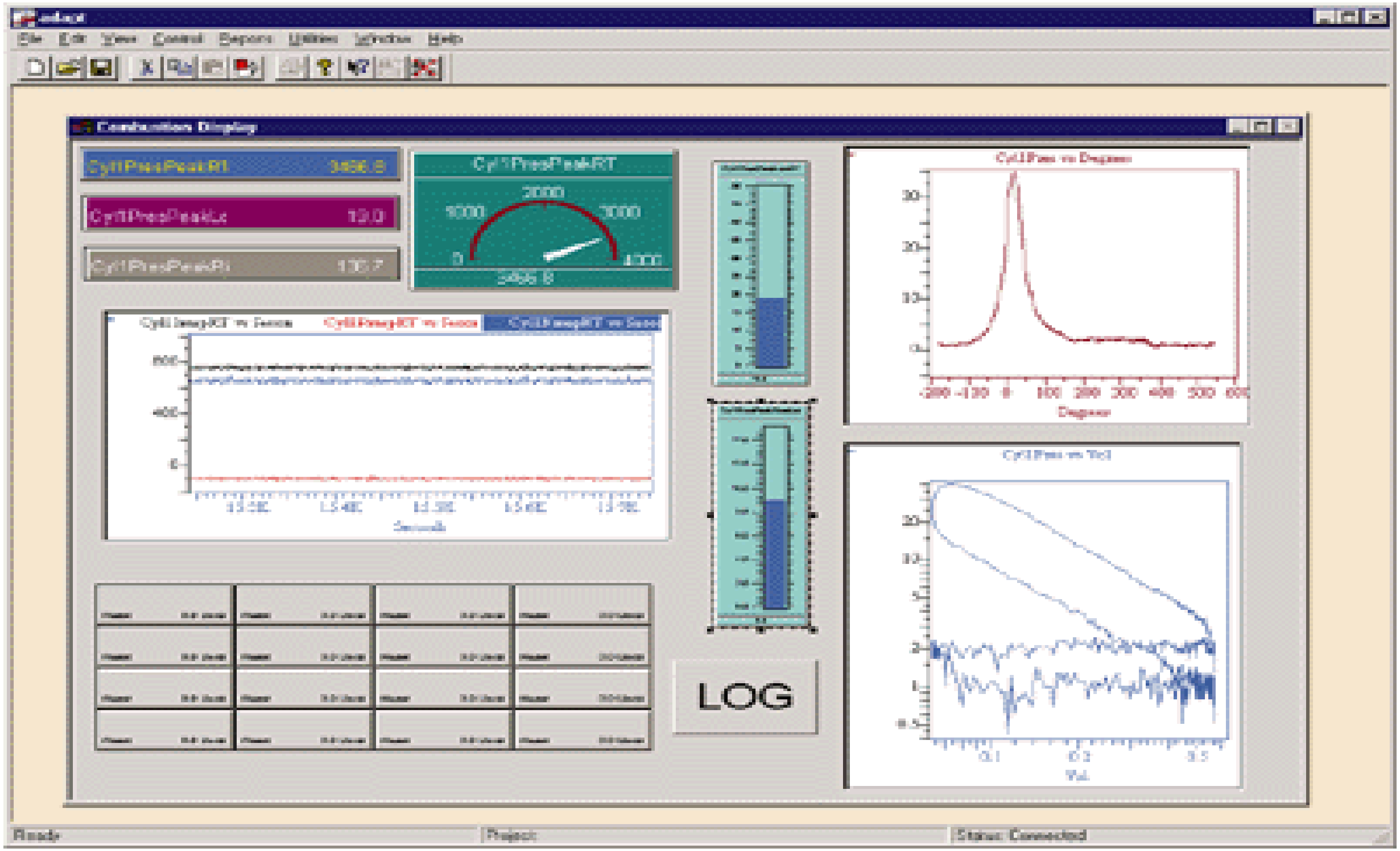


4-Stroke Cycle Process
P
Clearance
Volume
IT
Swept volume
TDC
BDC
V

Working PV diagram made 9th May 1876 by Mr Otto



What you would see on your screen

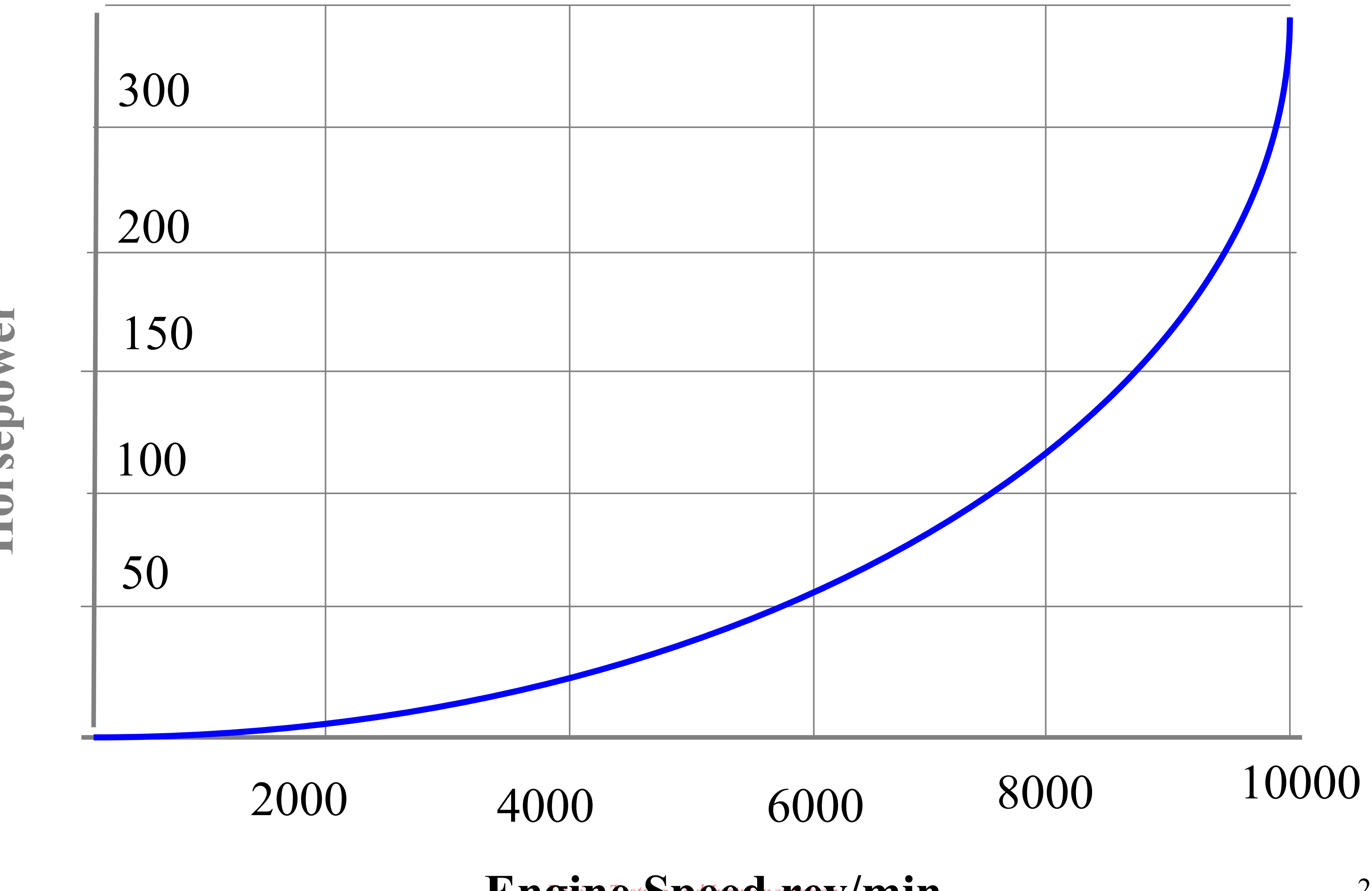


Phasing Efficiency

- Overall engine loss when spark timing differs from overall engine MBT
- Individual cylinder loss when individual cylinder MBT differs from overall engine MBT
- Individual cycle loss when individual cycle phasing (CA50) differs from optimal phasing

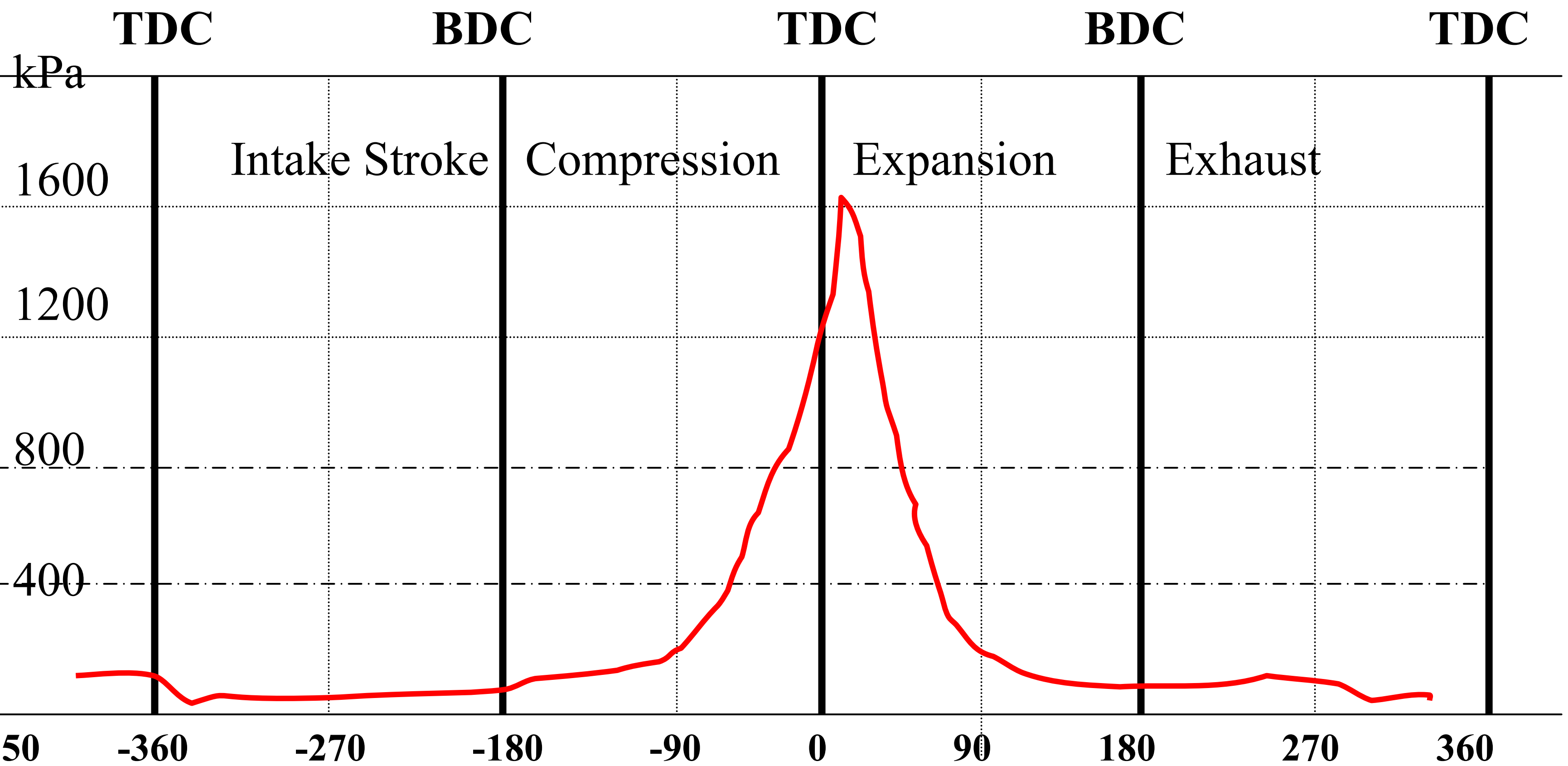
➢ There will always be phasing efficiency loss

Power required to overcome rotating and reciprocating losses



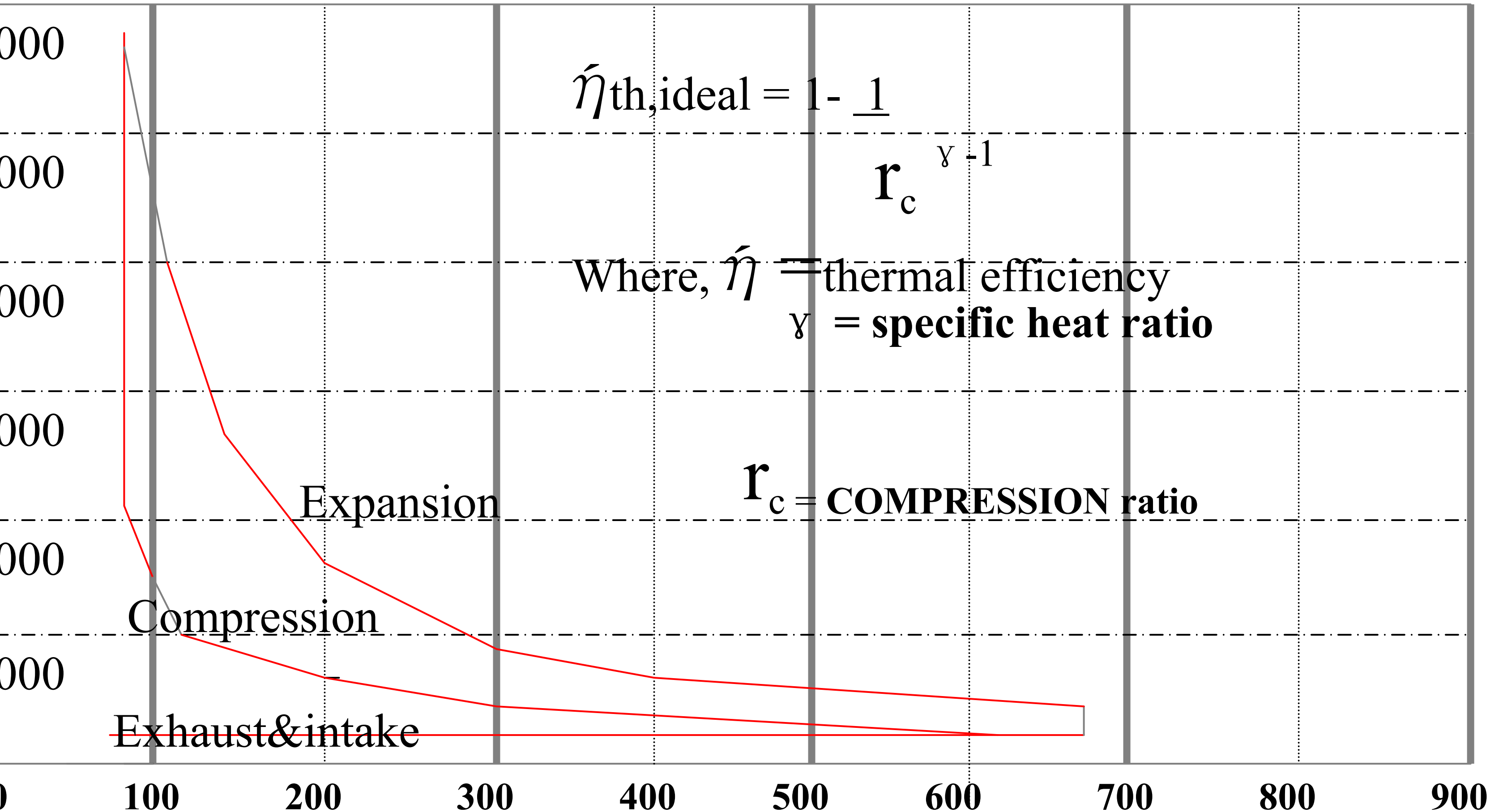
Cylinder Pressure Measurements

Cylinder Pressure vs.Crank Angle



Otto Cycle

Cylinder Pressure (kPa) vs.Cylinder volume (cc)



$$\eta_{th,ideal} = 1 - \frac{1}{r_c^{\gamma - 1}}$$

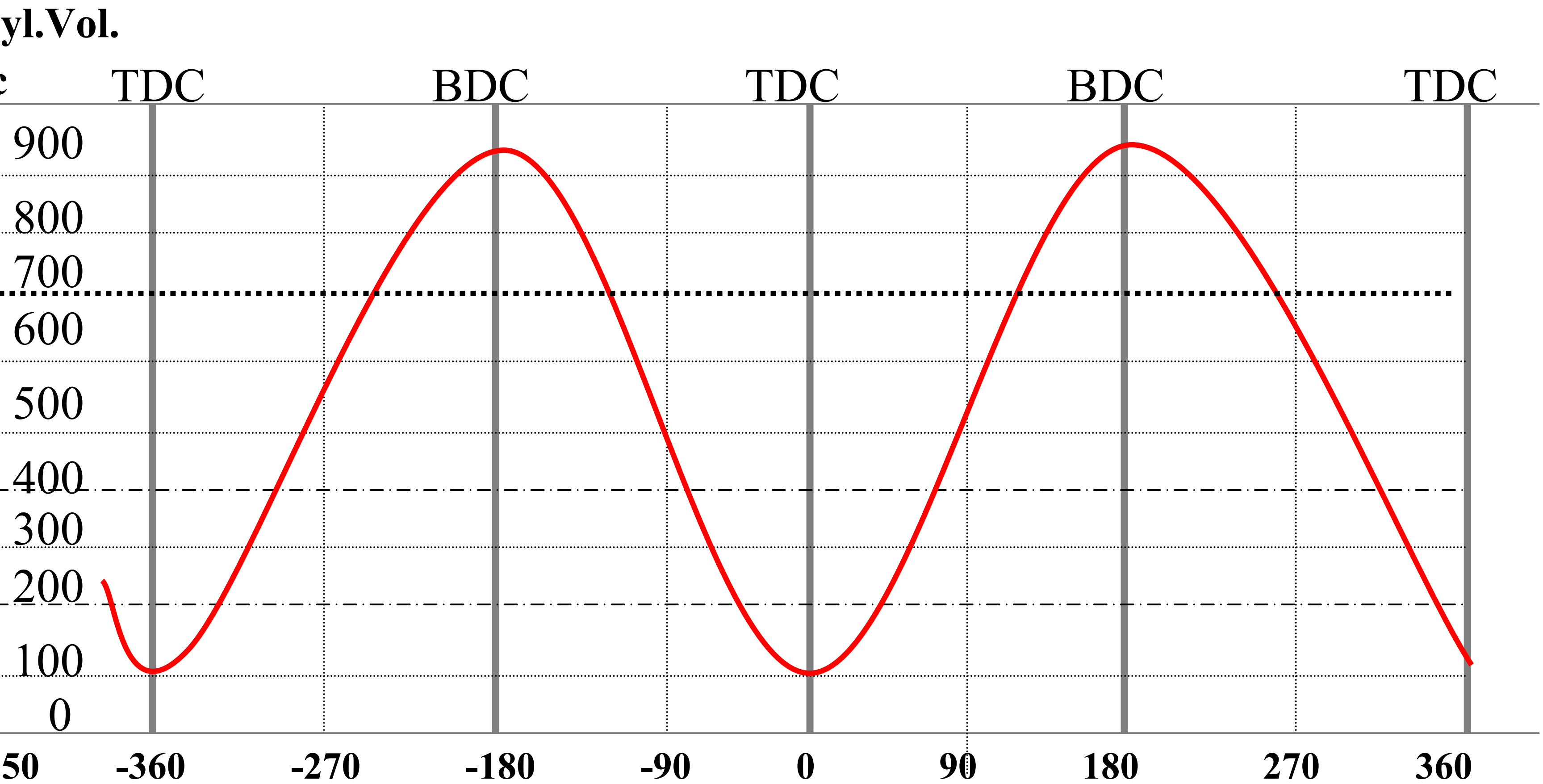
Where, η = thermal efficiency

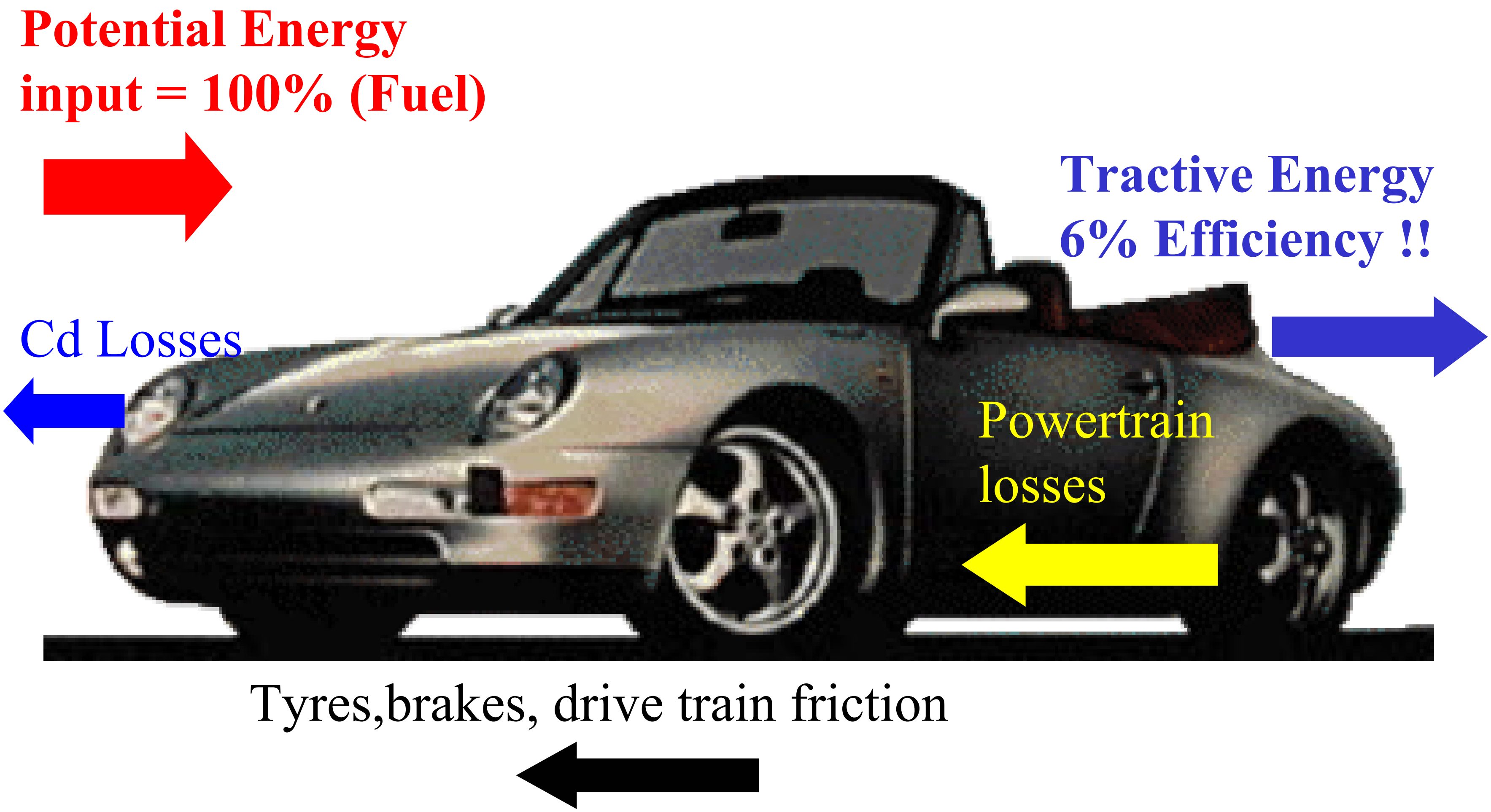
γ **= specific heat ratio**

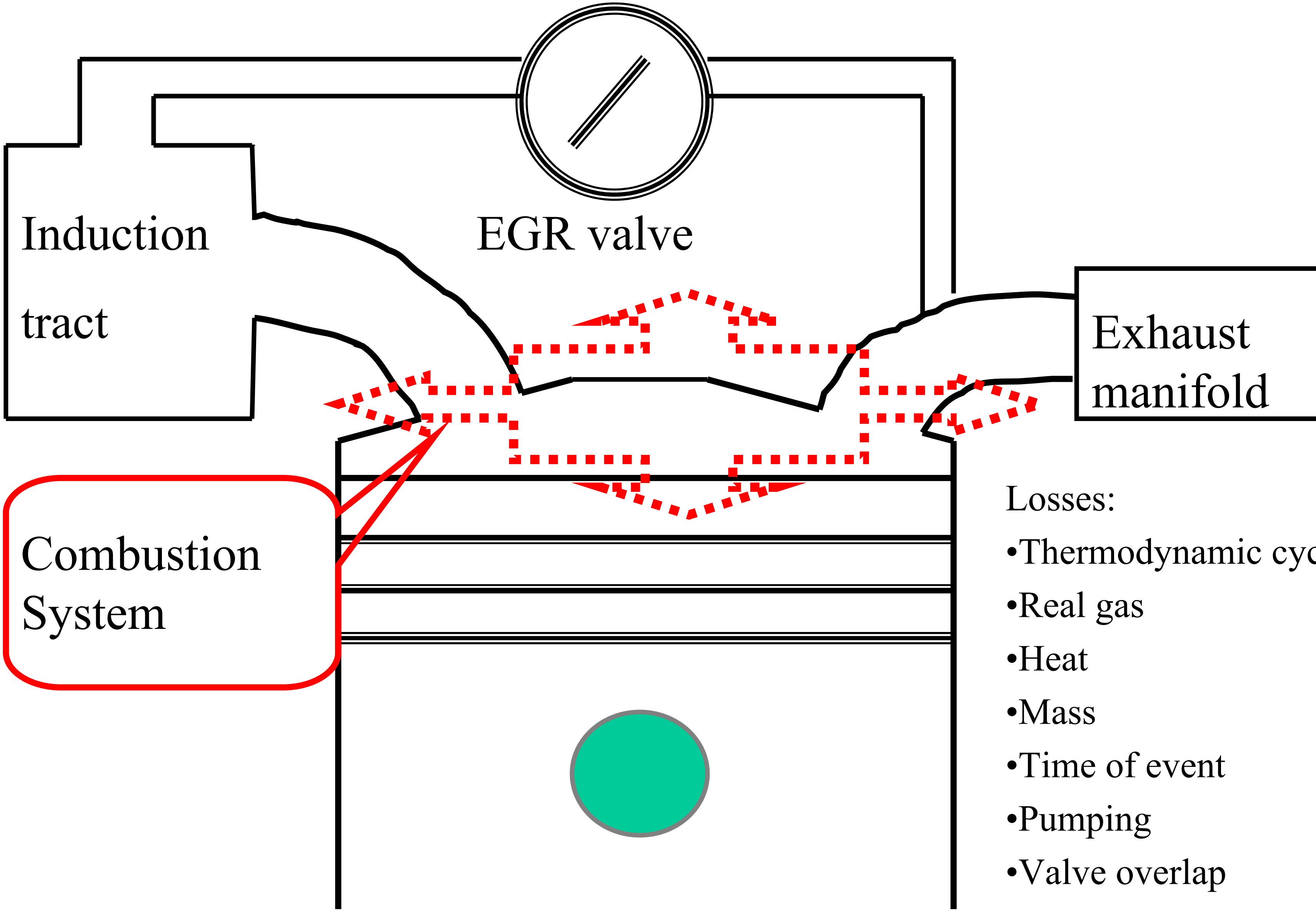
r_c = **COMPRESSION ratio**

Cylinder Pressure Measurements

Cylinder Volume vs.Crank Angle



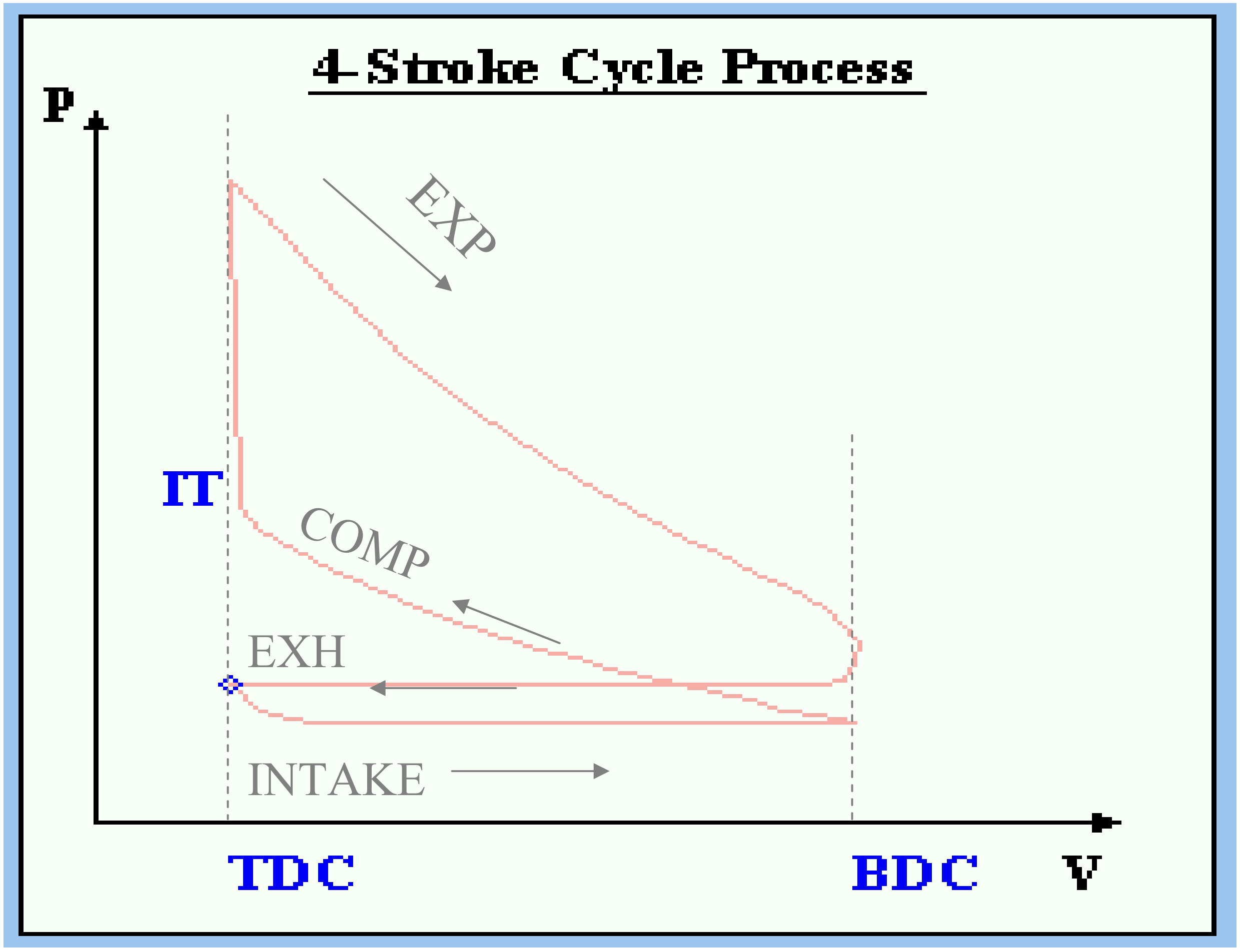

Potential Energy
input = 100% (Fuel)
Tractive Energy
6% Efficiency !!
Cd Losses
Powertrain
losses
Tyres,brakes, drive train friction



Losses:

- Thermodynamic cycle
- Real gas
- Heat
- Mass
- Time of event
- Pumping
- Valve overlap
- Mechanical losses

PV Diagram

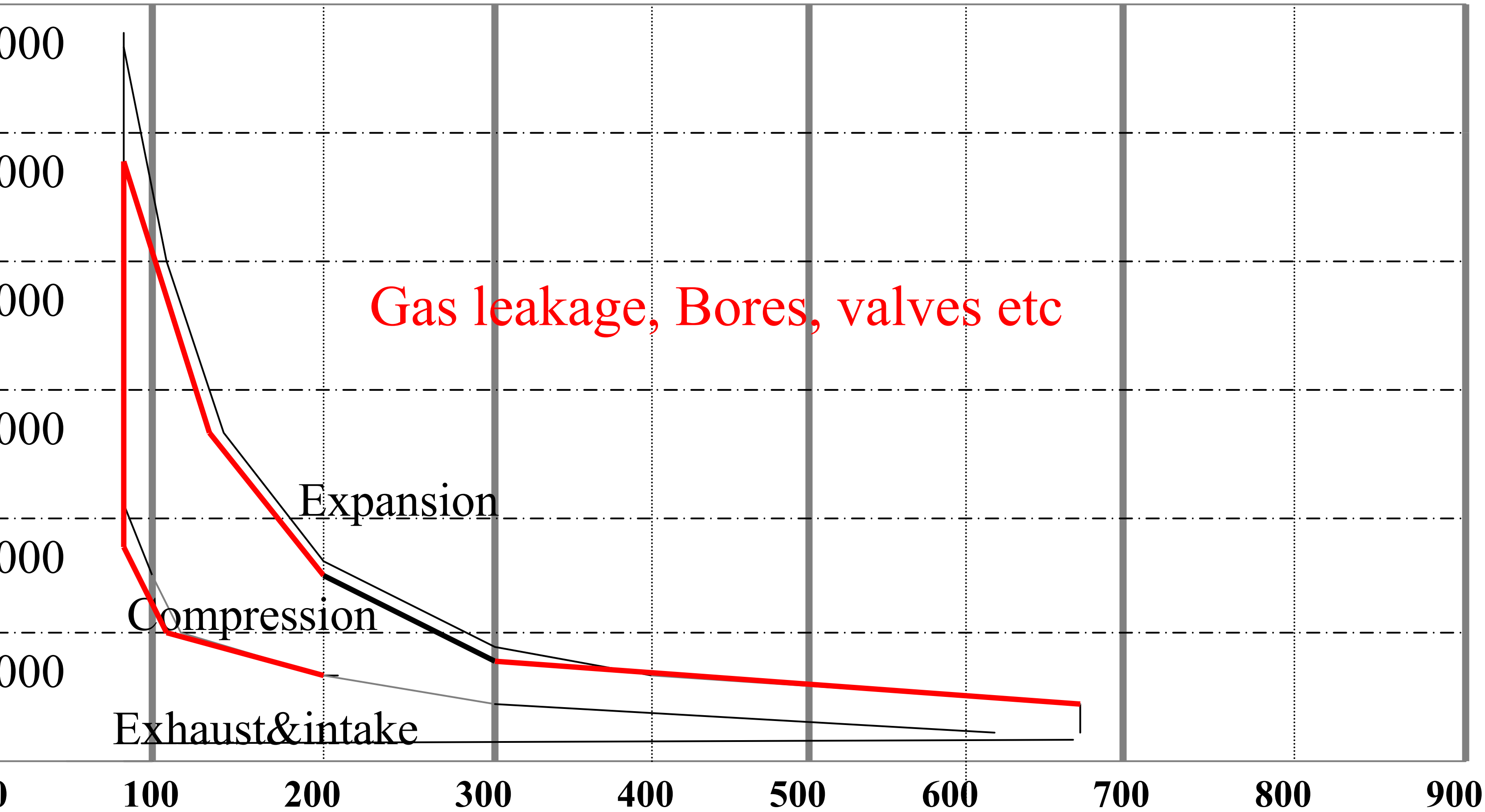


Cylinder Pressure(kPa)

Cylinder Volume (cc)

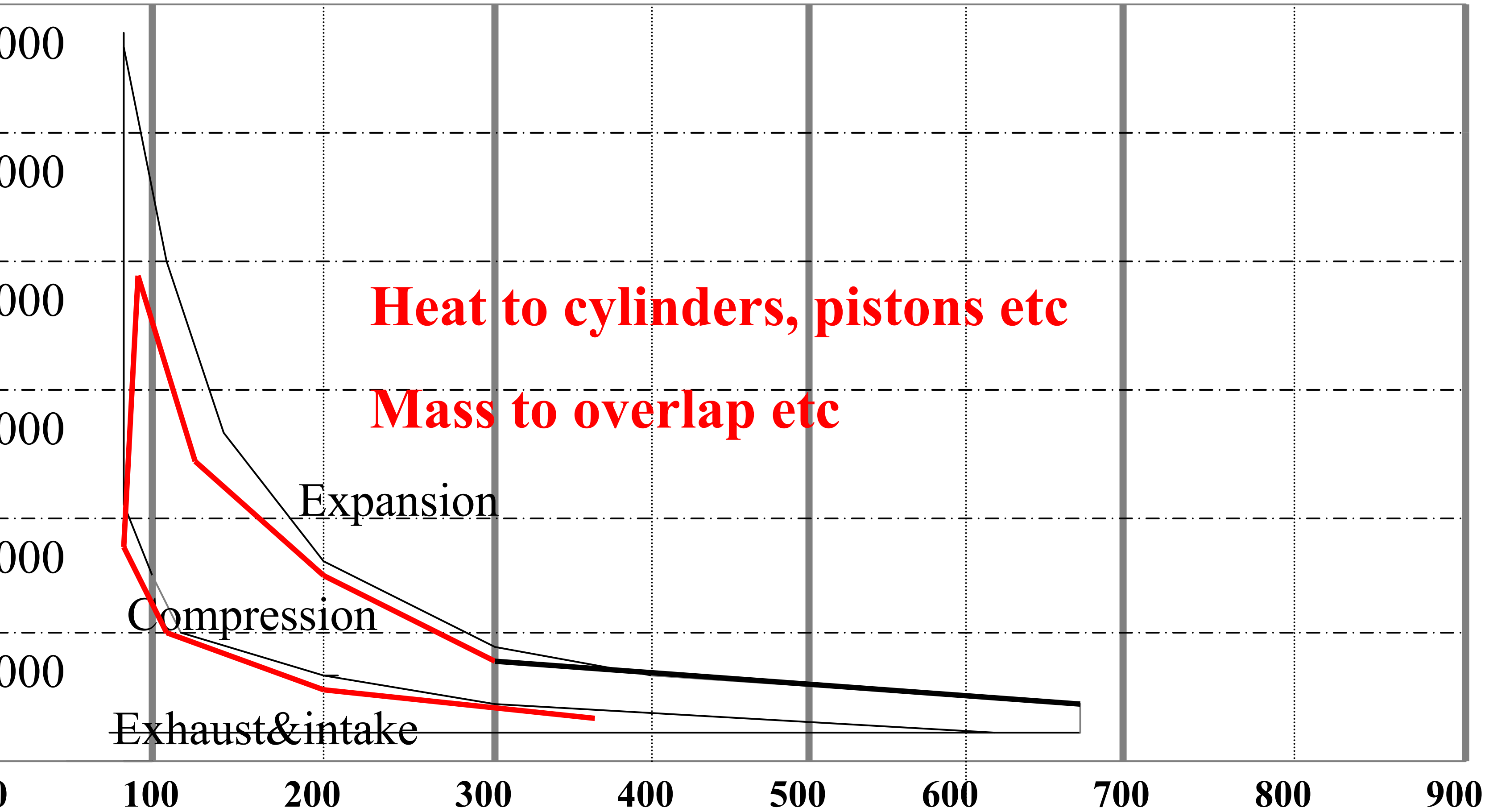
Real Gas Loss

Cylinder Pressure (kPa) vs.Cylinder volume (cc)



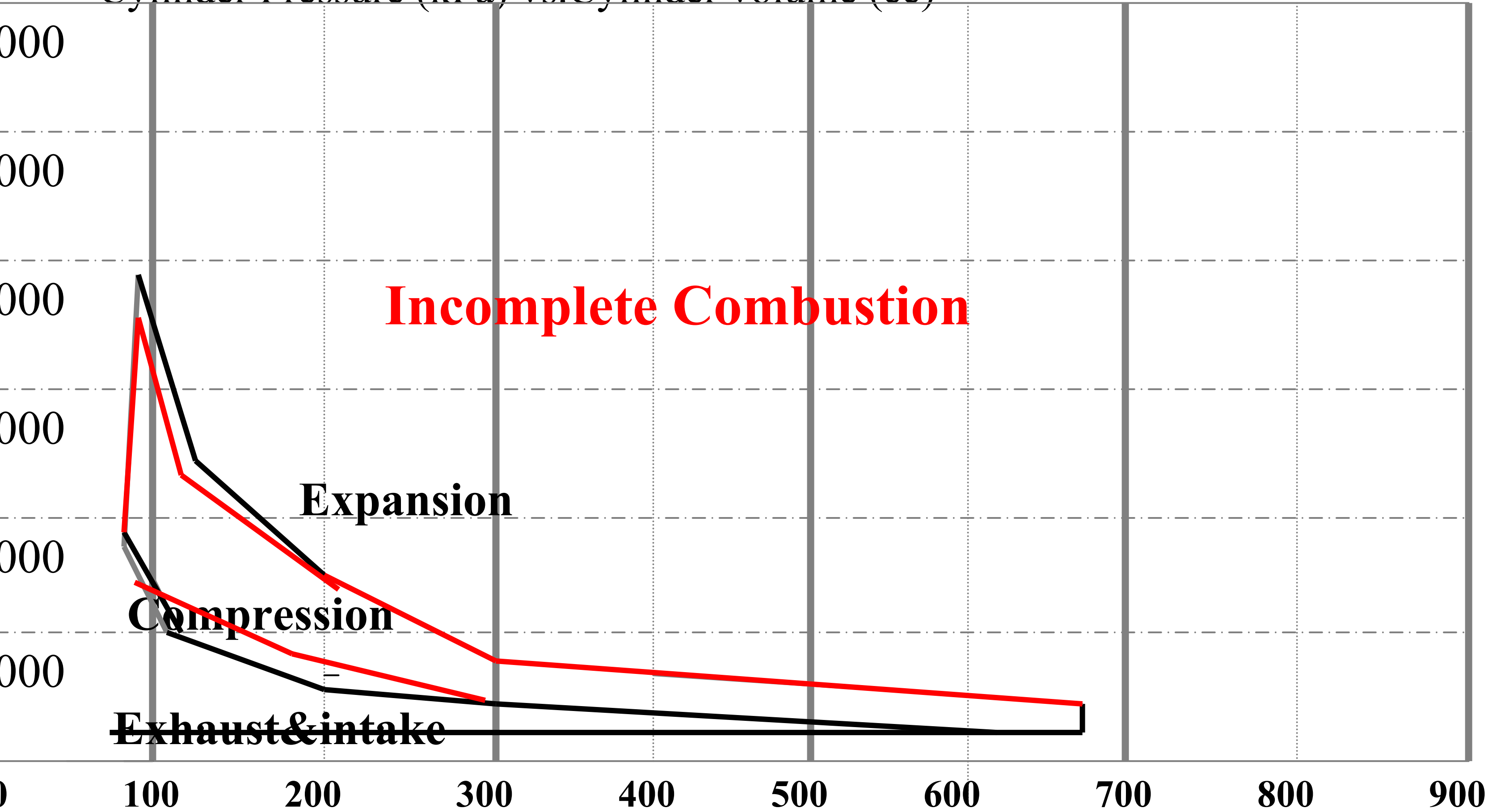
Heat and mass Losses

Cylinder Pressure (kPa) vs.Cylinder volume (cc)



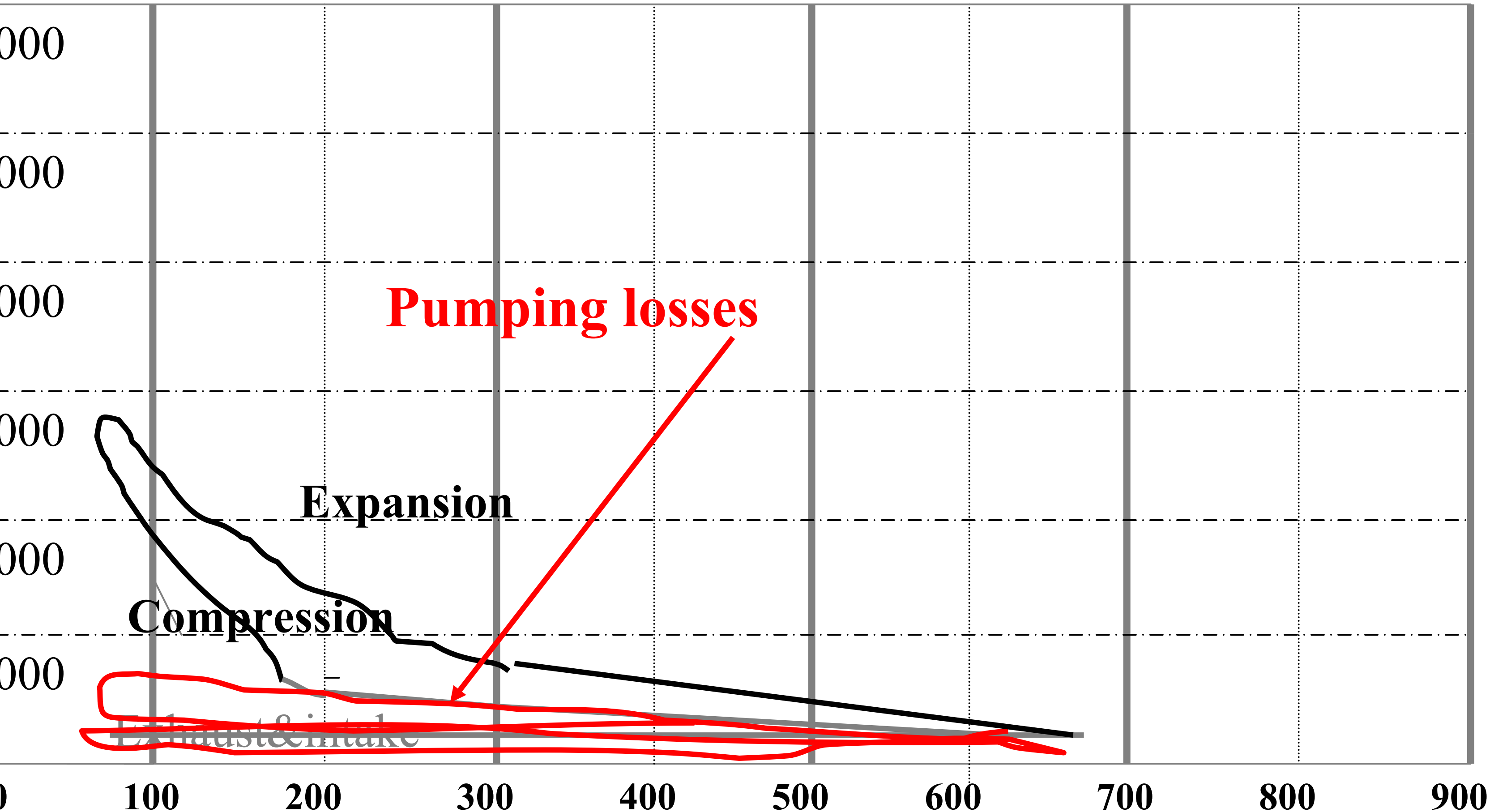
Incomplete combustion Losses

Cylinder Pressure (kPa) vs.Cylinder volume (cc)



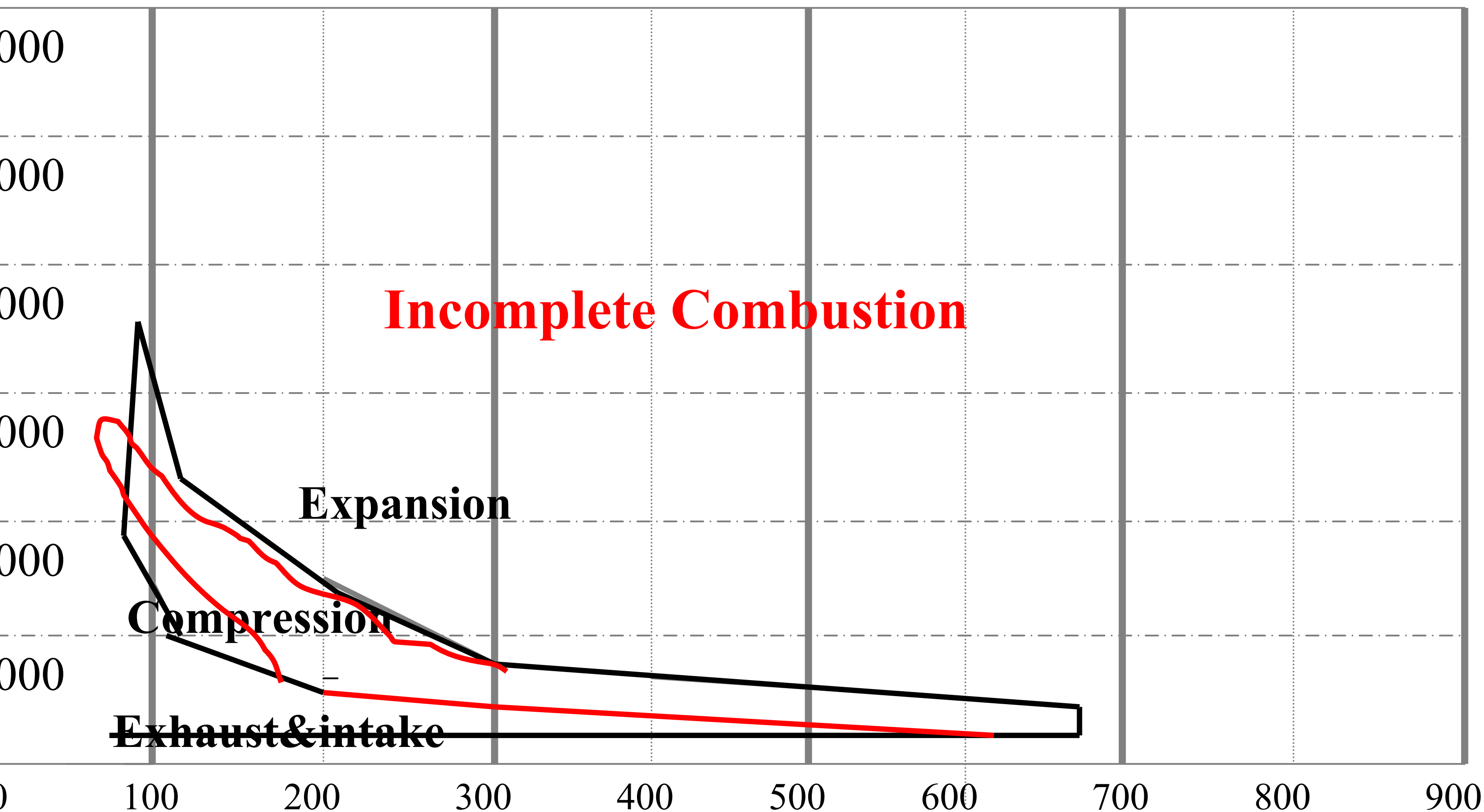
Pumping Losses

Cylinder Pressure (kPa) vs.Cylinder volume (cc)



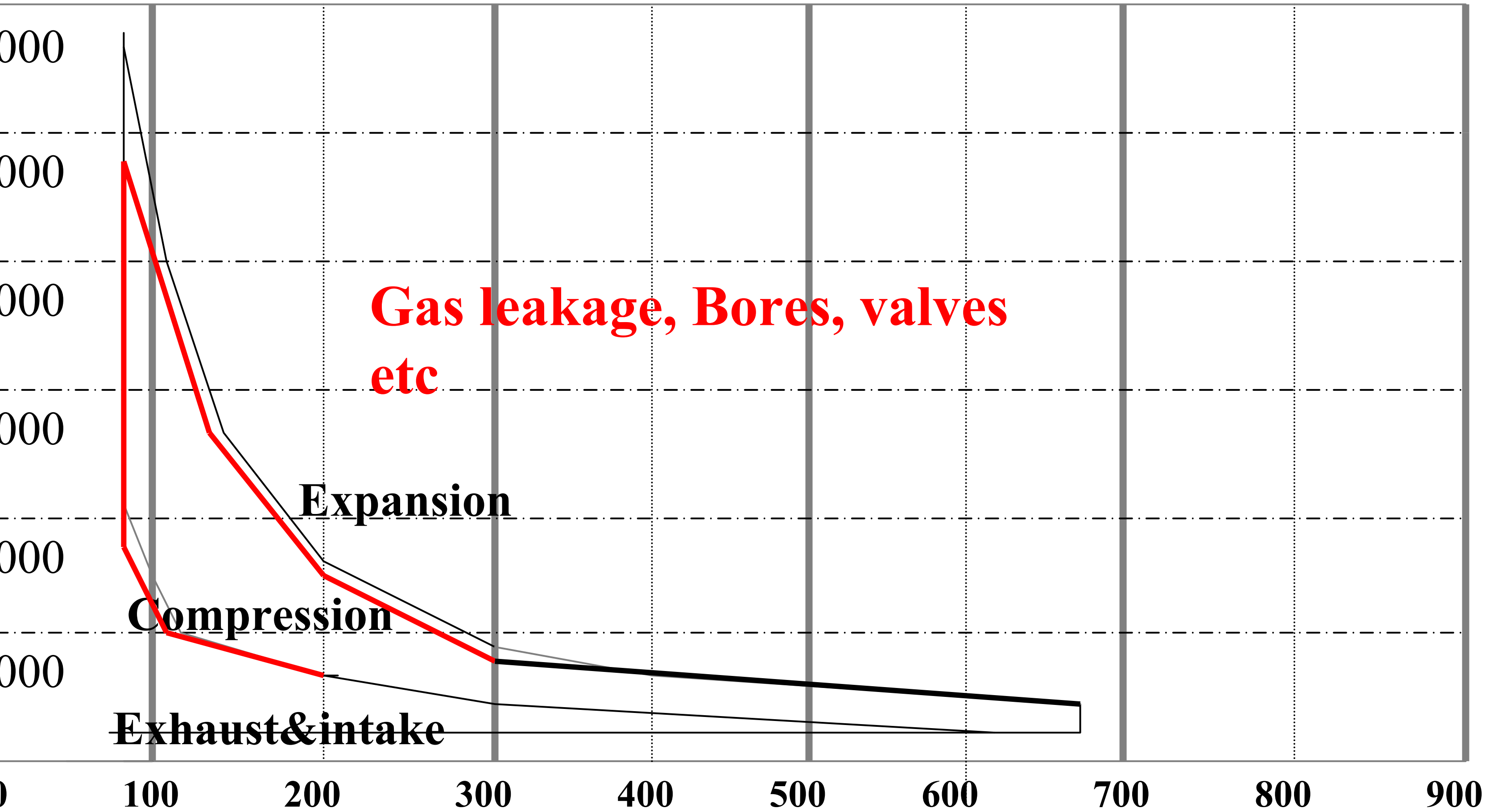
Time to combust Losses

Cylinder Pressure (kPa) vs.Cylinder volume (cc)



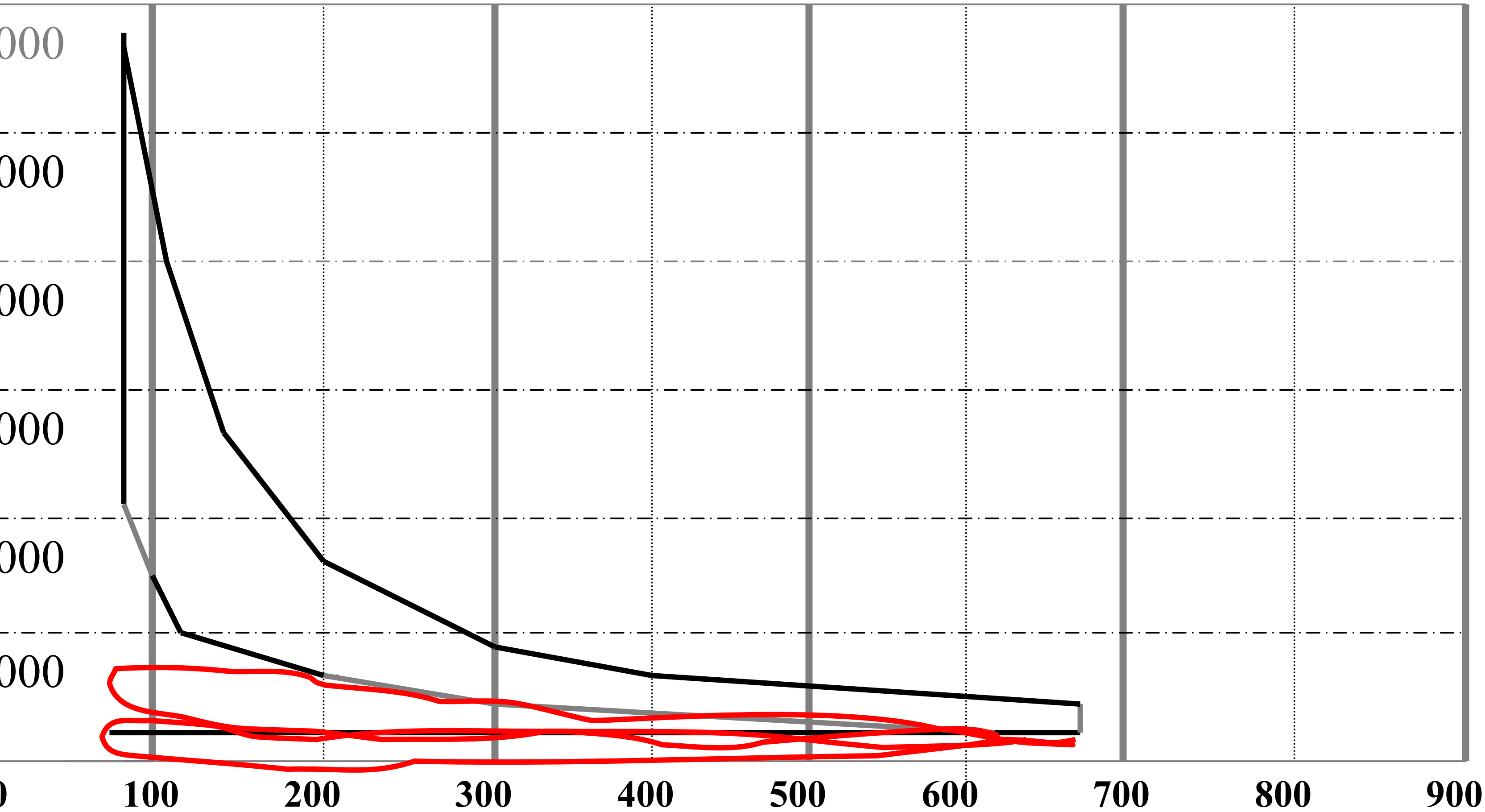
Real Gas Loss

Cylinder Pressure (kPa) vs.Cylinder volume (cc)

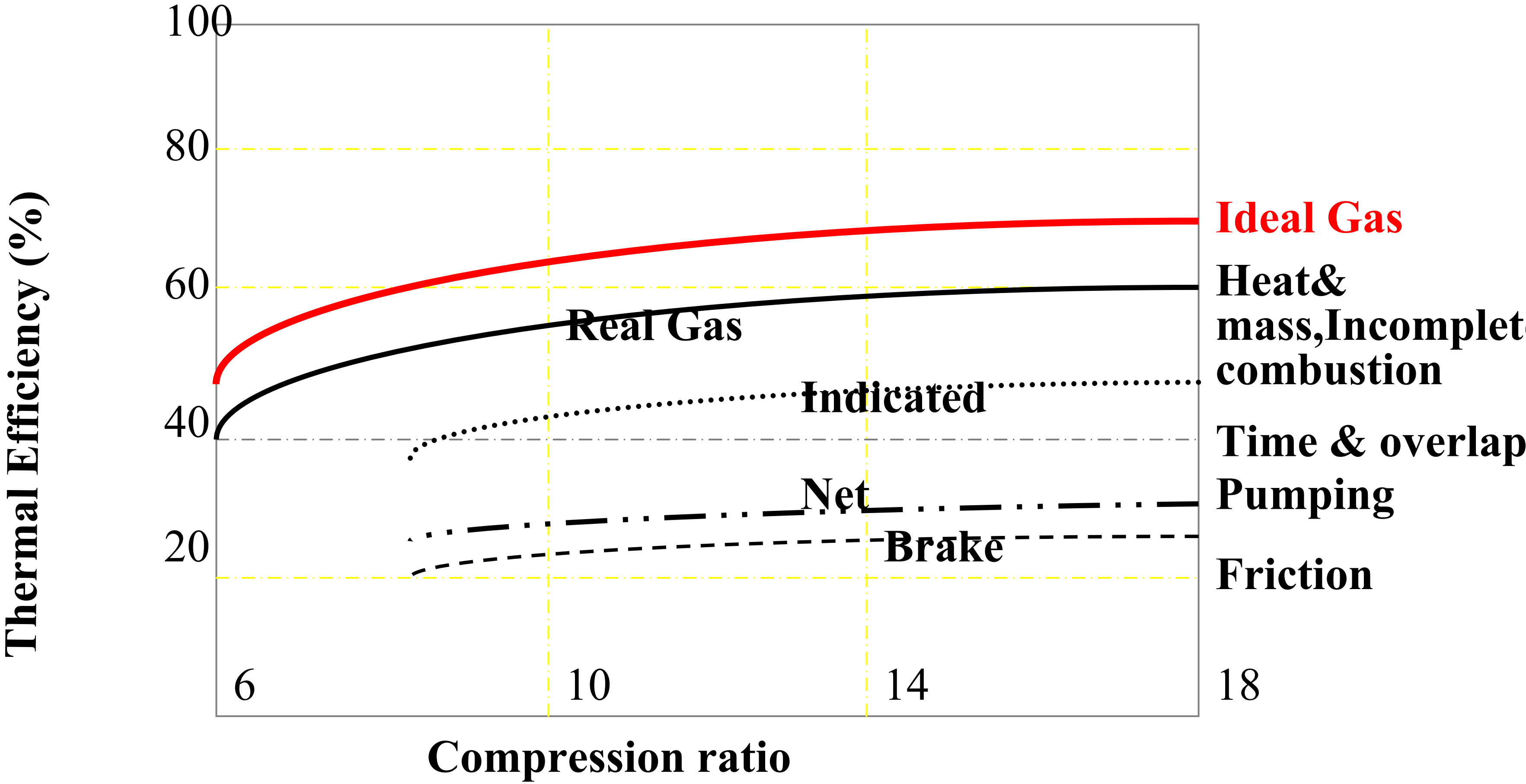


Otto Cycle

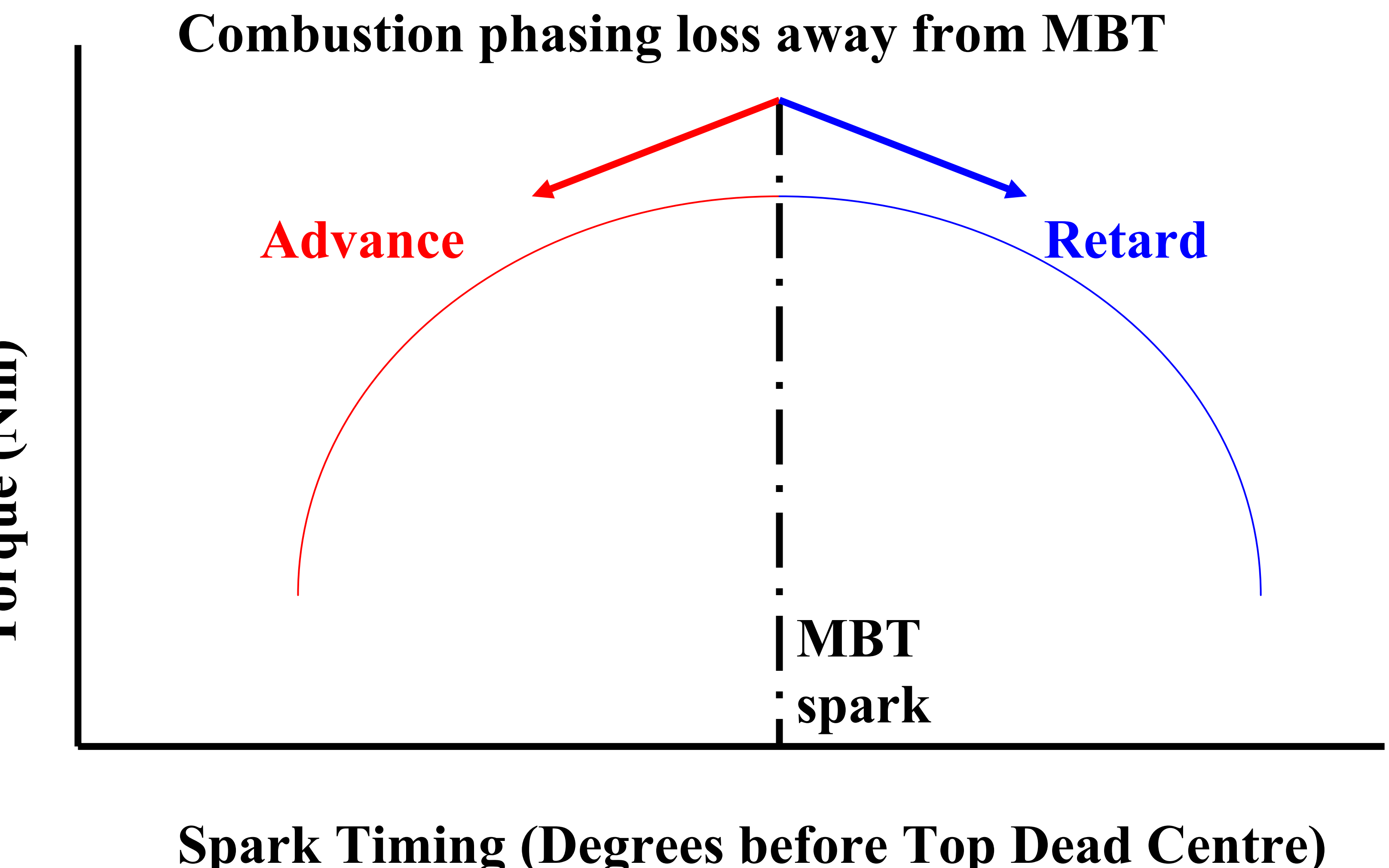
Cylinder Pressure (kPa) vs.Cylinder volume (cc)



Magnitude of efficiency losses

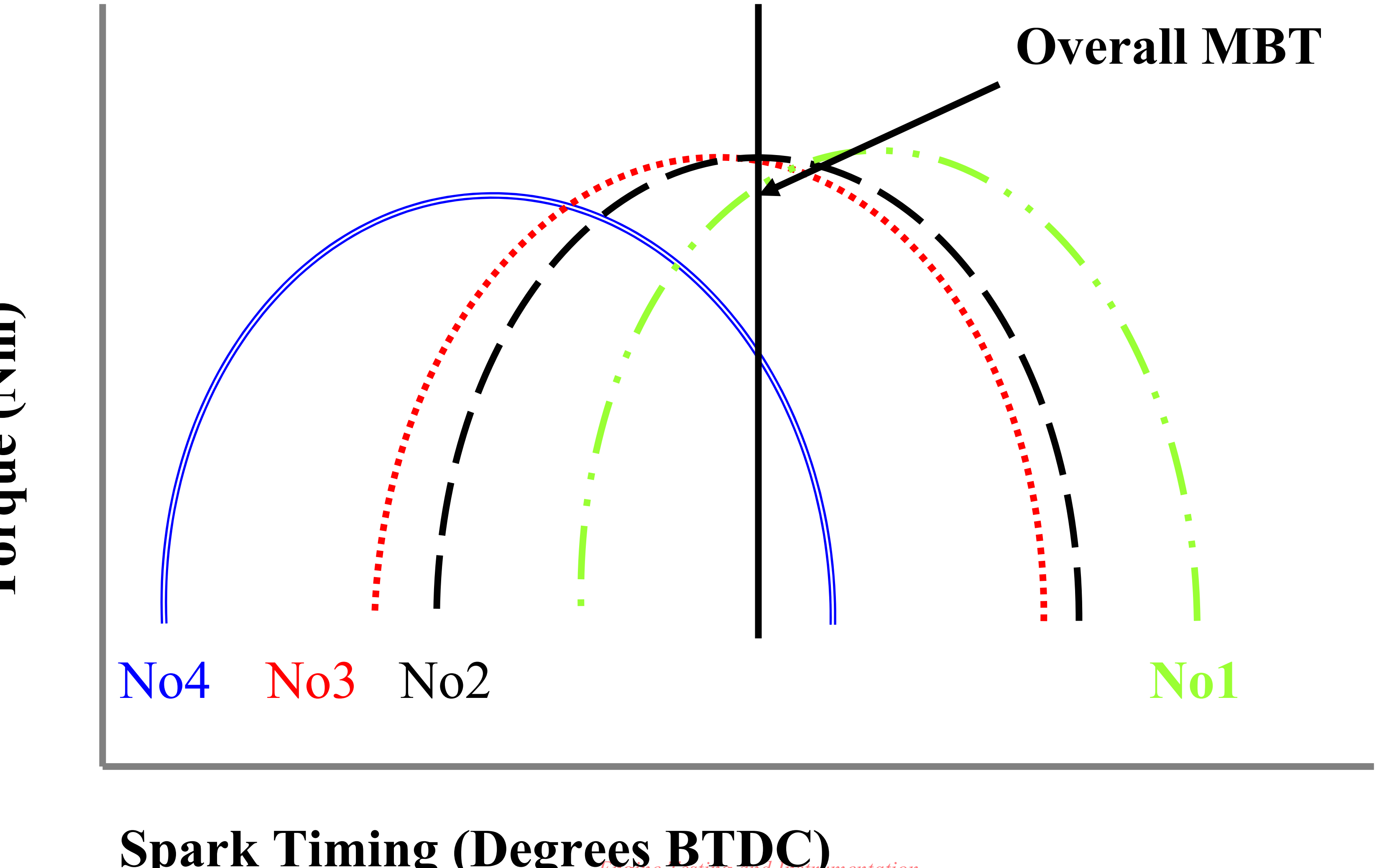


Torque versus spark timing for a complete engine



Phasing loss

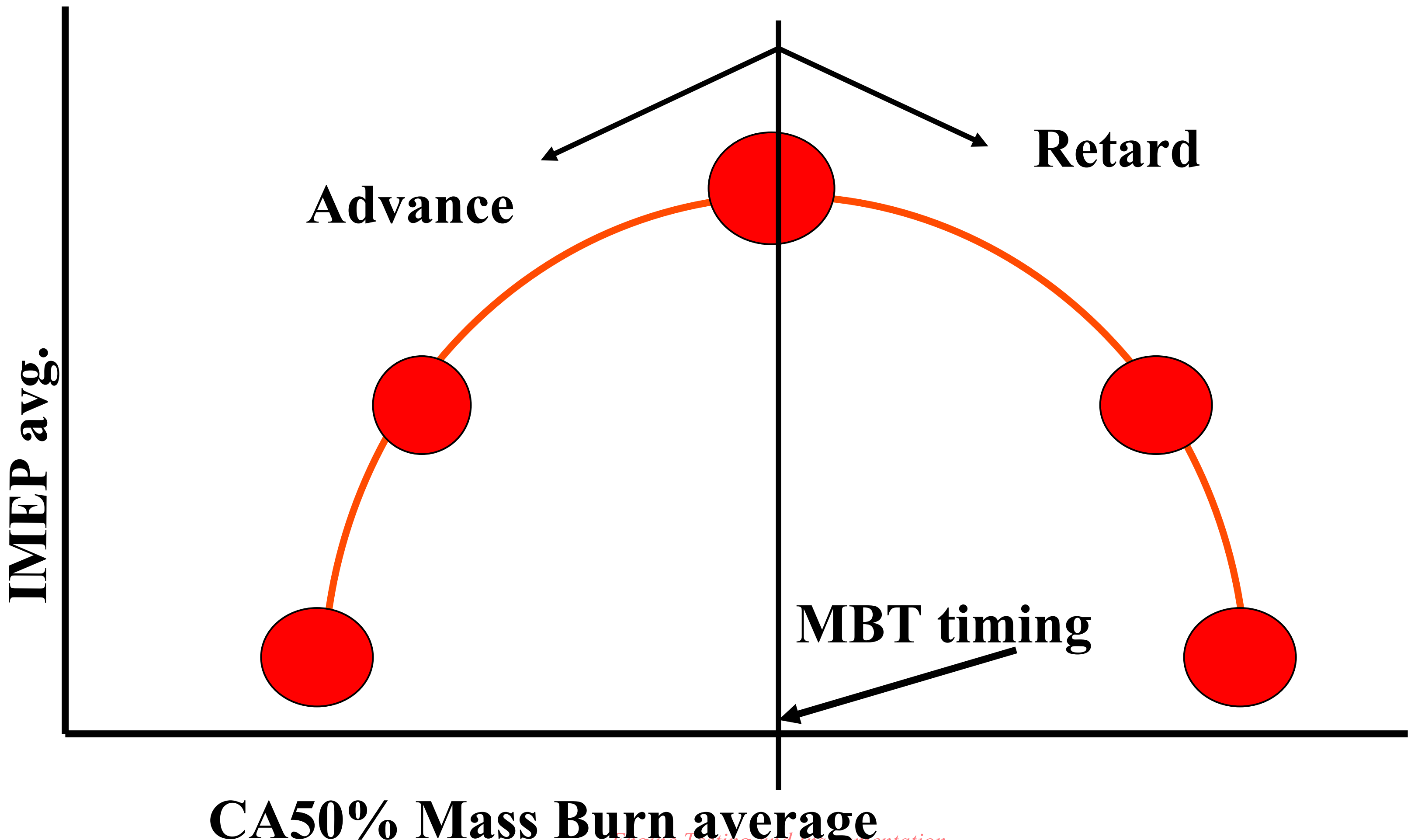
Individual cylinder MBVT is not equal to the overall engine MBT



IMEP v CA of 50% mass burned

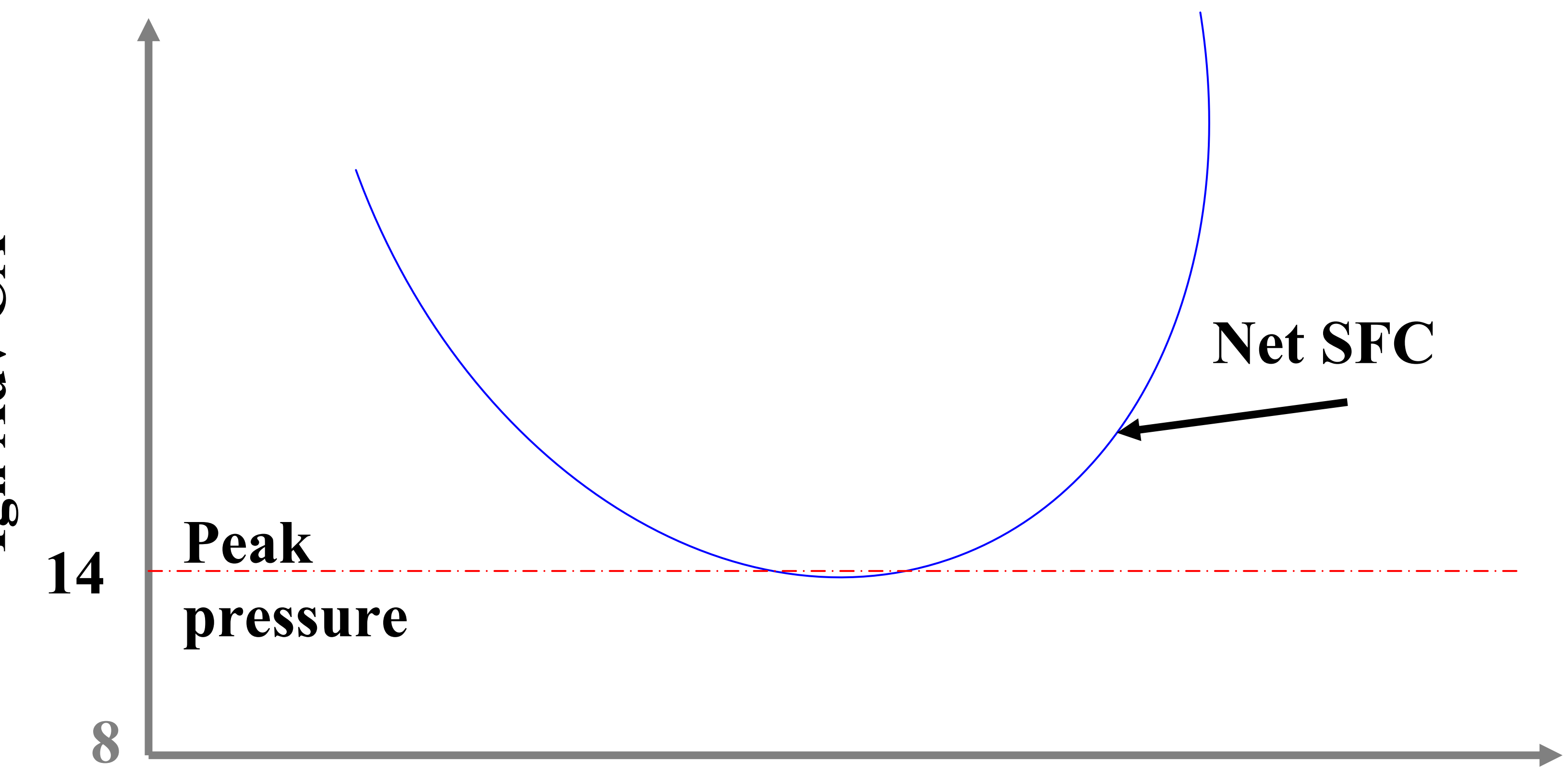
One cylinder average at 5 different spark timings

Combustion phasing loss deducted from individual cylinder MBT

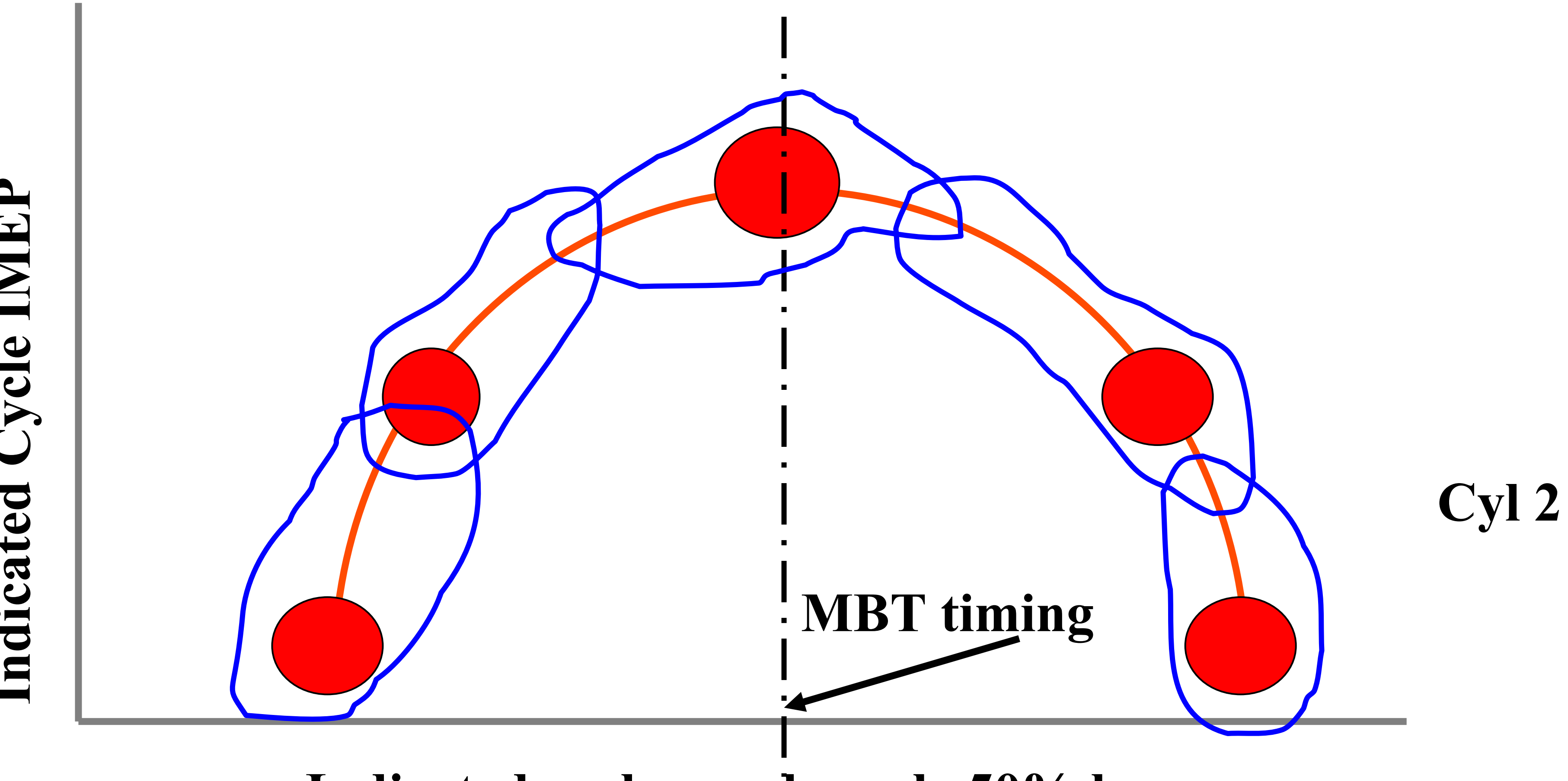


Cyl 2

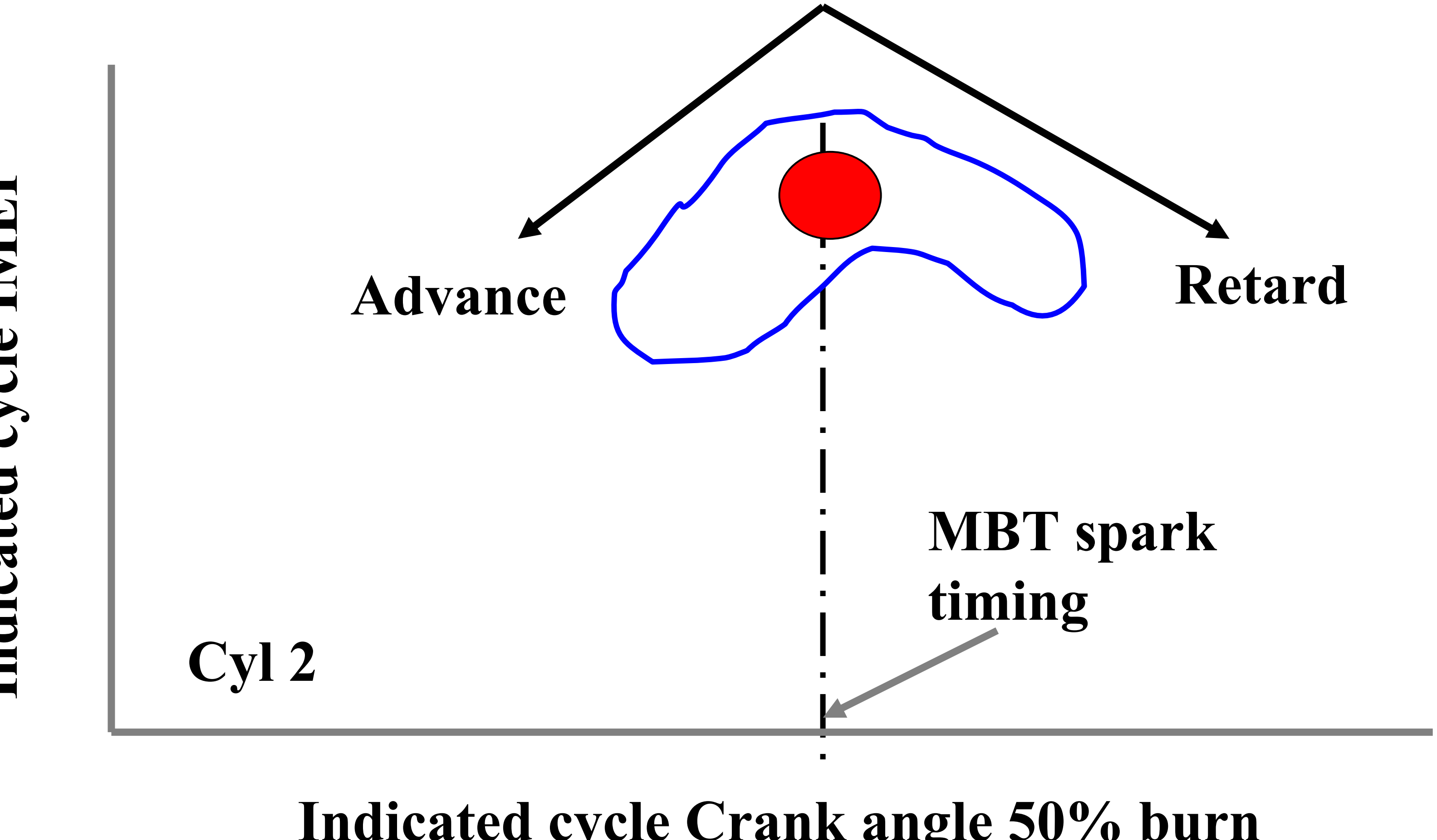
MBT Ignition and Fuel



IMEP vCA50 mass burned, individual cycles at five different spark timings



Combustion phasing loss away from MBT

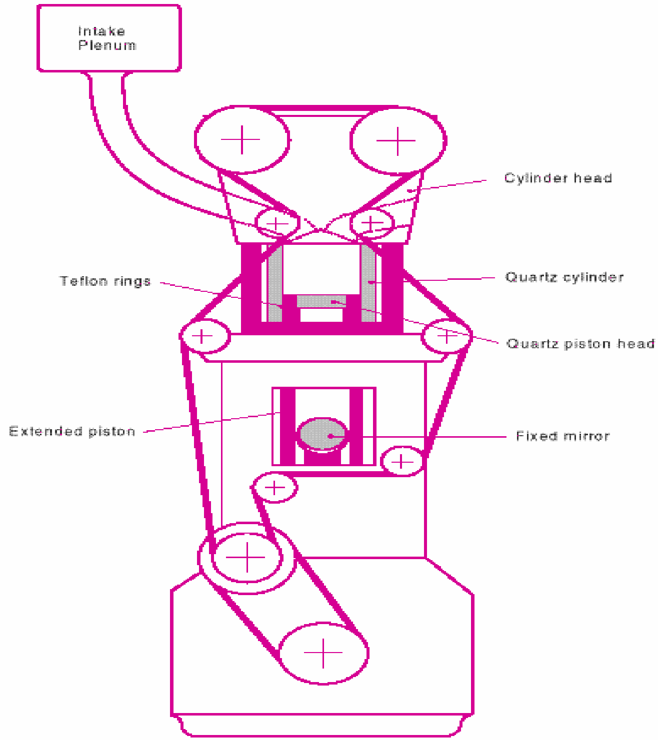


Phasing Efficiency Loss Summary

- Overall engine loss when spark timing differs from overall engine MBT
- Individual cylinder loss when individual cylinder MBT differs from overall engine MBT
- Individual cycle loss when individual cycle phasing (CA50) differs from optimal phasing

➢ There will always be phasing efficiency loss

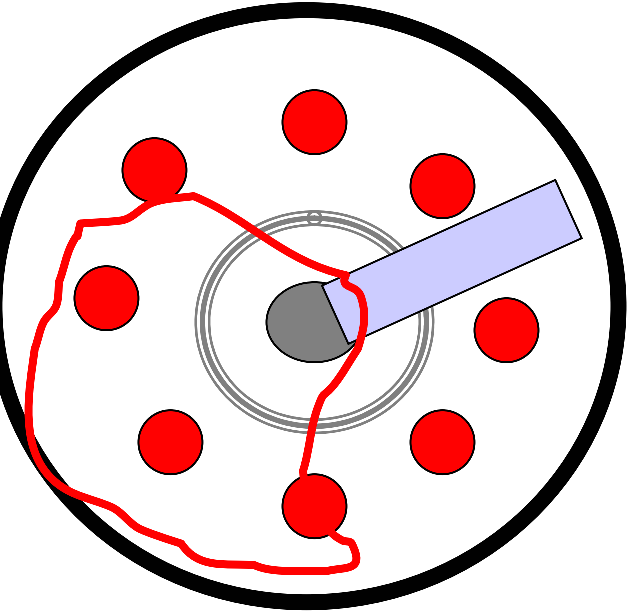
Types of Combustion Diagnostics



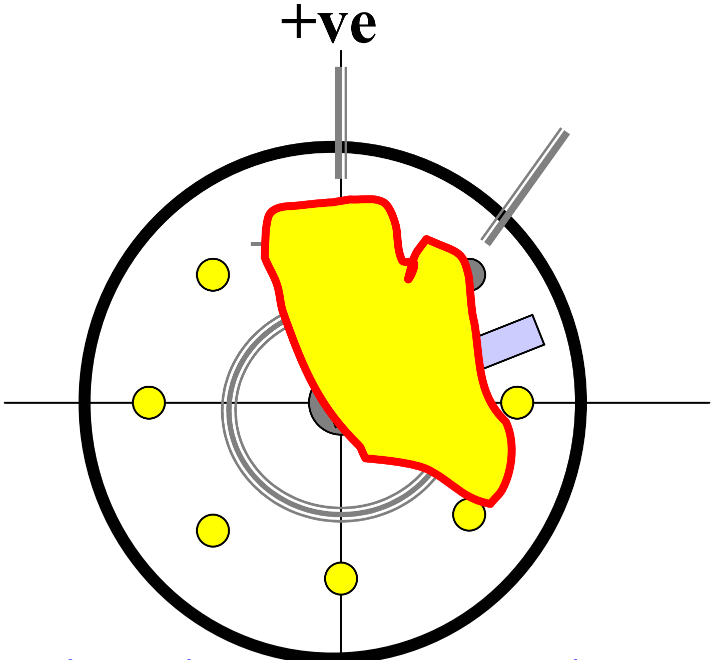
Understanding what is happening inside the combustion space

- **In cylinder pressure measurement**
- **Optical**
- **Ion Gap**

AVL optical sparking plug. *8 fibre optic tubes look at the light generated by the burn



FEV Ion Gap



Ionisation energy level

Cylinder-Pressure Based Combustion Analysis

Measurement and interpretation of
combustion chamber pressure to determine:

- Piston and crankshaft loads
- Torque produced from the burning air/fuel charge
- Torque required to induct the fresh charge and exhaust the burned charge
- Time required for the combustion flame to develop and propagate
- Spark timing relative to MBT
- Presence and magnitude of knock
- Cycle to cycle and cylinder to cylinder variability

Cylinder-Pressure Based Combustion Analysis

Some uses of combustion analysis

- Assessing inlet/exhaust port and manifold geometries
- Optimising combustion chamber shape
- Quantifying compression ratio trade offs
- Comparing spark plug parameters
- Selecting valve timing overlap and duration
- Optimising fuel injector timing and opening duration
- Investigating transient response
- Measuring mechanical friction
- Automated mapping (MBT,Knock/Pre ignition control)
- Calibration optimisation

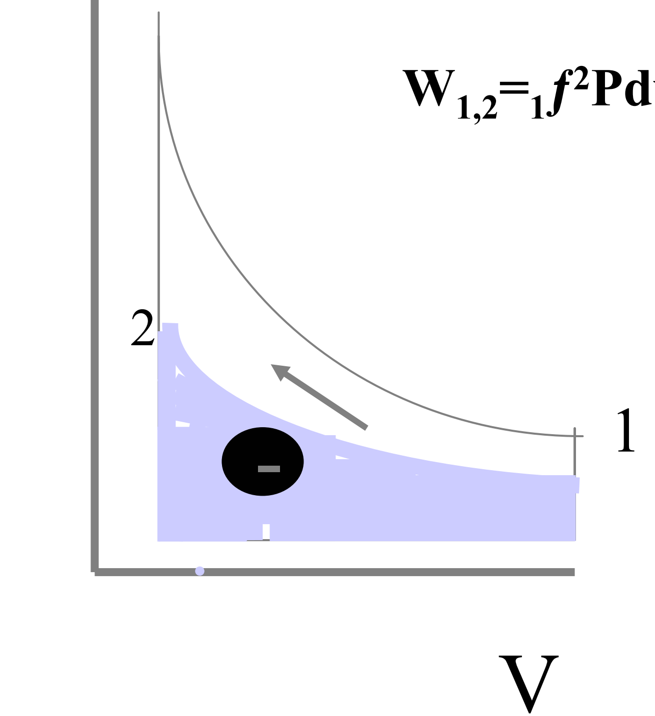
Combustion Performance Parameters

- Mean Effective Pressure
- Combustion Phasing
- Cyclic Variability
- Heat Release
- Equation Summary

Indicated Work IMEP

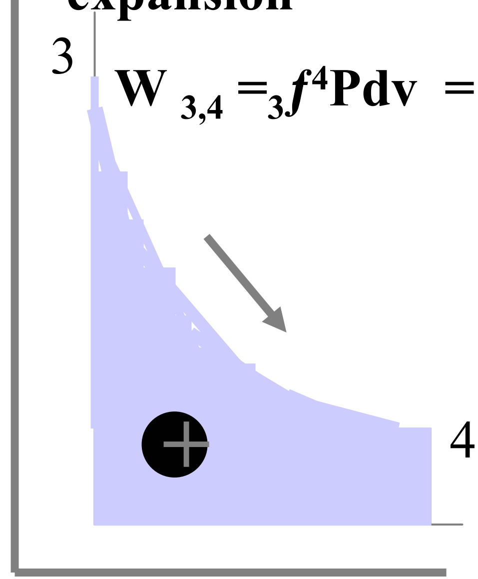
Negative work done by piston due to charge compression

$W_{1,2} = {}_1\int^2 P dv$ +



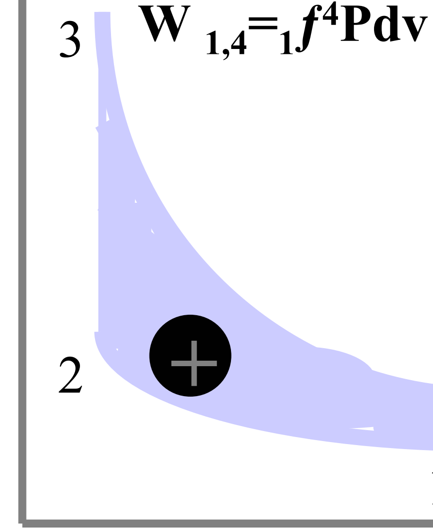
Positive work done to the piston due to heat release & expansion

$W_{3,4} = {}_3\int^4 P dv$ =



+ve work done b cycle *indicated work*

$W_{1,4} = {}_1\int^4 P dv$

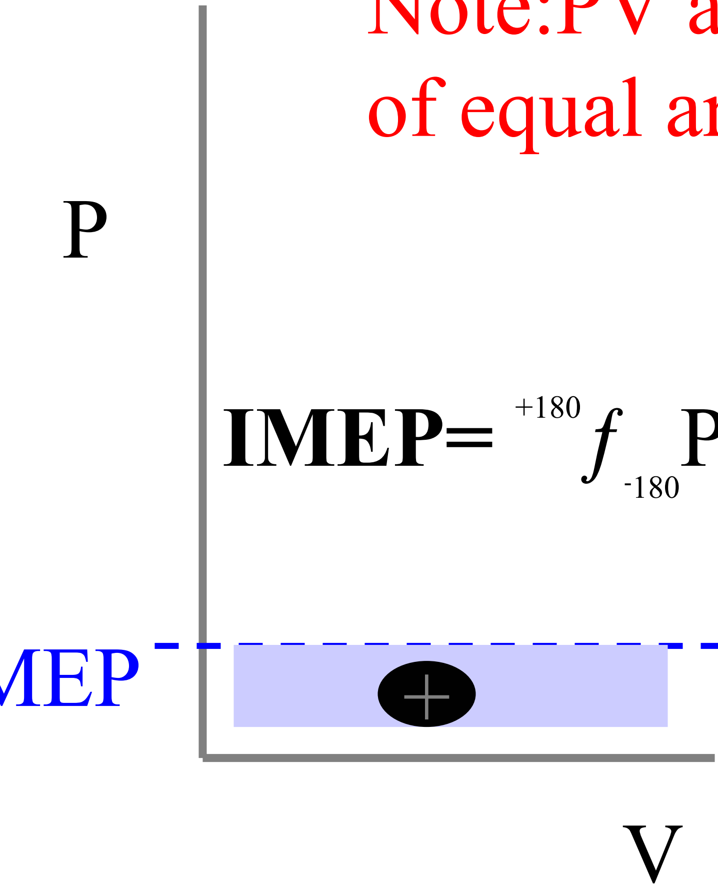


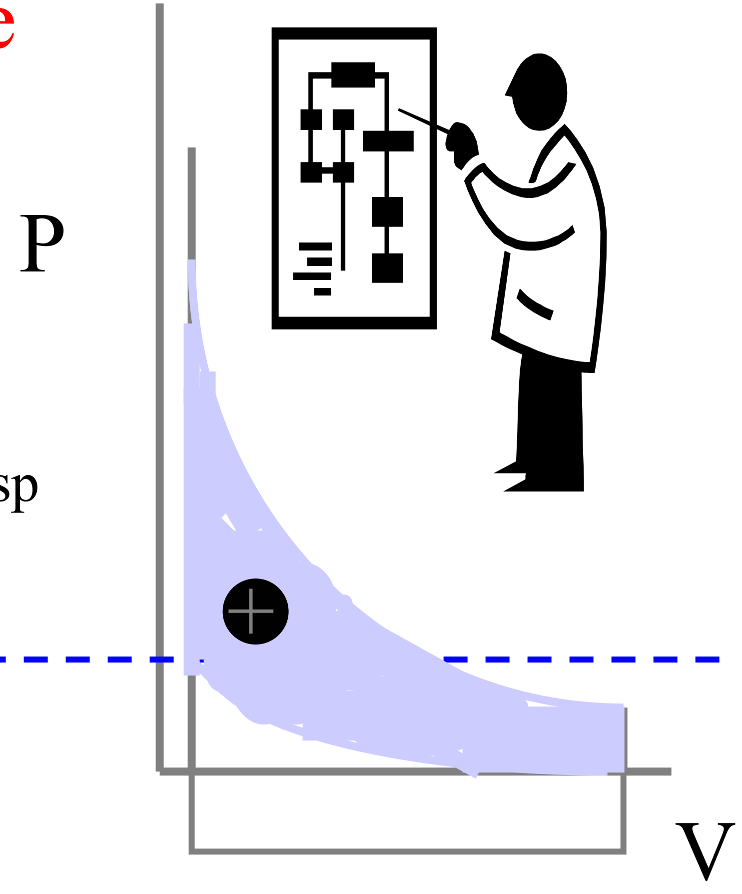
$$W_i = \int P dv$$

Indicated Pressure IMEP

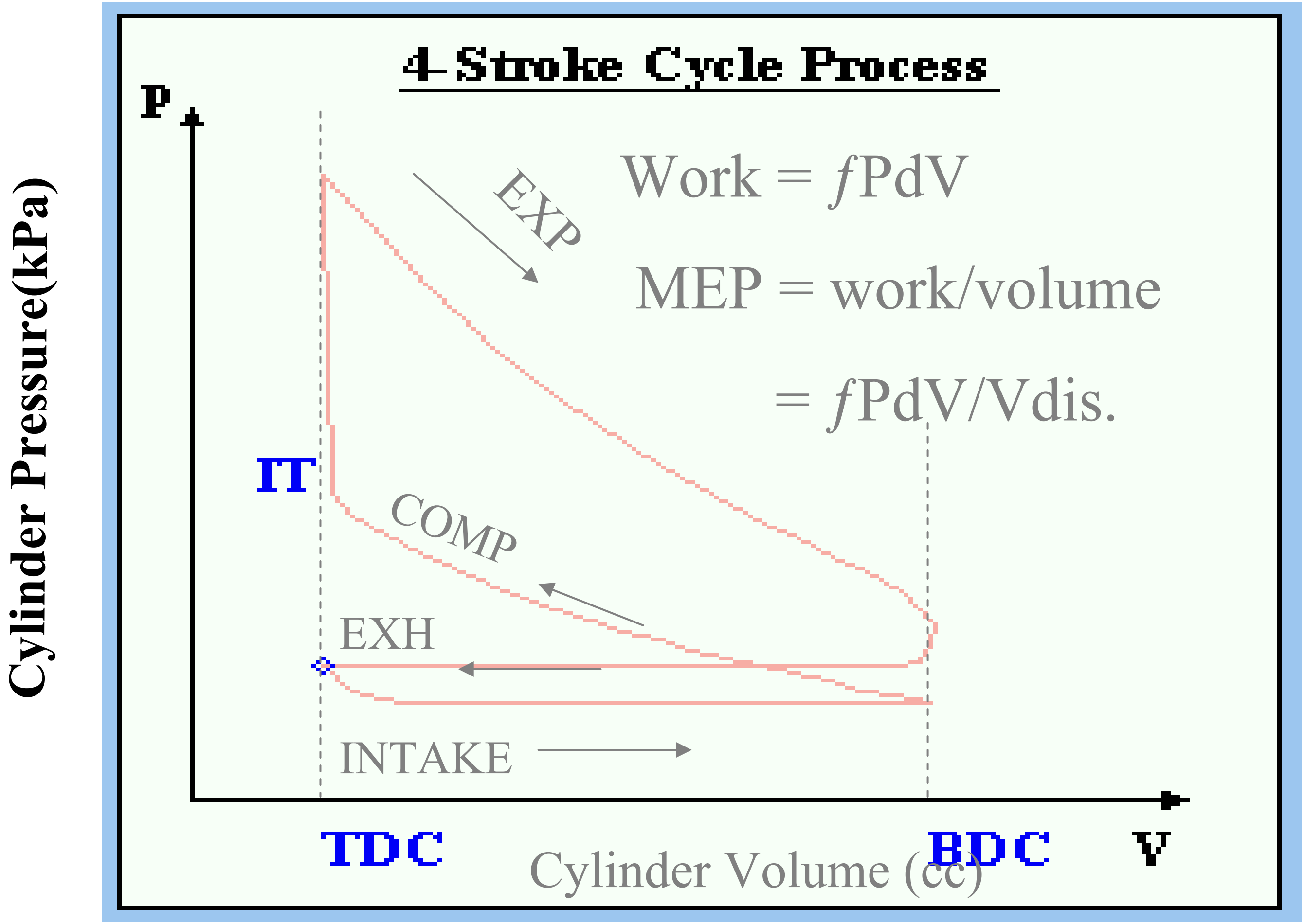
Note:PV areas are of equal area

$$IMEP = \int_{-180}^{+180} PdV / V_{disp}$$



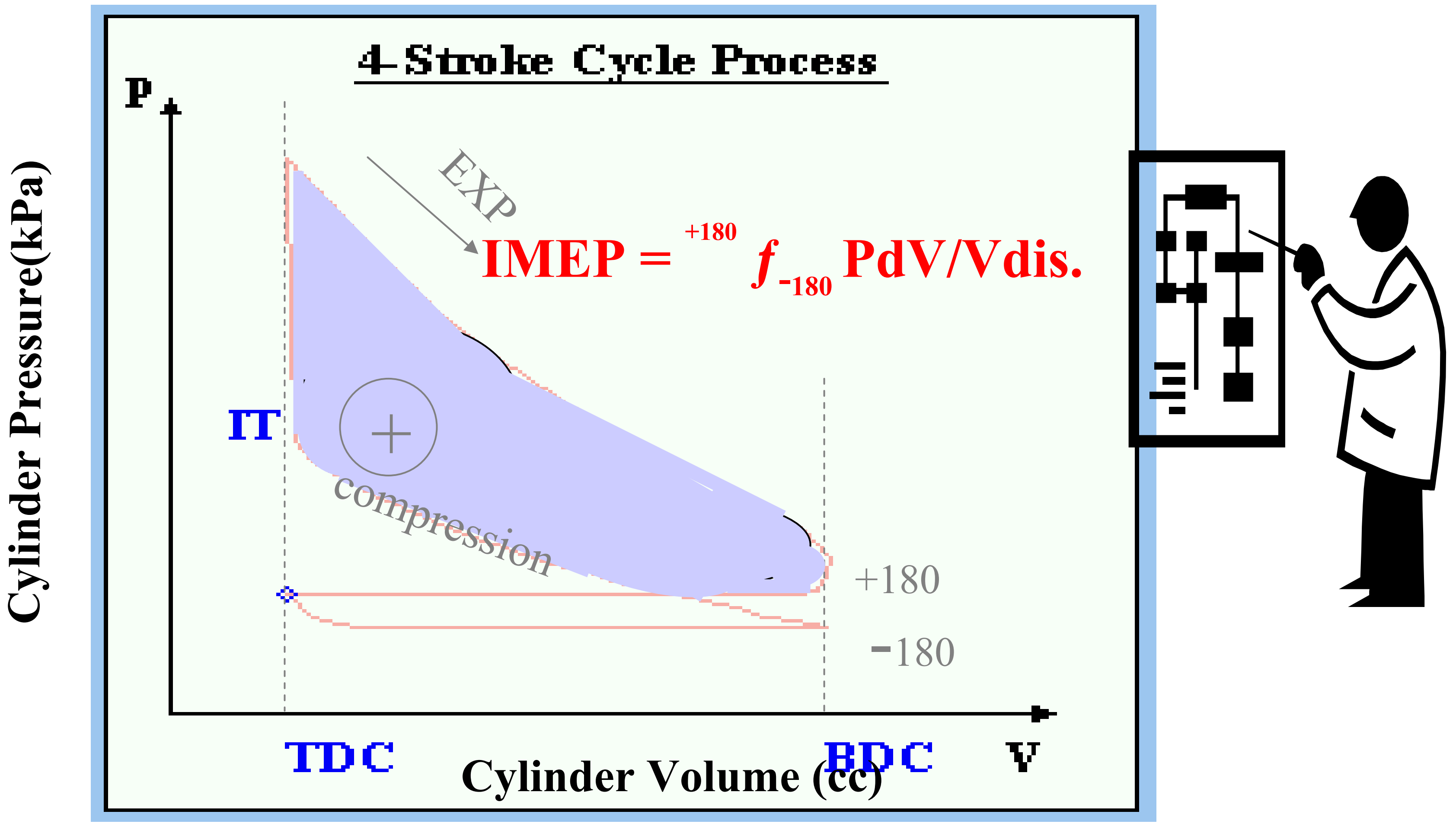


PV Diagram



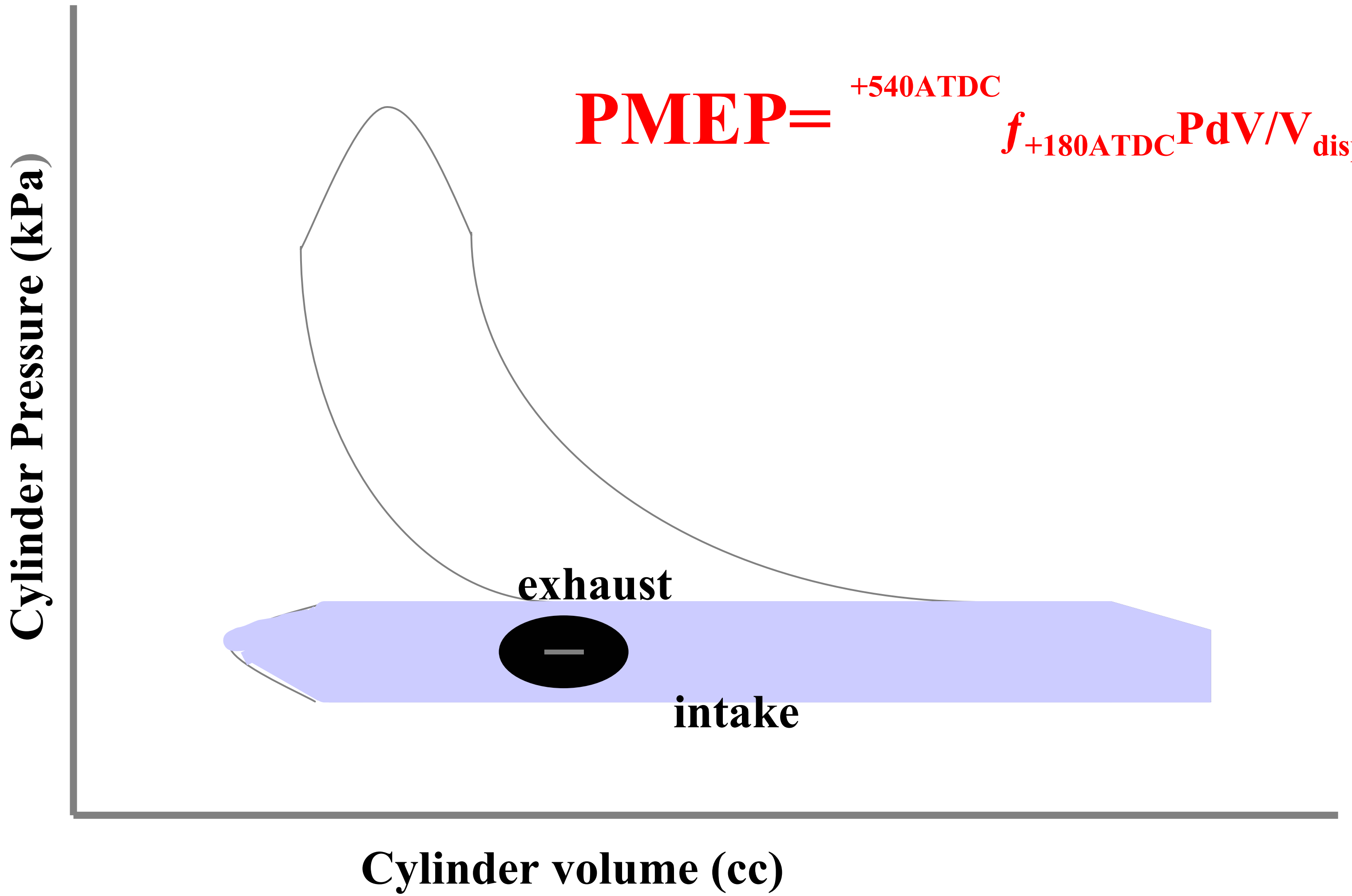
4-Stroke Cycle Process
P
Cylinder Pressure(kPa)
Work = ƒPdV
MEP = work/volume
= ƒPdV/Vdis.
EXP
IT
COMP
EXH
INTAKE
TDC
BDC
V
Cylinder Volume (cc)

PV Diagram



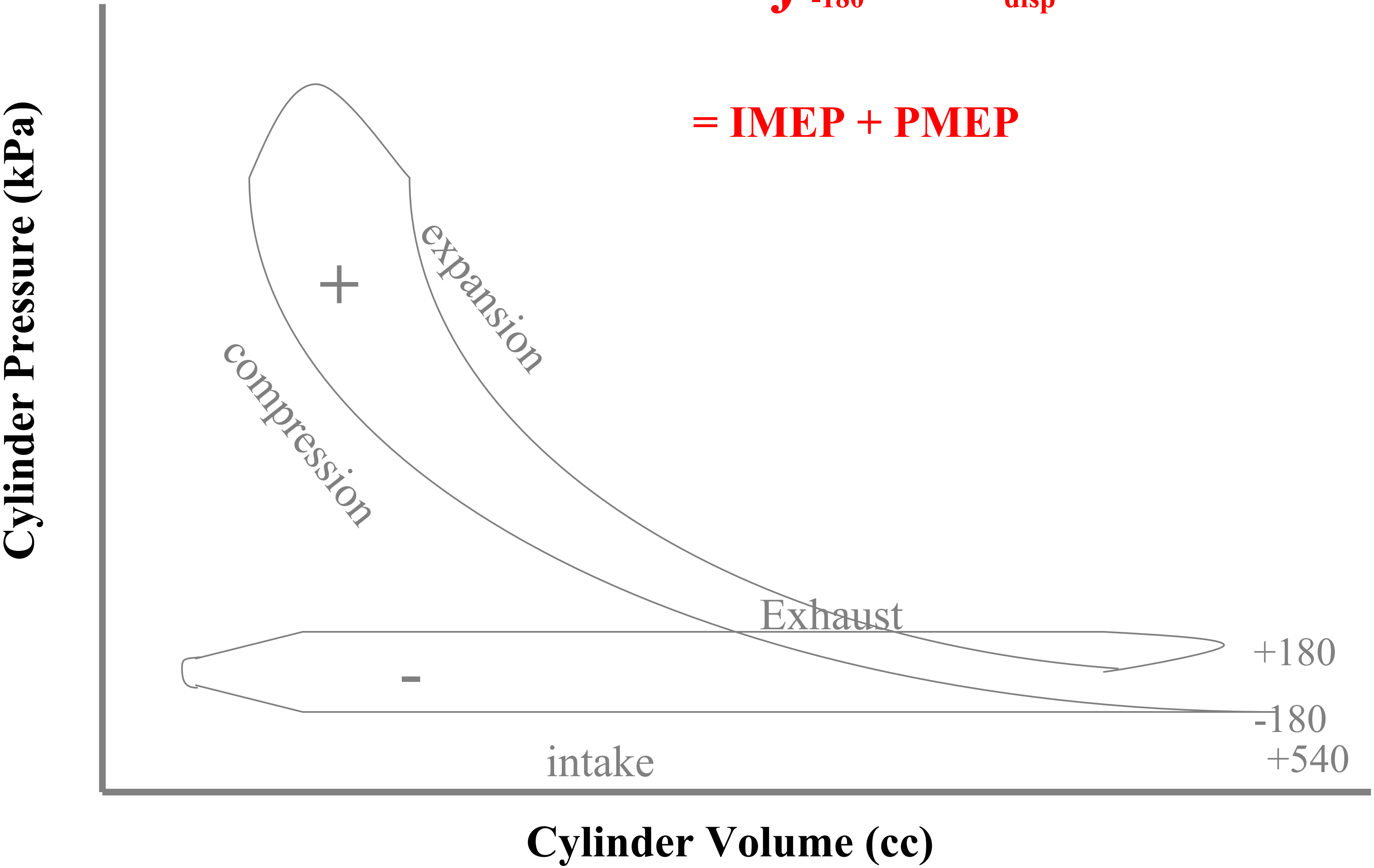
4-Stroke Cycle Process
P
Cylinder Pressure(kPa)
EXP
IMEP = ∫ PdV/Vdis.
+180
-180
IT
compression
+180
-180
TDC
BDC
V
Cylinder Volume (cc)

$$PMEP = \int_{+180ATDC}^{+540ATDC} PdV/V_{disp}$$



$$NMEP = \int_{-180}^{+540} PdV/V_{disp}$$

$$= IMEP + PMEP$$

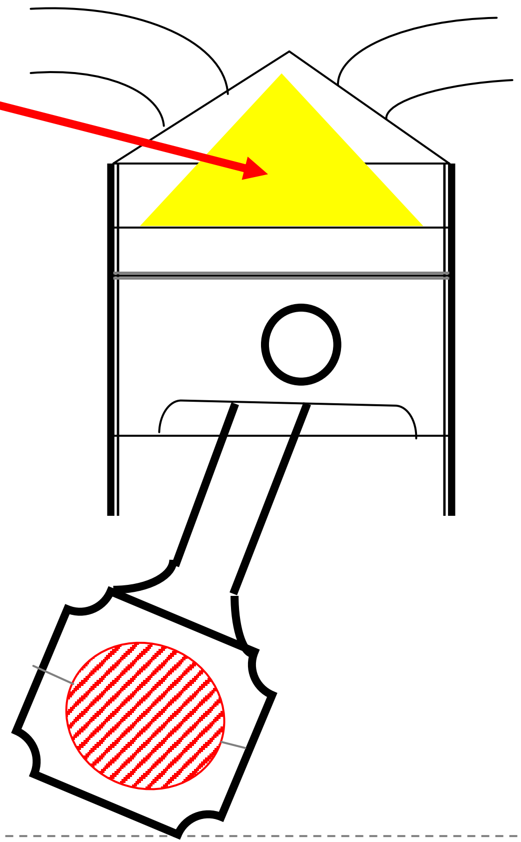


MEP Summary

Indicated

Compression,Combustion and expansion

Diff= Pumping



Net

Adds Intake & Exhaust Processes

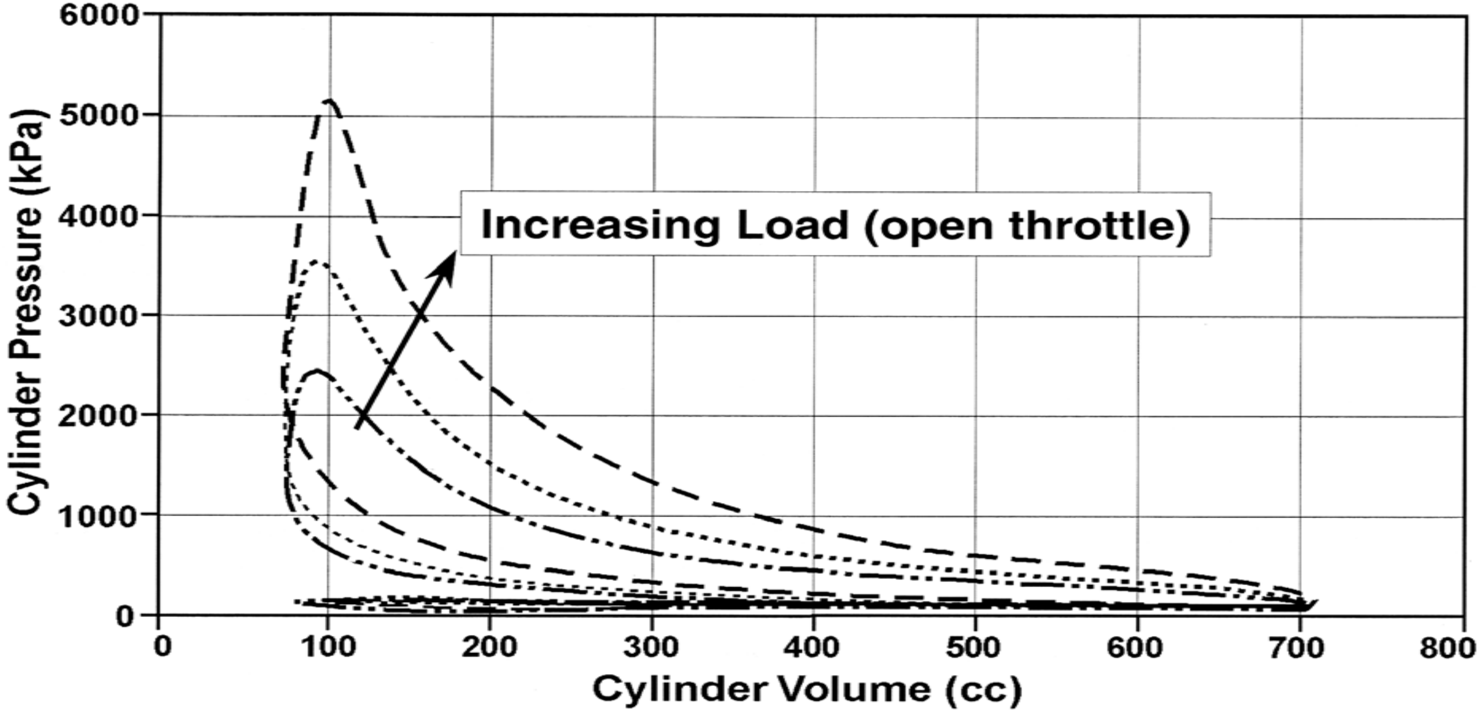
Diff = Friction

Brake

Adds Rubbing Friction Losses

Combustion Performance Parameters

Cylinder Pressure vs Cylinder Volume-Influence of Load



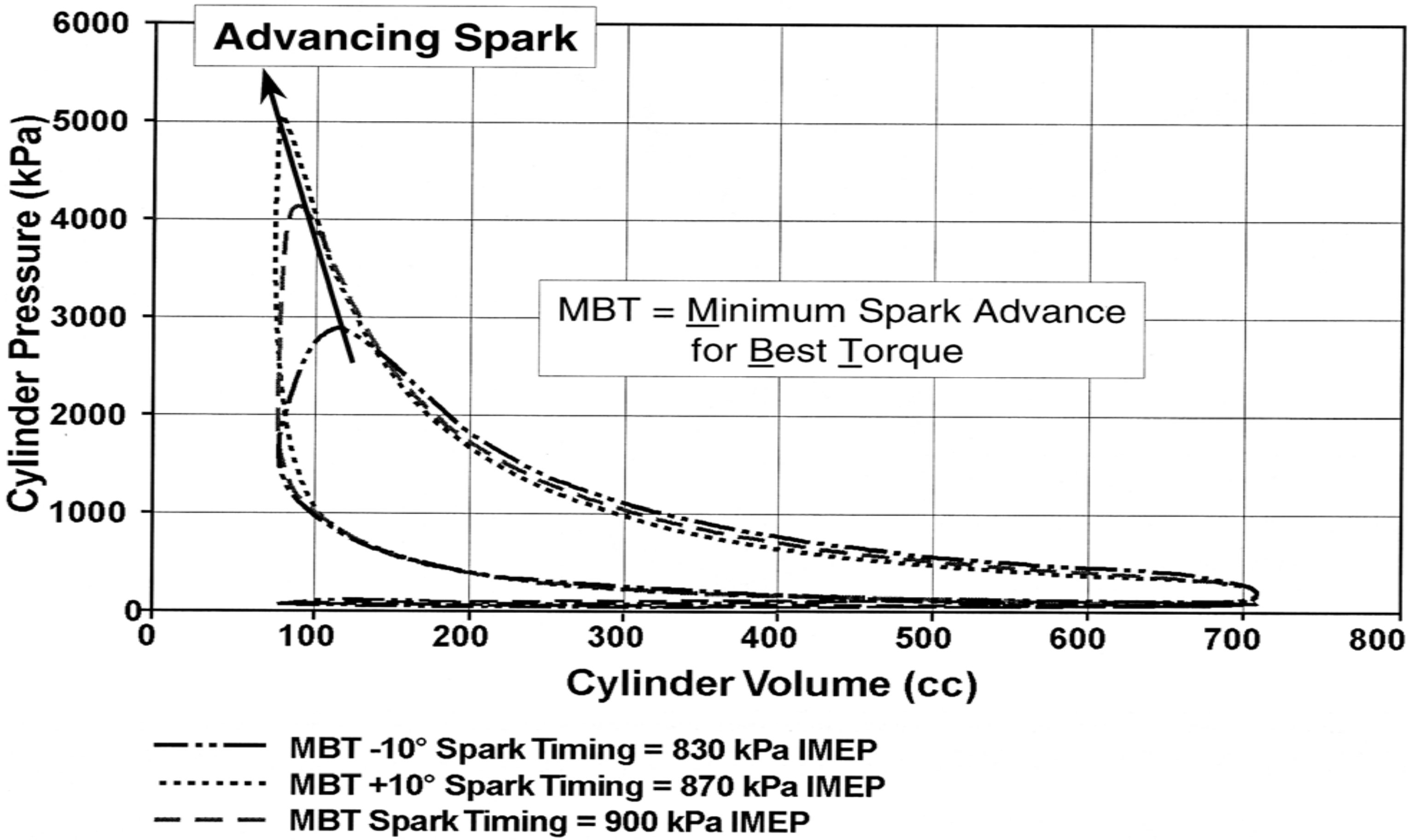
@ 50 kPa MAP , IMEP = 420 kPa, PMEP = -48 kPa, NMEP = 372 kPa

@ 70 kPa MAP , IMEP = 750 kPa, PMEP = -33 kPa, NMEP = 717 kPa

@ 100 kPa MAP , IMEP = 1180 kPa, PMEP = -7 kPa, NMEP = 1173 kPa

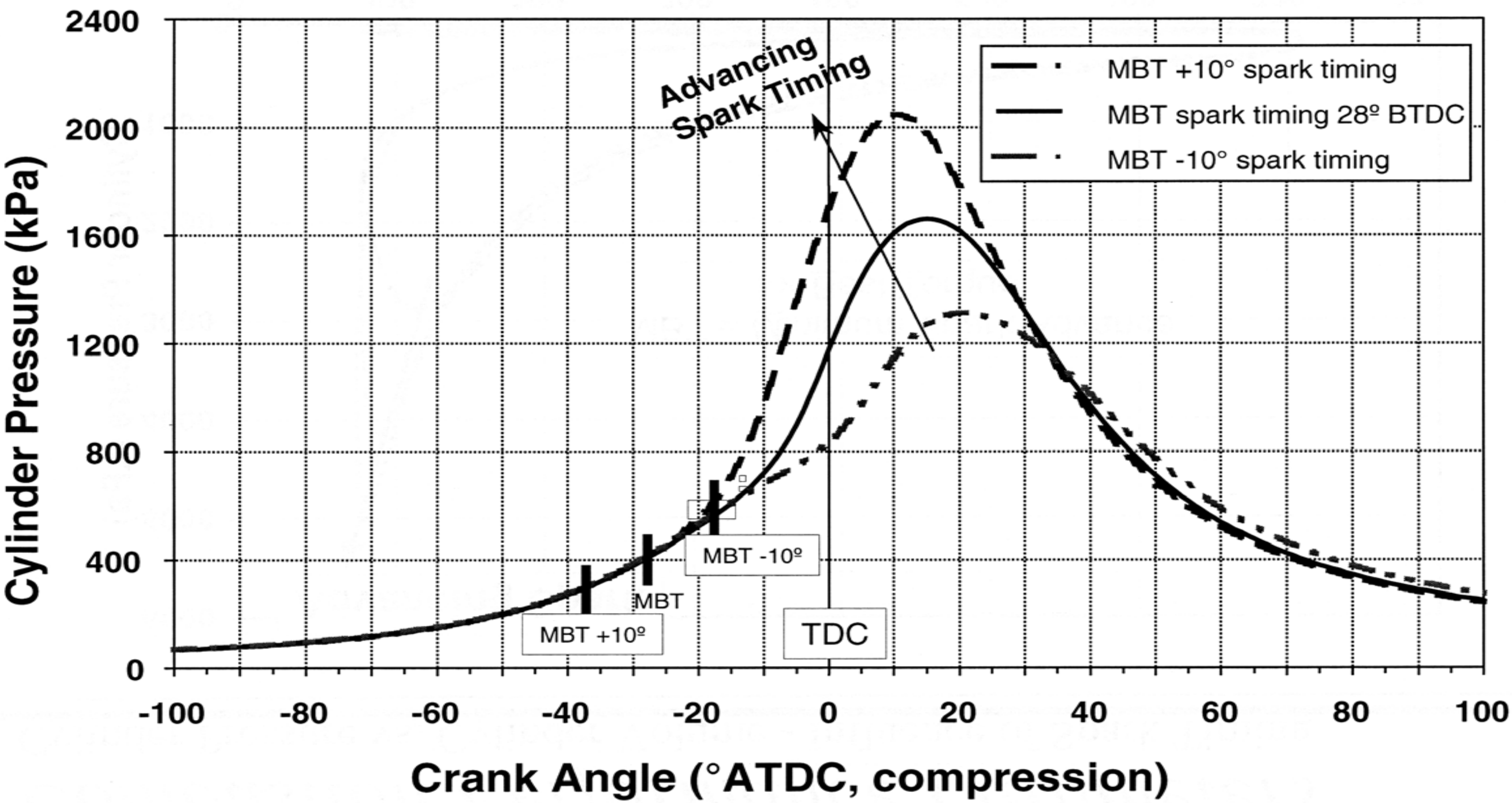
Combustion Performance Parameters

Cylinder Pressure vs Cylinder Volume-
Influence of Spark Timing

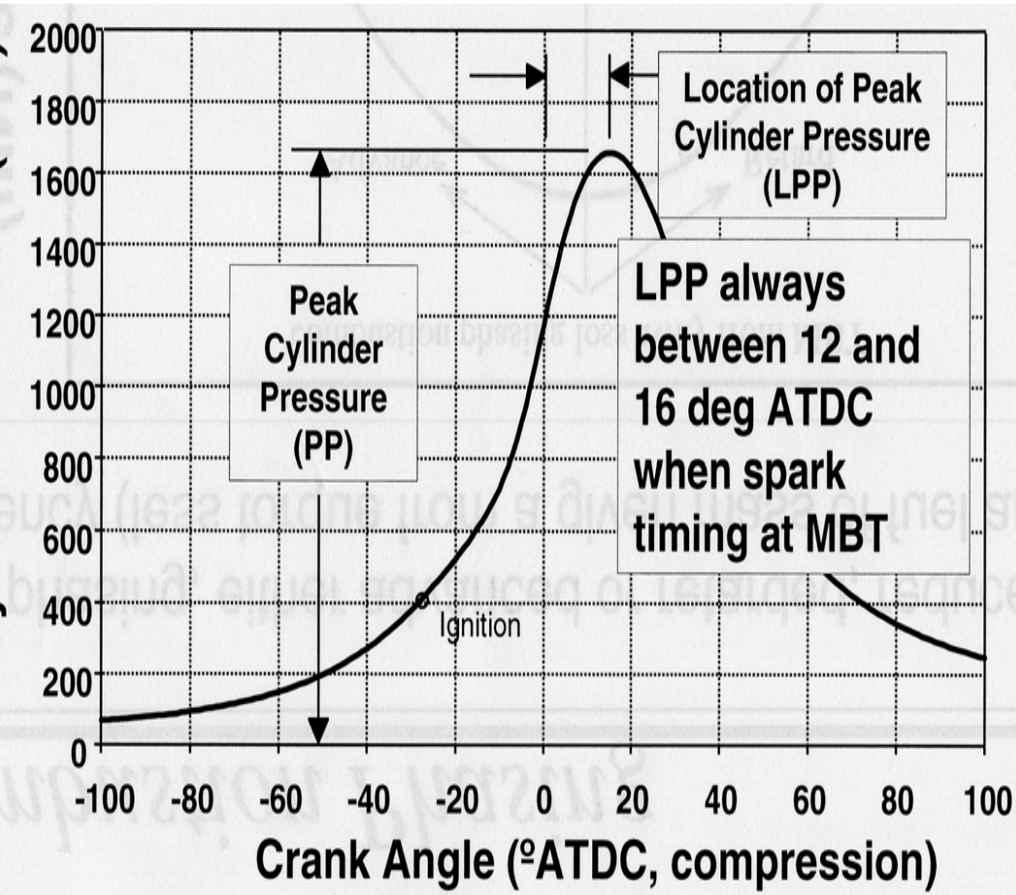


Combustion Performance Parameters

Cylinder Pressure vs Crank Angle- Influence of Spark Timing

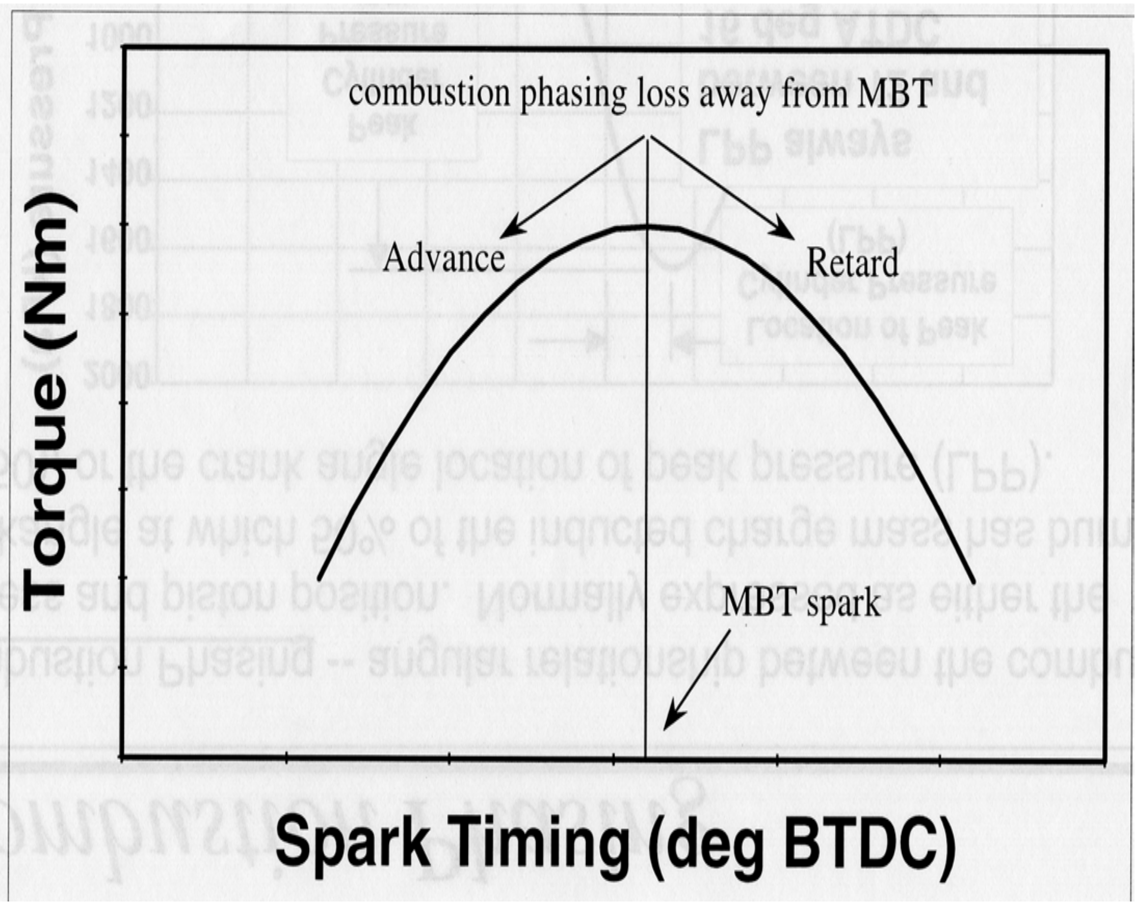


Combustion Phasing



Angular relationship between the combustion process and piston position. Normally expressed as either the crank angle at which 50% of the inducted charge mass has burned(CA50),or the crank angle location of peak pressure (LPP)

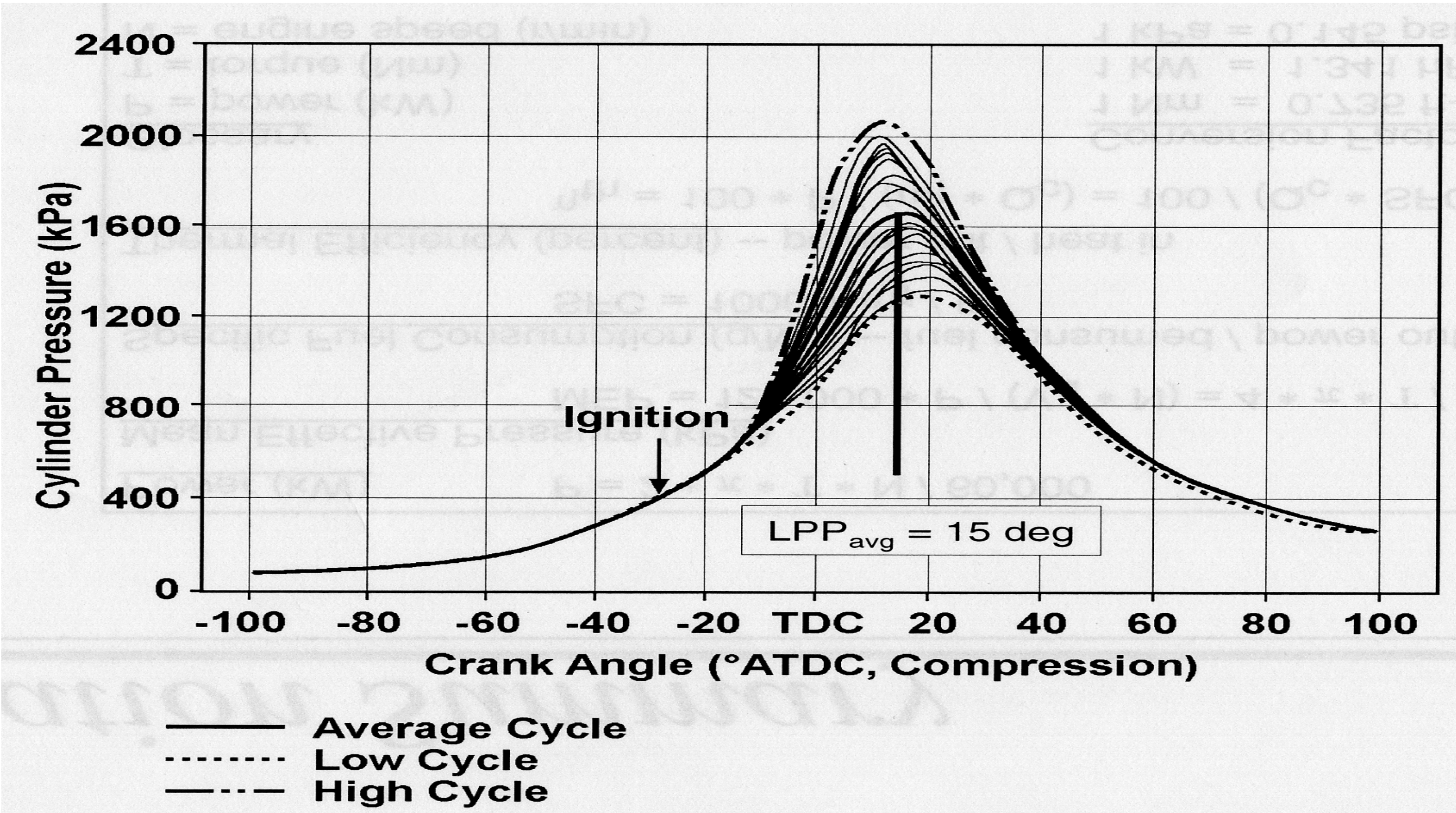
Combustion Phasing



Poor phasing, either advanced or retarded, reduces efficiency (less torque from a given mass of fuel and air)

Combustion Phasing

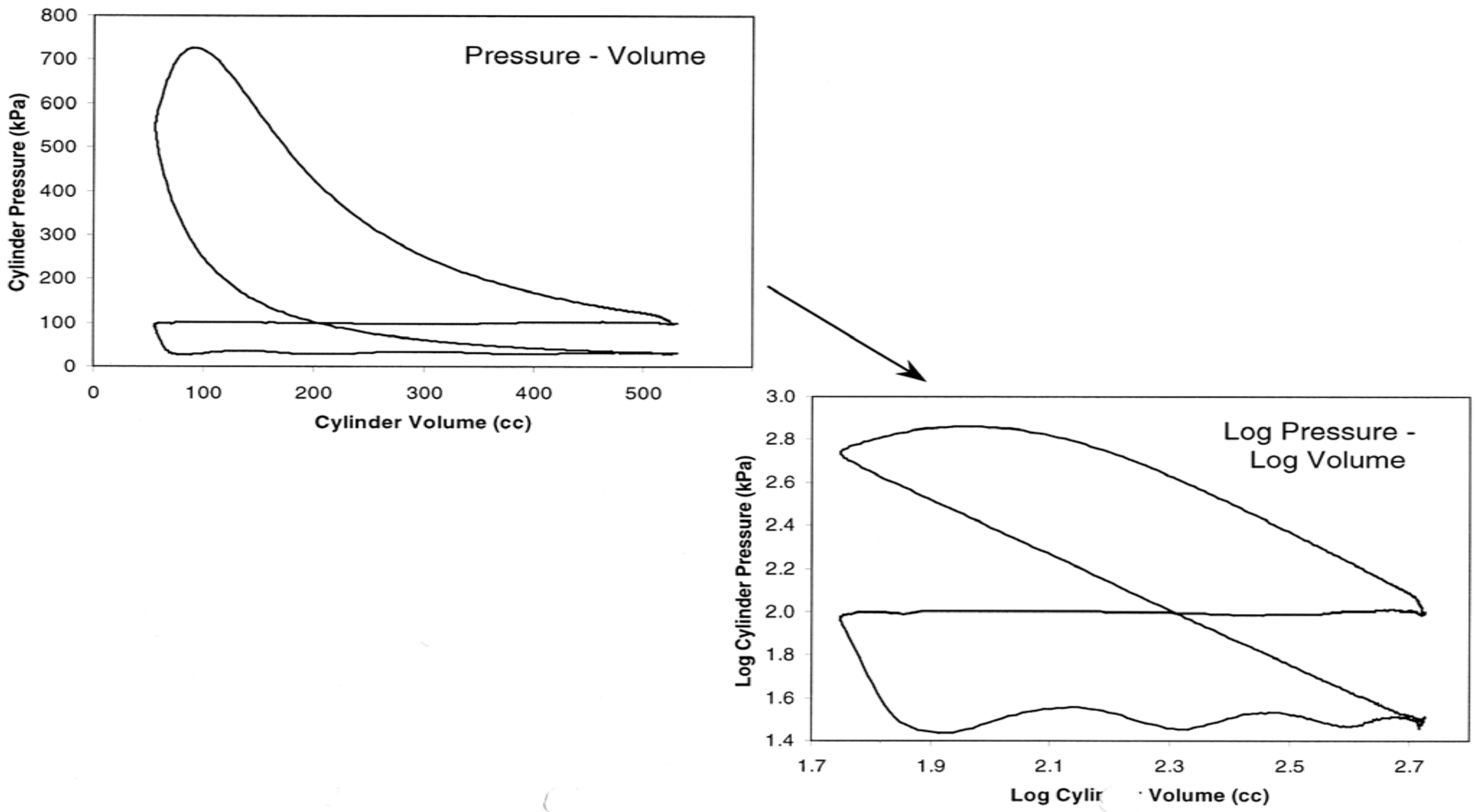
Cyclic combustion variability produces cyclic phasing varaibility



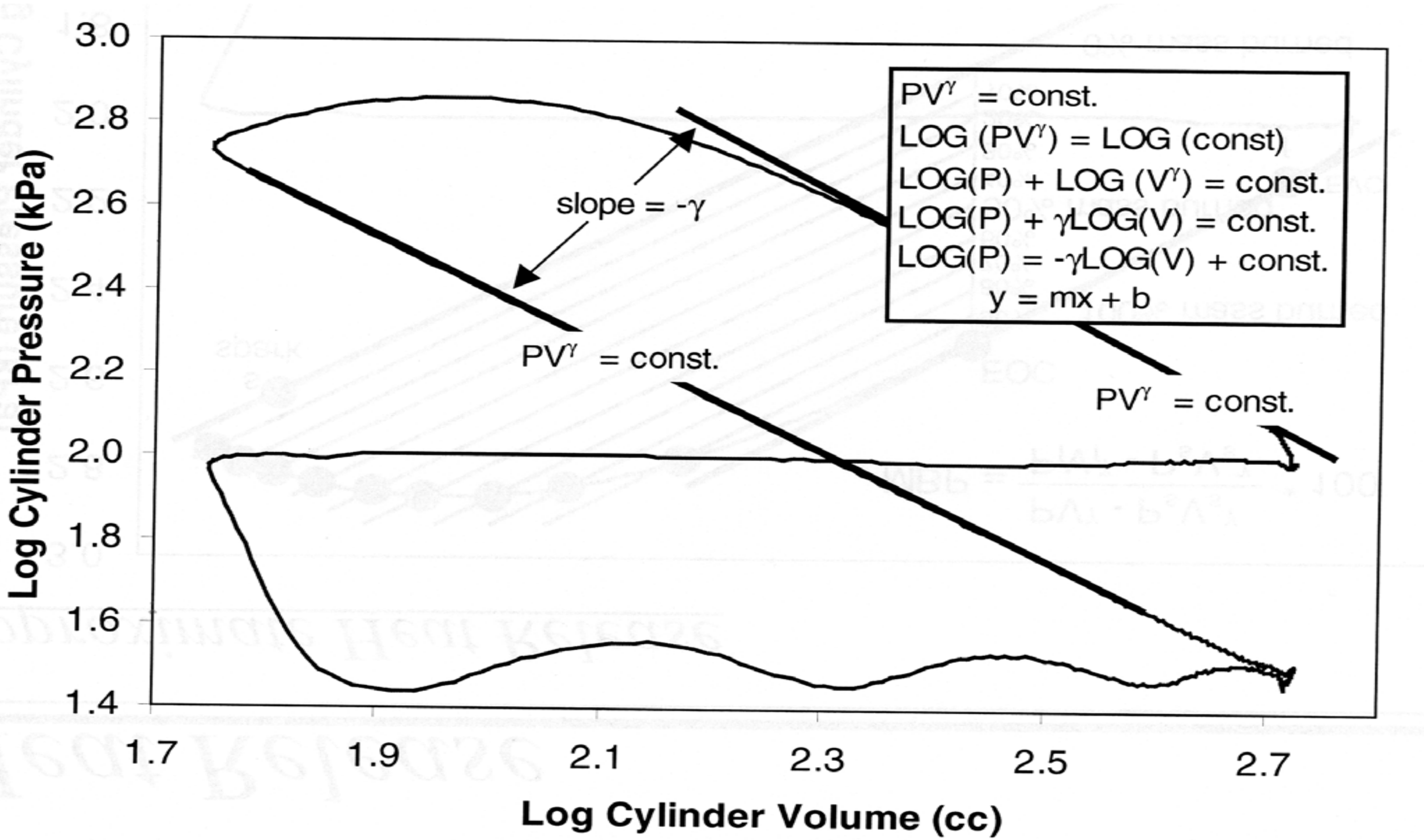
Heat Release

Analysis of cylinder pressure from a firing engine to determine the burn history of the combustion event on a crank-angle –by- crank-angle basis

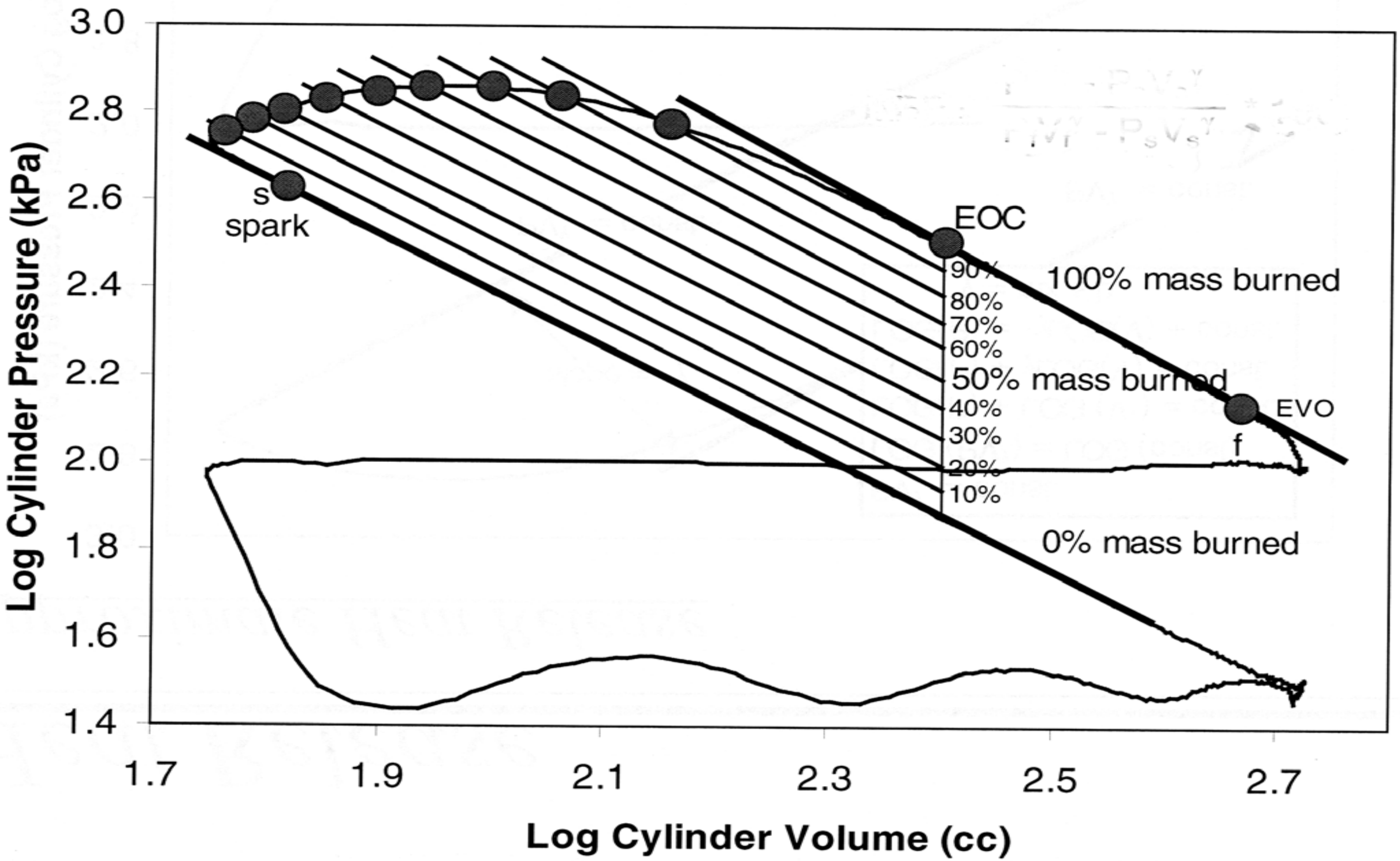
Approximate Heat Release



Approximate Heat Release



Heat Release
Approximate Heat Release



Heat Release

Approximate Heat Release

- **Advantages**
  - Computationally simple—can be performed in real time
  - Requires relatively few, readily available inputs
- **Major assumptions**
  - All cycles have 100% combustion efficiency
  - Polytropic coefficients are equal and constant
- **Recommended Application**
  - Stable operating condition with no partial burns

Heat Release

<u>Thermodynamic Heat Release</u>

Advantages:

- Thermodynamically tracks the mass of fuel burned on an individual – cycle basis, permitting..
  - Quantifying partial burns and misfires
  - Quantifying residual fraction and residual composition
  - Quantifying heat losses
- Provides accurate statistics on burn rate variability

Heat release

- **Thermodynamic Heat Release**
- **Assumptions:**
  - Heat transfer can be modelled by an empirical correlation (modified Woschni)
  - Pressure data and other inputs are accurate
- Other Inputs:
  - Swirl number, fuel flow, stoichiometry,combustion efficiency, lower heating value of fuel, combustion chamber surface area, valve timing
- **Recommendations:**
  - Combustion evaluation at conditions with high cycle variability

Heat Release

Processing Options for CAS

- Approximate -- as in ACAP currently
- Modified Thermodynamic -- First Law without heat loss term -- greatly simplifies analysis ** CAS Real Time **

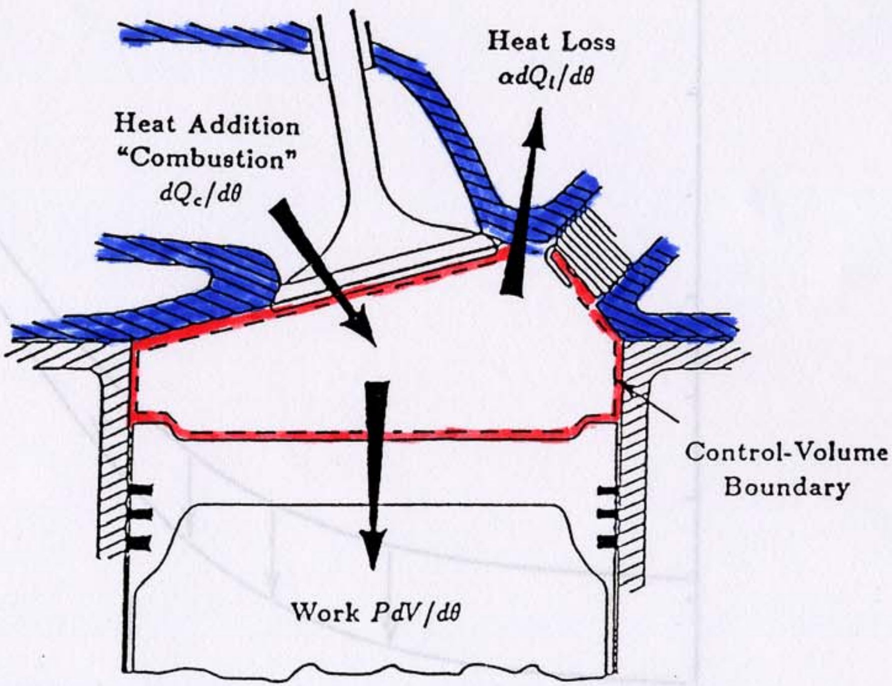
$$\delta Q(i) = \frac{1}{\gamma - 1}\left[\gamma P \partial V + V \partial P\right] = \frac{1}{\gamma - 1}\left[\gamma P_i (V_i - V_{i-1}) + V_i (P_i - P_{i-1})\right]$$

- Full Thermodynamic ** CAS Post Process **

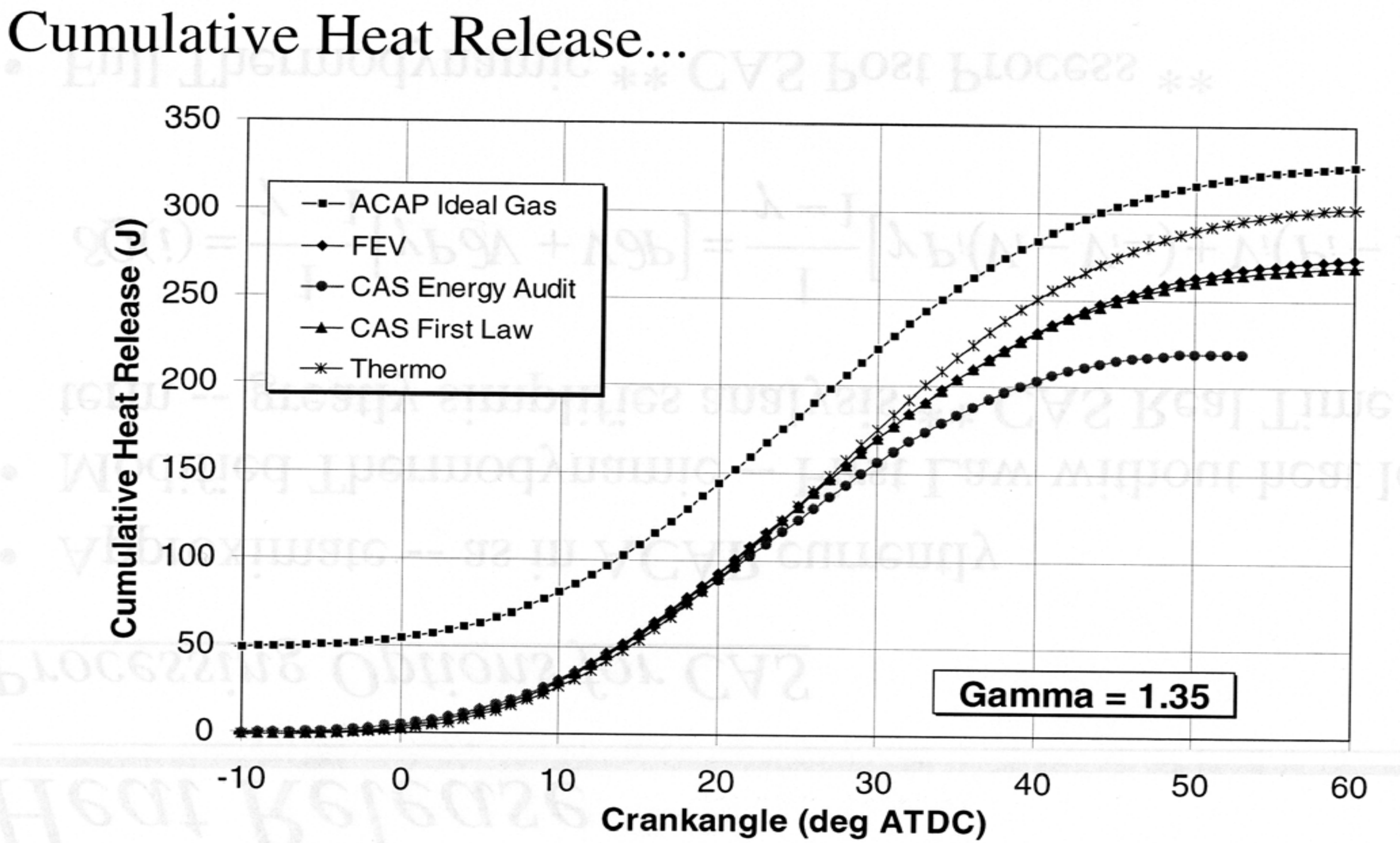
Heat Release
Thermodynamic Heat Release

First Law $$\delta Q = \Delta U + \Delta KE + \Delta PE + \Delta Q + \delta w$$

δQ = heat released,
ΔU = internal energy = $mC_V\partial T$,
ΔKE = kinetic energy,
ΔPE = potential energy,
ΔQ = heat losses (and mass losses),
δw = work performed = $\int PdV$,
m = trapped mass,
C_V = specific heat at constant volume,
T = bulk average cylinder temperature,
P = cylinder pressure, and
V = cylinder volume.

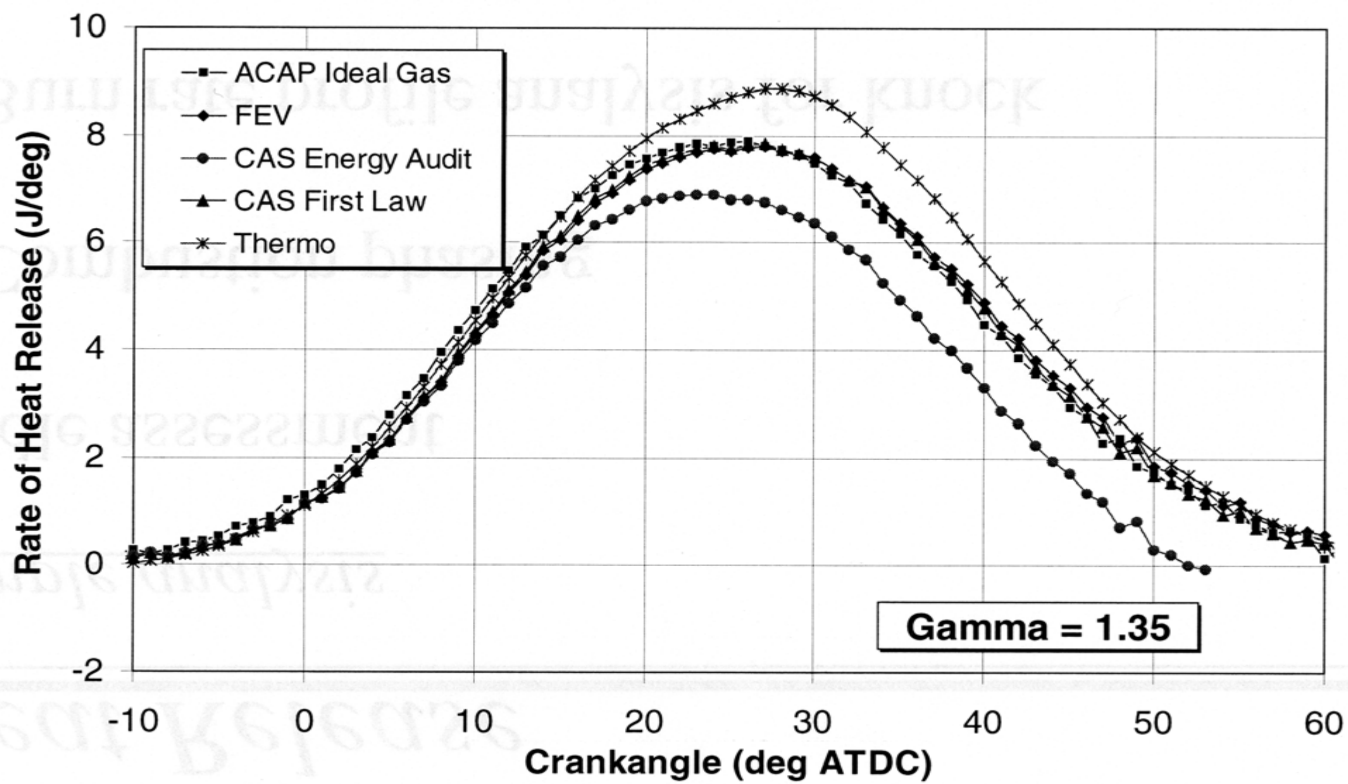


Heat Release
Processing Options for CAS, cont..

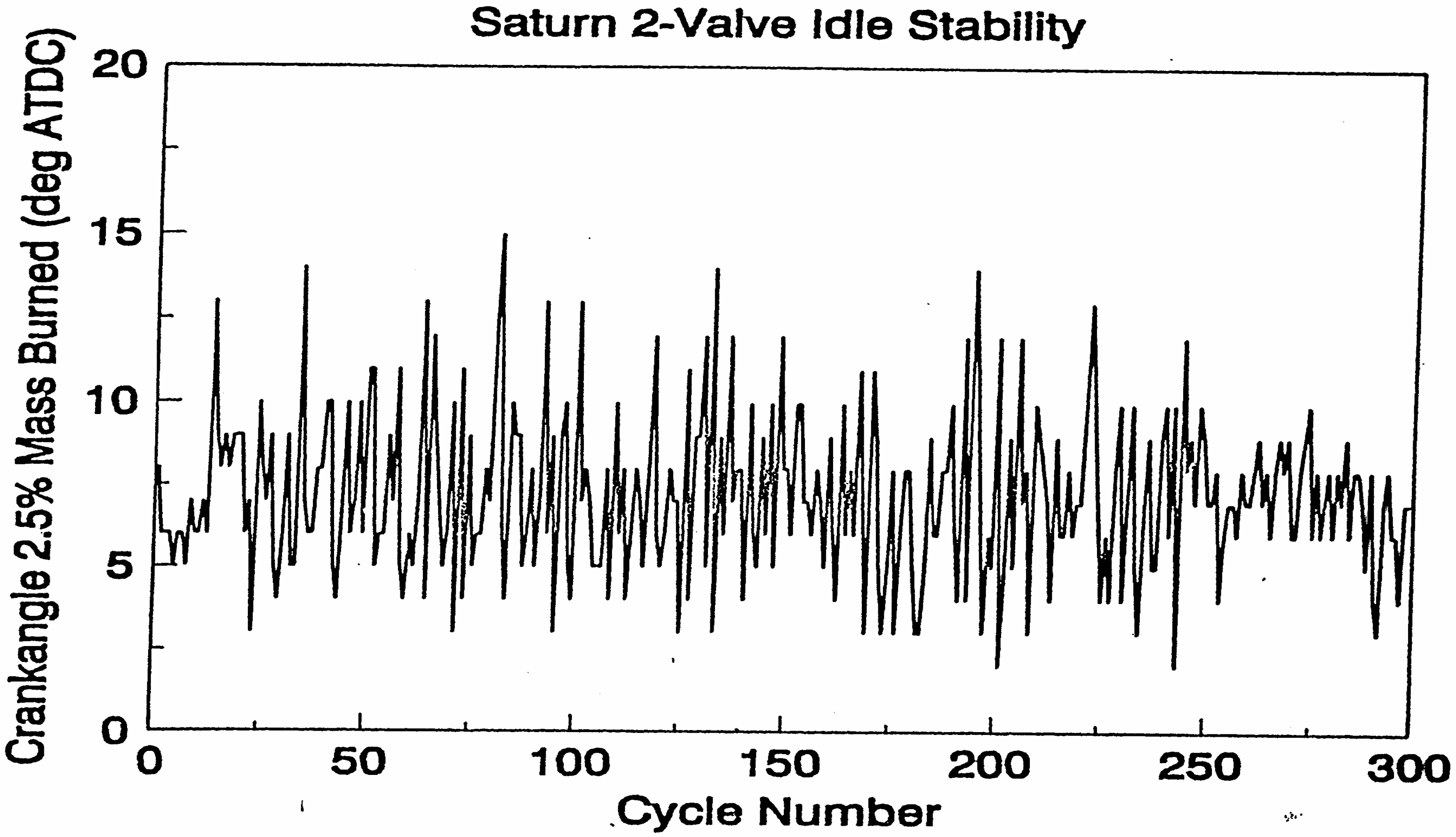


Heat Release
Processing Options for CAS cont.

Rate of Heat Release...



Look again at cycle to cycle differences !!!



Heat Release

<u>Sample Analysis</u>

- Idle assessment
- Combustion phasing
- Burn rate profile analysis for knock

Combustion Variability

<u>What is it ?</u>

Variation in combustion (IMEP) from cycle-to-cycle and cylinder-to-cylinder.

Engine cycles are like fingerprints--- no two are the same.

Combustion Variability

How does it manifest itself

- **Engine roughness**
  - Cyclic and cylinder-to –cylinder variations in torque and engine speed
- **Compromised torque/power**
- **Lower resistance to knock**
- **Efficiency losses**
  - Higher emissions
  - Lower fuel consumption
    - Compromised spark timing
    - Compromised dilution tolerance

Combustion Variability

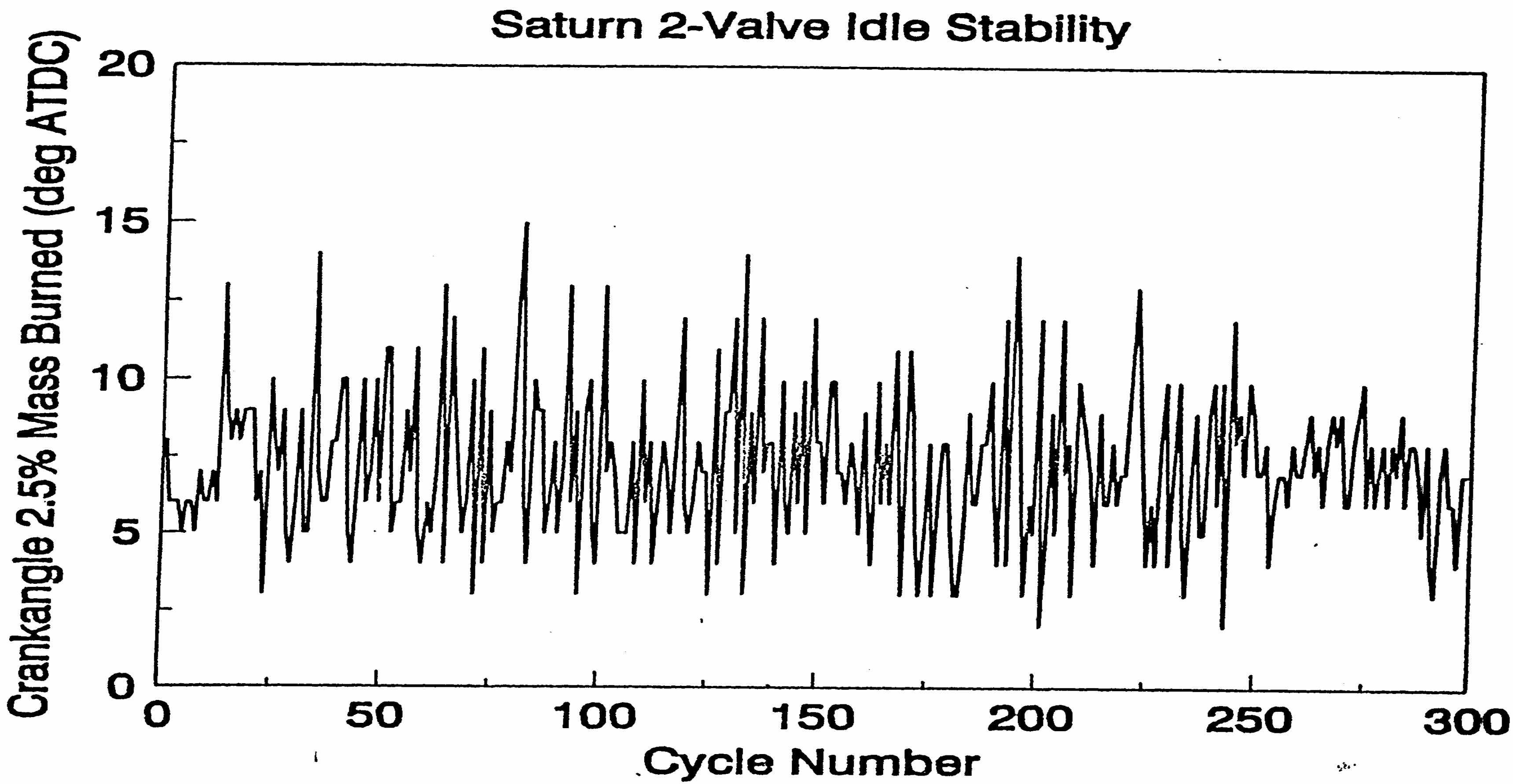
Causes

- Mixture motion at the location and time of spark
- Variation in the amount of air and fuel inducted each cycle
- Mixing of the air,fuel, and exhaust residuals
- Fuel preparation(droplet size,cone angle,targeting)
- Long burn duration due to poor combustion system hardware design
- Low ignition energy,small plug gap

Combustion Variability

- Combustion variability impacts engine performance at all operating conditions:
  - **Idle**
    - Instability is typically driven by variations in fuel flow and exhaust residuals
  - **Part-Load**
    - Variability is driven by fuel flow variations and EGR
  - **WOT**
    - Combustion instability is typically dictated by variations in airflow

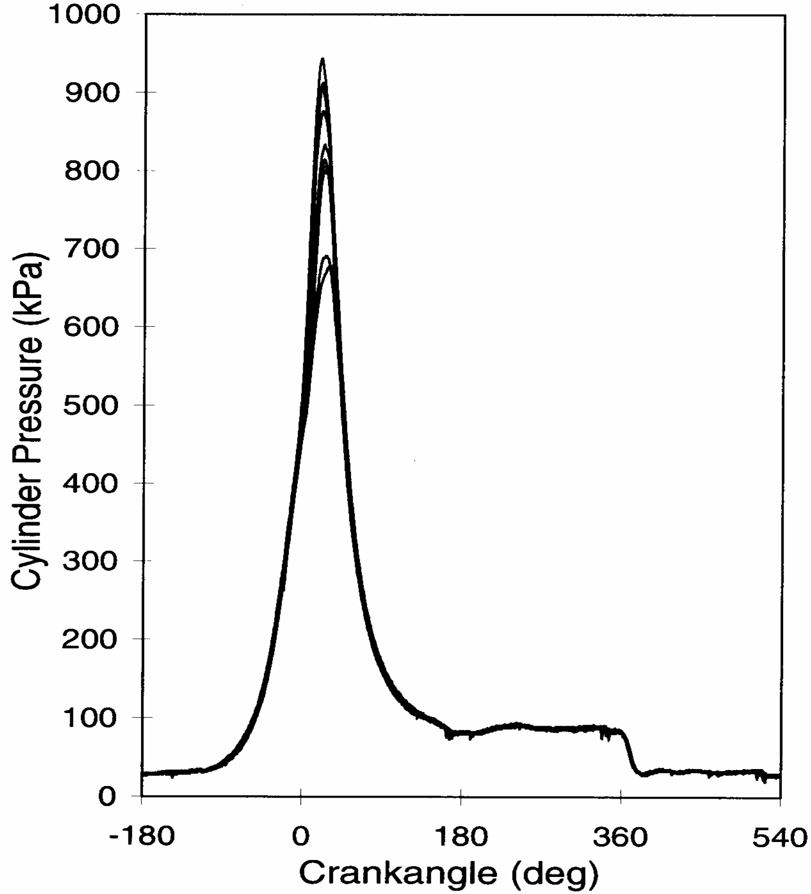
Combustion Variability



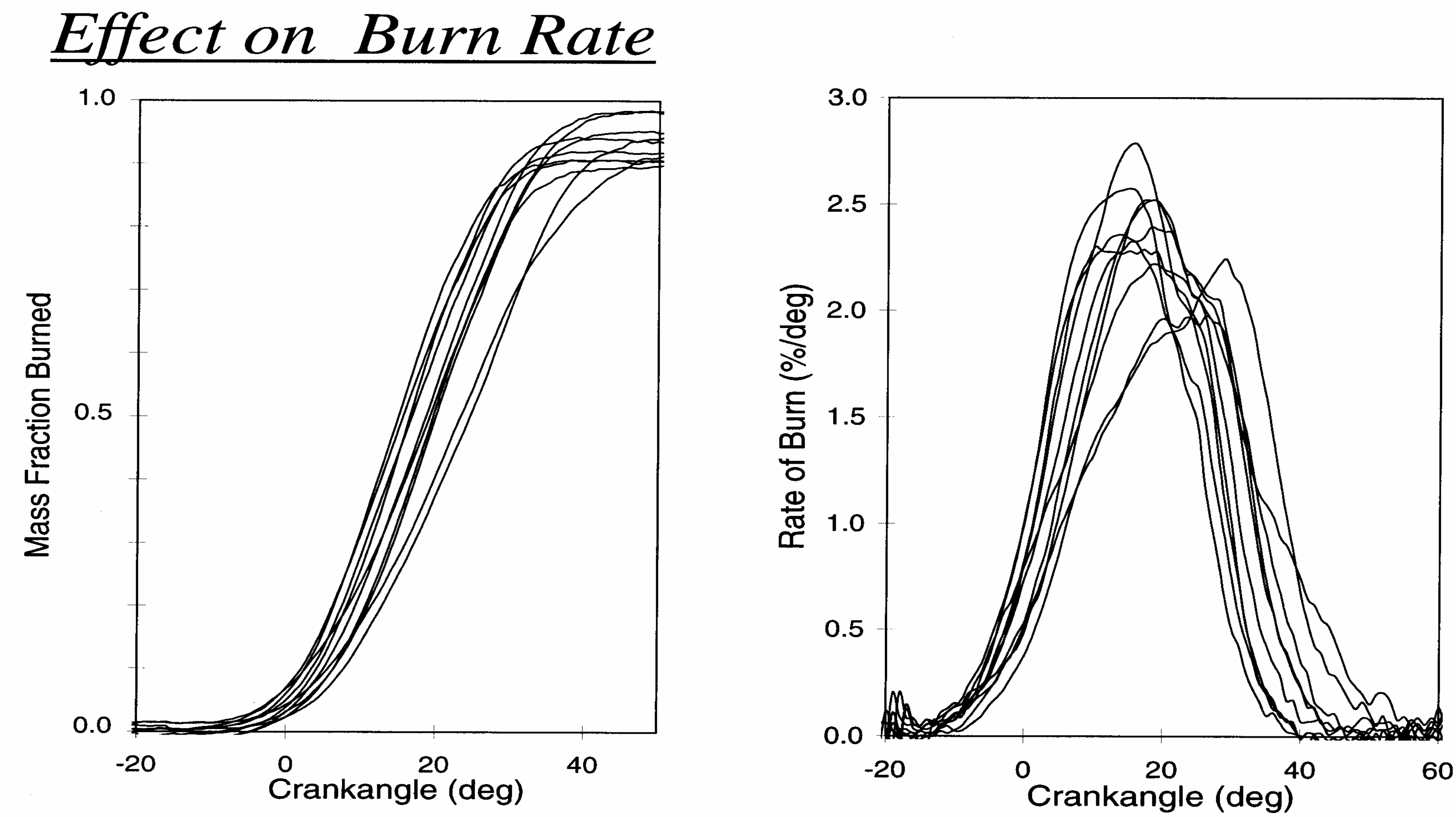
Combustion Variability

How is it Identified?

- Analysis of cylinder pressure versus time for 10 consecutive engine cycles shows that substantial variation exists.
- This variation is being dictated by cyclic combustion variability.
- Similar variability is present from cylinder-to-cylinder



Combustion Variability



Combustion Variability

How is it Quantified ?

- The most common methods to quantify cycle-to-cycle and cylinder-to-cylinder variability includes:
  - Standard deviation of IMEP
  - Coefficient of variation of IMEP
  - Lowest normalized value of IMEP
  - Standard deviation of rev/min
  - IMEP imbalance
  - RMS of the Delta IMEP
  - Variation of burn parameters

Combustion Variability

Standard Deviation of IMEP

- Standard deviation of the IMEP quantifies how widely values are dispersed from the mean:

$$STDEV\ of\ IMEP = \sqrt{\frac{n\sum_{i=1}^{n}(IMEP_i - \overline{IMEP})^2}{(n-1)}}$$

$$where:\ i = sample\ of\ interest$$

$$n = number\ of\ samples$$

  - This calculation can be performed on an individual cylinder to quantify cyclic variability, or on all cylinders to globally characterize engine stability (EAIMEP; STD, ELSIMEP; STD)

Combustion Variability

Coefficient of Variation of IMEP

- COV of IMEP quantifies variability in indicated work per cycle by expressing the standard deviation as a percentage of the mean IMEP:

$$\text{COV of IMEP} = \frac{\text{STDEV of IMEP}}{\text{IMEP}} * 100$$

  – While opinions vary, a degradation in vehicle driveability can typically be noticed when the COV of IMEP exceeds 3% - 5%.

Combustion Variability

<u>Lowest Normalized Value of IMEP</u>

- LNV of IMEP,an indicator of misfires and partial burning cycles,is determined by normalizing the lowest IMEP value in a data set by the mean:

$$\text{LNV of IMEP} = \frac{\text{IMEP}_{\text{min}}}{\text{IMEP}} \mathbf{*100}$$

  - LNV < 0 for a misfire
  - 0<LNV<89 indicates partial burn

Combustion Variability

IMEP Imbalance

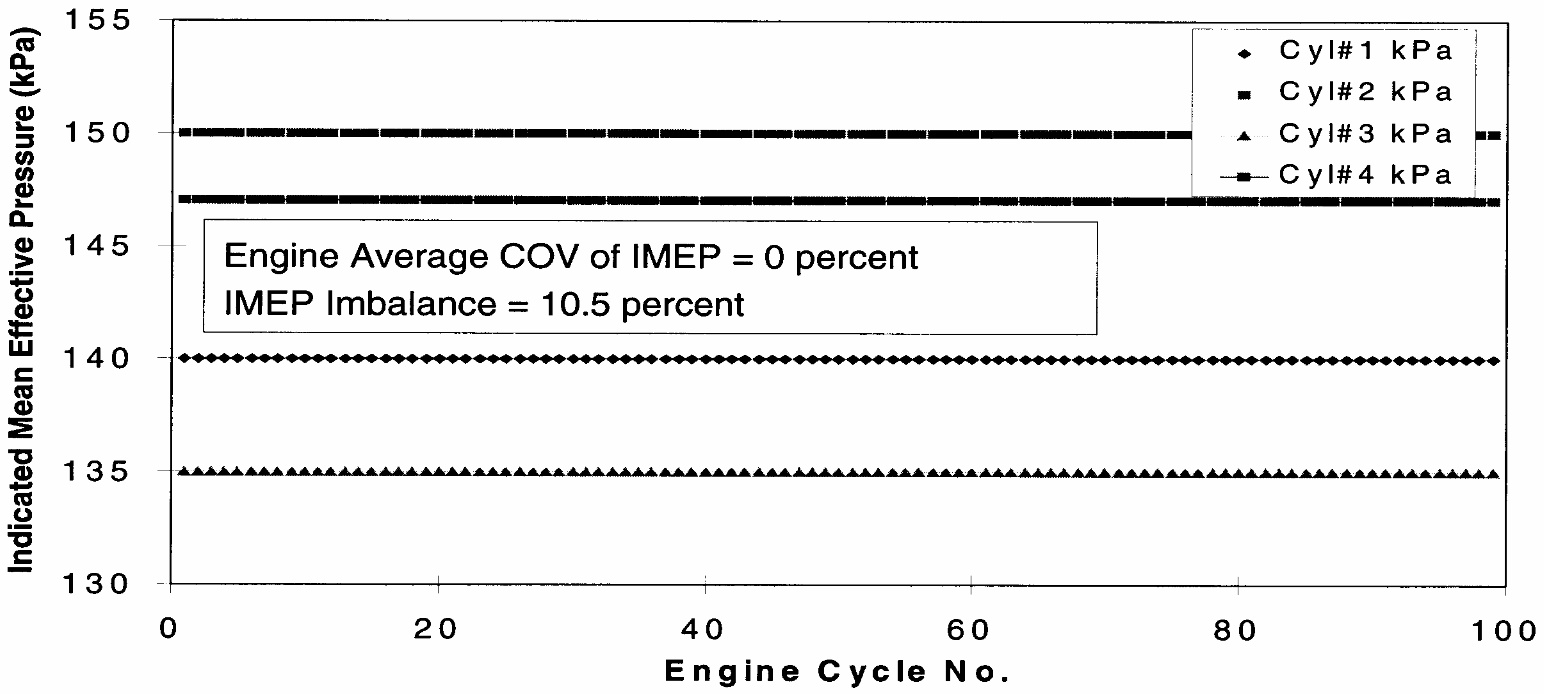
- IMEP imbalance, a measure of cylinder-to-cylinder variation, is quantified by subtracting the average IMEP in the weakest cylinder from the average IMEP in the strongest cylinder, and then normalising by the mean IMEP

$$IMEP_{imbalance} = \frac{IMEP_{i,max} - IMEP_{i,min}}{IMEP_{engine}} * 100$$

Combustion Variability

Potential Pitfall

- Engine average COV of IMEP can be misleading:



Combustion Variability

Some thoughts to ponder

- Do the combustion stability metrics already discussed provide the best measure of

  combustion stability?
- What does the driver feel?
- What about the difference in work from each cylinder event in firing order ?
- Is the phasing of the cylinder events important

Combustion Variability

RMS of the Delta IMEP

- RMS of the delta IMEP characterizes the difference in work performed each cylinder event, in firing order

$$RMS\ of\ \ \Delta IMEP = \sqrt{\frac{\sum \Delta IMEP^2}{(n_c * x) - 1}}$$

where:

$$n_c = number\ of\ \ cylinders$$

$$x = number\ of\ \ cycles$$

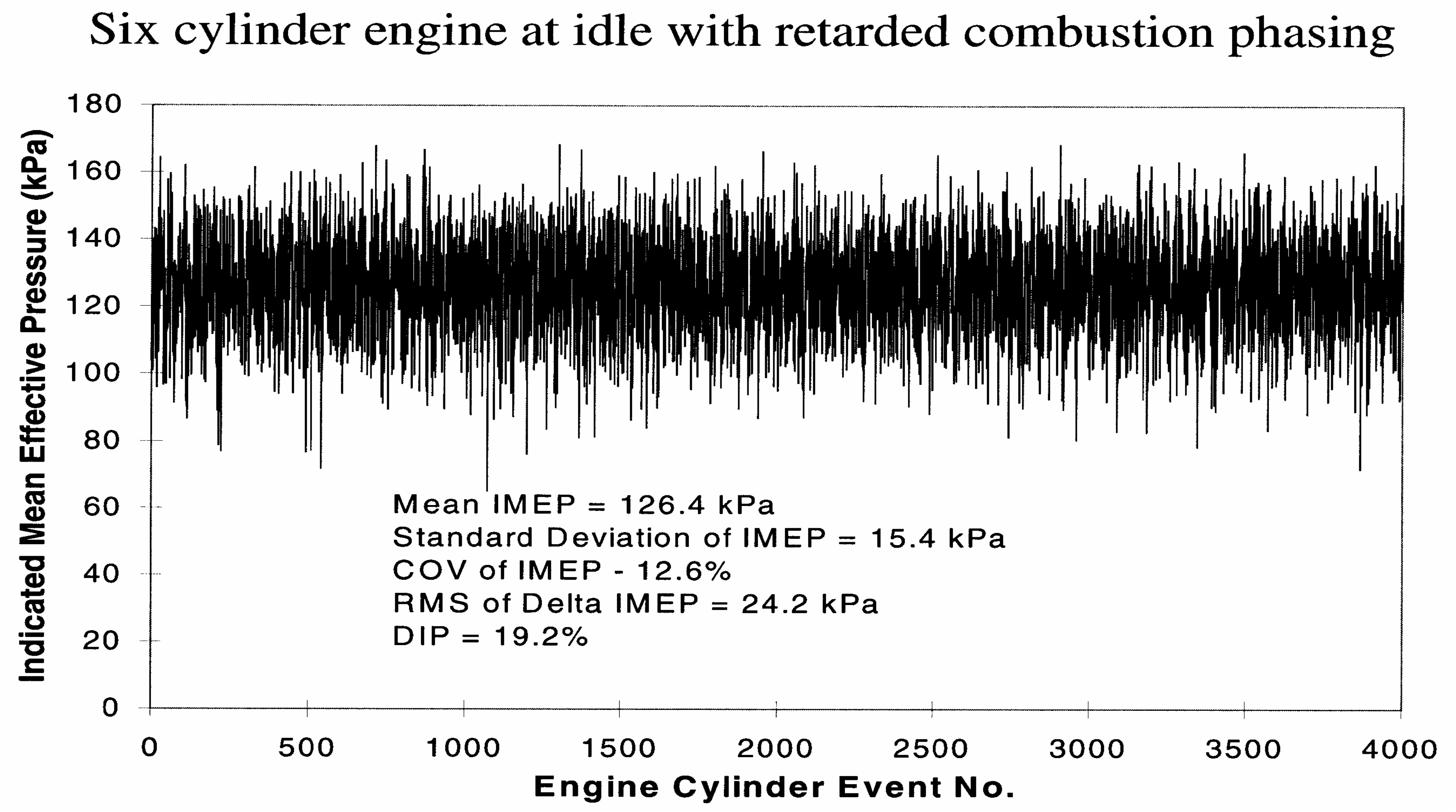
Combustion Variability

Differential Imbalance Percentage

- DIP quantifies the variation in the indicated work done between cylinder firing events by expressing the RMS as a percentage of the mean:

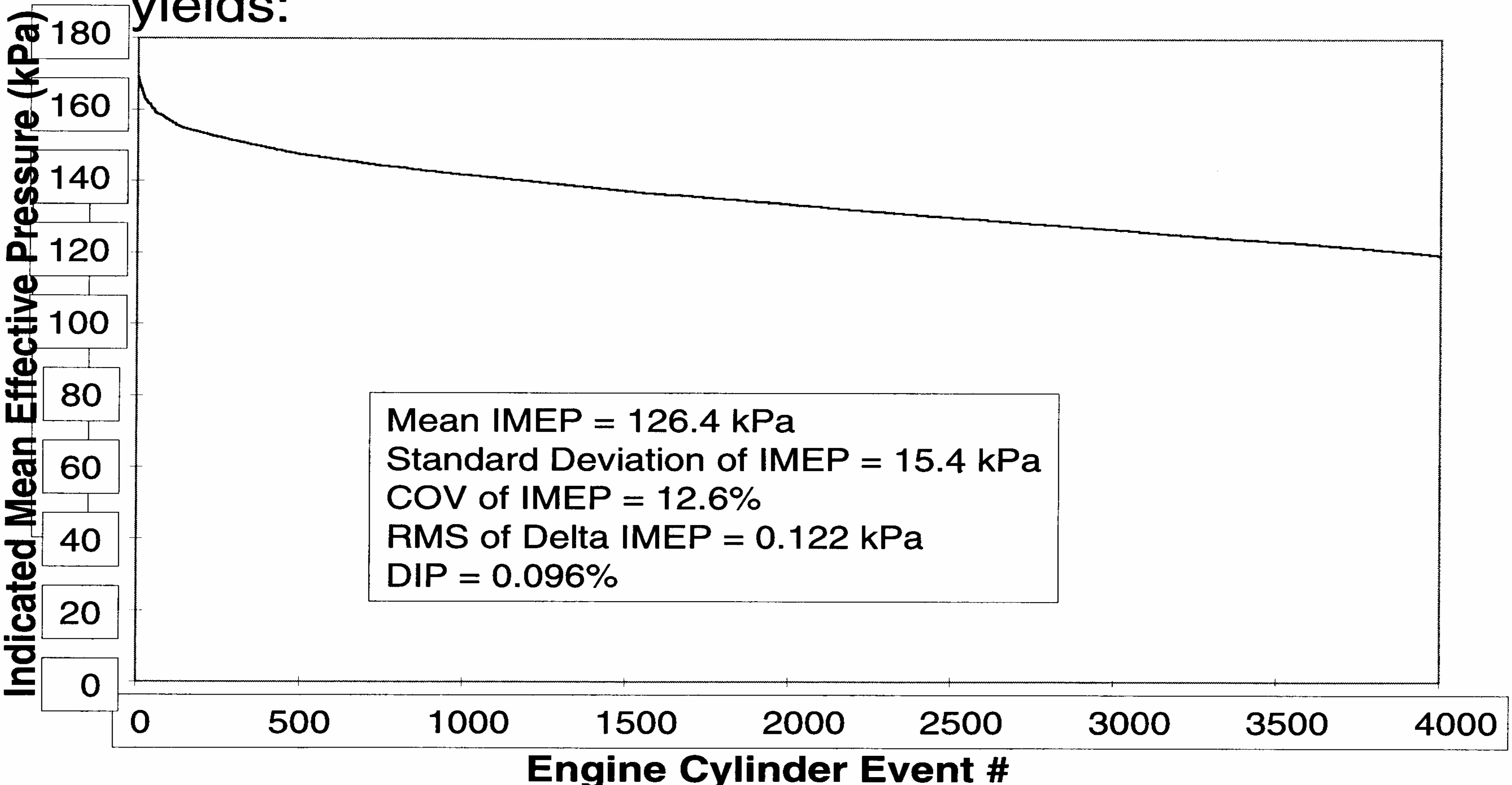
$$\text{Differential imbalance Percentage} = \frac{\text{RMS of } \Delta IMEP}{\overline{IMEP}} * 100$$

Combustion Variability



Combustion Variability

Sorting the same data from highest to lowest IMEP yields:



Combustion Variability

How is it Quantified ?

- Variations in Burn Duration are sometimes used to quantify combustion variability
  - A significant amount of combustion instability is driven by variation in the development of the flame kernel (0-2.5 to 10% mass burn duration)

Combustion Variability

- Still, none of the combustion stability metrics discussed comprehend the physical phasing of the events
  - What happens if the cylinder events are unevenly spaced ?

Combustion Variability

Rules of Thumb ** -

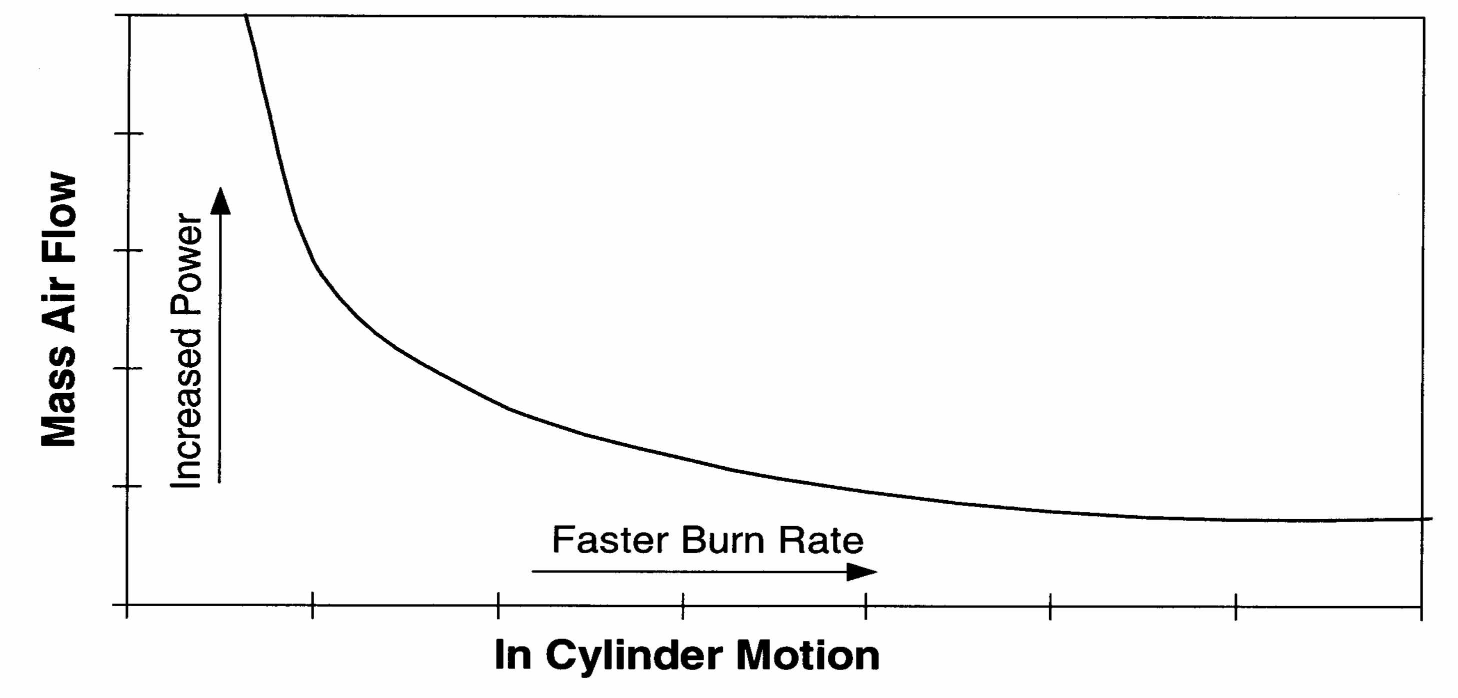
- Combustion stability improves with…
  - Increased speed and load
  - Higher compression ratios
  - Lower overlap cams
  - Higher energy (at the gap) ignition systems
  - Higher temperature
  - Lower humidity

**** These generalities do not always hold true !**

Combustion Variability

rade offs-

Unfortunately, there is typically a trade off between high airflow for power and high -cylinder motion for increased burn rates and less combustion variability



Combustion Variability

Steps to improve stability

- Well balanced combustion system hardware
  - Equal-length, replicated intake/exhaust runners & ports
  - Replicated combustion chambers (fast burning)
  - Good EGR, air,fuel,PCV & purge distribution
  - Good fuel injectors
    - Small droplets
    - Good targeting (back of valve, minimize wall-wetting)

Combustion Variability

Steps to improve stability

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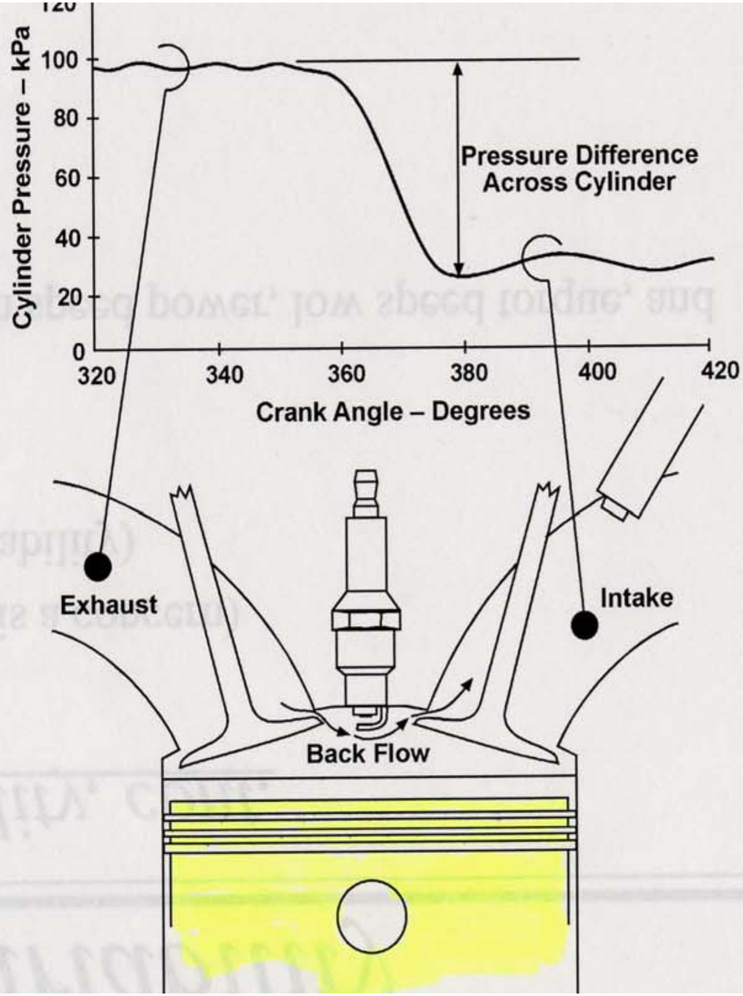
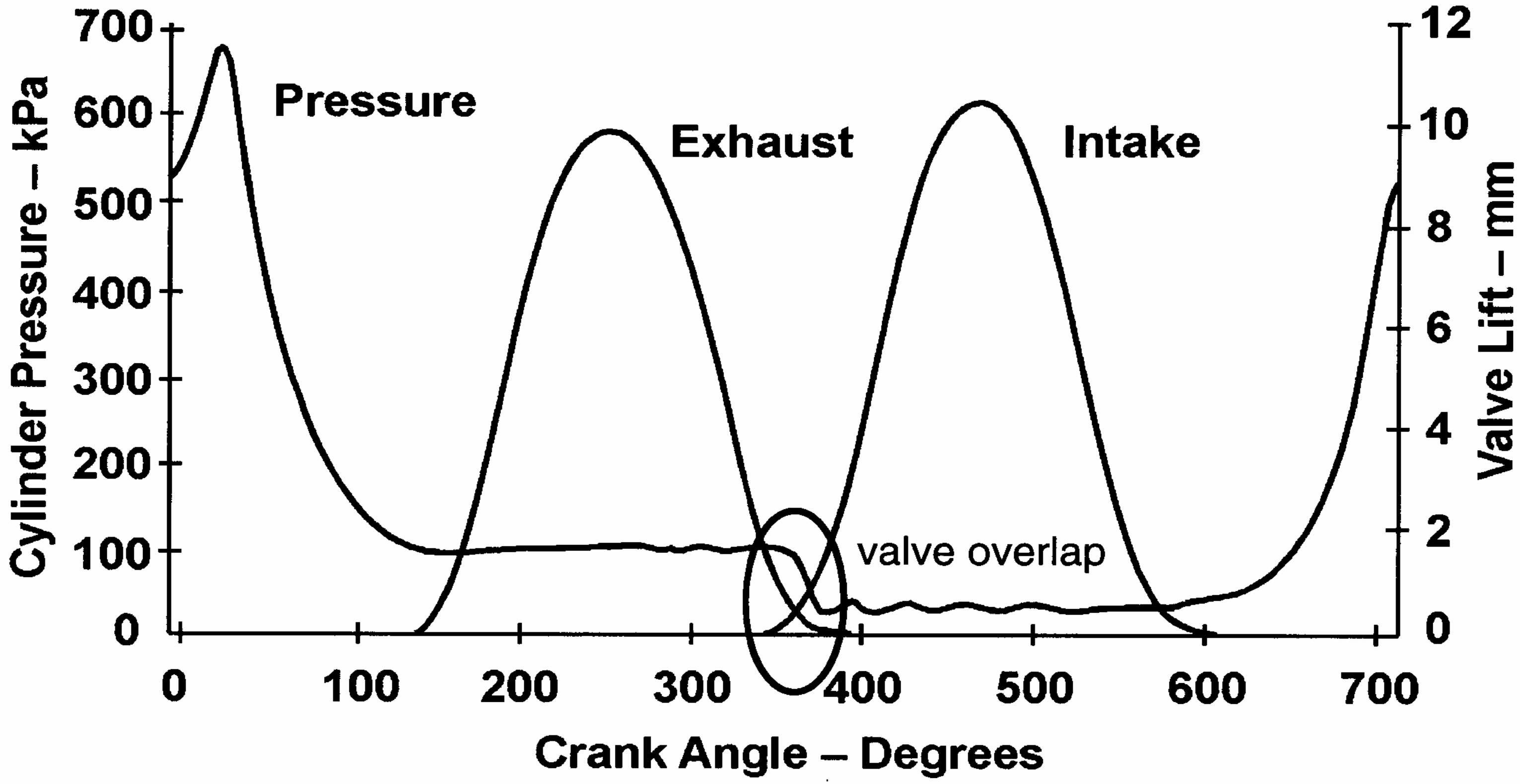
  - Good fuel injectors
    - Small droplets
    - Good targeting (back of valve, minimize wall-wetting)

Residuals

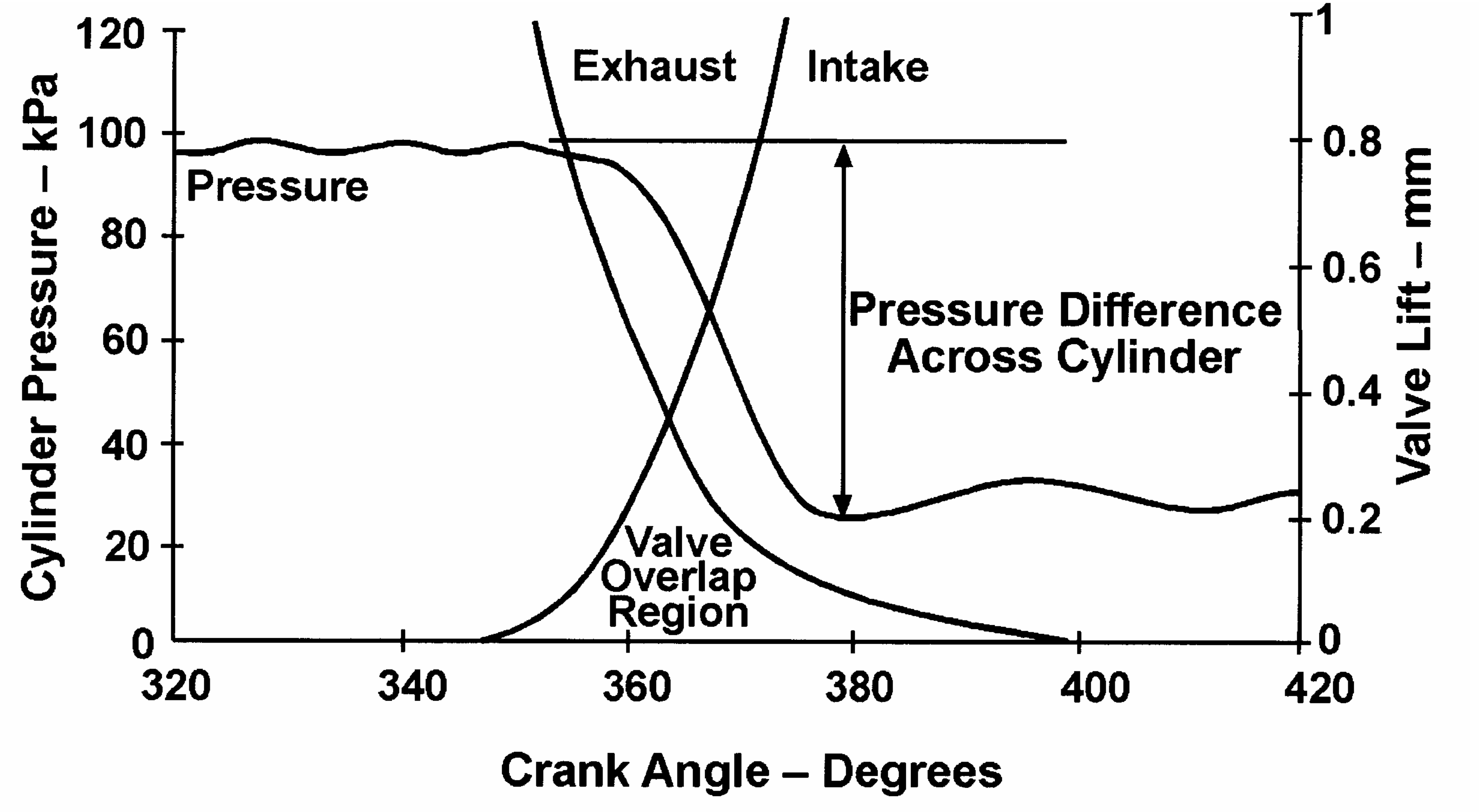
Residuals -- combustion products in the combustion chamber left over from the previous engine cycle



Residuals – Backflow of exhaust gas into the intake system occurs during valve overlap.



Residuals



Cylinder Pressure – kPa
120
100
80
60
40
20
0
Exhaust
Intake
Pressure
Pressure Difference
Across Cylinder
Valve
Overlap
Region
1
0.8
0.6
0.4
0.2
0
Valve Lift – mm
320
340
360
380
400
420
Crank Angle – Degrees

Residuals

Residuals are increased by:-

- Large valve overlap area
- Low engine speed (more time for back flow)
- Low induction manifold pressure
- High exhaust back pressure
- Low compression ratio

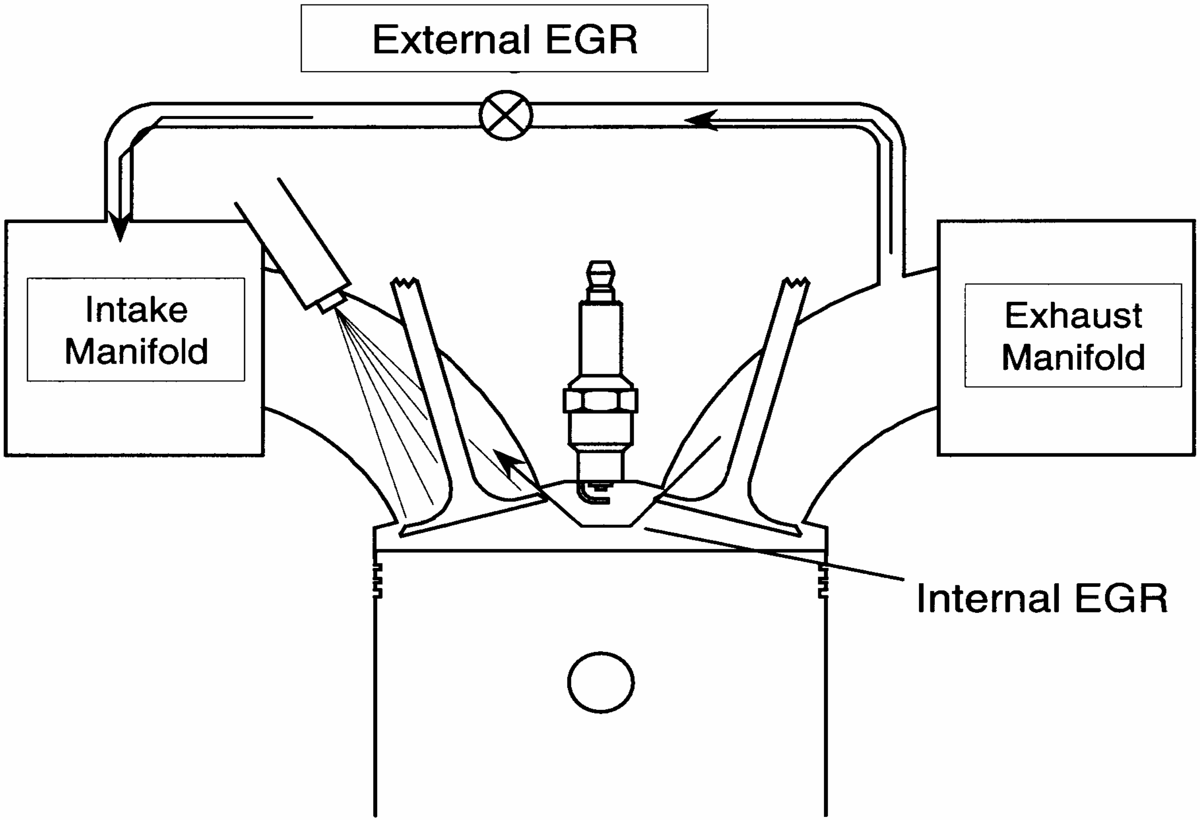
Residuals – SAE Paper 931025

presents a regression equation derived to predict residual fraction as follows:-

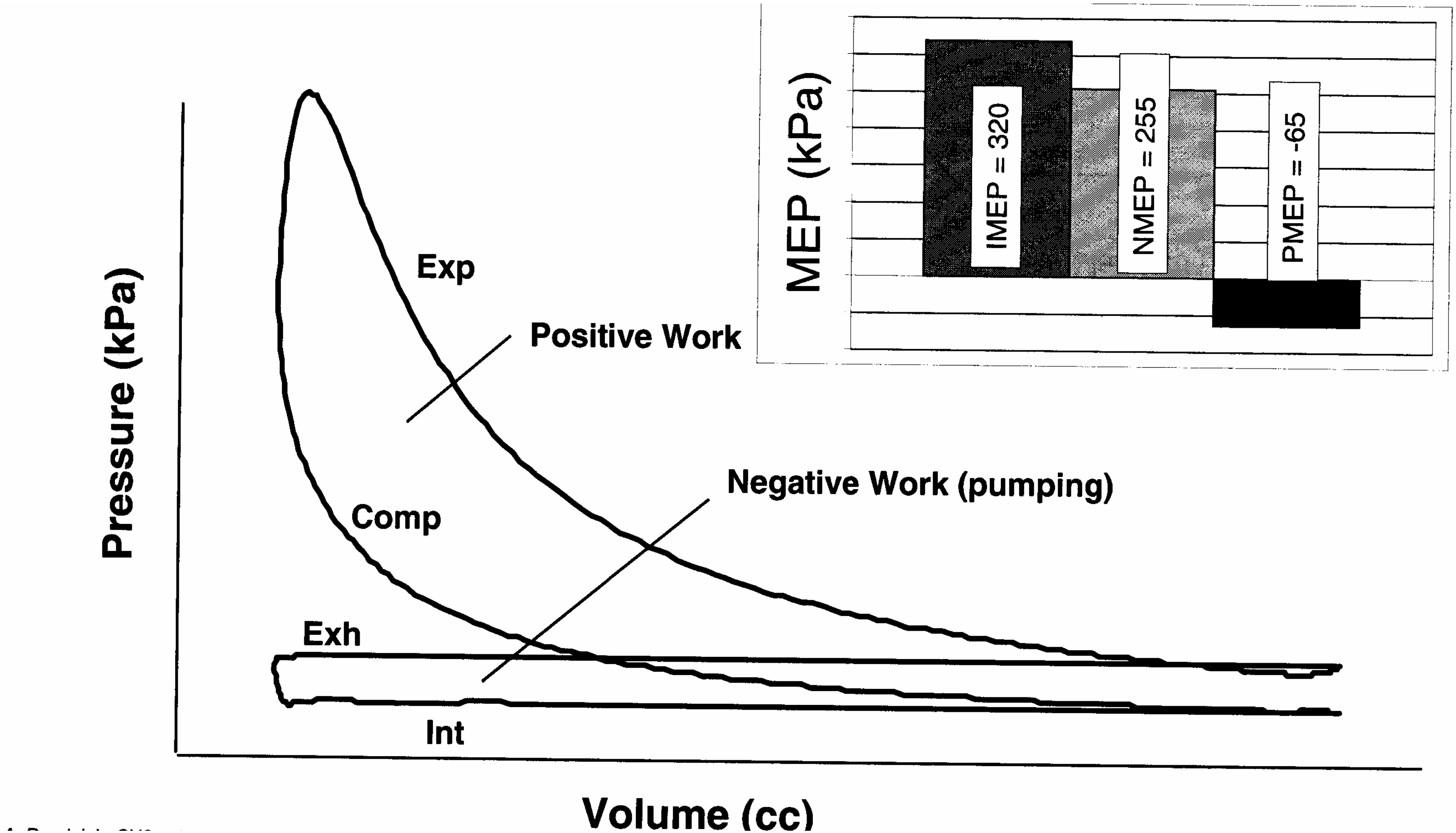
$$\chi_r = 1.266\,\frac{OF}{N}\left(\frac{P_i}{P_e}\right)^{-0.87}\sqrt{\left|P_e - P_i\right|} + 0.632\,\frac{\Phi\left(\frac{P_i}{P_e}\right)^{-0.74}}{r_c}$$

where, χ_r = residual fraction,
OF = overlap factor,
N = engine speed,
P_i = intake pressure,
P_e = exhaust pressure,
Φ = equivalence ratio, and
r_c = compression ratio.

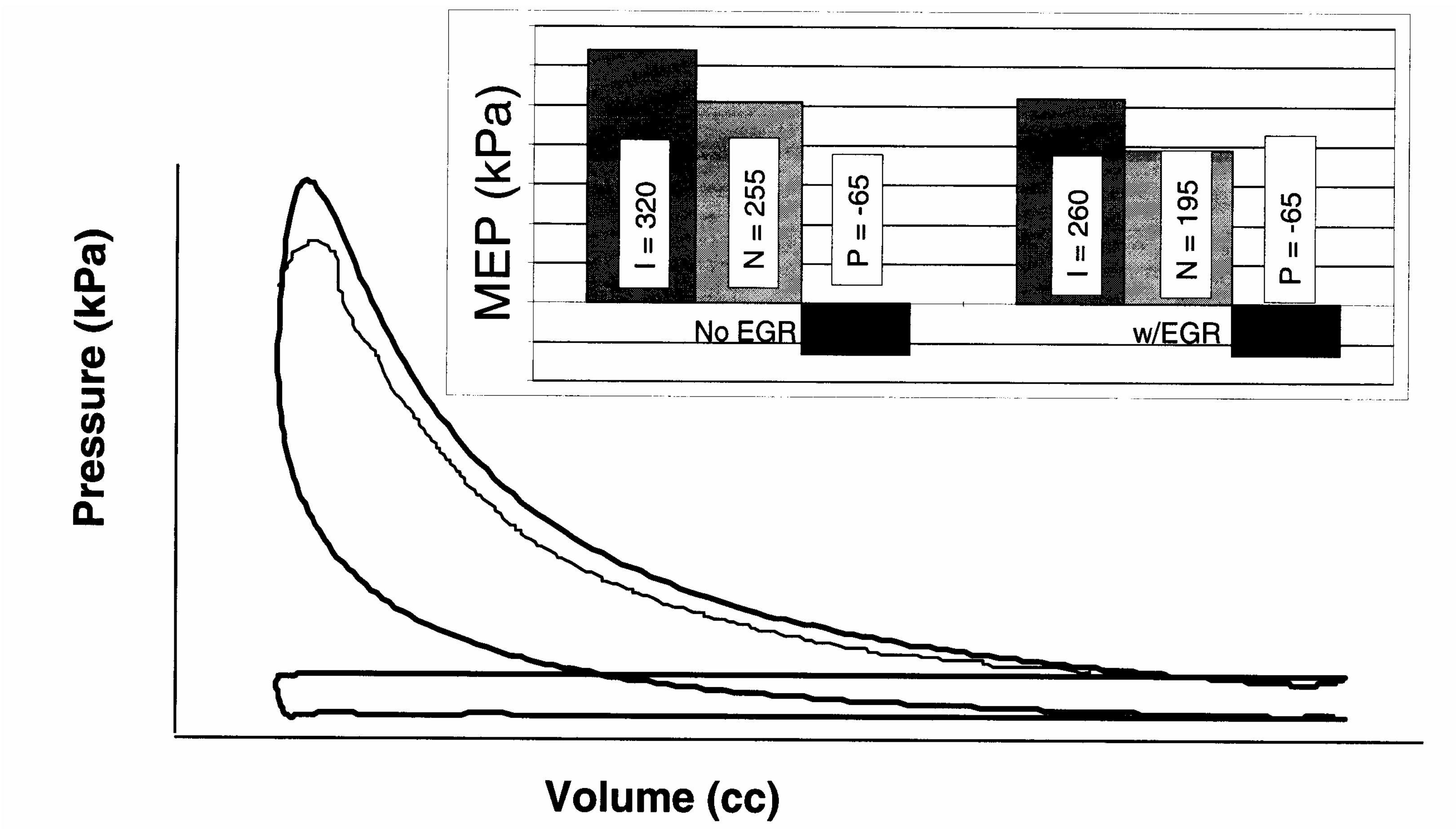
Exhaust Gas Recirculation (EGR)



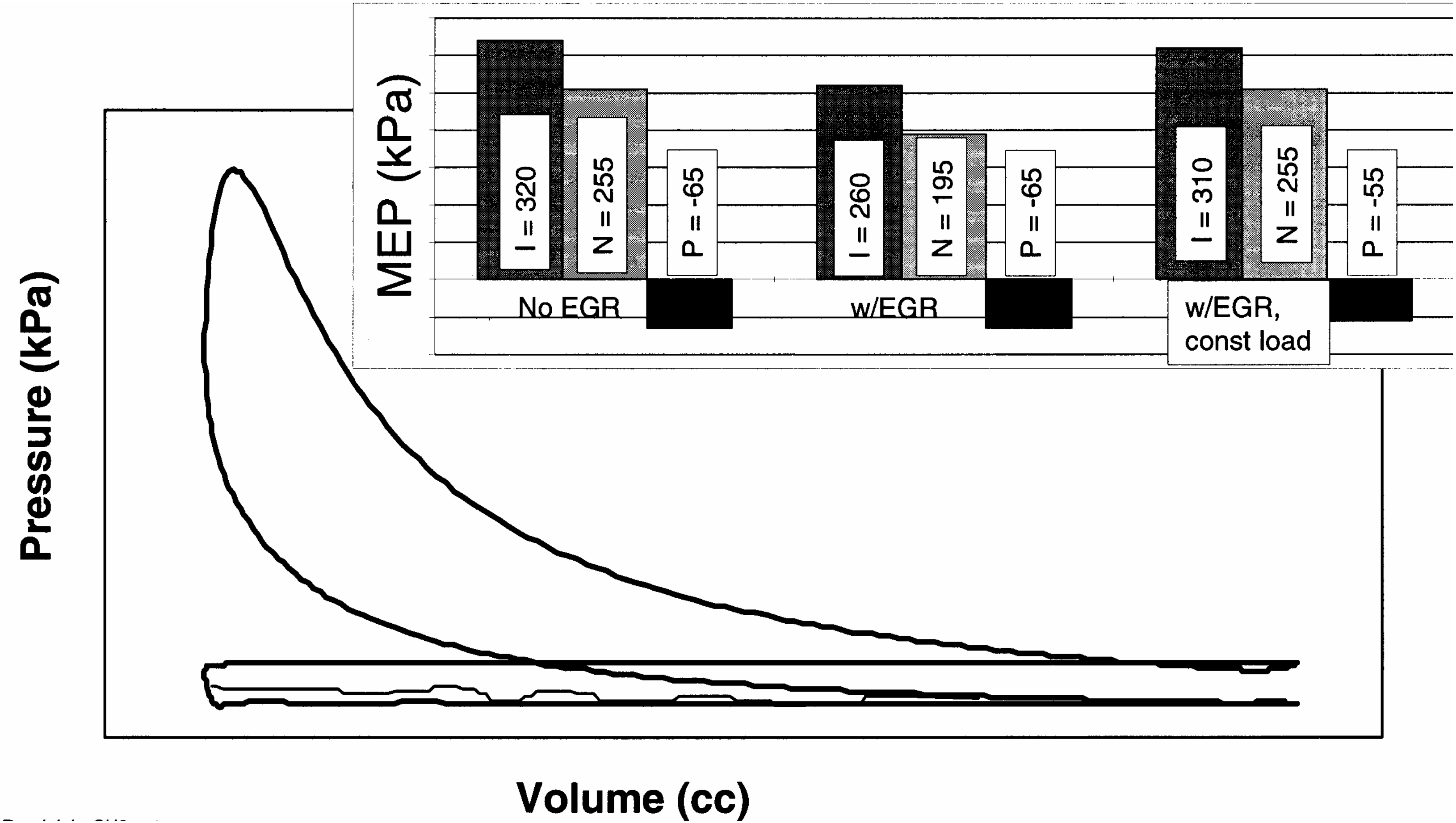
EGR- Increases net thermal efficiency by reducing pumping work



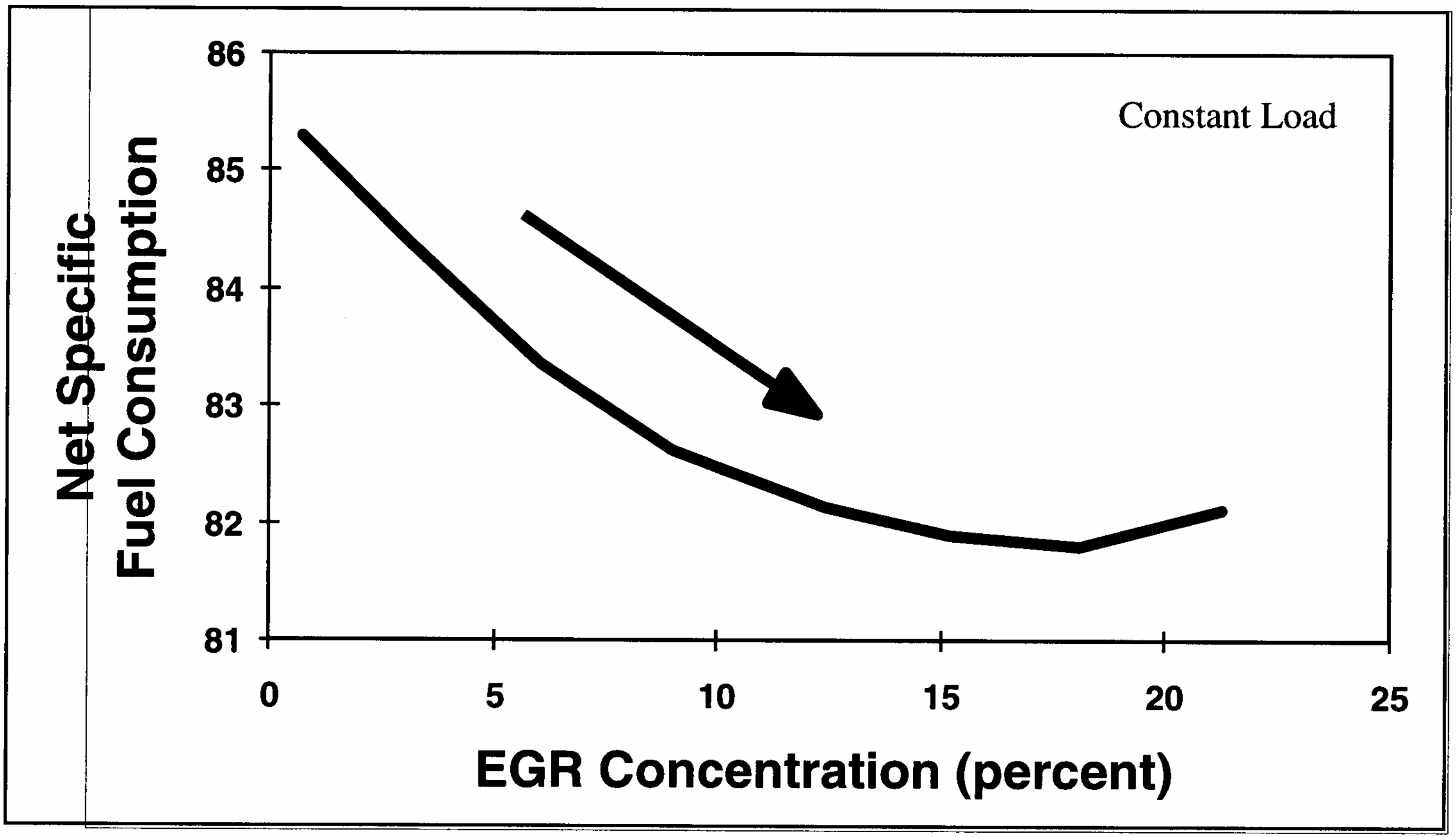
EGR-Output reduced with addition of EGR at constant manifold pressure



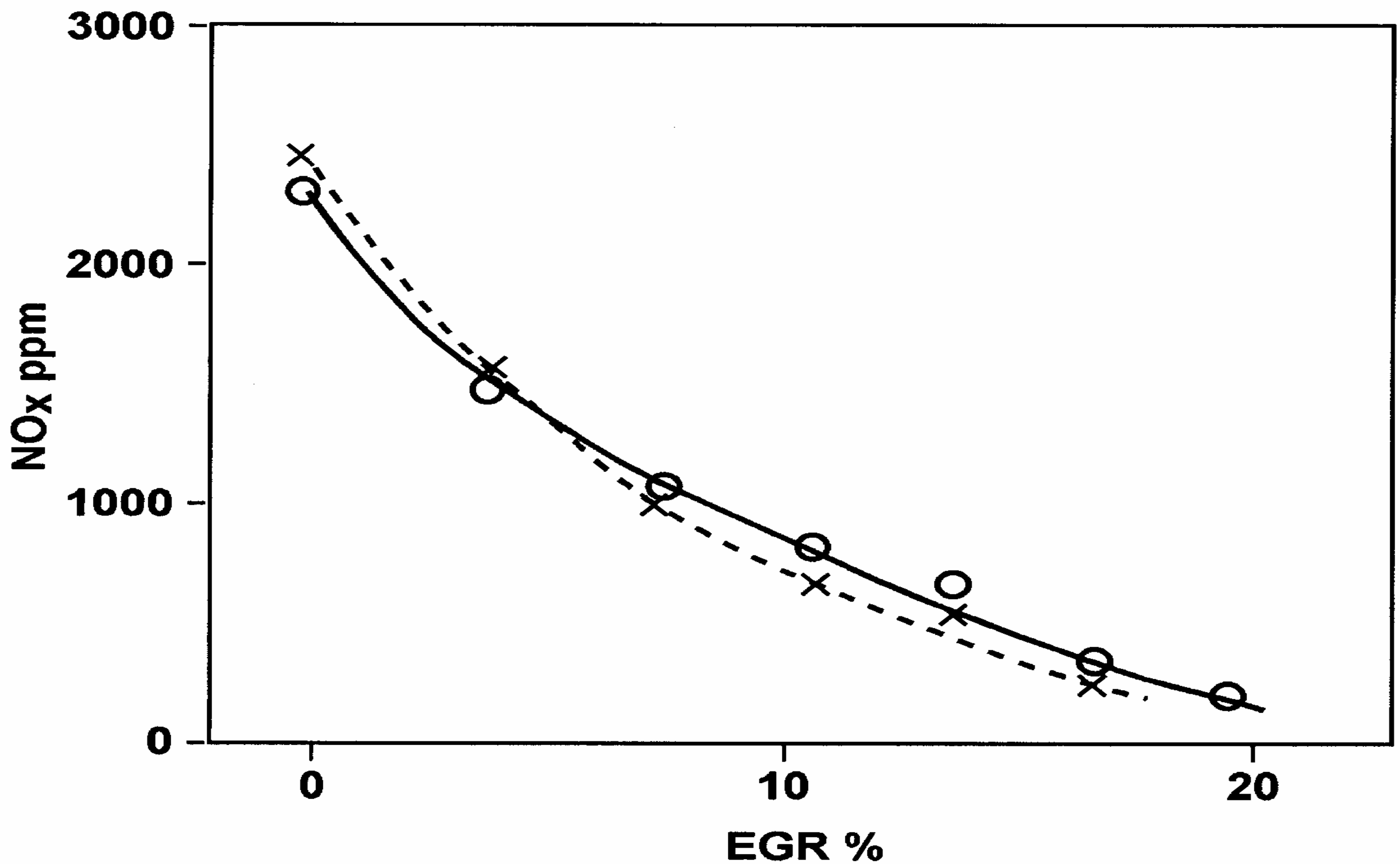
EGR – Must open throttle to recover load, thereby reducing pumping loss (spark ignition only)



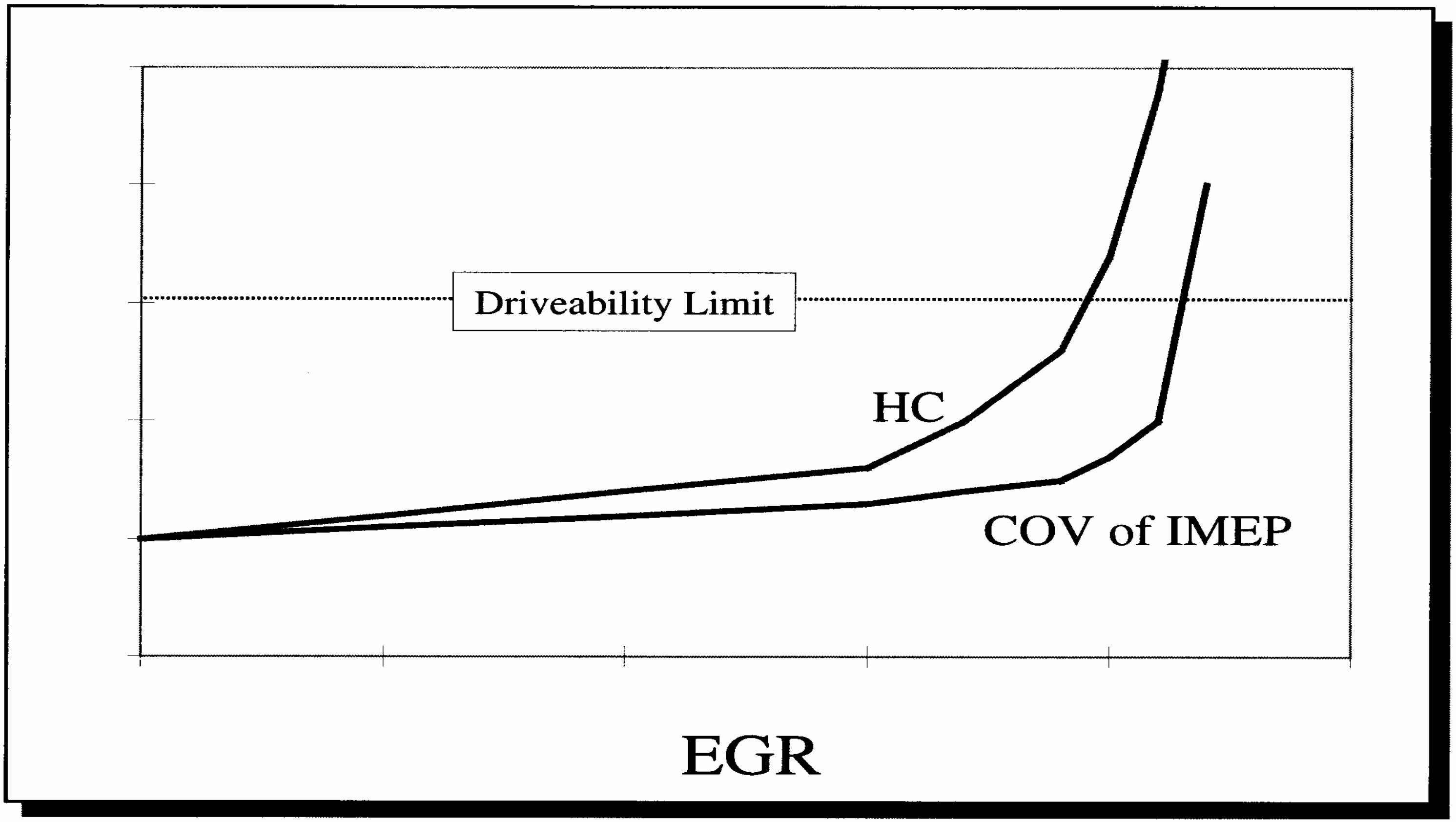
EGR – Performs the same function as the throttle, with out the associated pumping work (Spark ignition only)



EGR – Reduces NOx emissions by reducing the combustion temperatures



EGR – To much has distinct disadvantages !!!!!



EGR trade offs

- High EGR
  - Positive aspects
    - **Increases efficiency (improve fuel economy)**
    - **Reduces NOx emissions**
- High EGR
  - Negative aspects
    - **Increases HC emissions**
    - **Decreases combustion stability**
    - **Complicates transient control**

Abnormal Combustion

- Incomplete burn (misfires and partial burns)
- Pre-ignition
- Knock

Incomplete Combustion

Misfires and **Partial Burns** occur when flame propagation is either never properly initiated, or fails to propagate fully across the combustion chamber prior to exhaust valve opening.

``

Flame Initiation

S I Application

Misfire occurs without proper spark discharge

Incomplete Combustion

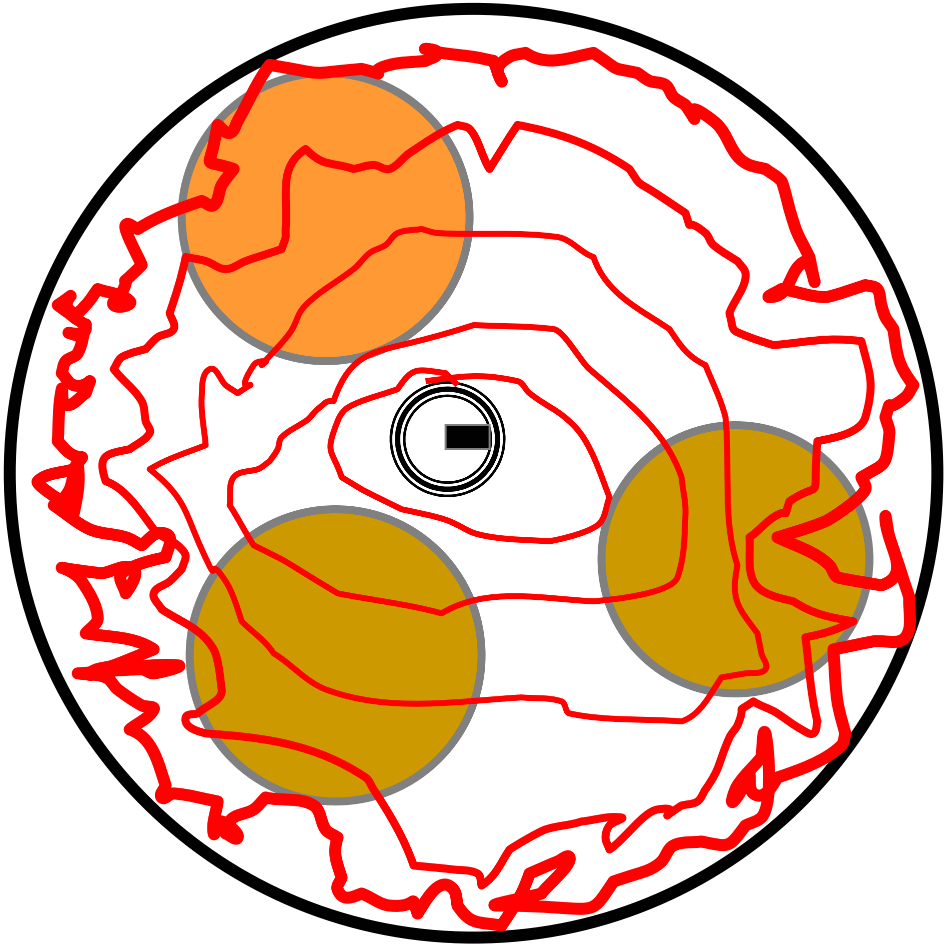
Flame Propagation

Misfire occurs likewise if the rate of conductive heat losses exceeds the rate of heat production from combustion

Incomplete Combustion

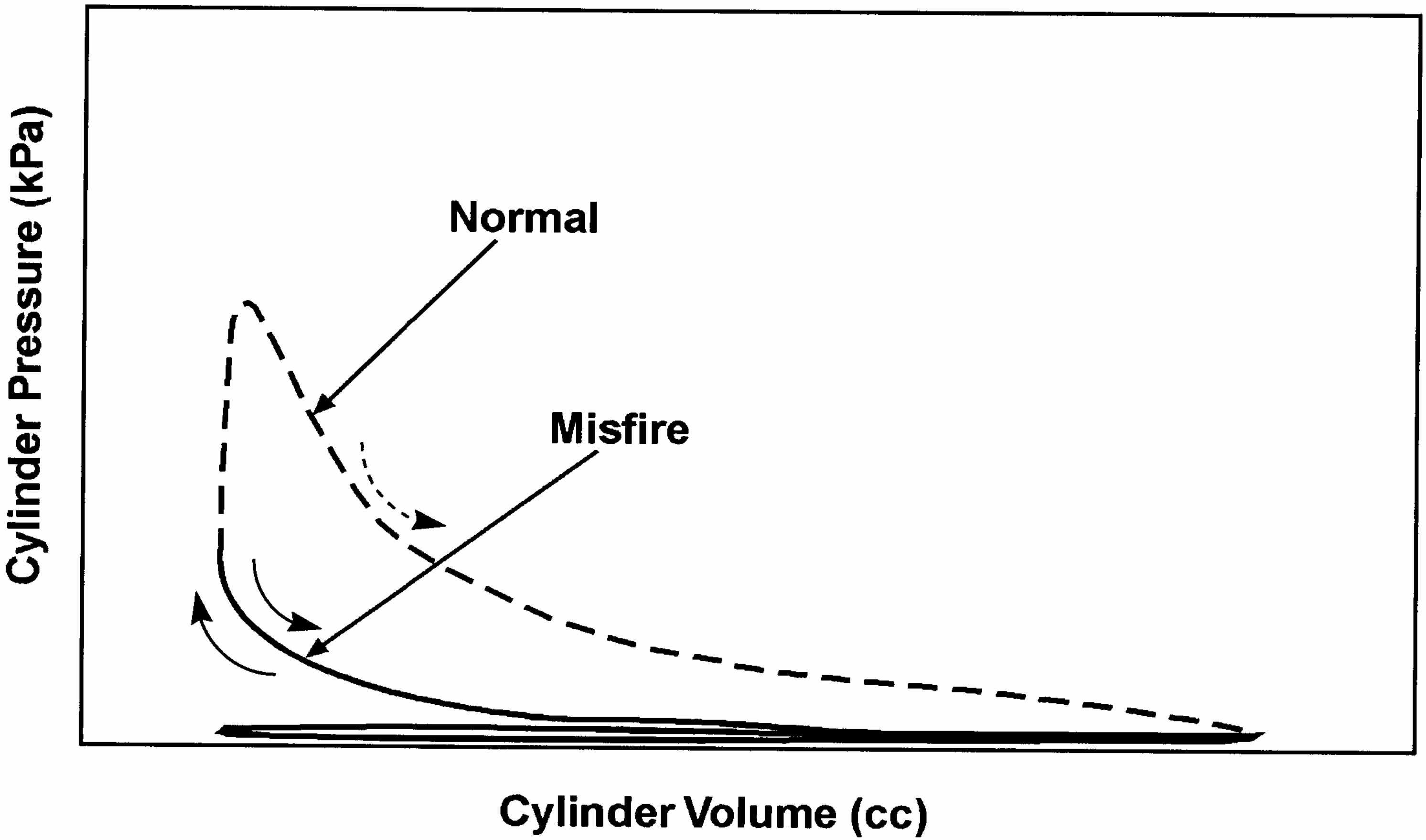
Complete Burn

Burn is complete when the flame fully propagates across the combustion chamber

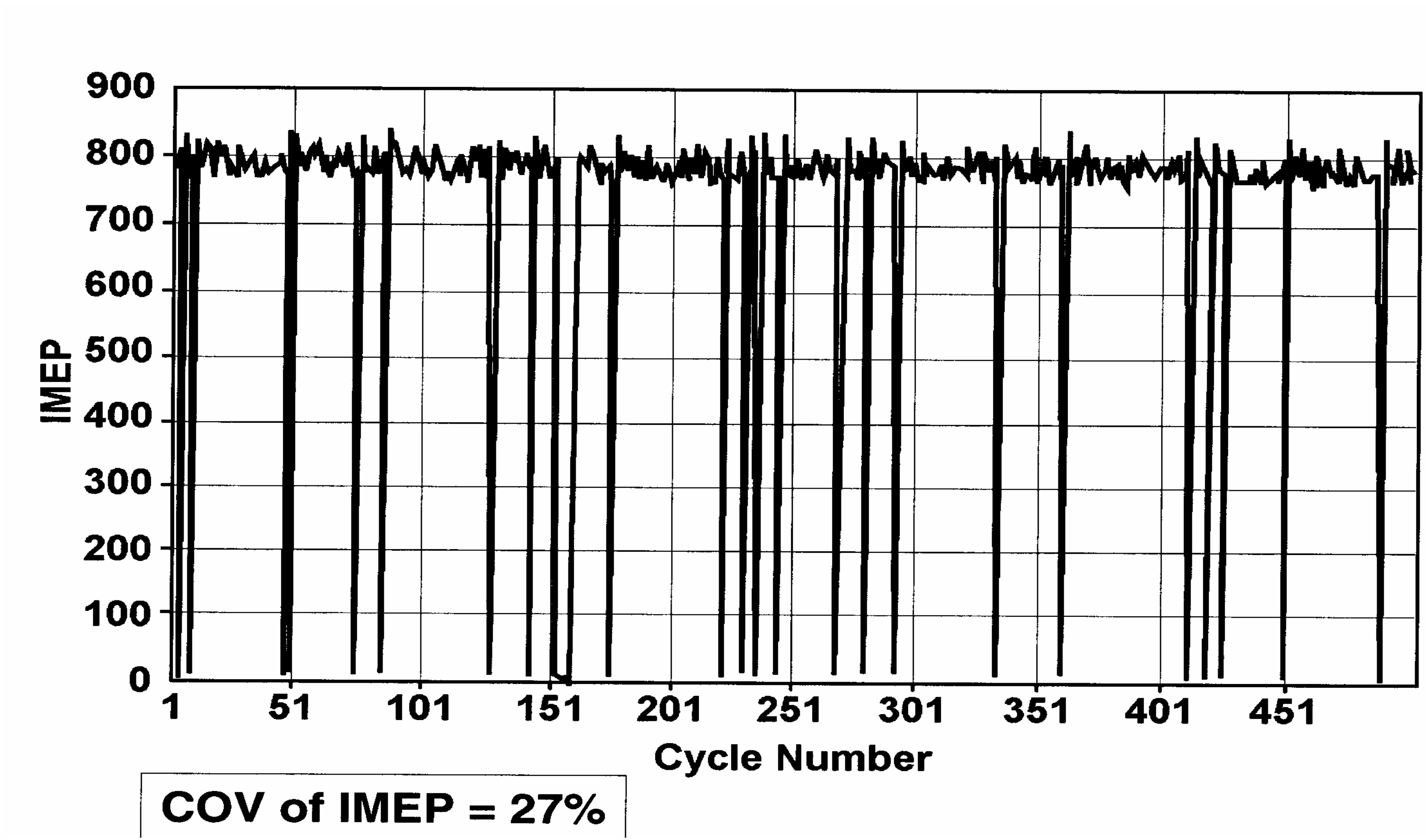


Incomplete Combustion

Misfire



Incomplete Combustion
Misfire



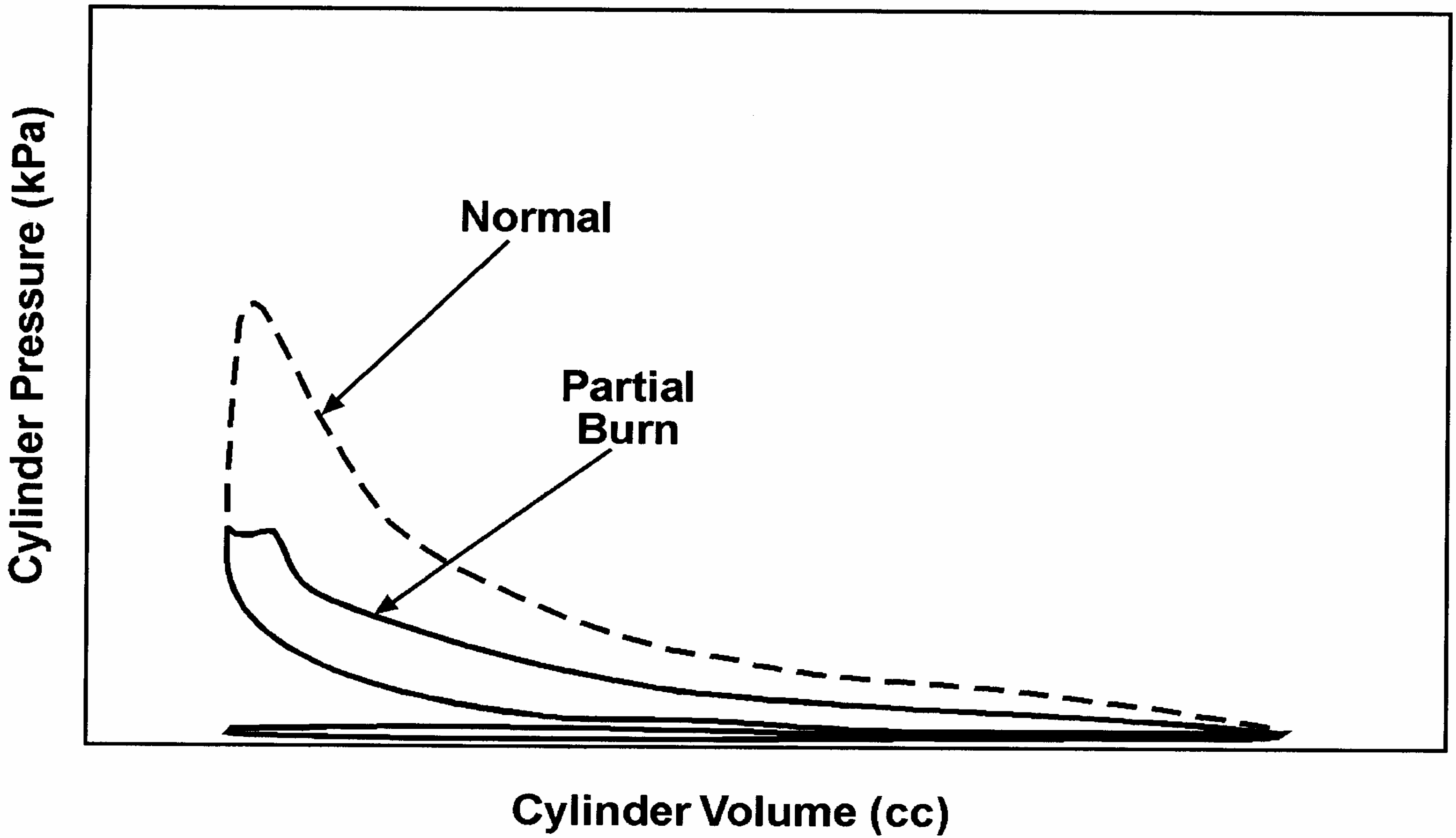
Incomplete Combustion

<u>Causes of Misfire</u>

- Insufficient ignition energy (spark or compression ~ cetane number !)
- Conditions at the spark plug at time of spark(S.I.Engine)that are not conductive to ignition
  - **Excessive residuals**
  - **Excessive EGR**
  - **Air/fuel ratio (Too lean or too rich)**
  - **High compression pressures**
  - **Low temperatures**
  - **Mean flow velocity too high (+ 320feet/min)**
  - **S.I.Engine excessive plug fouling**

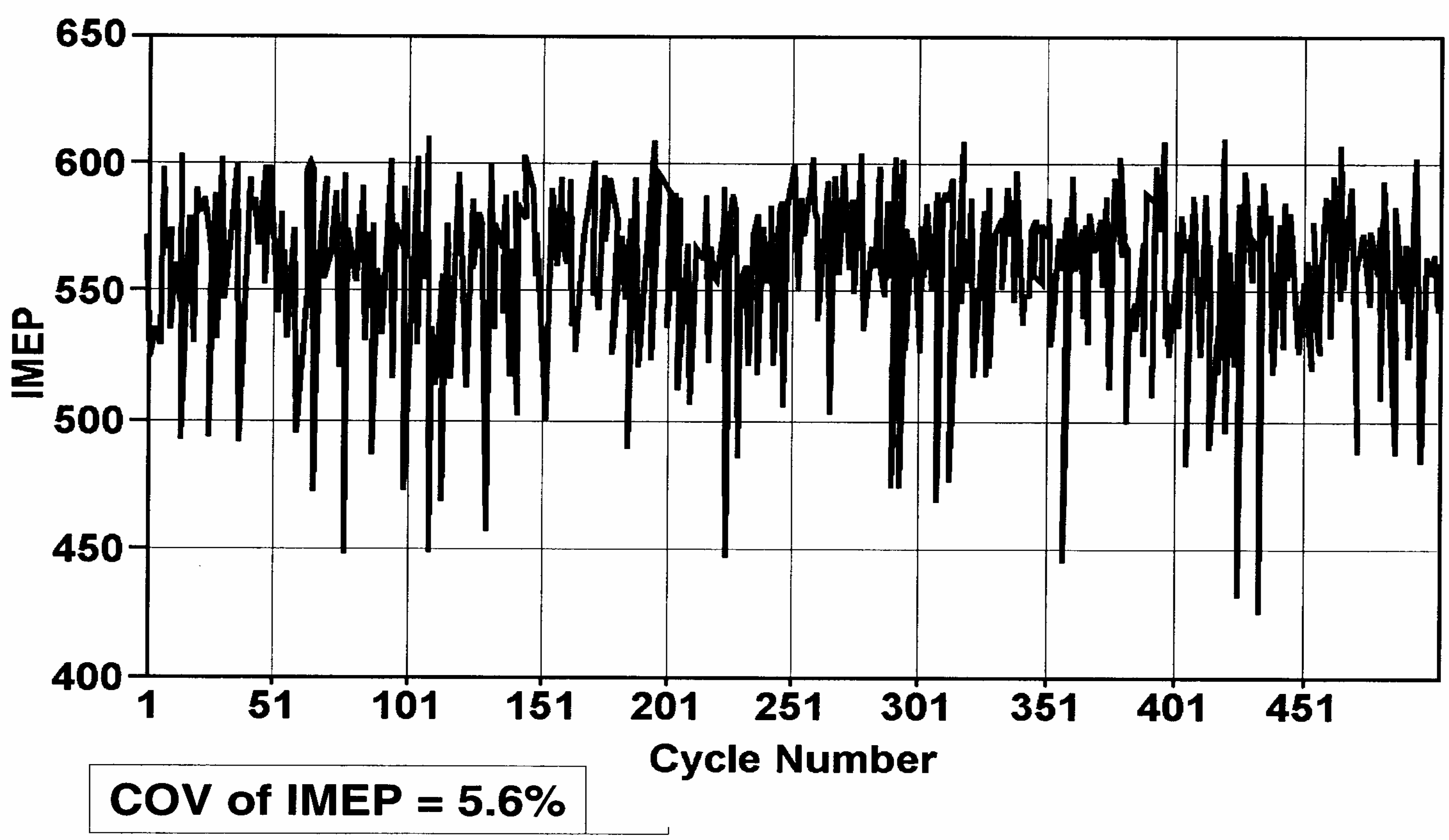
Incomplete Combustion

Partial Burn



Incomplete Combustion

Partial Burn



Incomplete Combustion

<u>Causes of Partial Burns</u>

- Burn duration too long (slow burn)
  - **Insufficient charge motion**
  - **Low compression pressures**
  - **Excessive dilution (residual exhaust, air, EGR)**
- Spark timing is too retarded (Diesel injection is too retarded)
- Fuel/air cylinder contents are not well mixed

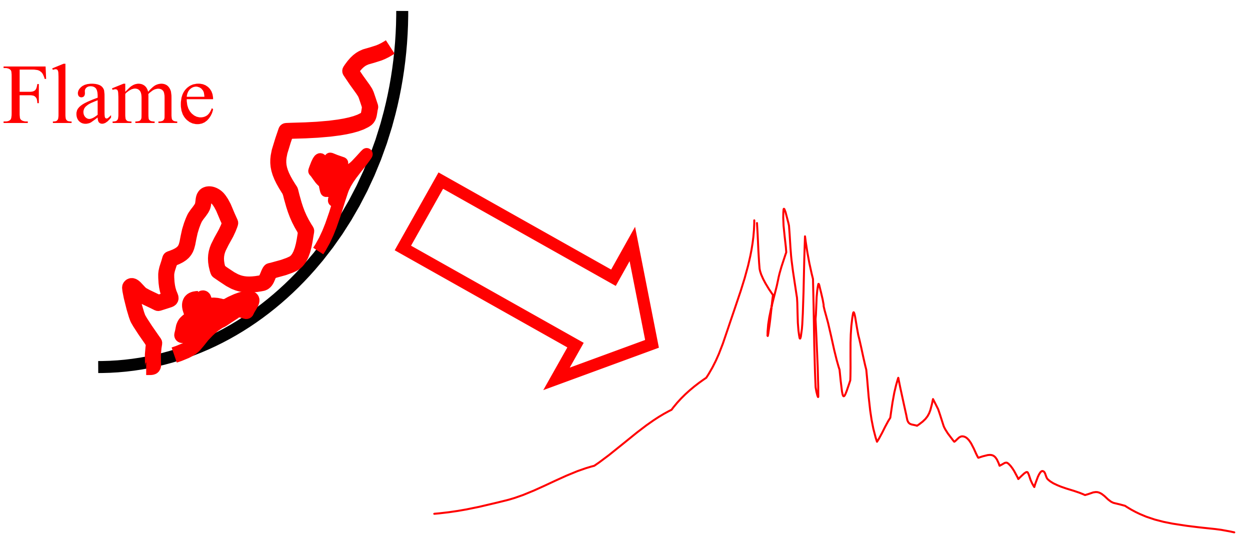
Combustion Variability

Steps to improve stability

- Well balanced combustion system hardware
  - Equal-length, replicated intake/exhaust runners & ports
  - Replicated combustion chambers (fast burning)
  - Good EGR, air,fuel,PCV & purge distribution
  - Good fuel injectors
    - Small droplets
    - Good targeting (back of valve, minimize wall-wetting)

Knock

Explosive spontaneous ignition of fuel-air mixture ahead of the normal propagating flame and the subsequent cylinder pressure oscillations



Knock

Knock is not:

- Any combustion-induced noise
  - Knock is the result of uncontrolled auto – ignition and will respond to changes in fuel octane
  - Rumble is the result of high pressure rise rate and will not respond to changes in fuel octane
- Detonation
  - Typical knock induced pressure oscillations are acoustic (sonic). Detonation is supersonic !
- Preignition
  - Preignition is the initiation of combustion prior to spark discharge, often the result of a hot spot induced by knock

Knock

<u>Who needs to worry about it ?</u>

- Fuel Formulation Chemists
- Base Engine Designers
- Calibration Engineers

Knock

- **<u>When does knock occur ?</u>**

$\int Temp\ dt$ **is high**

- Engine speed is low and MAP is high
- Combustion duration is long
- Temperatures are high (ambient,coolant, combustion chamber surface)
- Charge dilution is low
- Many particulate deposits
- Spark (point of injection) advance is high

Knock

Why is it a problem ?

Cost if it occurs:

- Potentially destructive
- Annoying to the customer

Cost of prevention:

- Fuel quality costs money
- Reducing compression ratio sacrifices power and fuel economy
- Retarding spark (point of injection) reduces torque and fuel economy
- Enriching the air-fuel ratio increases emissions and fuel consumption

Knock

How do we control it ?

Fuel Chemist:

- Blending agents (aromatics and MTBE) to raise octane
- Additive packages to minimise deposits

Base Engine Designer:

- Fast burn combustion chambers
- Low cyclic variability
- Low cylinder to cylinder mal-distribution
- Excellent structural cooling

Calibration Engineer:

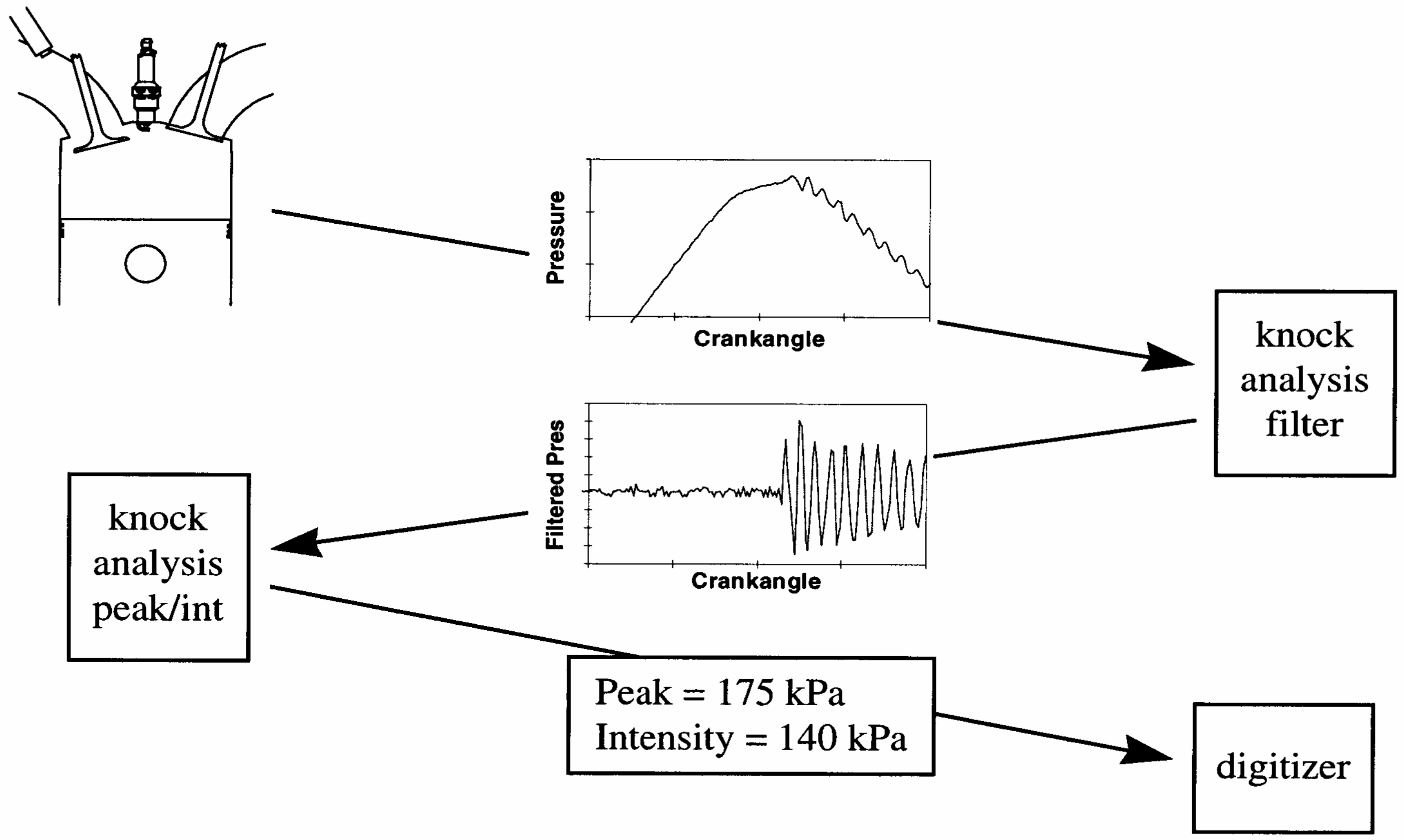
- Fuel Enrichment
- Spark (Diesel Injection) Retard

Knock

How does one quantify it ?

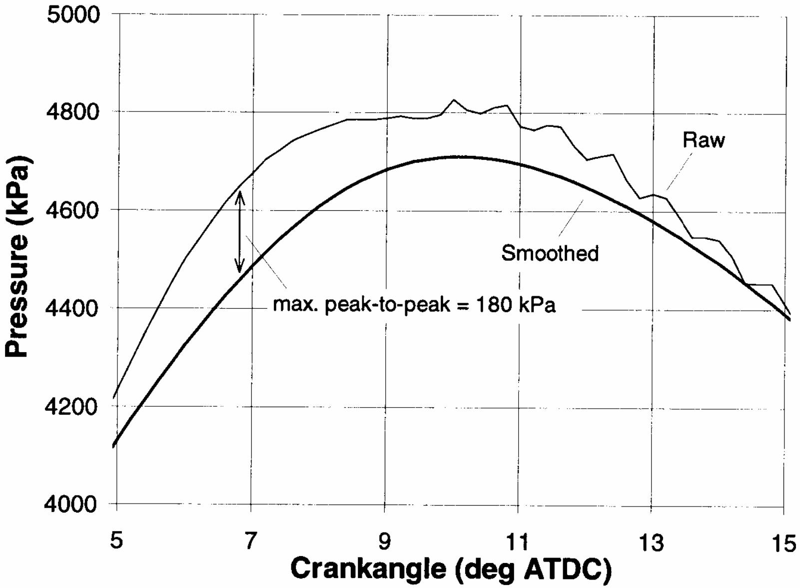
- Trained ear(customer, historic development engineer)
- Accelerometer (vehicle ECM)
- Cylinder pressure measurement
  (modern development engineer)
  - **Maximum rate of pressure rise**
  - **Peak and hold on filtered pressure trace**
  - **Peak and hold on smoothed pressure trace**

Knock
Example of cylinder-pressure based knock analysis



Knock
Data Processing Options

Smoothing...



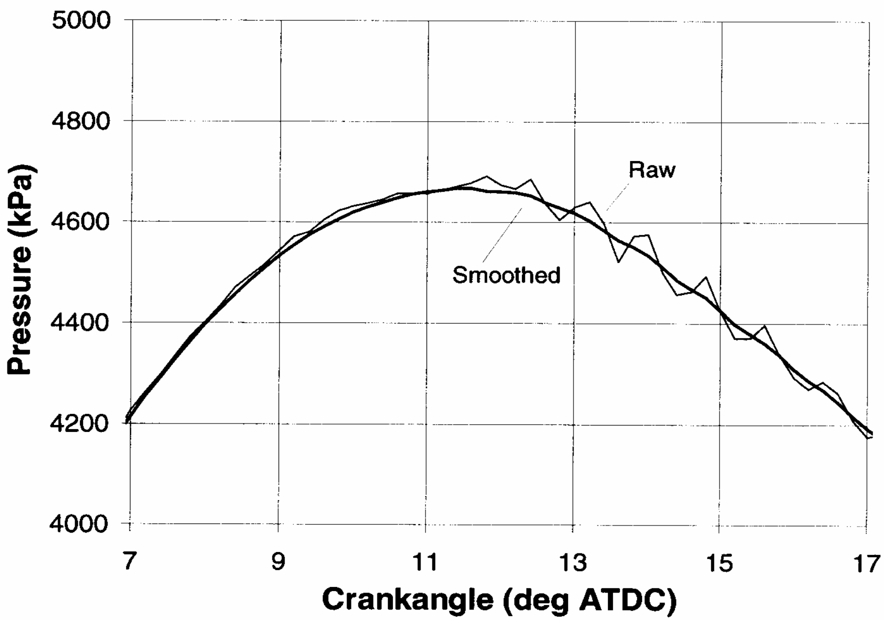
Fixed 41-point filter...

$$x_{i,smooth} = \sum_{i=-20}^{20} x_i \Big/ 41$$

NO GOOD!

Knock
Data Processing Options

Smoothing...



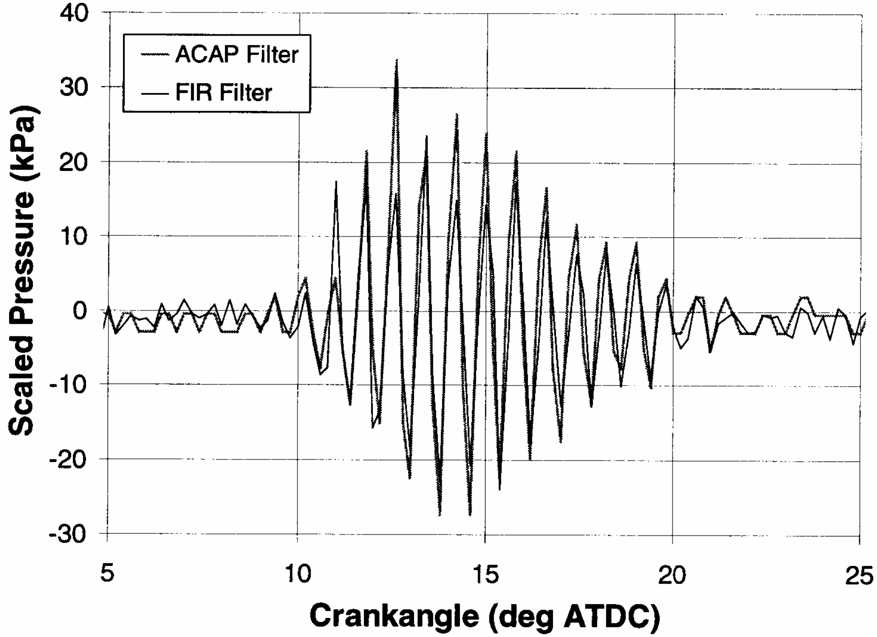
Two-period filter...

$$x_{i,smooth} = \sum_{i=-5}^{5} x_i \Big/ 11$$

GOOD!

Knock
Data Processing Options

Filtering...

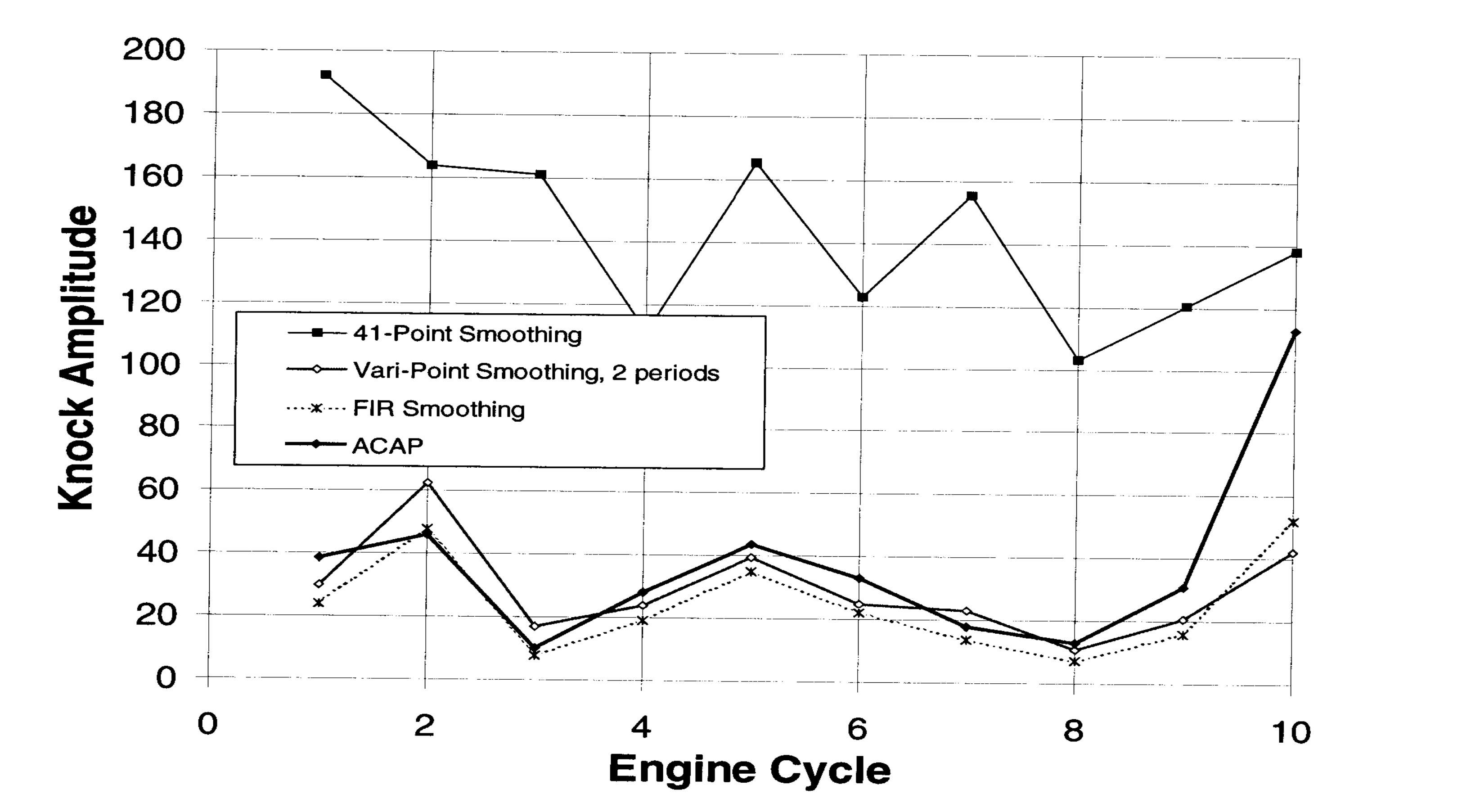


ACAP = analogue band-pass (4kHz - 12kHz)

CAS = digital FIR high pass (10-point)

BOTH GOOD!

Knock
Data Processing Options Comparison



Knock
System Summary

ACAP:

- Analogue band-pass filter in dedicated module

CAS:

- Smoothing to user-specified width}
- Smoothing to two-period width }user selectable
- Digital FIR filtering }

ALL SOFTWARE—NO DEDICATED MODULE

Knock
System Summary,continued

How does CAS (combustion analysis system) determine knock

- Encoder decimation allows user to increase or decrease encoder resolution within software
- Knock software will reside in it's own coprocessor, and will automatically set the encoder resolution to the appropriate level during the user-selected knock window
- Customer will need to purchase a knock coprocessor to enable knock calculations

Knock
Sample analysis, old vs.new

Problem:Excessive low-speed knock

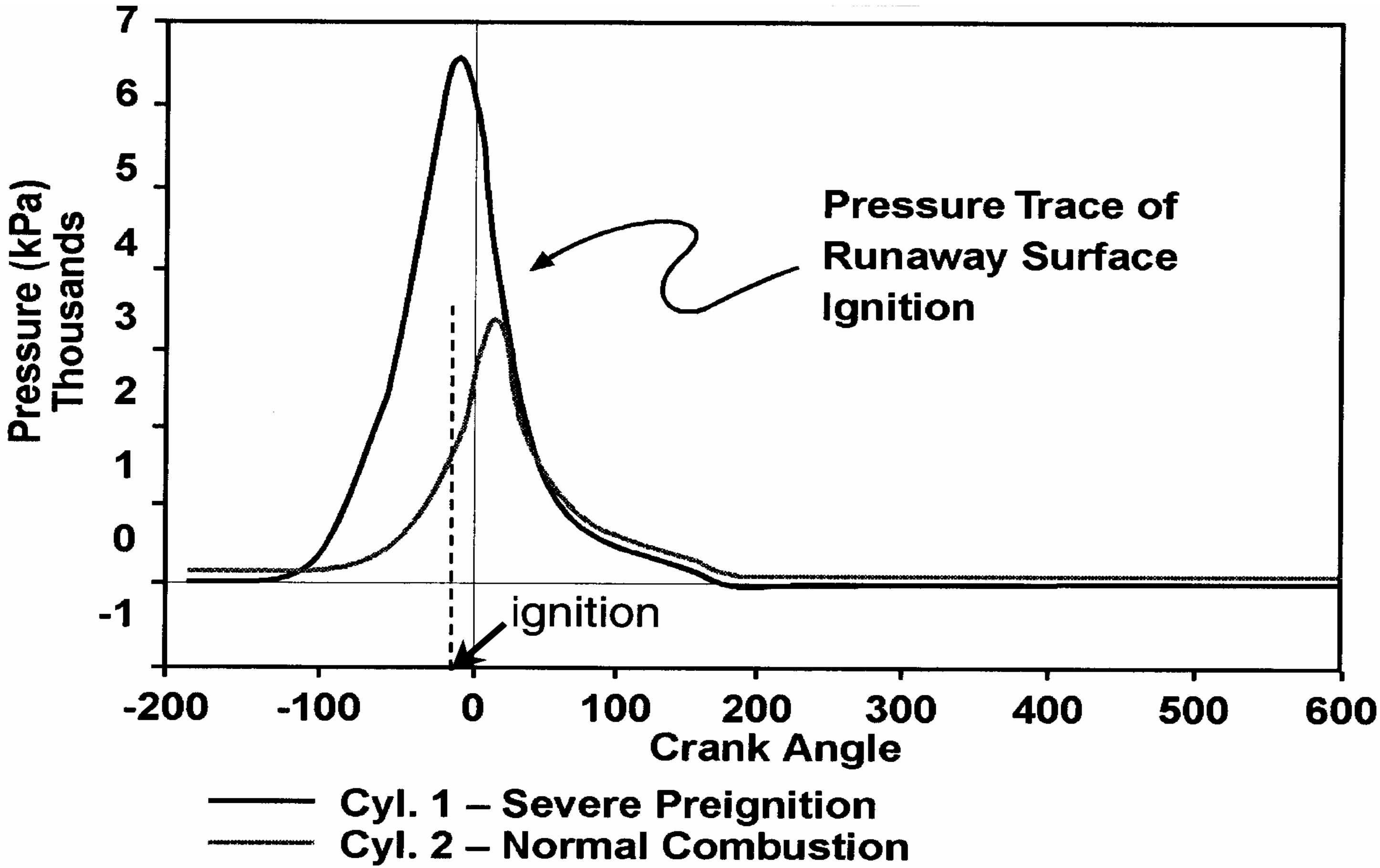
Solution:Lower compression ratio

WRONG !

Correct Solution

1. Is knock excessive in all cylinders?
2. Is combustion variability dictating knock?
3. What is the true knock limited torque?
4. Is the burn rate profile conducive to good knock limited performance?
5. Can we adequately detect knock?
6. Is the compression ratio too high?

Preignition –ignition in the combustion chamber prior to spark discharge. Where will NOx start ?

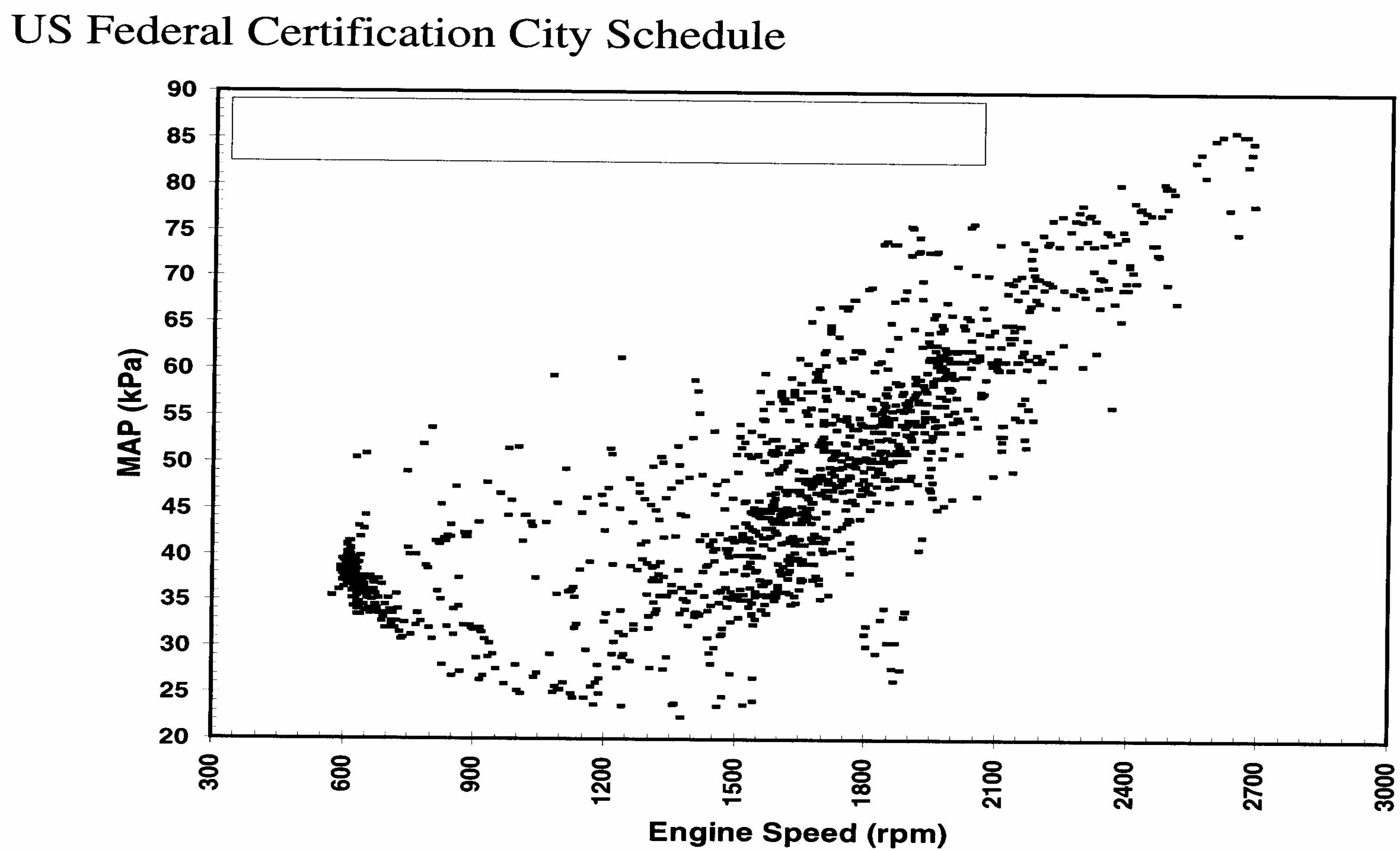


Preignition

<u>Preignition</u> is undesirable because:

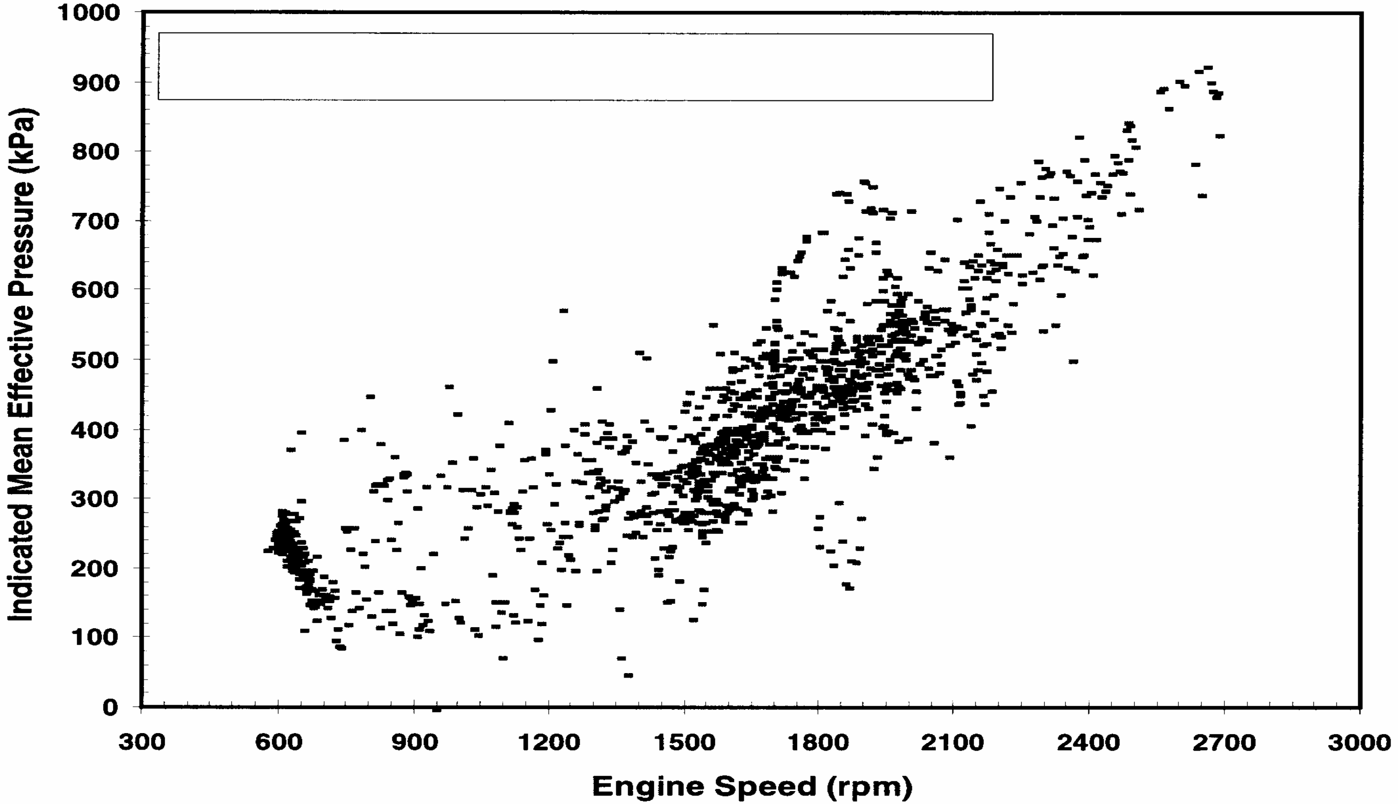
- Rapidly produces very high pressures and temperatures in the combustion chamber
- May cause piston to melt or break in the middle of the piston crown (top)
- May lead to some other form of catastrophic failure (crankshaft, connecting rod, valves etc,….)

Advanced Calibration Methodology $(17x10^3)x4$ data points



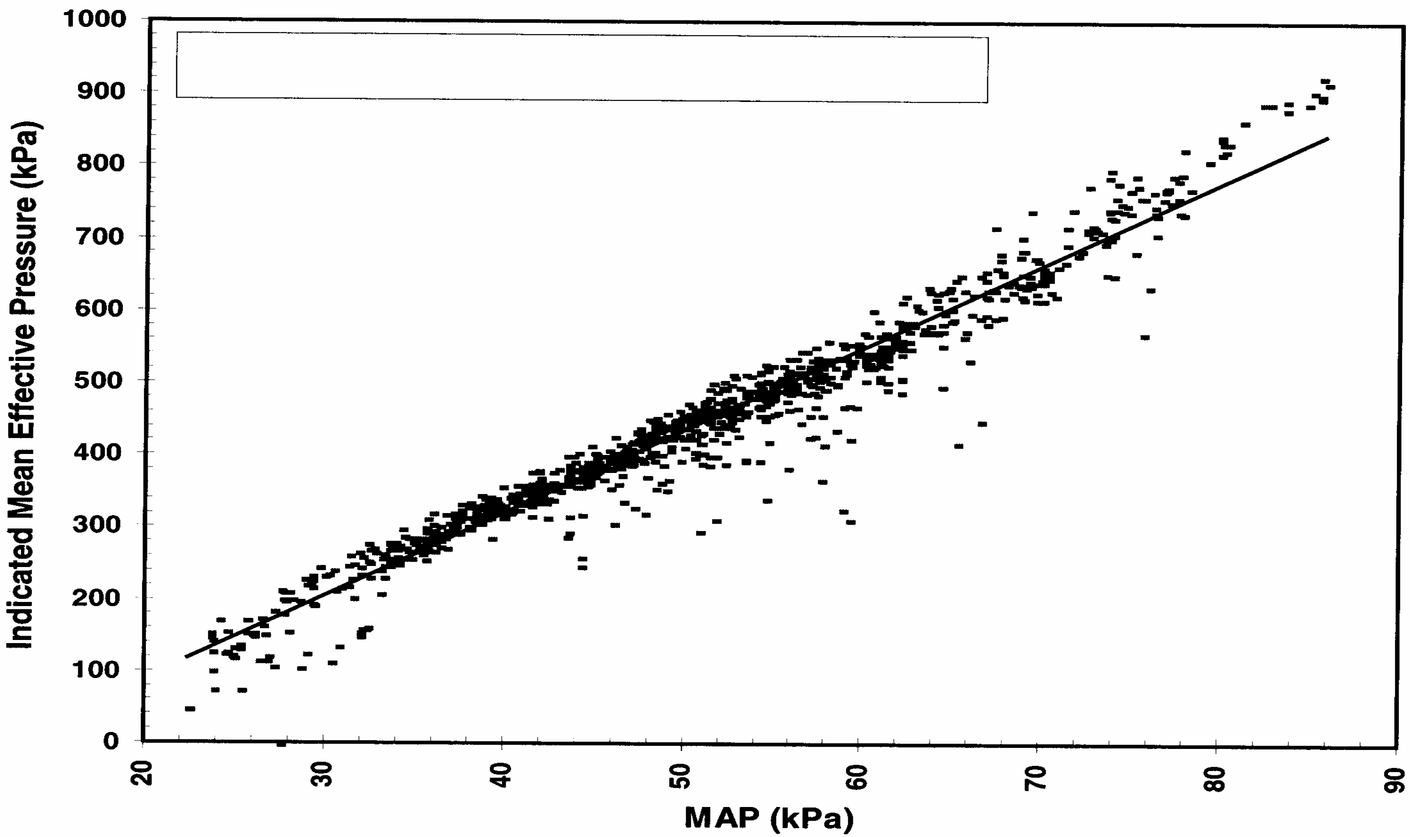
Advanced Calibration Methodology $(17x10^3)x4$ data points

US Federal Certification City Schedule

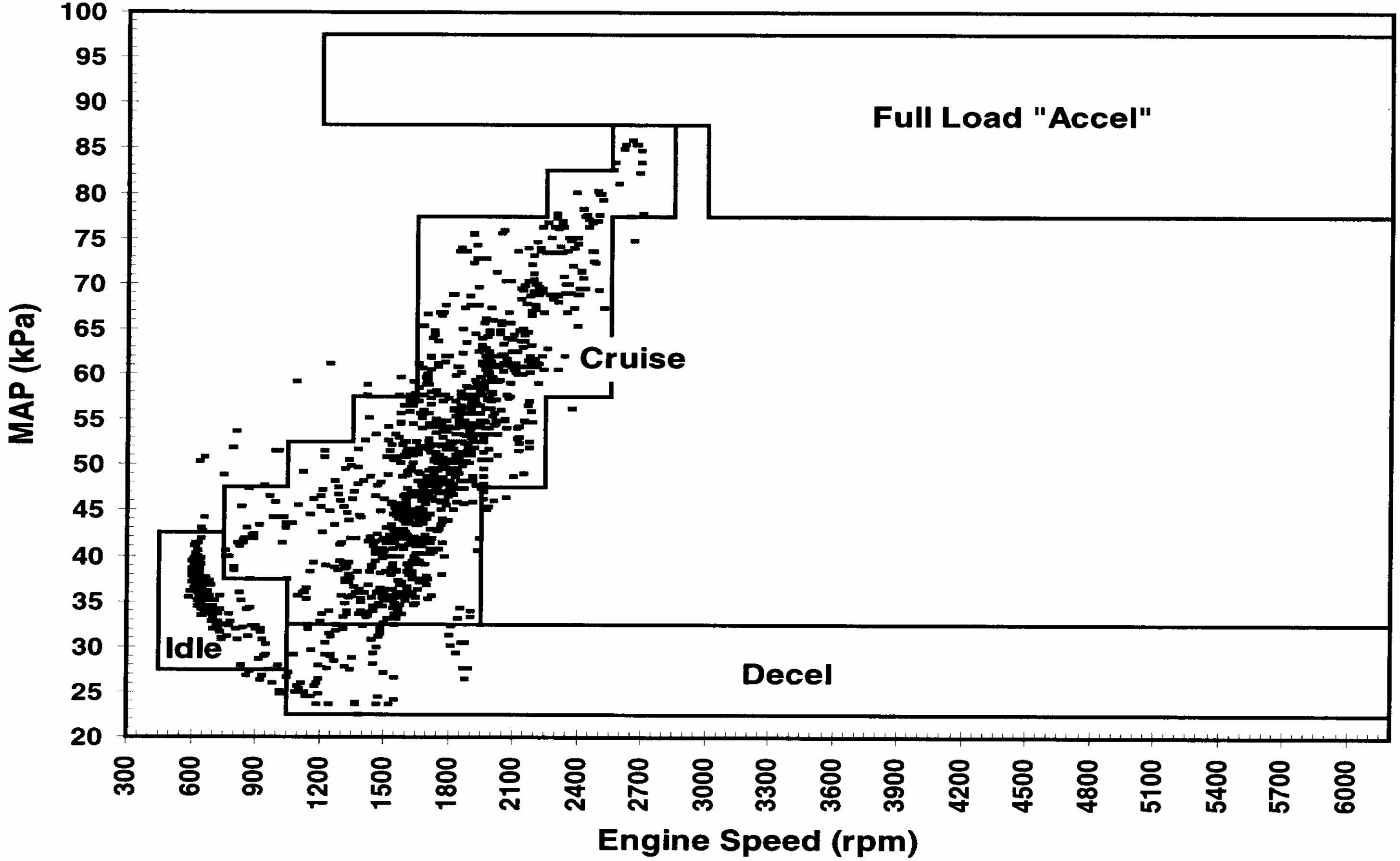


Advanced Calibration Methodology $(17x10^3)x4$ data points

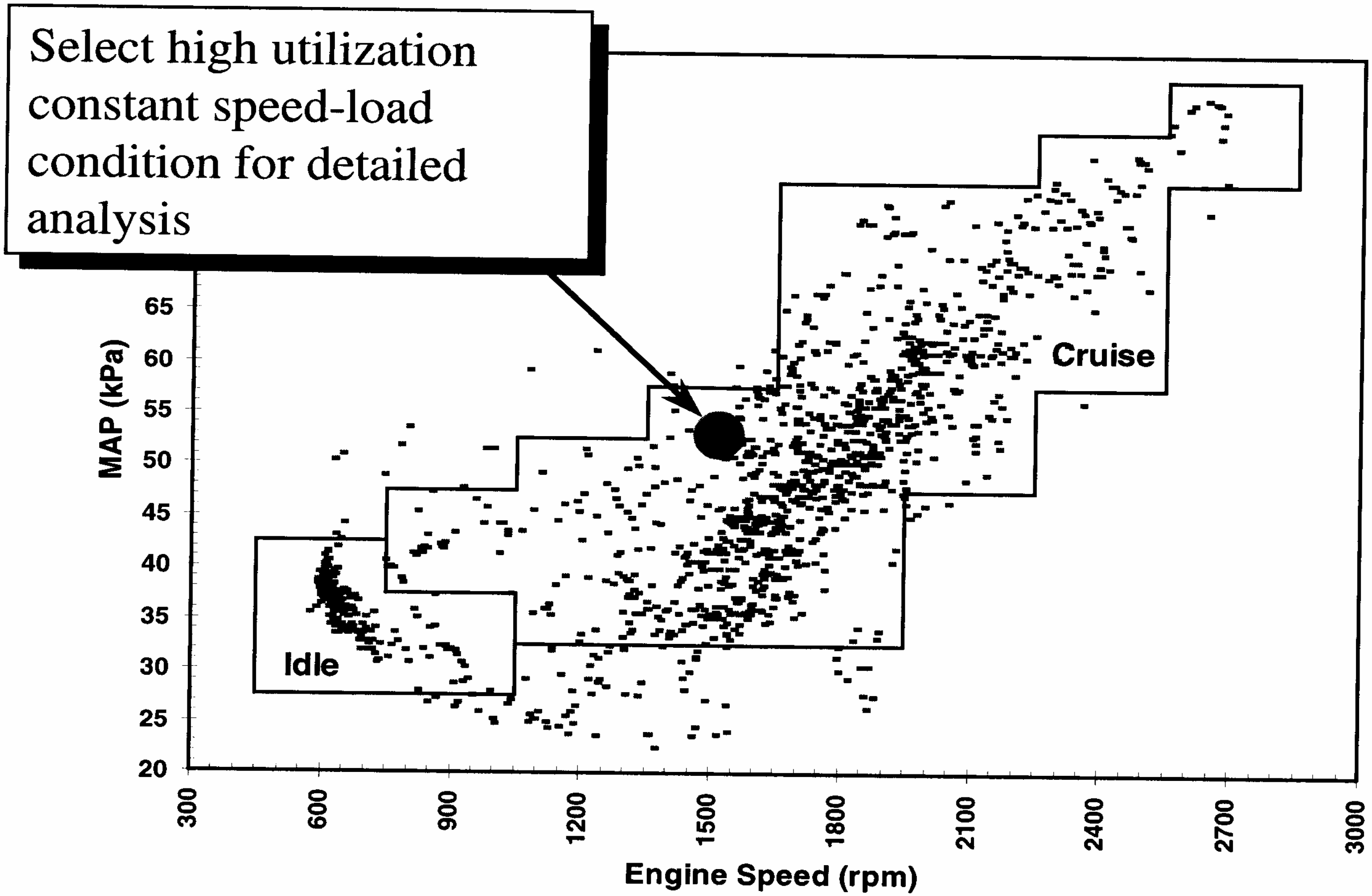
US Federal Certification City Schedule



Advanced Calibration Methodology $(17x10^3)$x4 data points

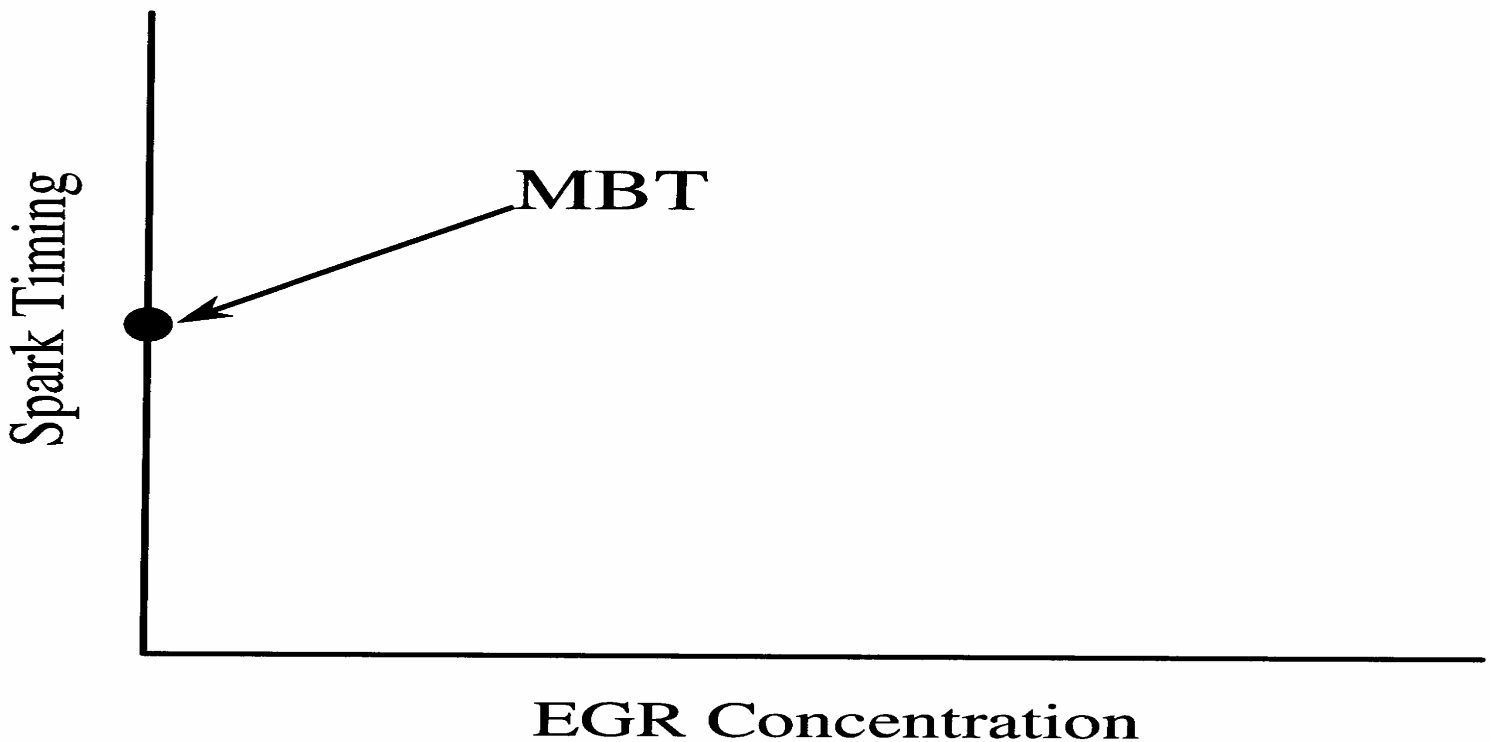


Advanced Calibration Methodology (17×10^3)x4 data points



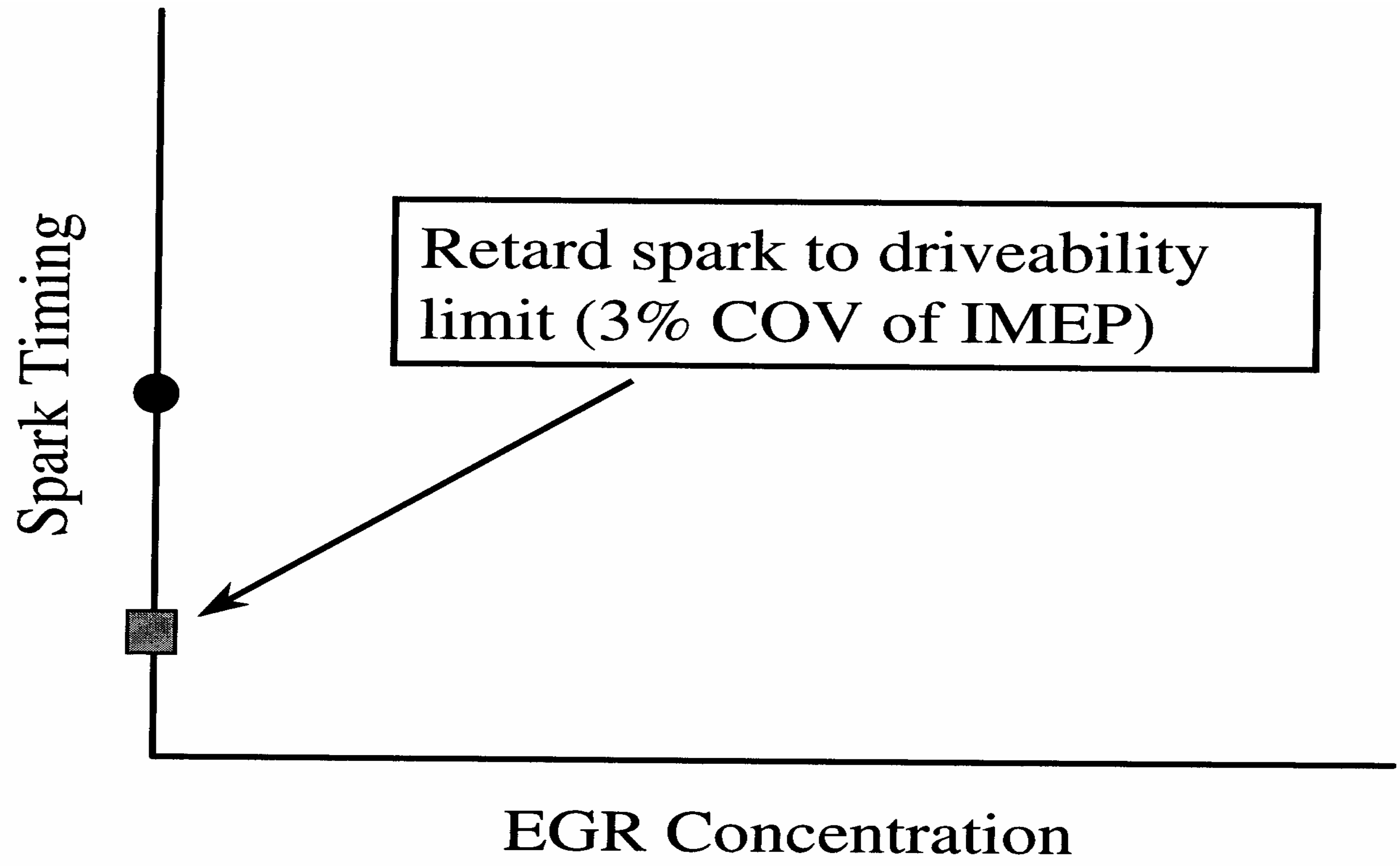
Advanced Calibration Methodology

Calibration Optimisation, Constant Speed Dilution Utilisation

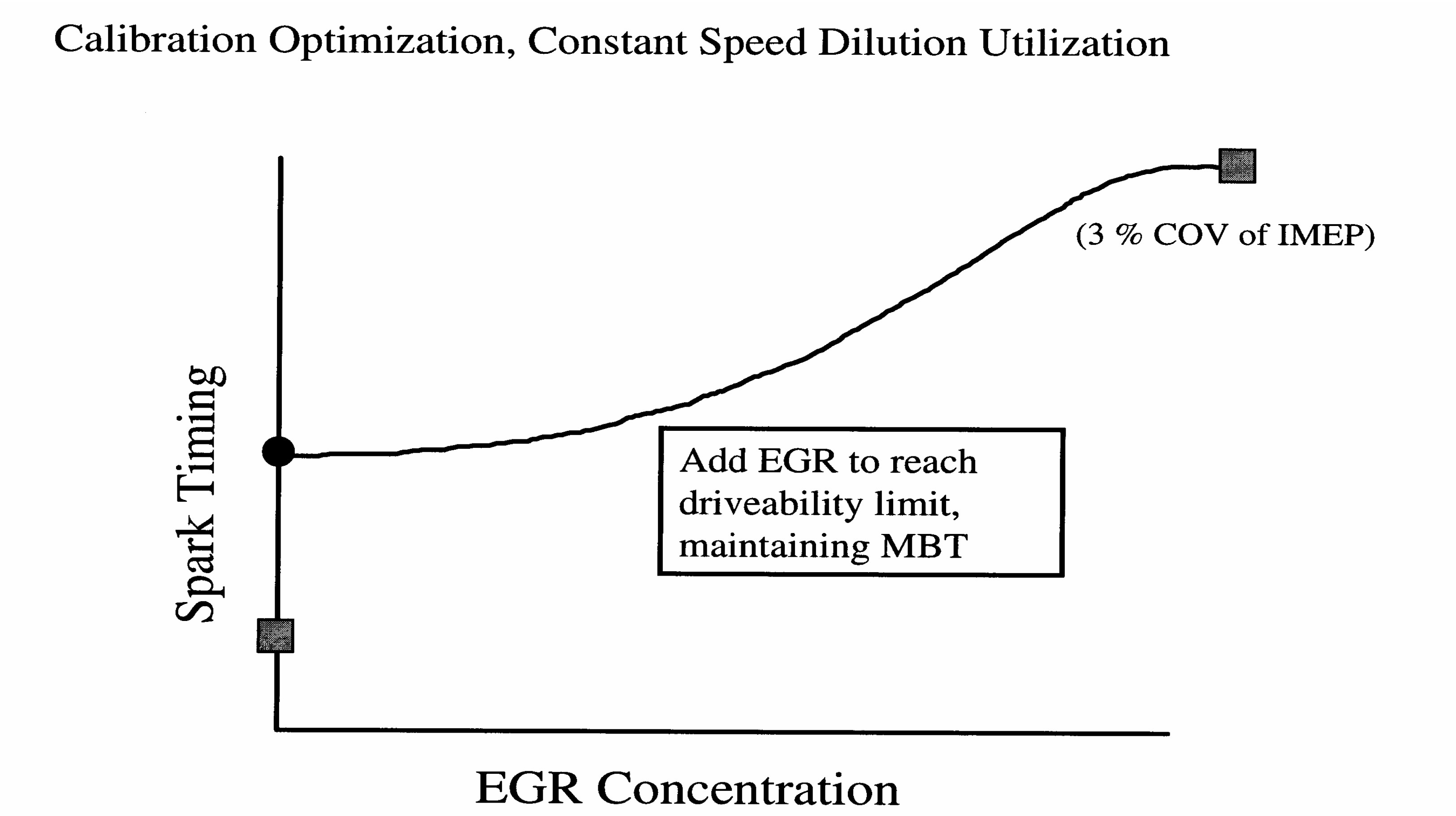


Advanced Calibration Methodology

Calibration Optimisation, Constant Speed Dilution Utilisation

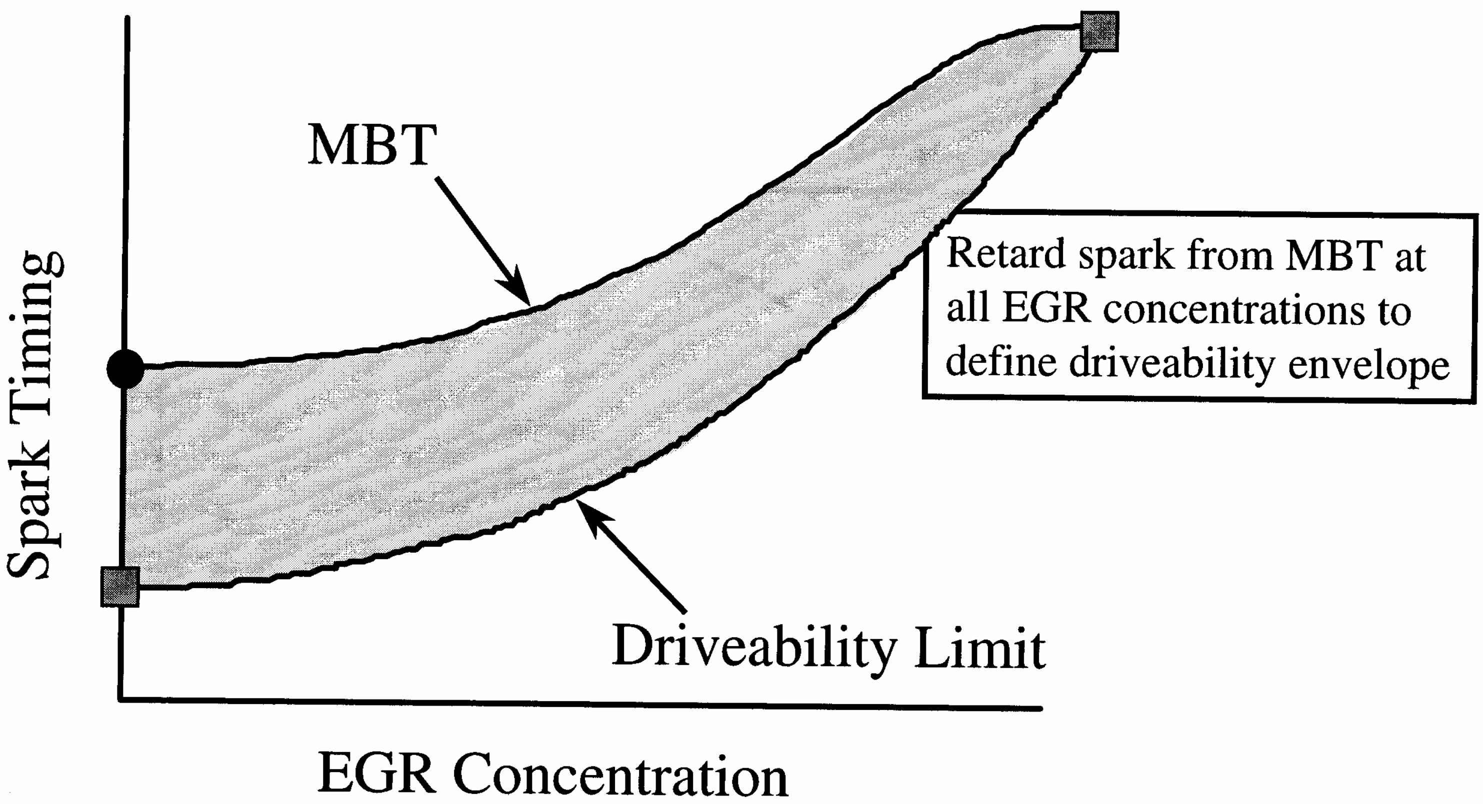


Advanced Calibration Methodology

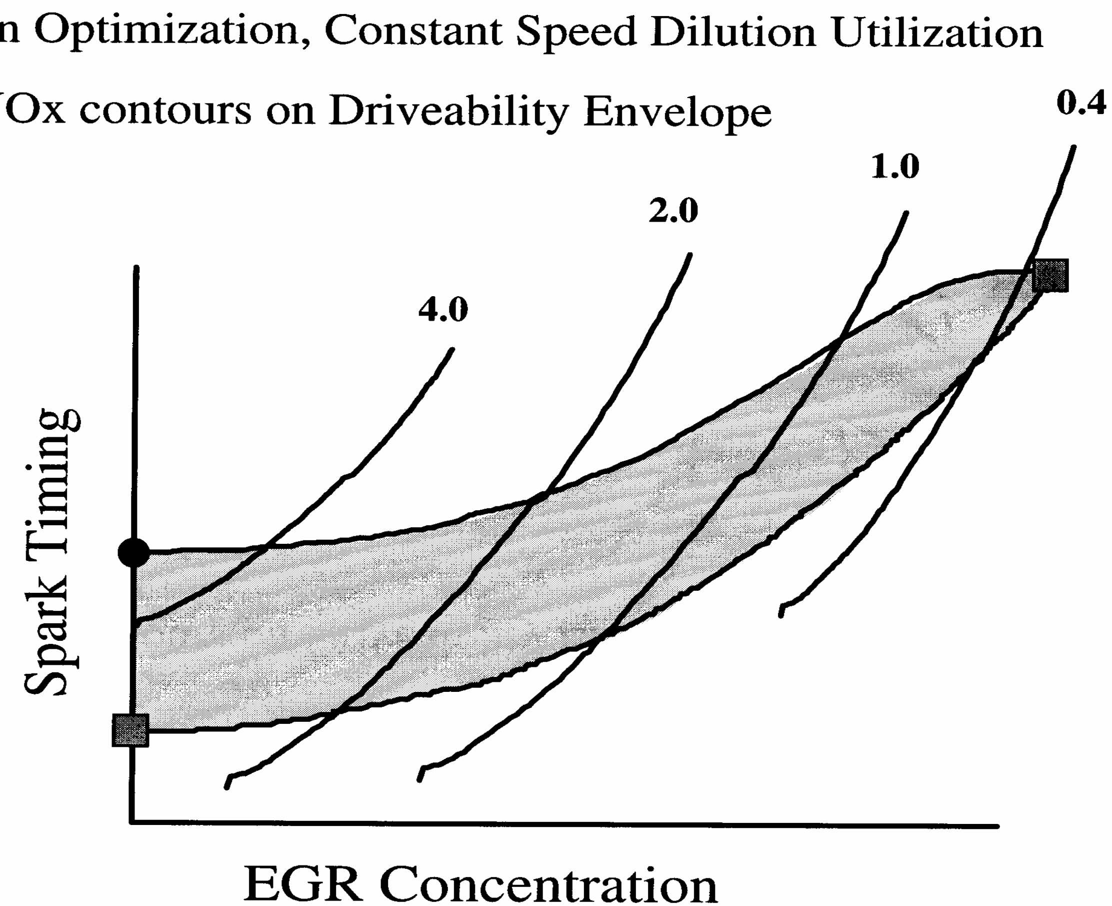


Advanced Calibration Methodology

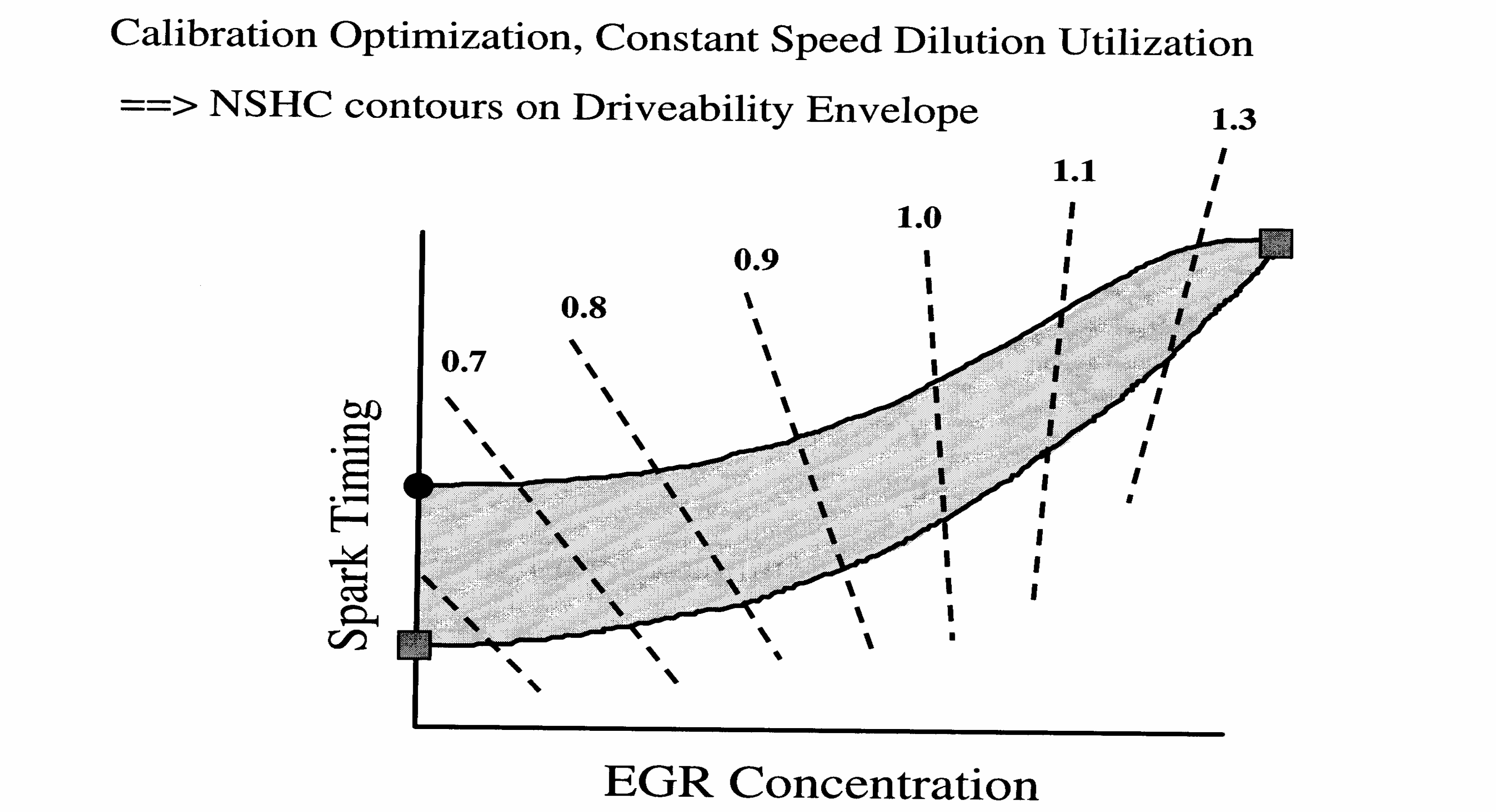
alibration Optimisation, Constant Speed Dilution Utilisation



Advanced Calibration Methodology



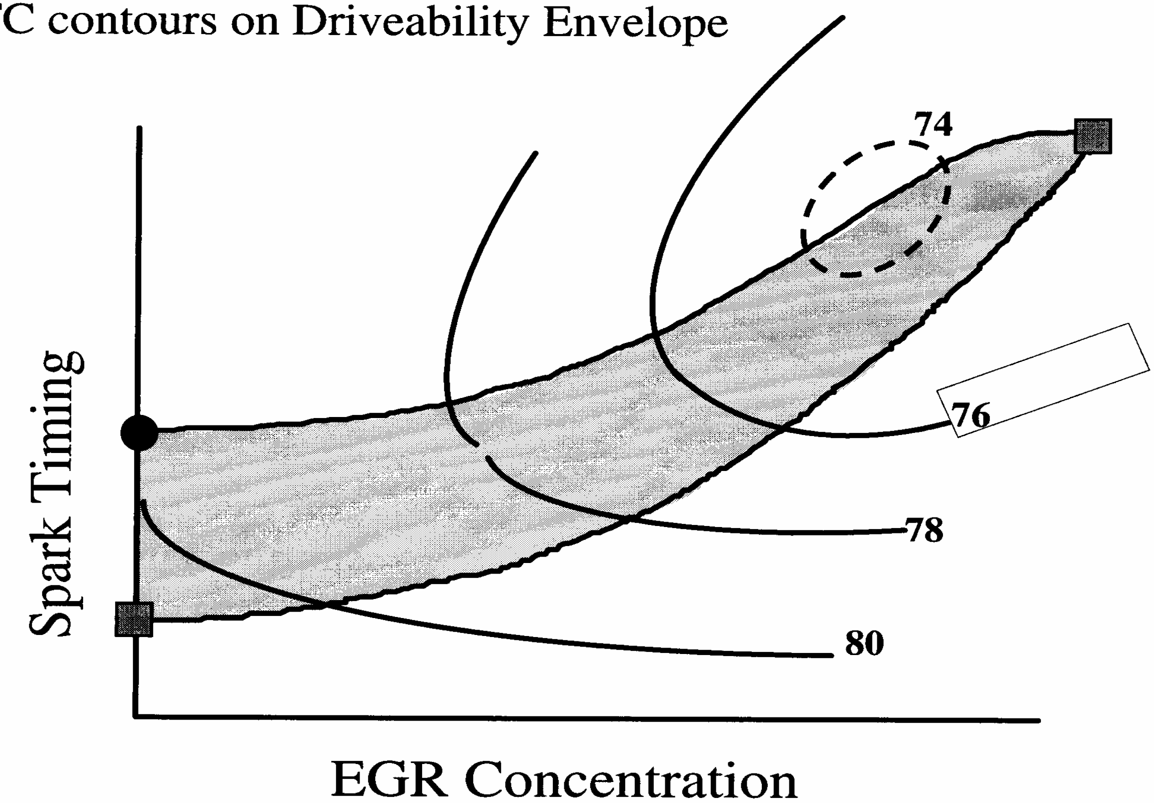
Advanced Calibration Methodology



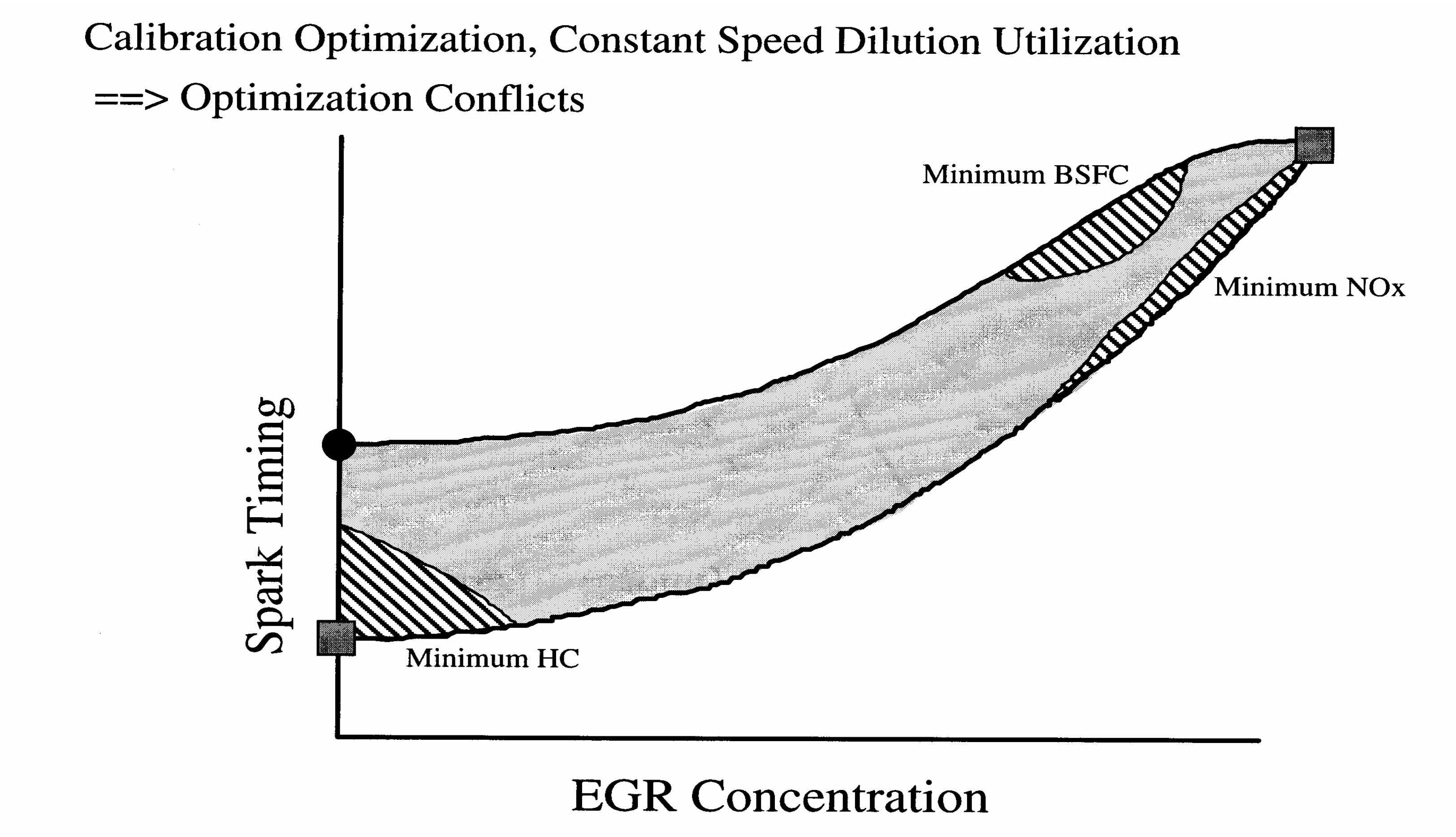
Advanced Calibration Methodology

Calibration Optimization, Constant Speed Dilution Utilization

==> NSFC contours on Driveability Envelope

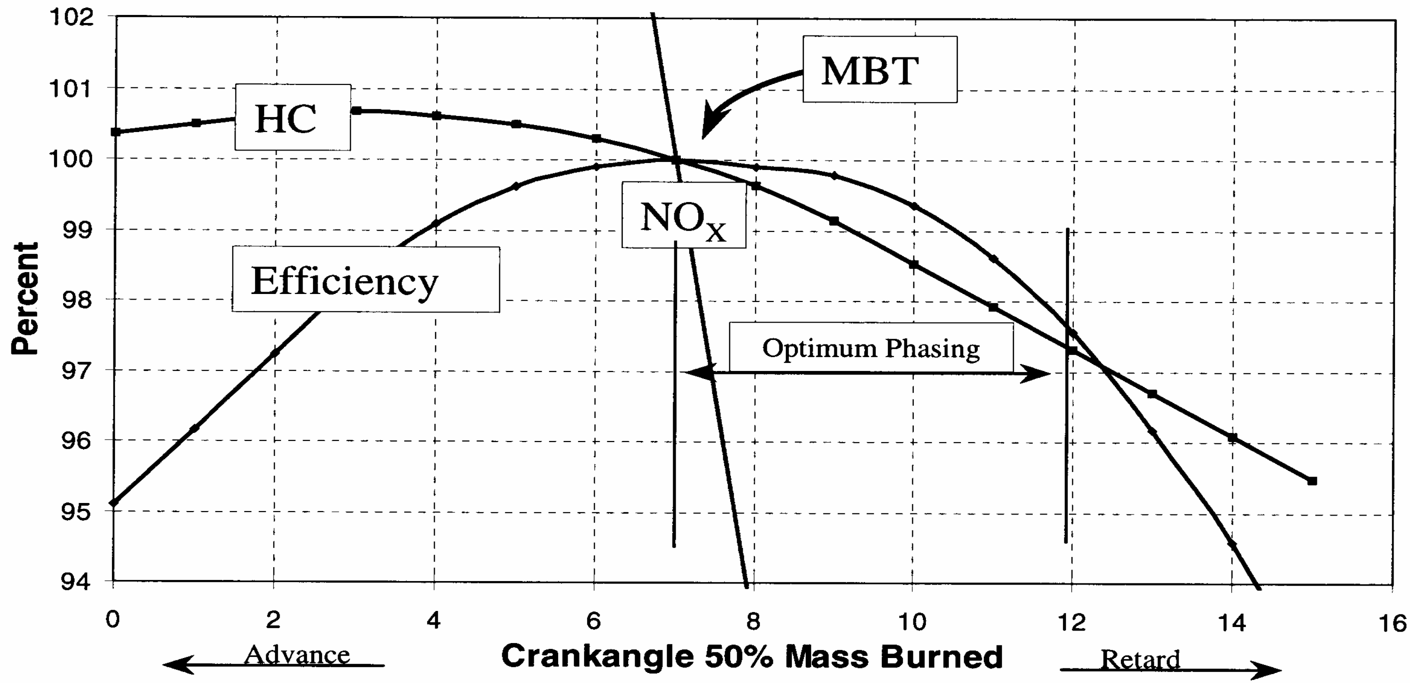


Advanced Calibration Methodology



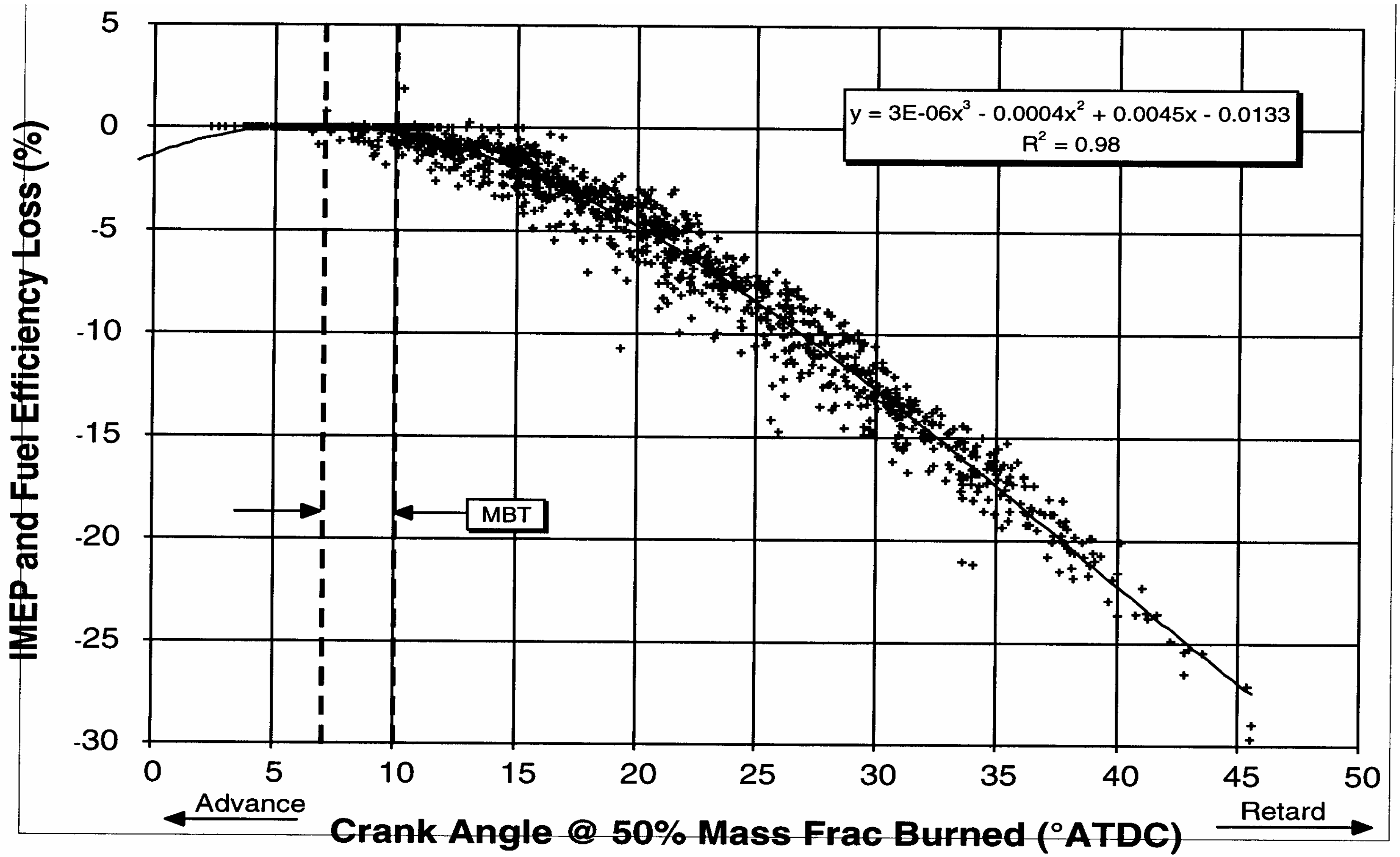
Advanced Calibration Methodology

Spark Timing Calibration Strategy



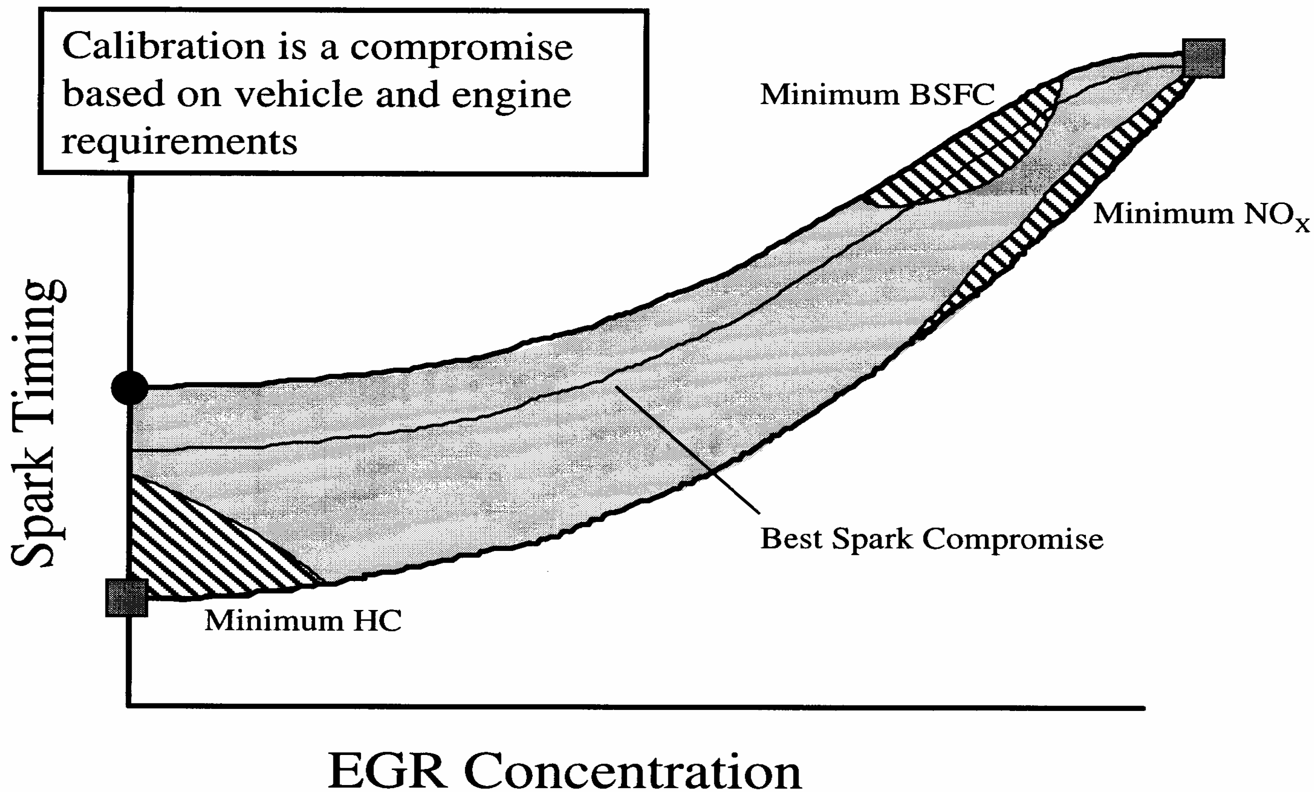
Retard spark slightly from MBT to optimize tradeoff between efficiency and emissions.

Advanced Calibration Methodology

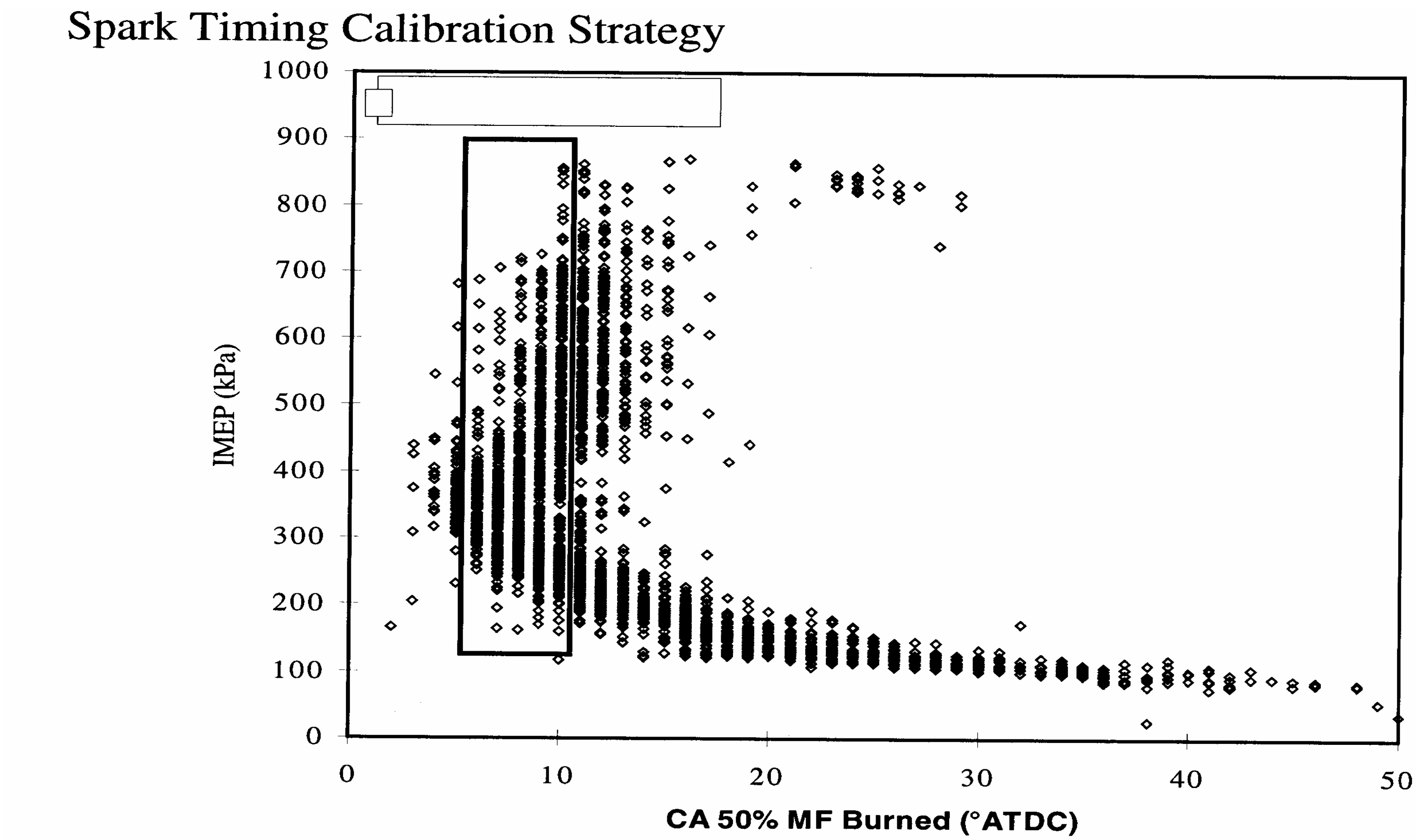


Advanced Calibration Methodology

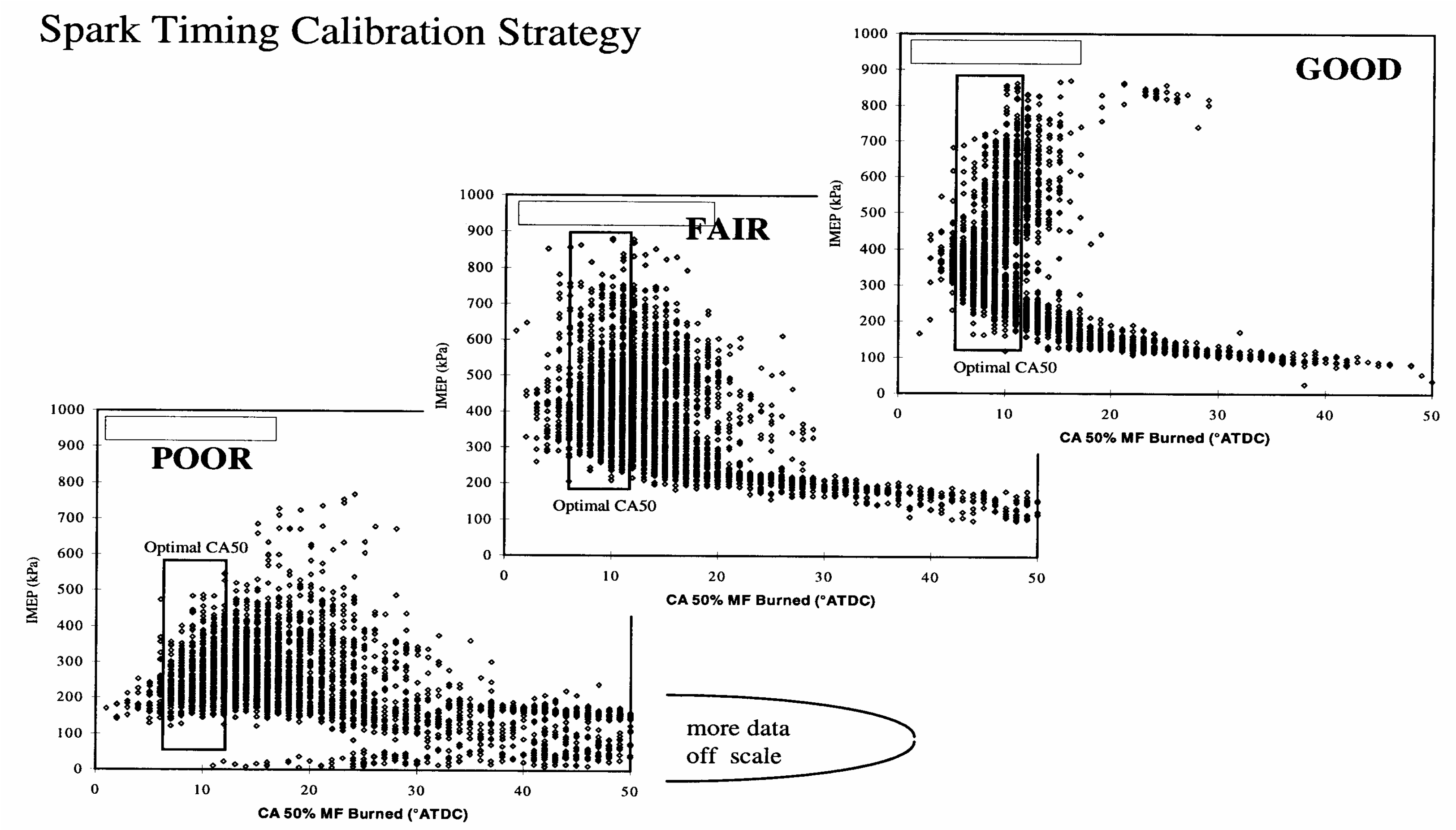
Spark Timing Calibration Strategy



Advanced Calibration Methodology

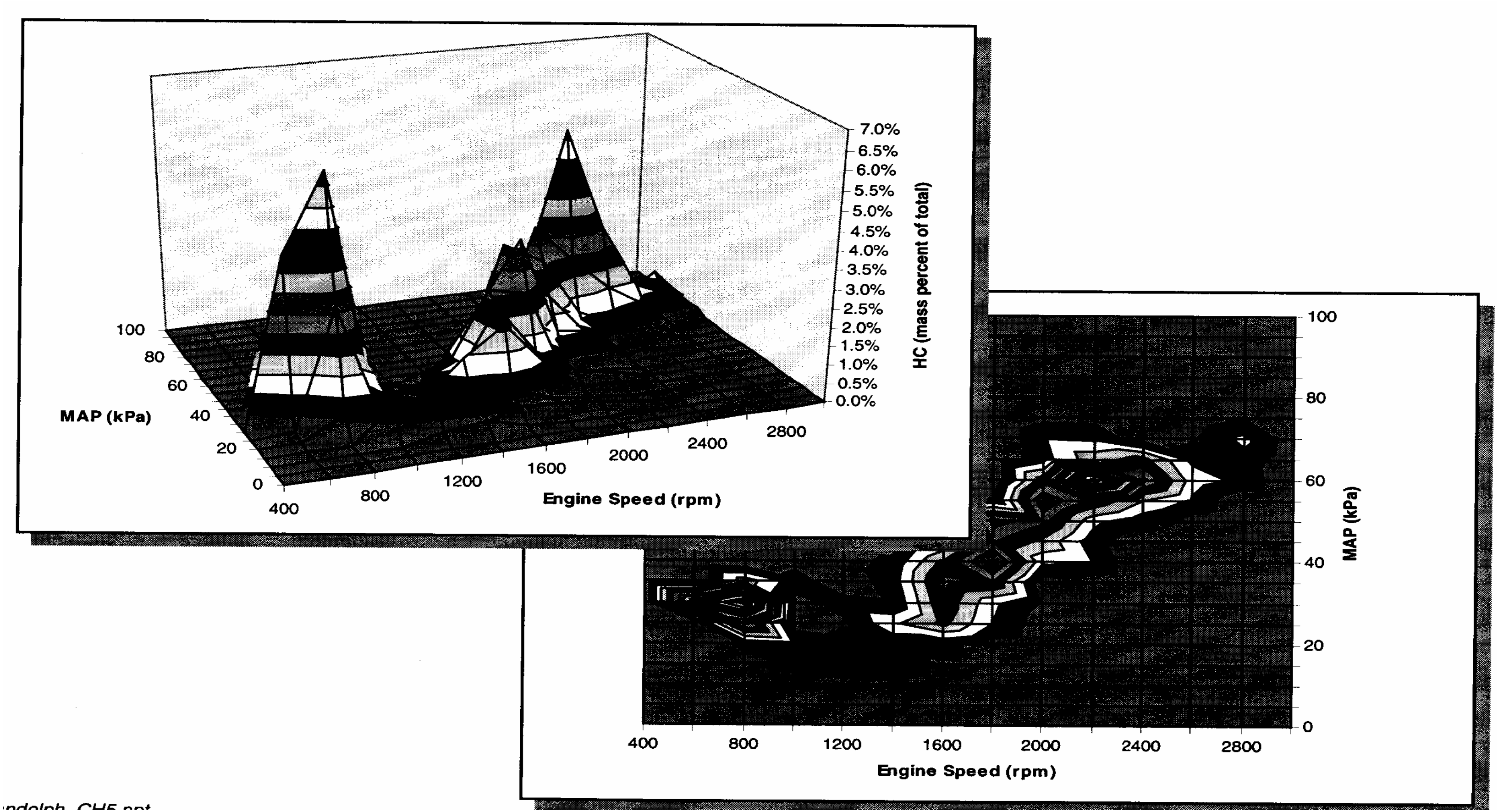


Advanced Calibration Methodology

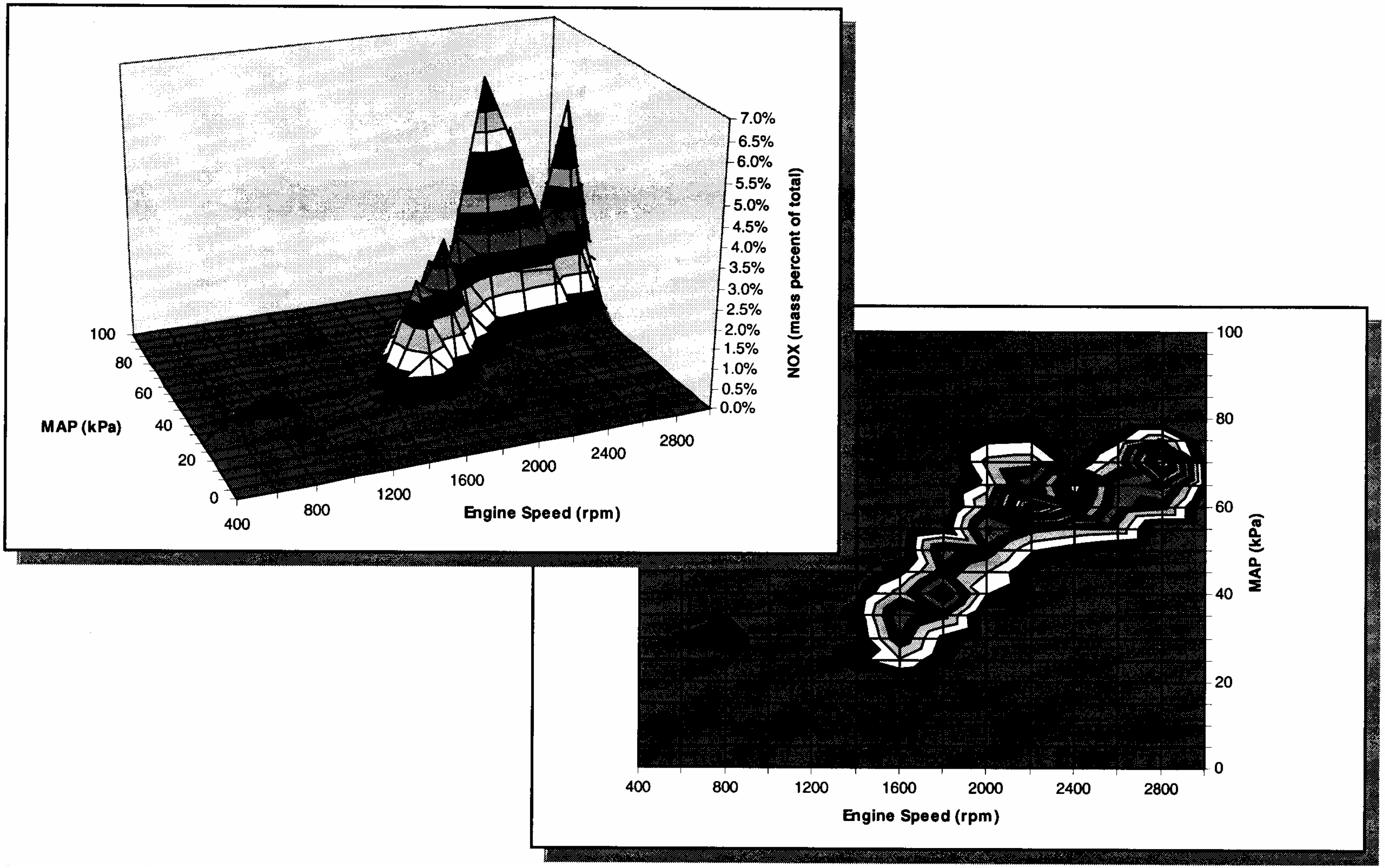


Advanced Calibration Methodology

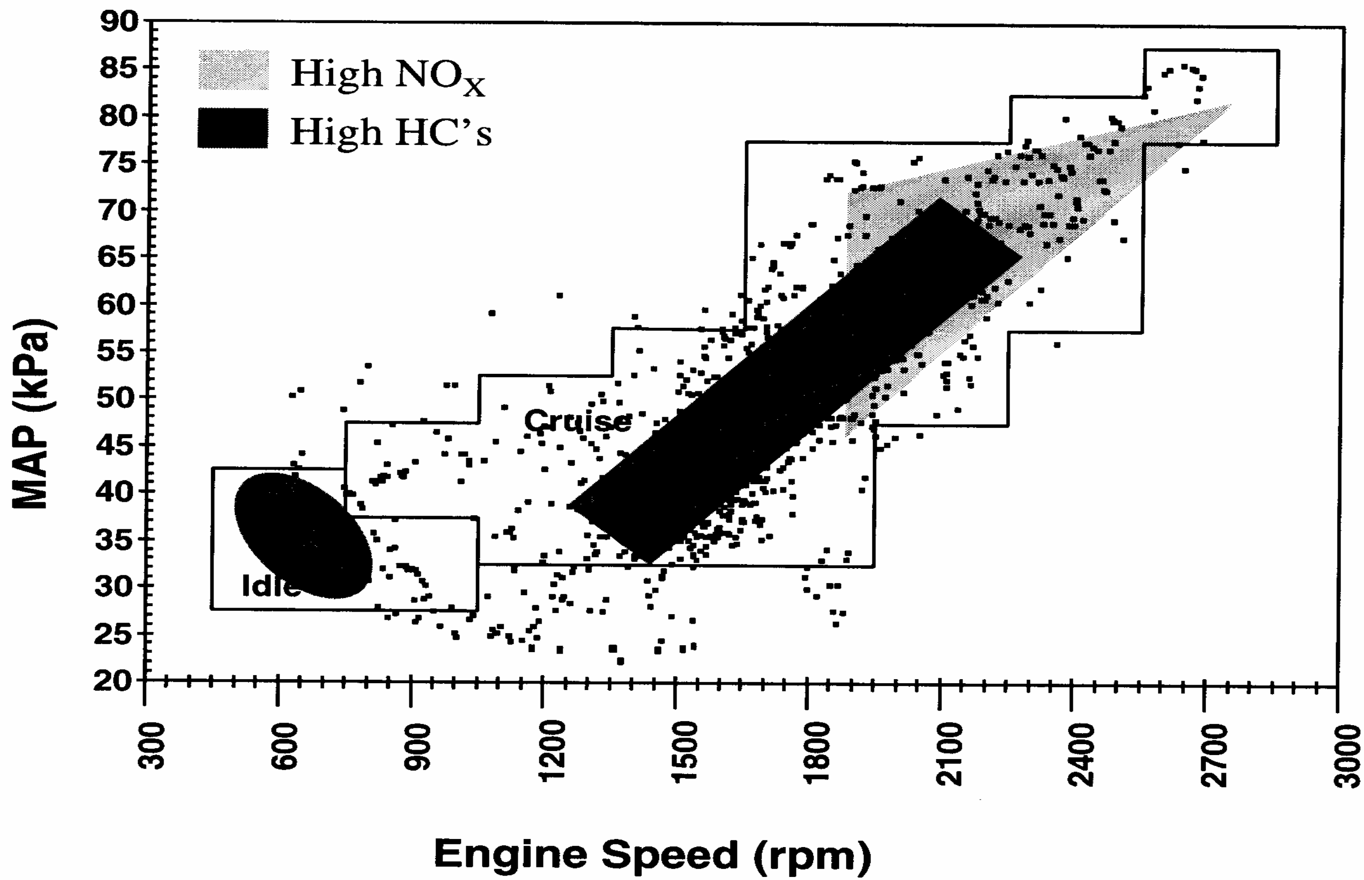
FTP City Cycle   Engine out HC



Advanced Calibration Methodology FTP City Cycle
Engine out NOx

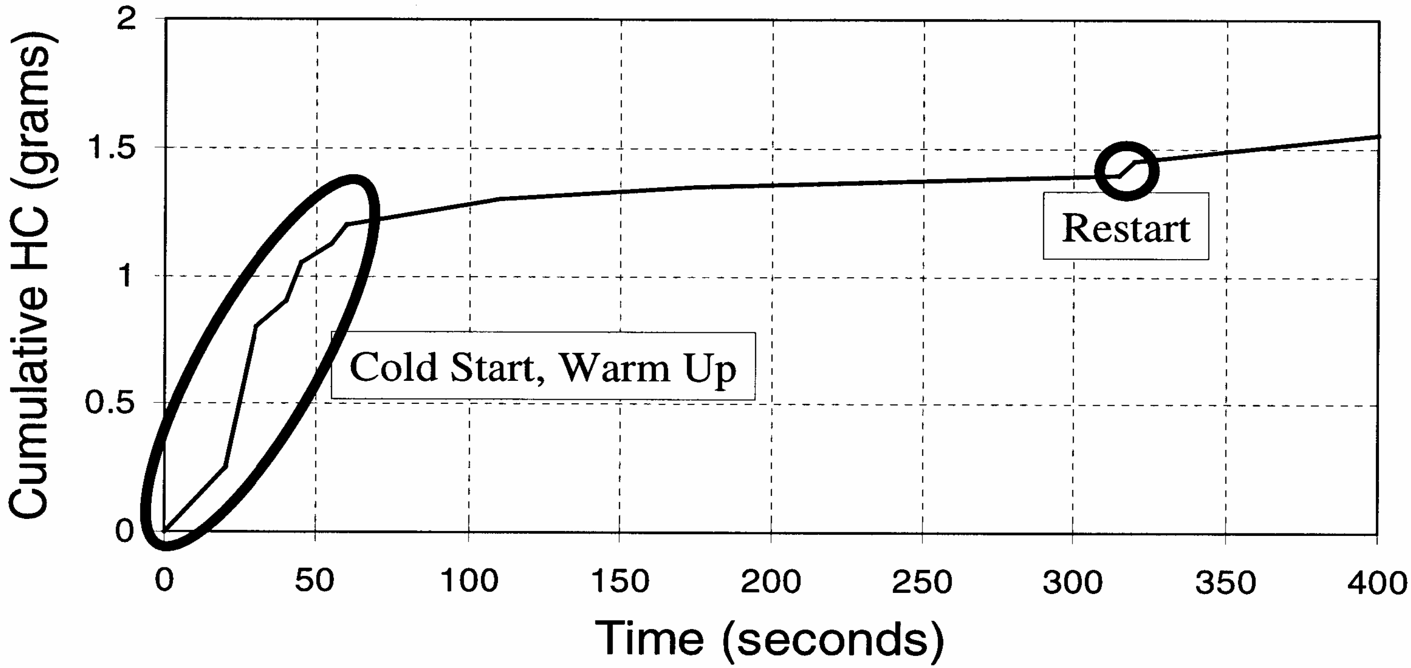


Advanced Calibration Methodology FTP City Cycle Engine out Emissions Summary



Advanced Calibration Methodology

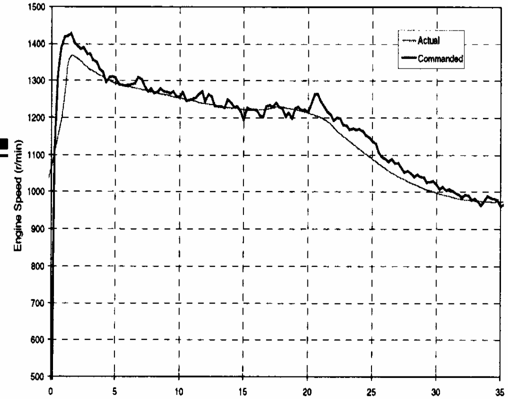
Vast majority of hydrocarbon emissions occur during cold start and subsequent warm up



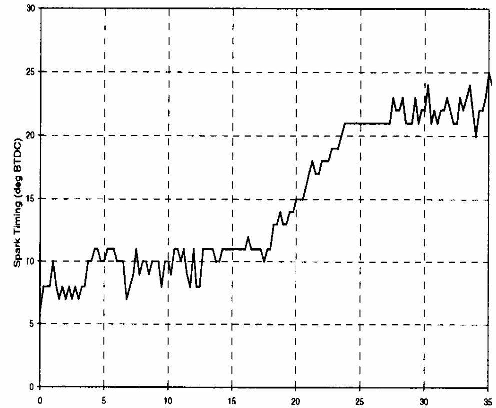
Adv Calibration

Cold Start

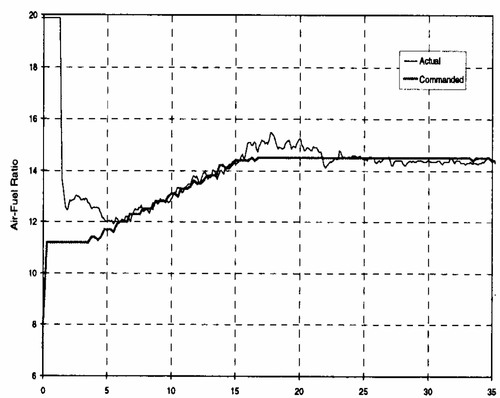
Engine Speed



Spark Timing



Air-Fuel Ratio

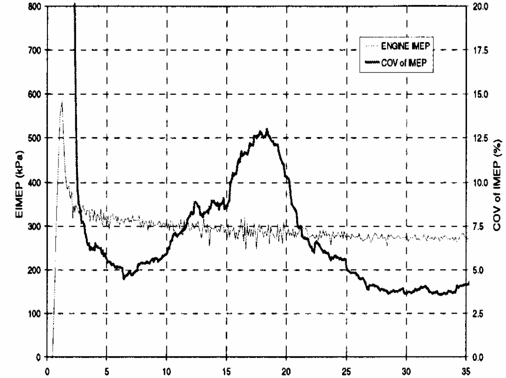


Degrees of crankshaft advance

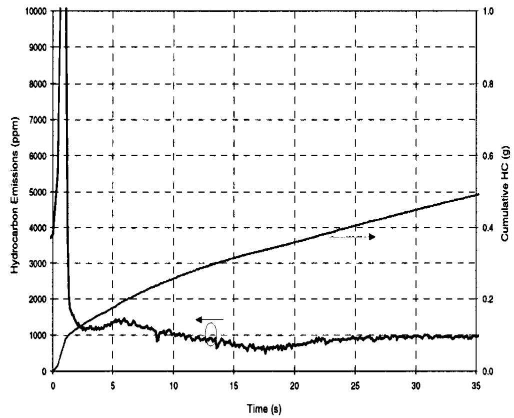
Adv Calibration

Cold Start, cont.

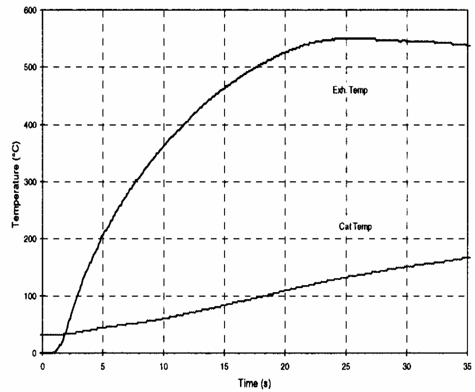
Combustion Stability



Engine-Out Hydrocarbons

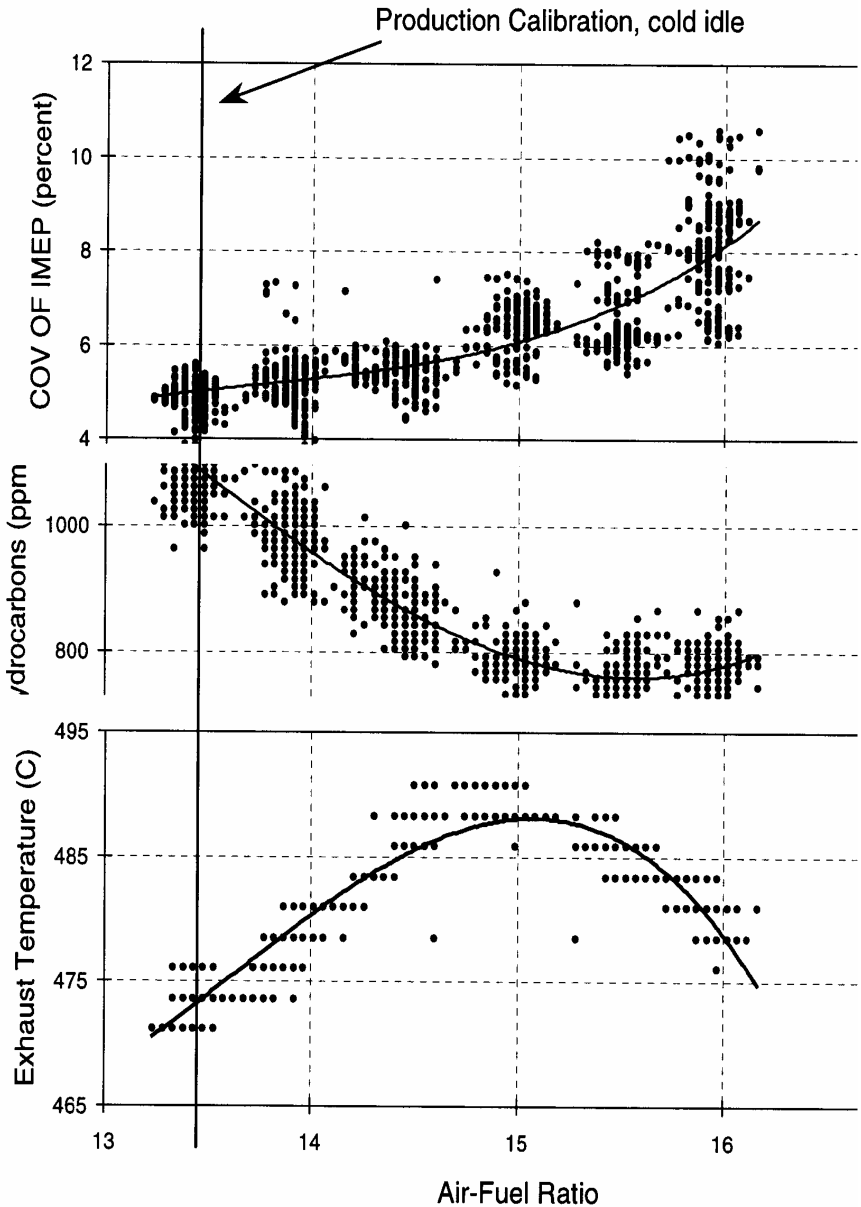


Exhaust Heat



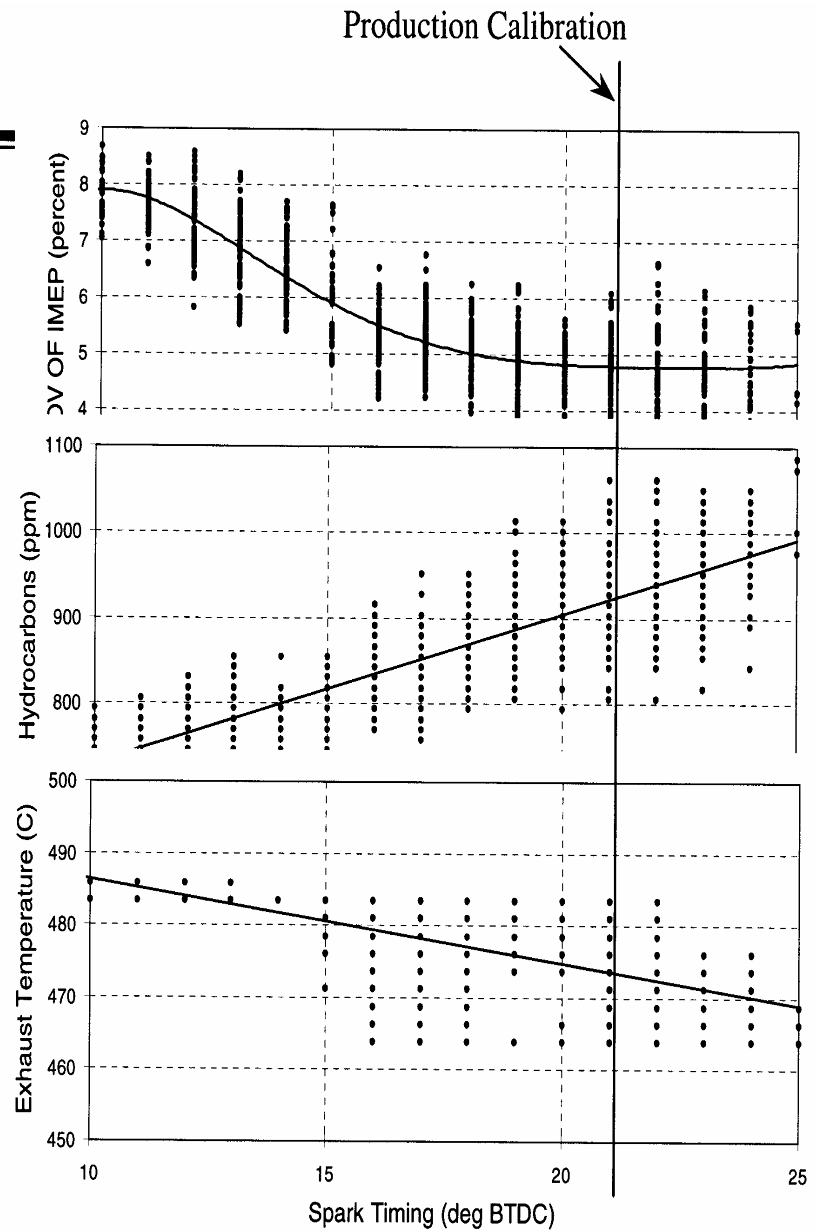
Adv Cal

Cold Start enlean sensitivity



Adv Cal

Cold Start spark retard sensitivity



Advanced Calibration Methodology

Sensitivity Summary

Lean off		Retard
COV ↑		COV ↑
HC ↓ ↓	== engine out ==	HC ↓
↑ Temp.exh*	= light off =	Temp.exh* ↑ ↑

*Heat flow

Advanced Calibration Methodology

Cold Start Calibration – What to do ?

- Calibrate to a specific combustion stability limit
- Operate at the highest engine speed acceptable from a noise and vibration perspective during the cold idle
- Optimise trade off between spark retard and air-fuel en-leanment to minimize cumulative HC emissions prior to catalyst light off

Advanced Calibration Methodology

Combustion as a Calibration Tool

- **Combustion Phasing:**map to an optimum phasing value (crank angle (CA) 50 of around 10deg.),use CA50 to check calibration 'precision'
- **Combustion Stability:**map within acceptable driveability limits, use COV of IMEP and IMEP imbalance to check calibration drivability
- **Knock and Preignition Monitoring:**map within acceptable knock and pre-ignition limits
- **OBDII Misfire Diagnostic Tuning:**tune diagnostic to trigger only on true misfires

Data Integrity

How is it achieved ?

By understanding the magnitude and causes of variation present in the combustion data acquisition process and then using that knowledge to identify and remove causes that do not occur naturally

Data Integrity

Understanding sources of variability

- Daily checks
  - Daily checks provide the information necessary to understand variability
  - Record combustion data daily at the same test condition
  - Control all variables to the greatest extent possible

Data Integrity

Daily Checks

- Ideally,record data under both firing and motoring conditions
  - Select a firing condition representative of the majority of actual test conditions
    - If most of your testing is done at low speeds and loads, select the daily check condition accordingly
  - Perform the motoring test at the same speed and WOT (Full rack)

Data Integrity

Daily checks: Maintain consistent engine and environmental conditions

- **Engine:**
  - Follow the same warm-up procedure
  - Constant speed
  - Constant load
    - Brake,torque,MEP, MAP
  - Always conduct motoring and firing tests in the same order (Always firing first)

- **Environment:**
  - Temperatures
    - Inlet air, coolant,oil, fuel
  - Pressures
  - Inlet air humidity
  - Same fuel type
  - Same test technician running the test if possible

Data Integrity

Daily Checks

- Now that you are conducting daily checks and gathering lots of interesting data, what are you going to do with it ?

Plot it on a Control Chart

Data Integrity

<u>What is a control chart ?</u>

- A statistical tool used to distinguish ***naturally*** occurring variation in a process from variation due to ***special causes***.
  - **Naturally occurring variation is inherent to any process over time and effects all outcomes**
  - **Special causes, or assignable causes, such as a failed pressure transducer or an air leak in an emission sampling tube,are not always present and do not affect all outcomes**

Data Integrity

<u>What will a Control Chart do for me ?</u>

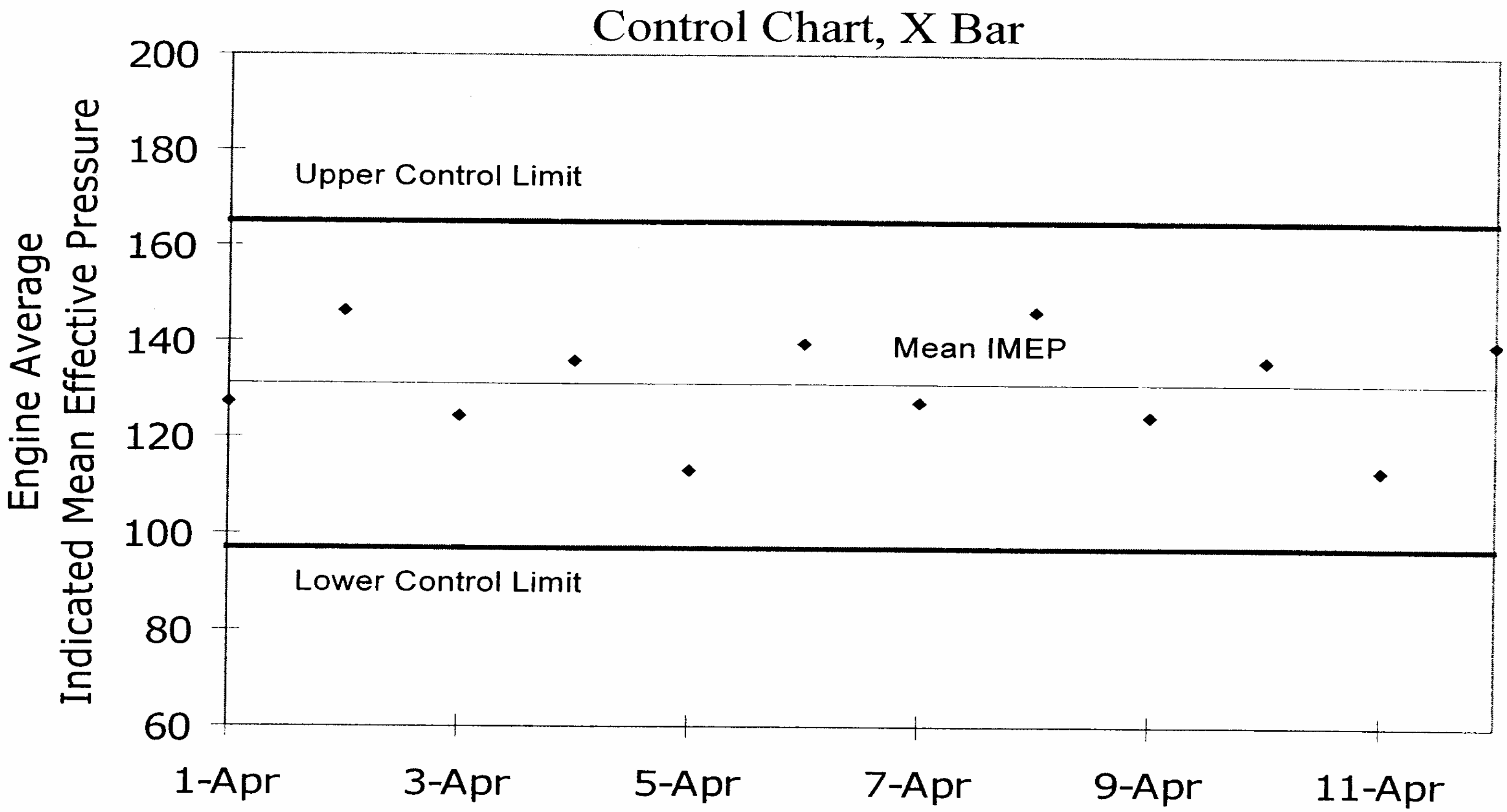
- Control charts are useful in identifying
  - Engine problems
    - Scuffing pistons, leaking rings, damaged camshaft lobes…
  - Insufficient break-in
    - Stability of emissions, friction…
  - Instrumentation problems
    - Dirty,damaged transducers
    - Failing emissions analyzers
    - Equipment ‘drift’

Data Integrity

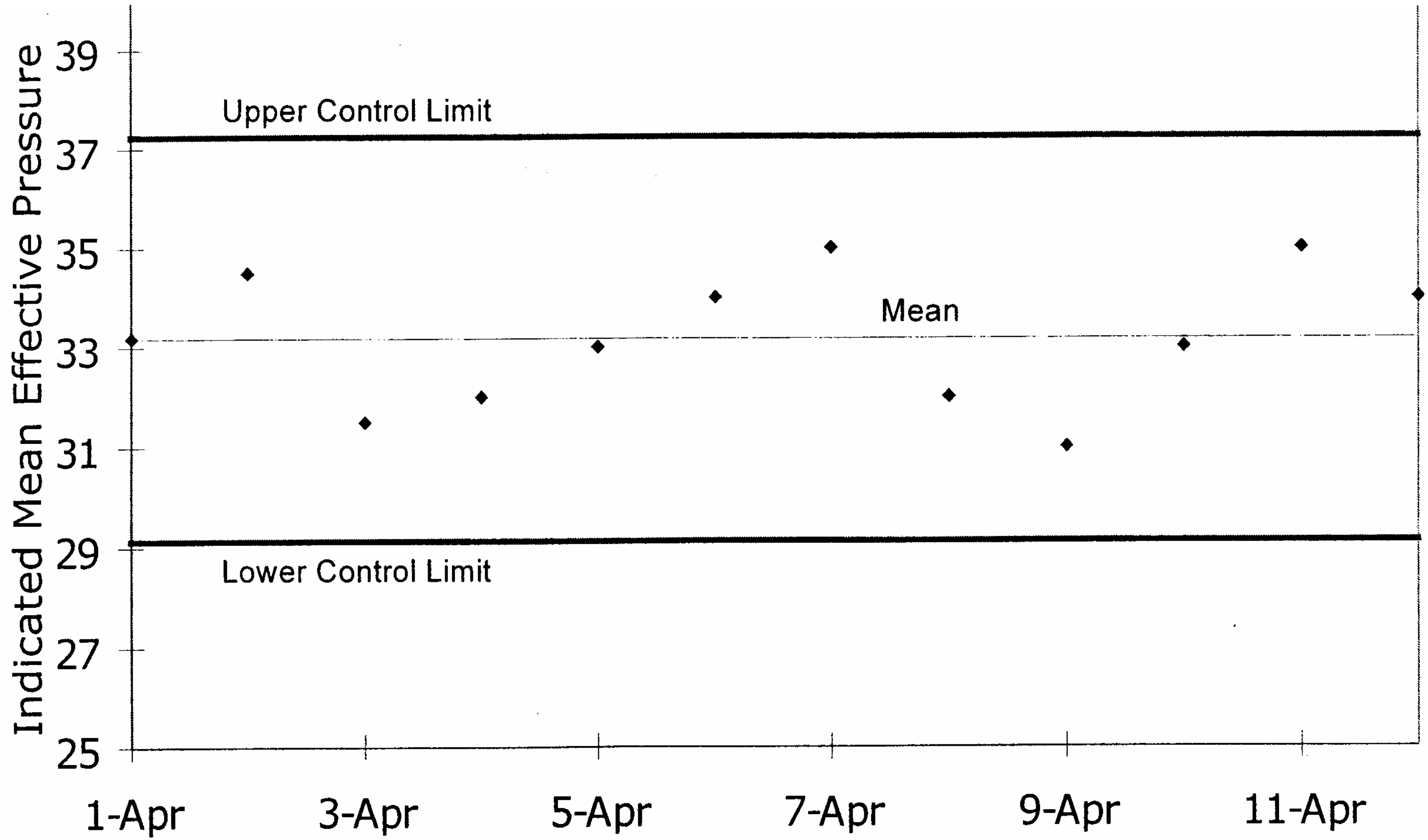
Control Charts

- Two types of control charts prove most useful for understanding variation in combustion data
  - X-bar
    - Tracks the value of a particular variable (engine average IMEP in following example)
  - Range
    - In this example, it quantifies the range (maximum value –minimum value) of IMEP between six cylinders

Data Integrity: Control Charts



Data Integrity: Control Charts



Data Integrity

Control Chart Set up and Maintenance

- Be diligent and keep good records
  - When you detect a value 'out of control' record the findings in a log
  - Review the charts regularly
  - Recalculate the limits only when a change has been made to the engine/data acquisition system
    - New camshaft,cylinder head, new fuel batch etc….

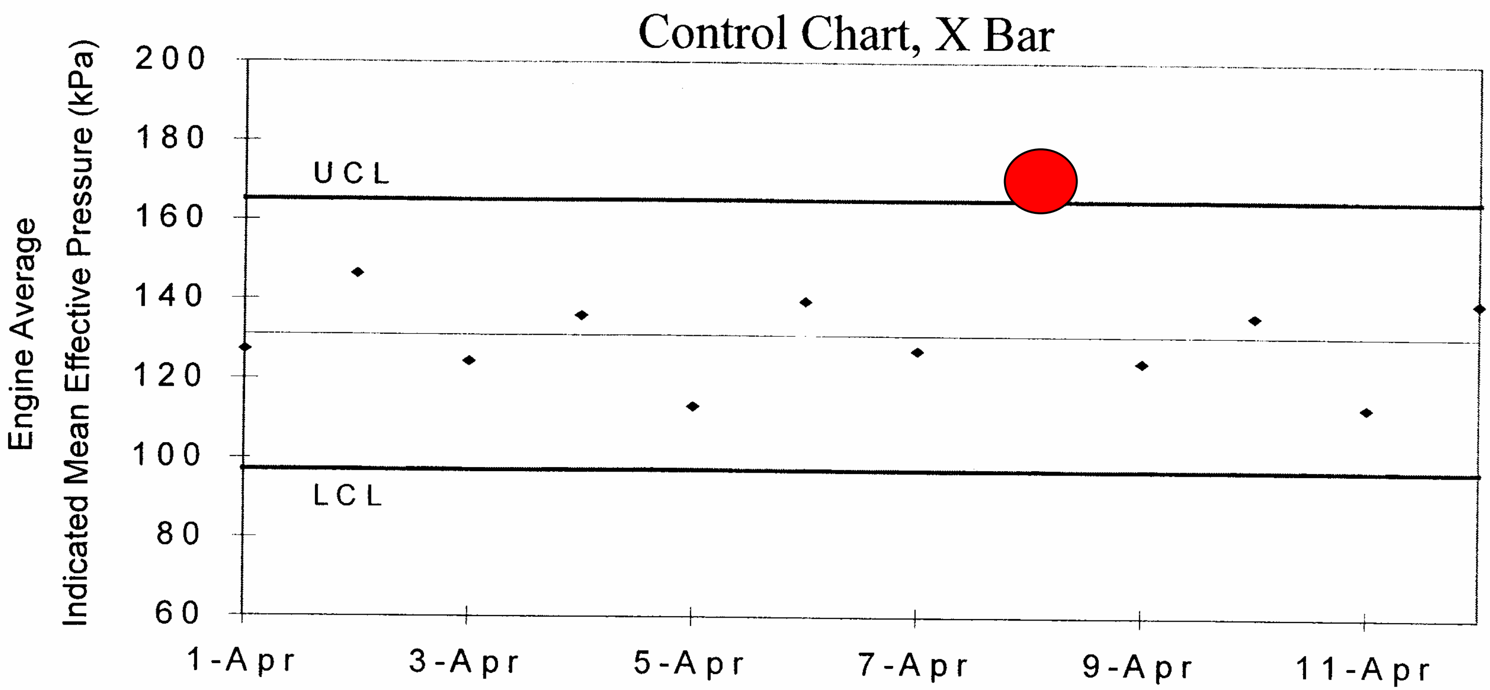
Data Integrity

<u>Interpreting Control Charts</u>

- The control chart provides the basis for taking action to improve a process
  - A process is considered in control when there is a random distribution of the plotted points within the control limits
  - If there are points outside the limits, or if the process is unstable
    - **Take action to remove the special cause of variation !**

Data Integrity
Interpreting Control Charts

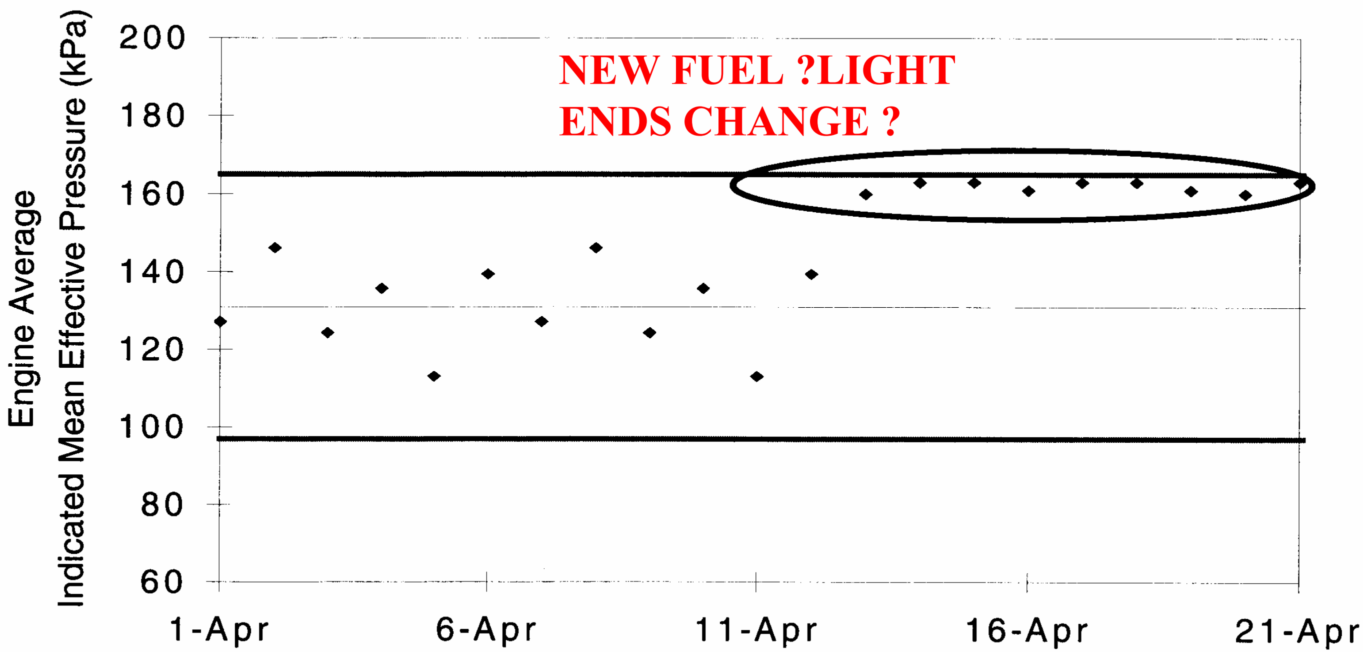
On April 8, the load was set to a brake torque. The *special cause* of the high IMEP was traced to a torque meter that needed to be recalibrated. The MAP would have been another good indicator that the process was unstable.



Data Integrity

Interpreting Control Charts

What caused IMEP to shift? new head gasket, fuel injectors, piston scuffing causing higher friction,...
Identify the cause and either fix the problem or recalculate the control limits and mean.



A. Randolph, CH7.ppt

Data Integrity

What data should one put on a Control Chart ?

- Firing Checks
  - IMEP, PMEP, NMEP, BMEP, FMEP, MAP,rev/min
    - All load should be in agreement
    - Variation may indicate dirty transducers,recalibration for torque meter.. Your conclusions can be supported with fuel flow or emissions data
  - HC, NOx, CO, CO_2
  - Carbon and Oxygen balance, A/F ratios, A/F from O2 sensor, fuel flow rate, air flow rate, BSFC
  - Polytropic coefficients, PP, LPP, CA50

Data Integrity

<u>What data should one put on a Control Chart ?</u>

- Motoring Checks
  - IMEP, PMEP, NMEP, BMEP, FMEP, MAP, rev/min
    - IMEP is a good indicator of transducer 'health'
  - PP, LPP
    - Motoring peak pressures and their location are relatively consistent.PP provides a good transducer check while LPP confirms encoder phasing
  - Polytropic coefficients
    - These coefficients typically do not vary much and a little change will cause them to exceed the control limits, you must use your judgement and cross reference.

Data Integrity

Good test practises

- Make redundant measures a part of normal testing !
  - Typically, any one measurement can be supported by several devices or other measurements- an example being Air Fuel Ratio

Data Integrity

<u>Redundant Measures</u>

- How many ways can you quantify/qualify your air fuel ratio ?
  - Carbon and oxygen-balance air fuel ratio
  - Exhaust O2 sensor
  - Inlet air and fuel measurement
  - CO emissions
  - Specific fuel consumption, cylinder pressure, torque,..

Take the time to understand and apply redundant measures wherever possible

Data Integrity

Good test practices

- Whenever possible, perform test replications-do not make a decision based on a single test
- Random test points
- Support your data by understanding the variability present in your equipment

Data Integrity

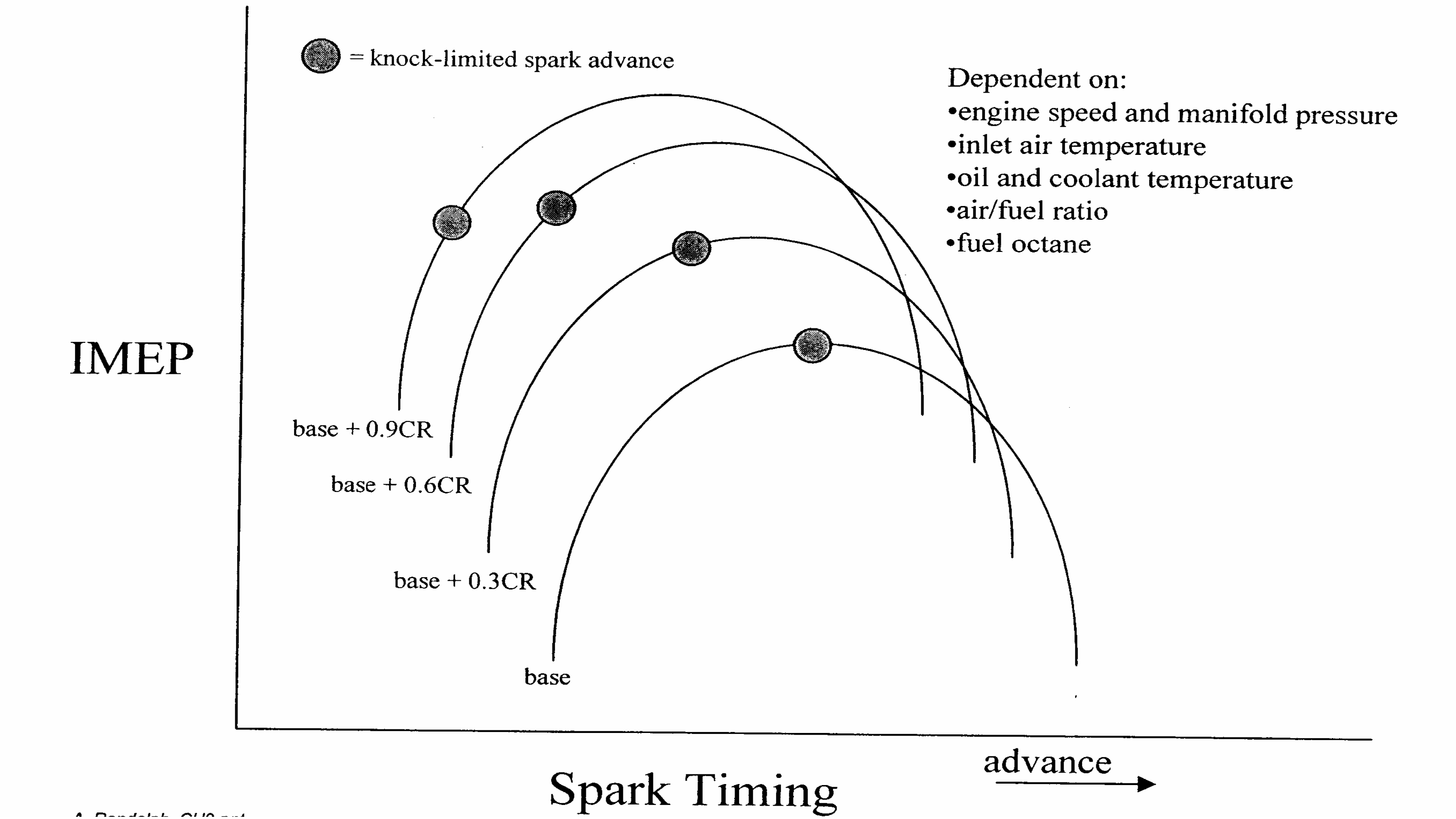
<u>How many cycles of combustion data should one record ?</u>

- Rules of thumb:
  - As variability increases, record more data
    - Idle-very low speed and light load >500-1000 cycles
    - Part-load-better combustion stability>300-500 cycles
    - High load,high speed >300 or fewer cycles-balance the number of cycles against things like propensity to knock..
    - Motoring- very repeatable pressure traces>less than 300 cycles

Data Integrity

- Daily checks, control charting, and redundant measures require a small investment of time to establish and maintain, but save many times the capital investment by reducing development and test time through improved data quality

Compression Ratio Optimisation (S I Application)



Compression Ratio Optimisation

Advantages of Maximising Compression Ratio

- Increased full-load torque through most of the engine speed range
- Reduced full-load combustion-induced engine noise
- Lower peak full-load combustion pressures
- Improved part-load fuel economy(approx 1.5% per 0.5\ratio)
- Increased dilution tolerance through faster burn
- Improved idle stability via lower residuals

Compression Ratio Optimisation

Disadvantages of Maximising Compression Ratio

- Higher part-load hydrocarbon and NOx emissions
- Greater reliance on knock sensing system
- Higher full-load exhaust temperatures
- Increased likelihood of pre-ignition

Compression Ratio Optimisation

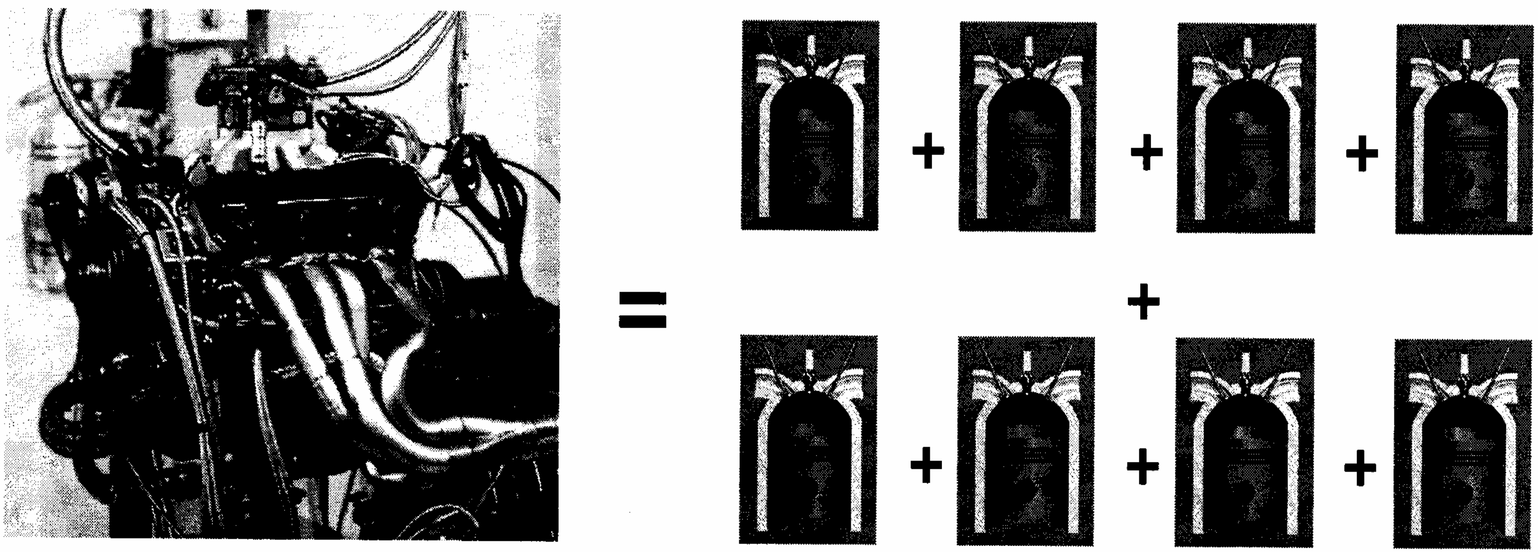
<u>Enablers of High Compression Ratio</u>

- Precise fuel control
- Good cooling of the chamber and combustion chamber
- Reliable knock sensing and control methodology
- Low engine – out emissions

Full Load
Performance Optimisation

- Example from a NASCAR Winston Cup race engine development exercise, which demonstrates the clear advantages of utilising combustion analysis techniques to enable accelerated development.

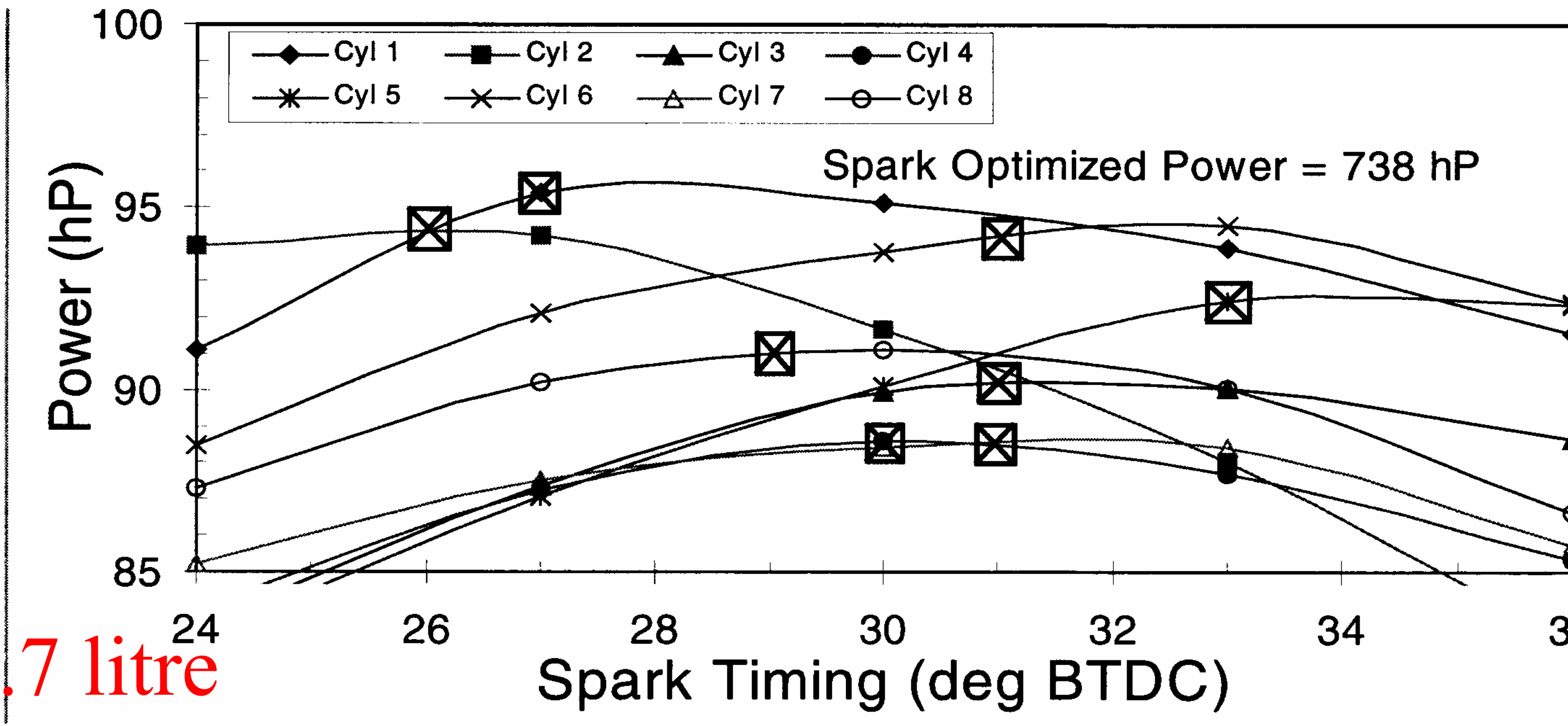
Full Load
Performance Optimisation



⇨ A multicylinder engine is a combination of several single cylinder engines, each of which must be optimized to obtain maximum performance.

Full Load
Performance Optimisation

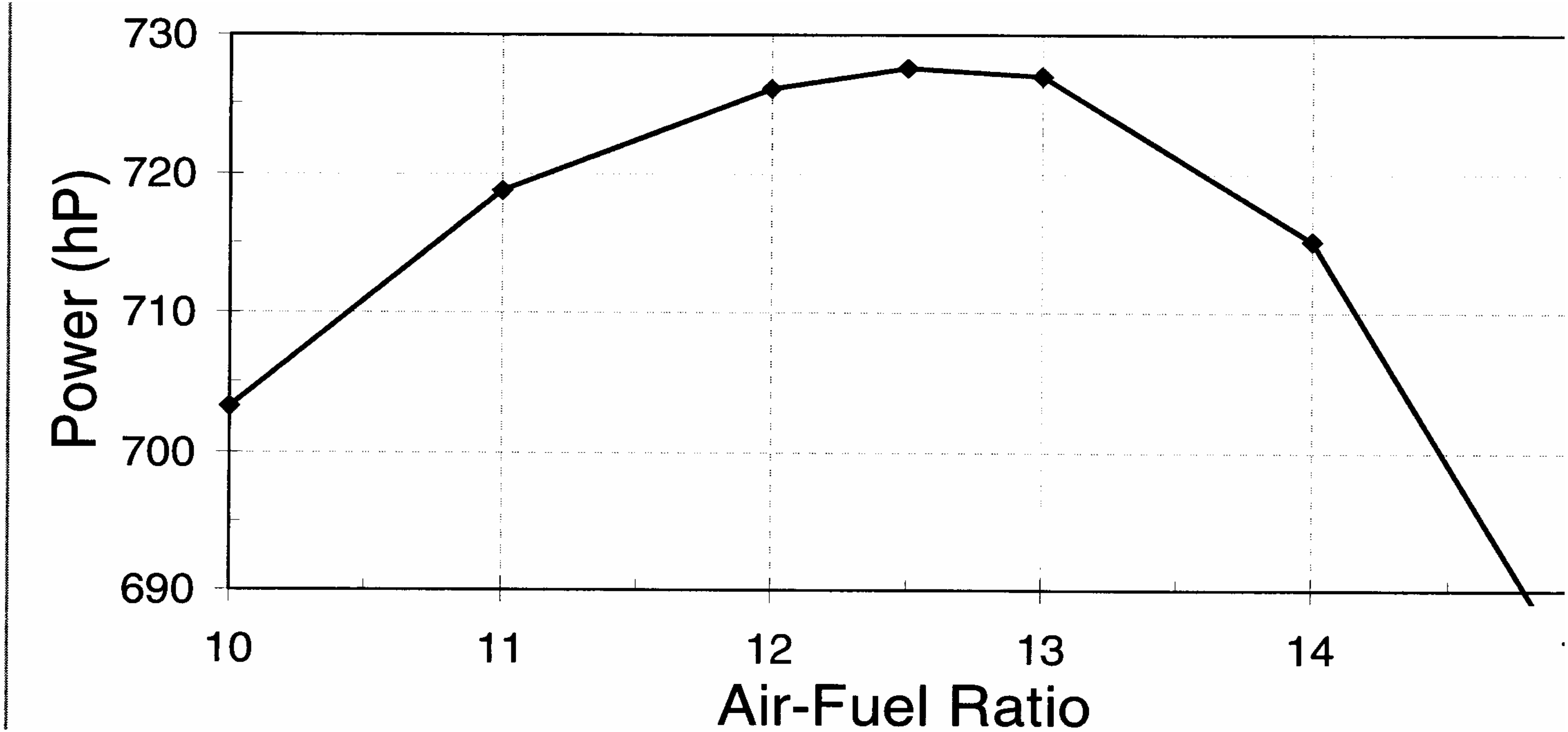
gnition timing is set to the value that maximises output from each individual cylinder, eading to a 10 BHP increase in total engine power



5.7 litre push rod

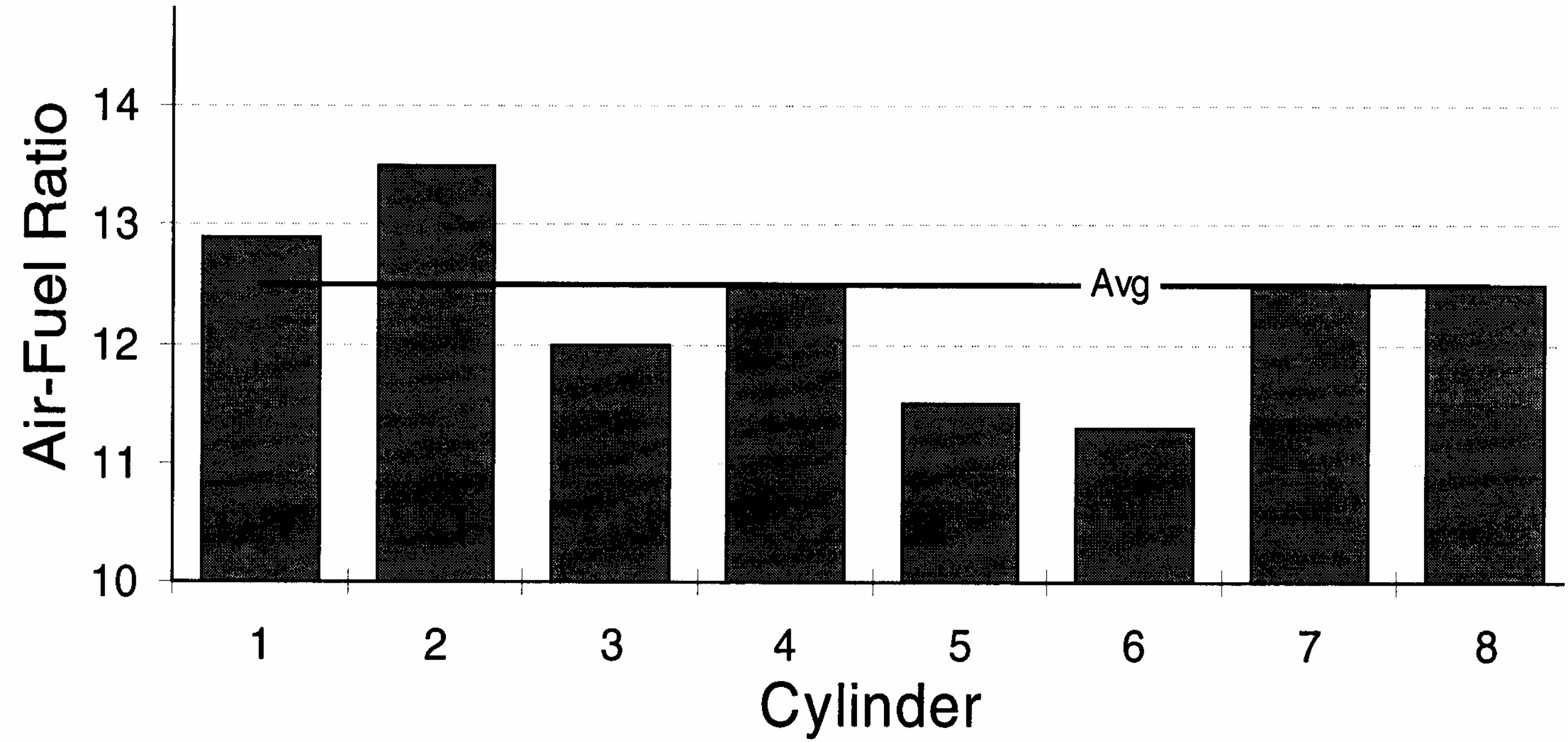
Peak Power: Sensitivity to Air-Fuel Ratio

ndividual cylinder air-fuel ratio mal-distribution also reduces total engine peak power



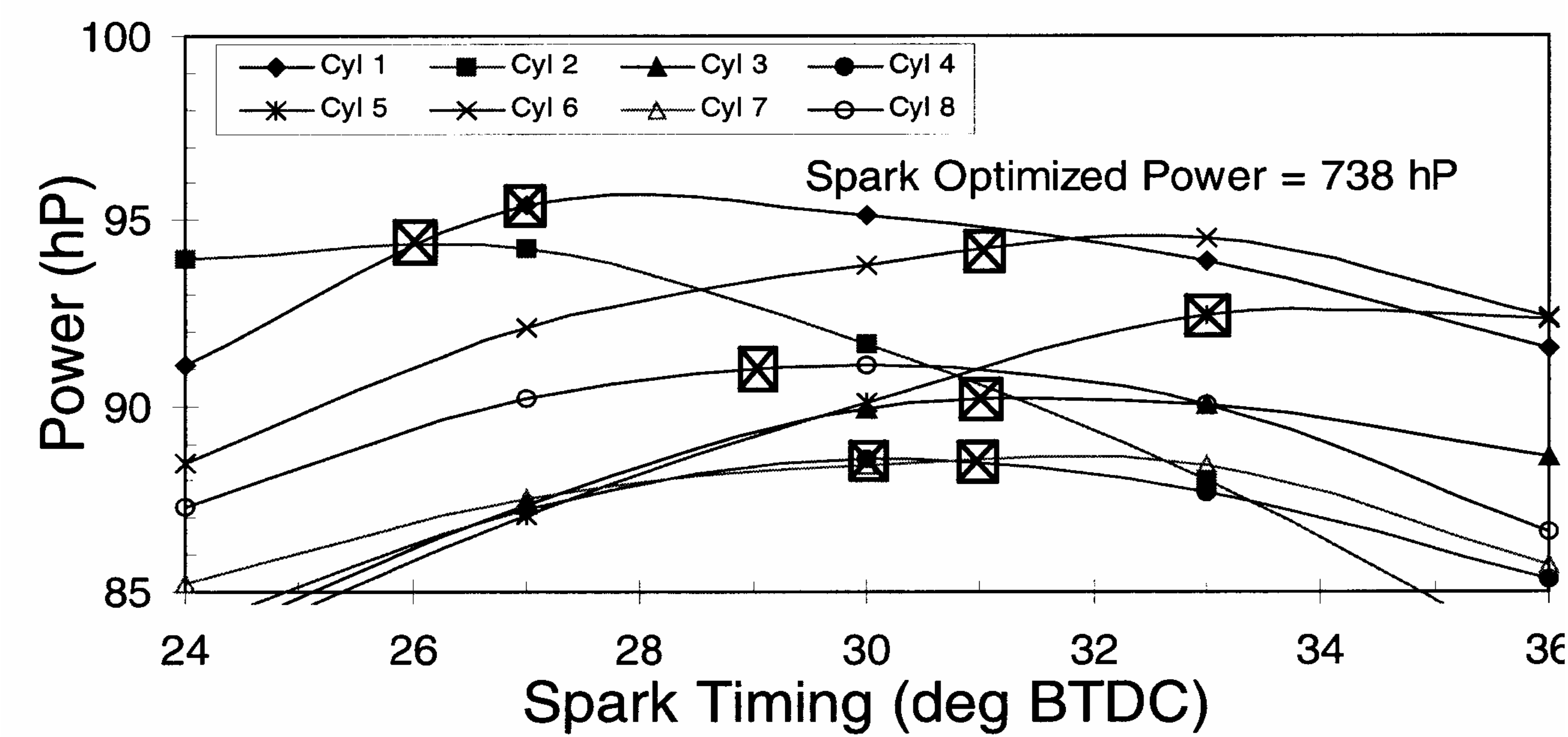
Peak Power: Air-Fuel Ratio Distribution

This amount of mal-distribution costs about 7 BHP when global spark timing is used and 4 BHP when individual cylinder spark optimisation is used.



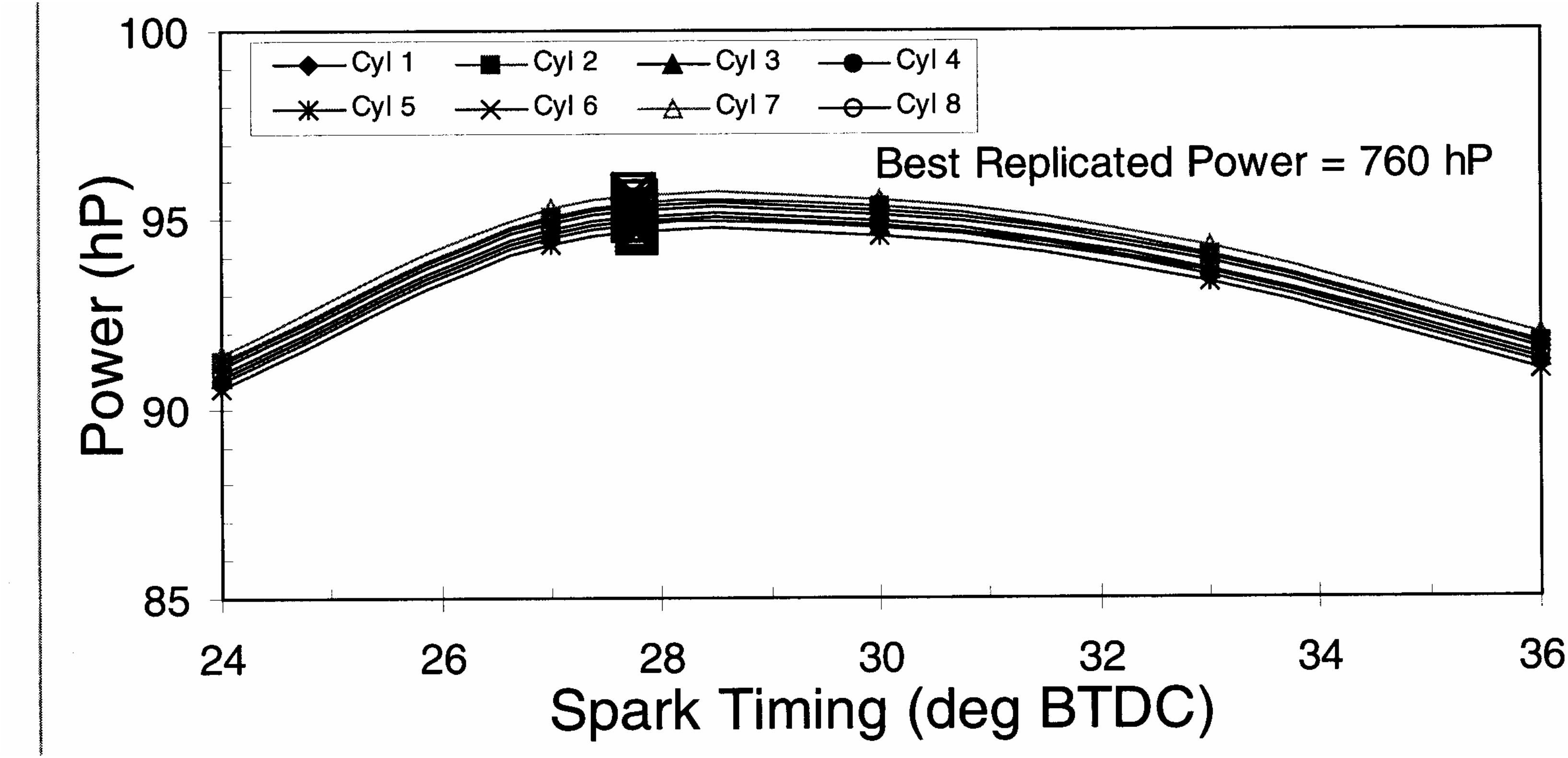
ndividual Cylinder
park Optimisation

Even with individual cylinder spark timing optimisation,power contributions of the individual cylinders differ significantly



Peak Power
Cylinder Replication

Goal is to have each cylinder perform as well as the best cylinder (potential 22 BHP gain)



Replicated Chambers, Ports & Runners

Cylinder-to-cylinder imbalance in any of a variety of areas degrades the combustion system performance:

- Air fuel ratio (air flow / fuel flow)
  - Intake restriction
  - Exhaust restriction
  - Tuning lengths
  - Fuel distribution
- Mixture motion
- Valve timing
- Compression ratio

Combustion System Replication

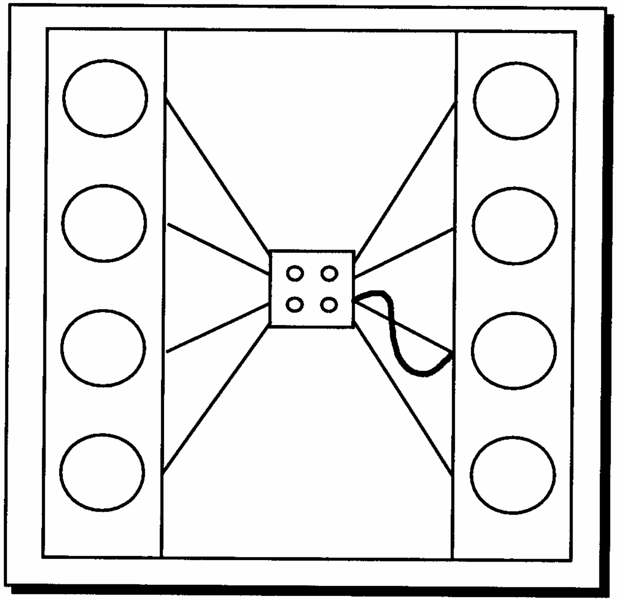
Design issues to achieve

- **Pastry cutter design replication of the combustion system, inlet runners, and exhaust runners**
- **Even firing intervals**
- **Control of the manufacturing process**

Combustion System Replication

Asymmetries are inherent in a single carburetor system ...

- distribute fuel and air uniformly
- equivalent static flow efficiency
- equivalent dynamic flow efficiency



⇨ Charge Flow (air + fuel) = POWER

Trapped Mass

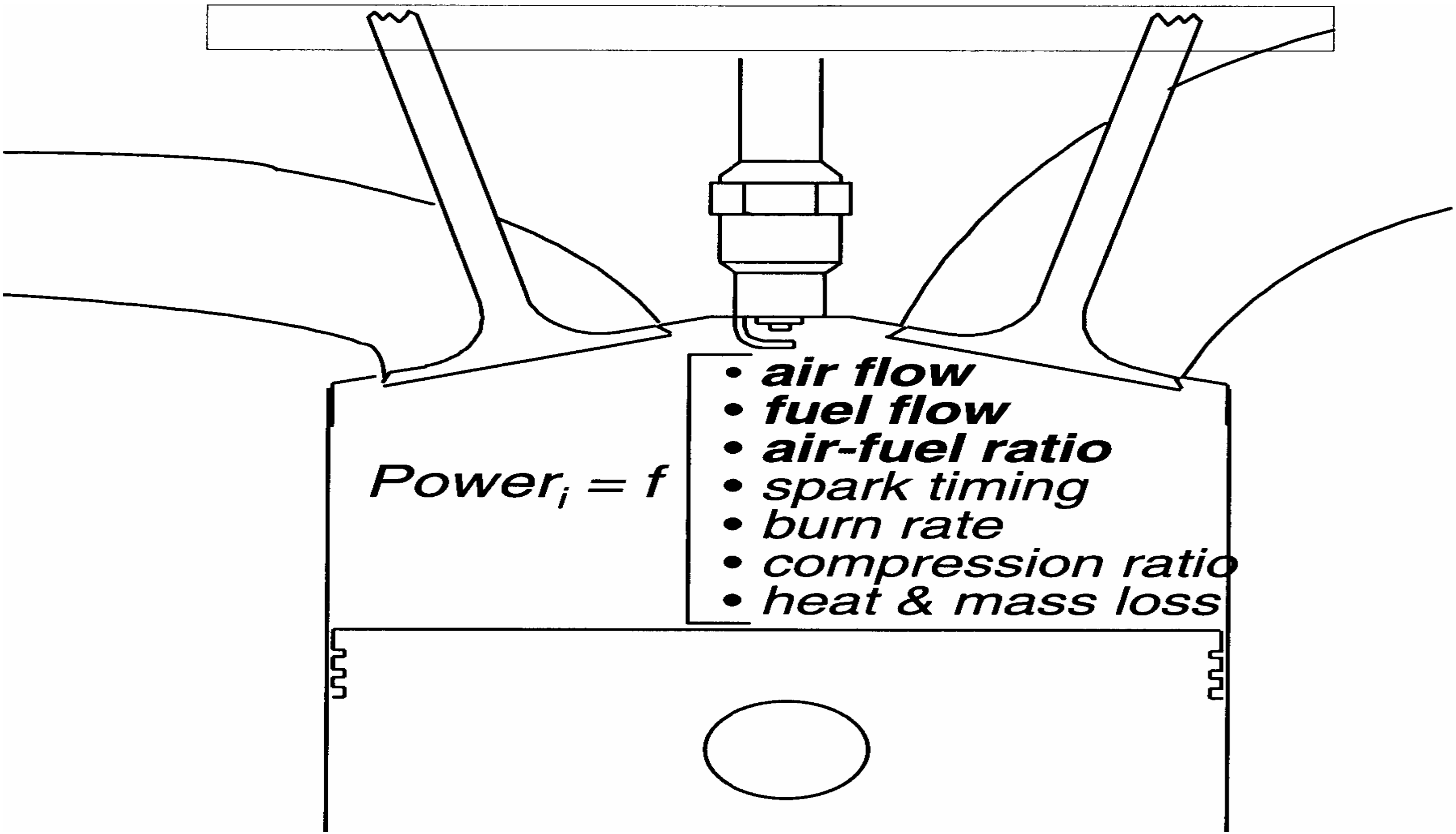
Volume of runners not the length is the critical factor

Combustion Variability

Steps to improve stability

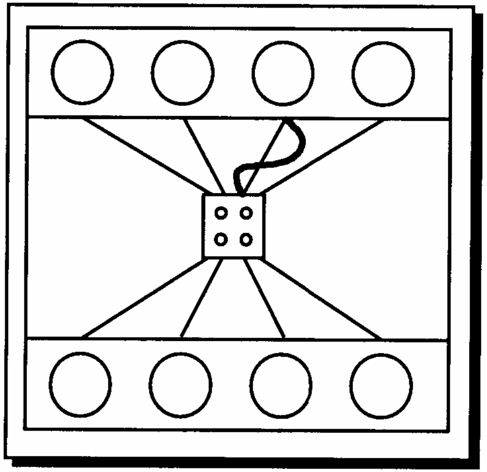
- Well balanced combustion system hardware
  - Equal-length, replicated intake/exhaust runners & ports
  - Replicated combustion chambers (fast burning)
  - Good EGR, air,fuel,PCV & purge distribution
  - Good fuel injectors
    - Small droplets
    - Good targeting (back of valve, minimize wall-wetting)

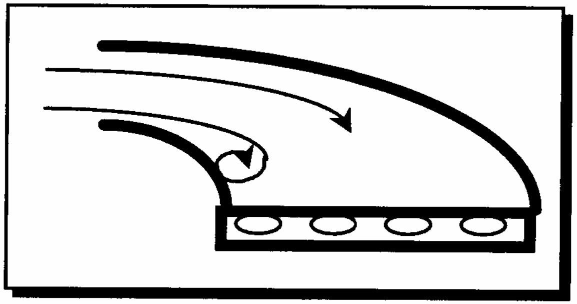
Trapped Mass Replication



Sources of Trapped Mass Assymetries

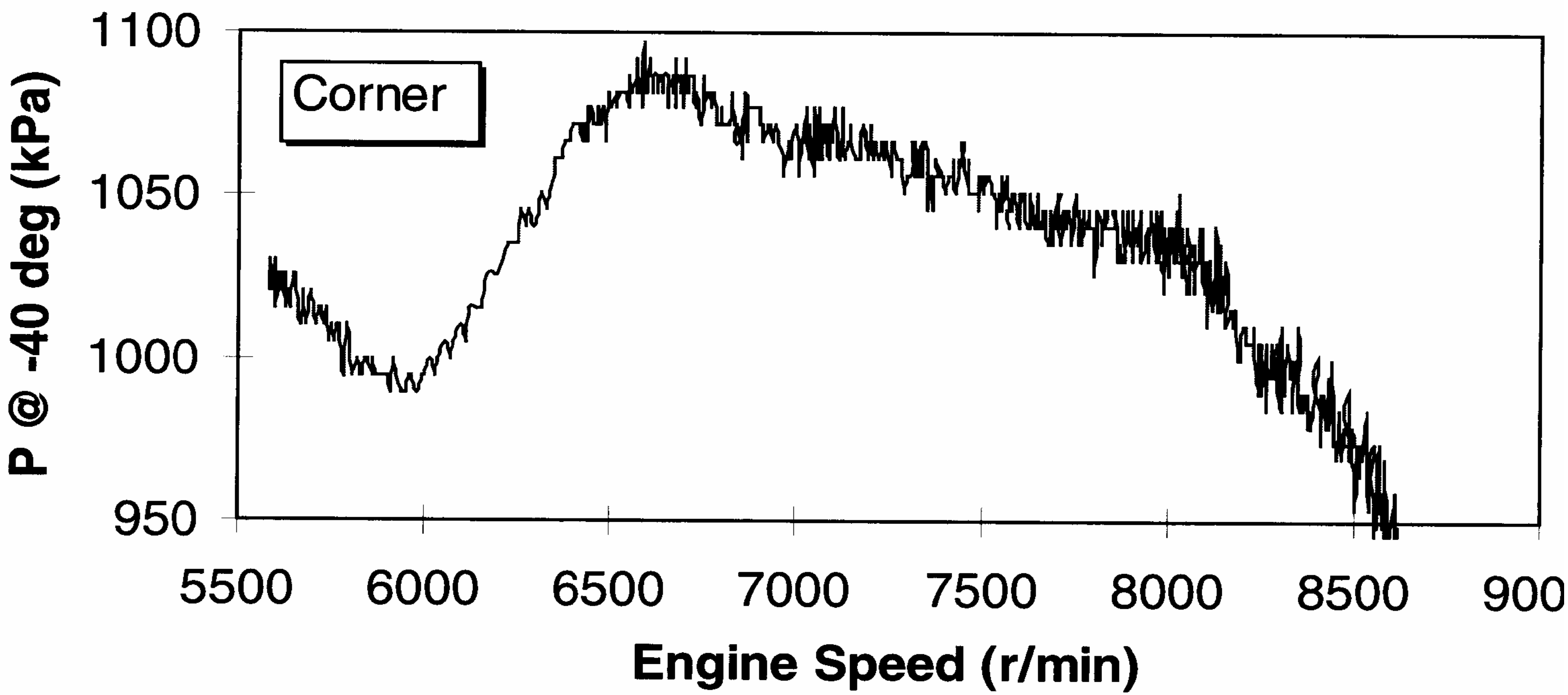
- single-point air introduction (throttle body, carburetor)
- single-point fuel introduction (TBI, carburetor)
- adjacent cylinders in a common plenum
- air box dynamics





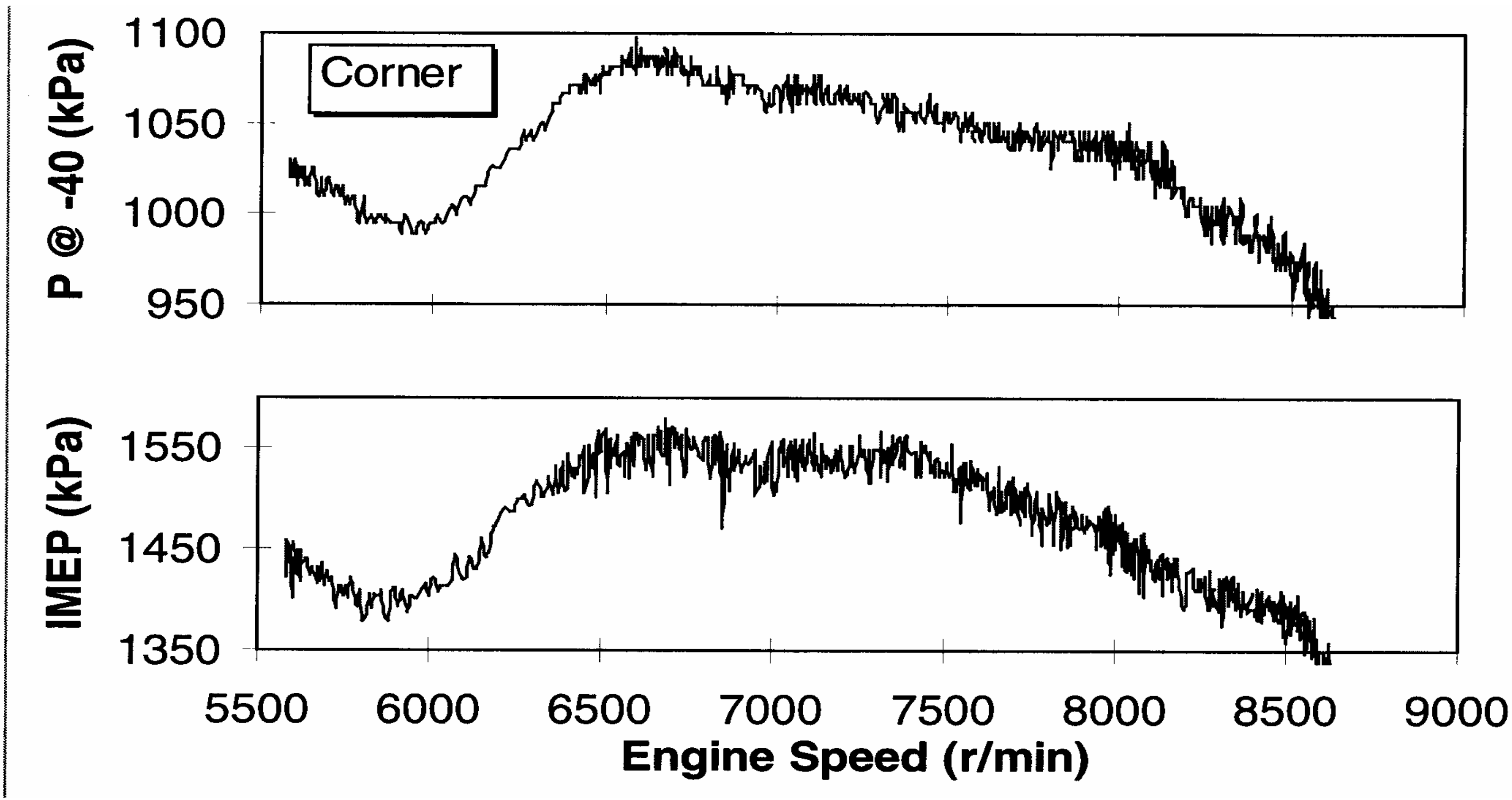
Trapped Mass
Single Cylinder

Trapped mass varies as a function of engine speed due to induction system tuning



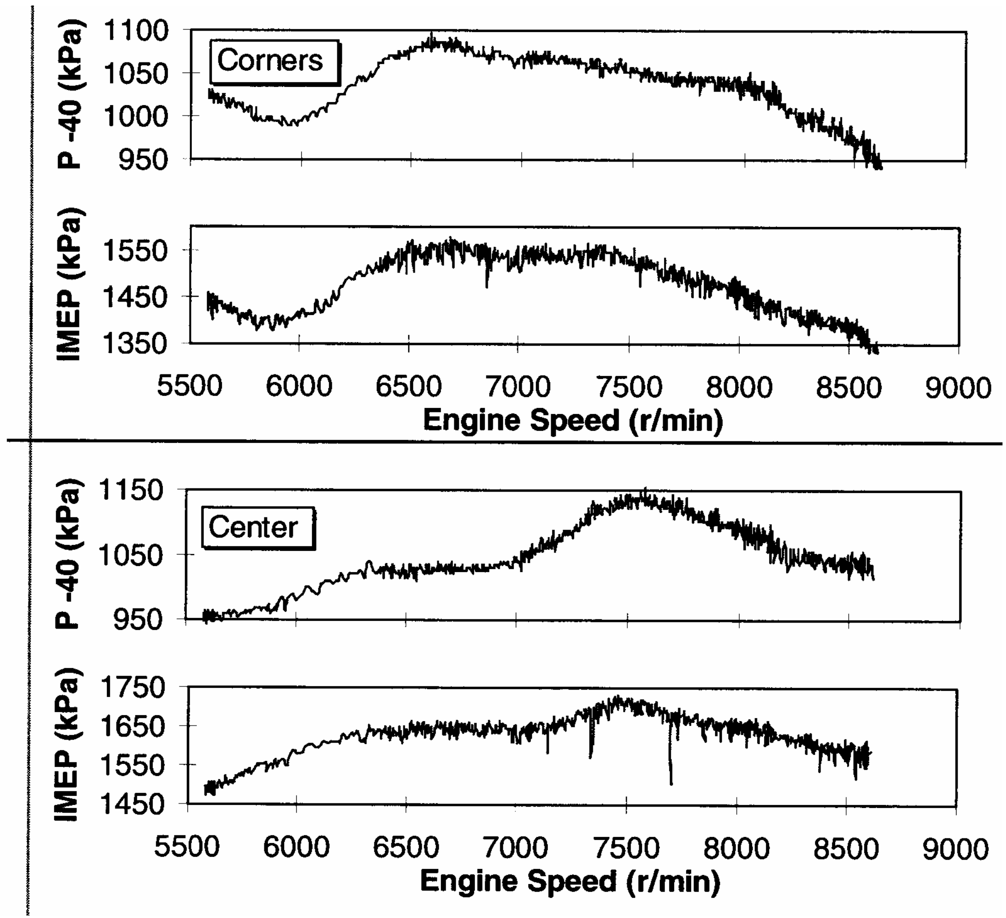
Trapped Mass & IMEP, Single Cylinder

Not surprisingly,trapped mass is an extremely accurate measurement of individual cylinder indicated torque (IMEP)



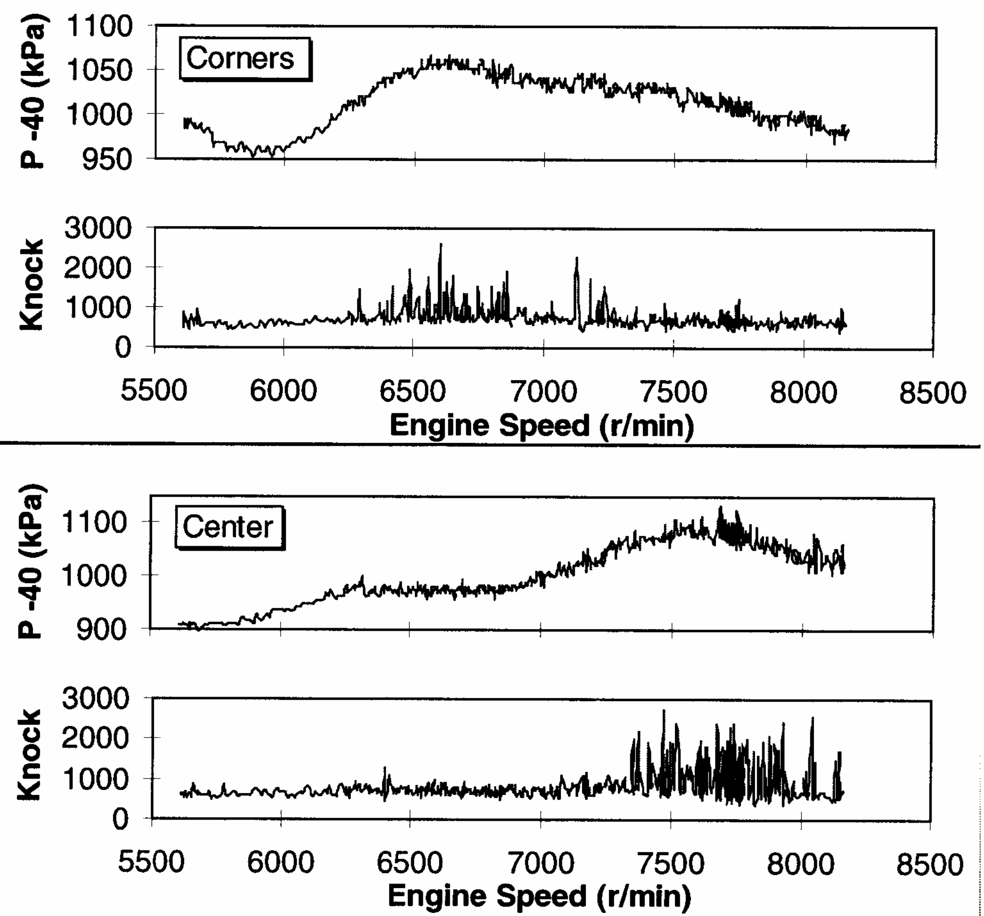
Trapped Mass & IMEP
Two Cylinders

Trapped mass, and thus indicated torque, differs considerably from cylinder to cylinder in most engines.

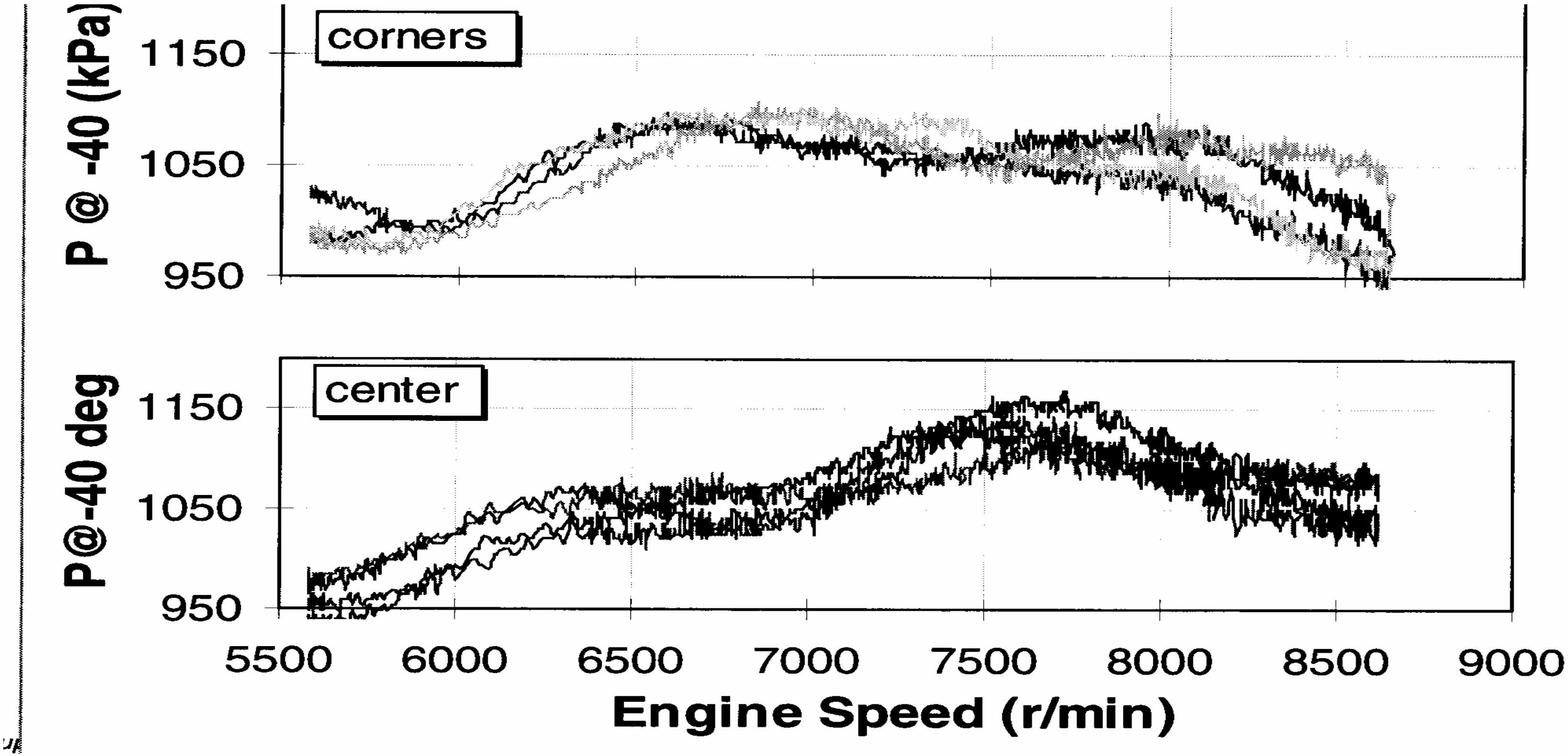


Trapped Mass & Knock Propensity

Knock occurs when trapped mass is high. Therefore, maldistribution in trapped mass leads to maldistribution in knock tendency.



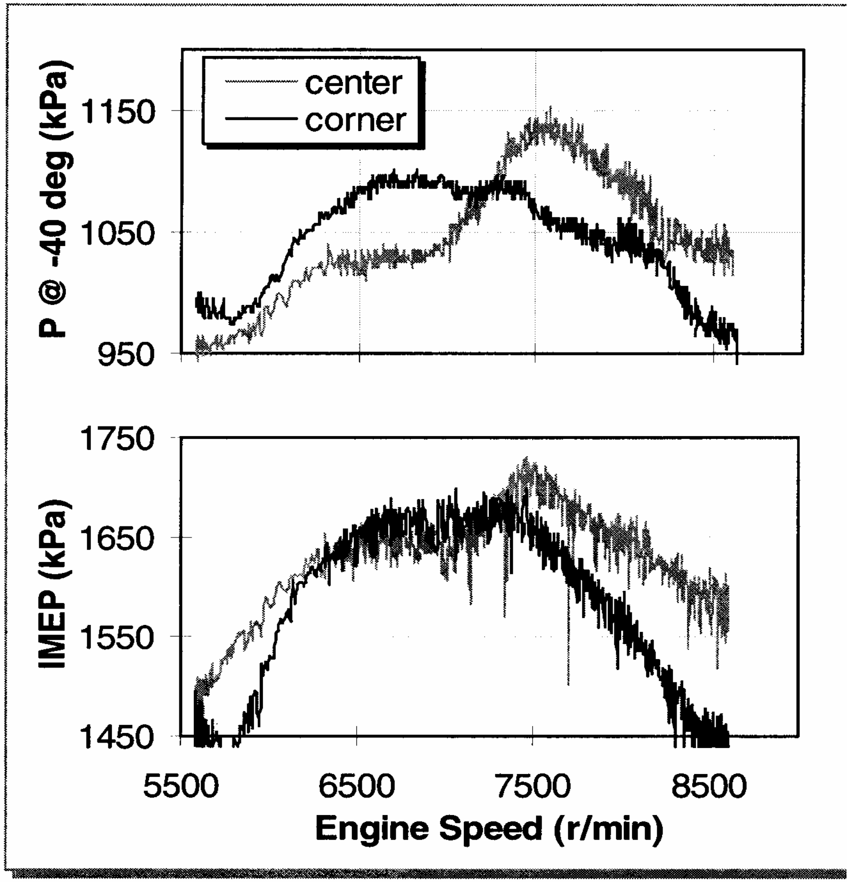
Trapped Mass, Corner & Centre Cylinders :**In this example, trapped mass is dictated by manifold tuning (primary intake runner length); thus, corner cylinders and centre cylinders behave differently**



Torque Curve Optimisation

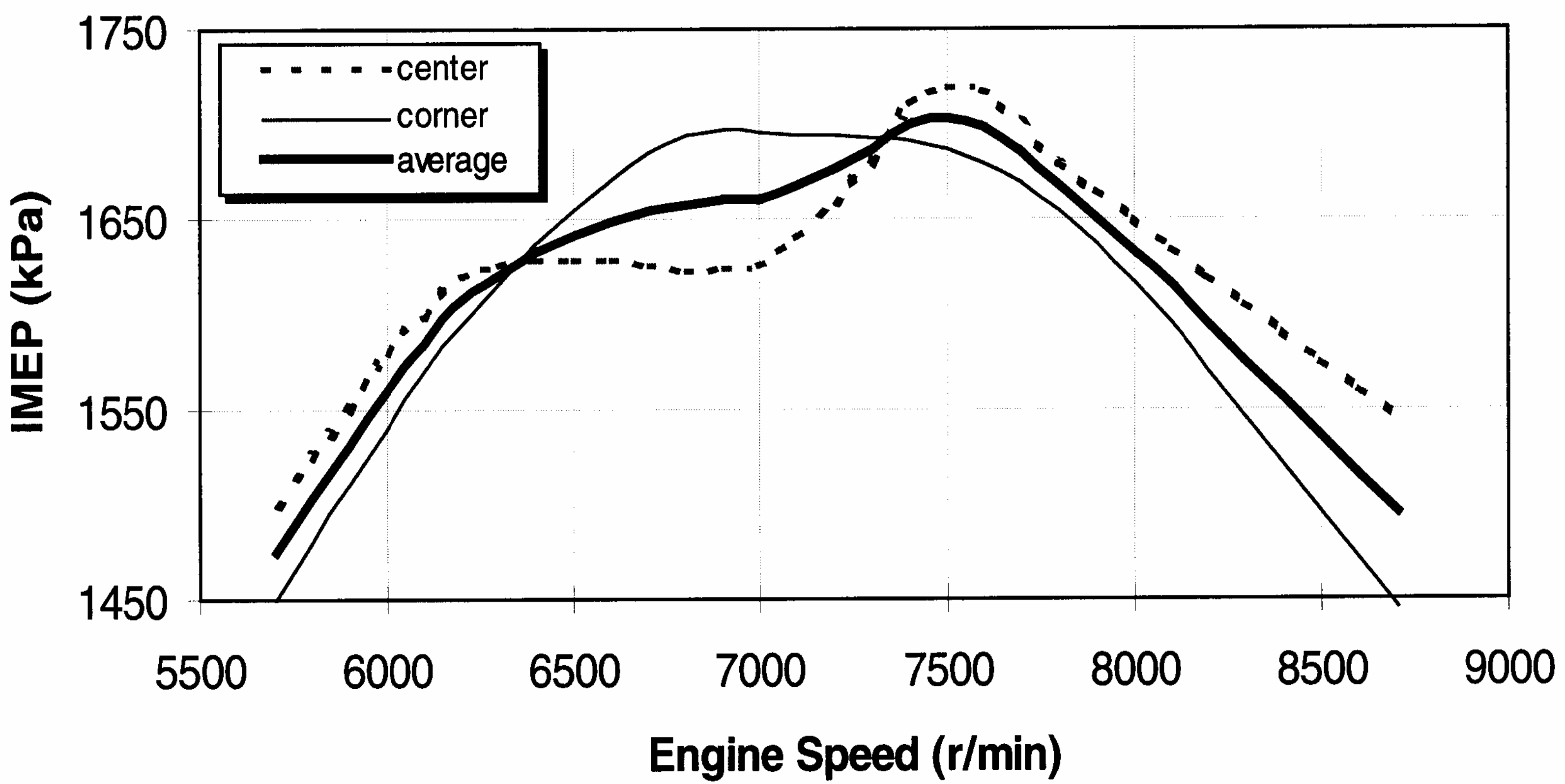
Overall engine torque is the sum of the individual cylinder torques, which are not optimized because trapped mass maldistribution drives maldistribution in:

- air flow
- fuel flow
- air-fuel ratio
- residual concentration
- effective compression ratio
- burn rate
- heat loss



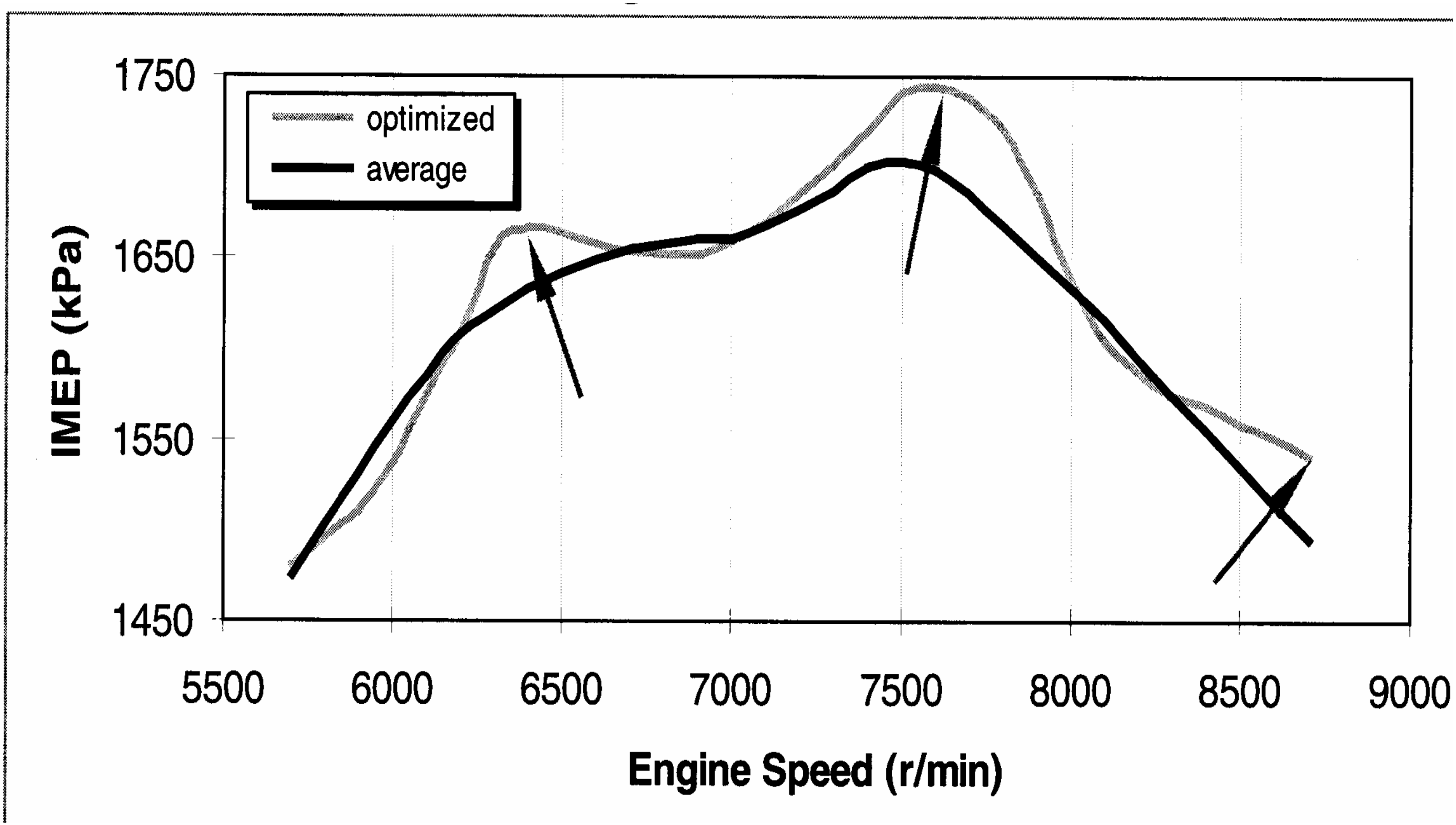
Torque Curve Optimisation

Average torque curve is broad and non-optimum



Torque Curve Optimisation

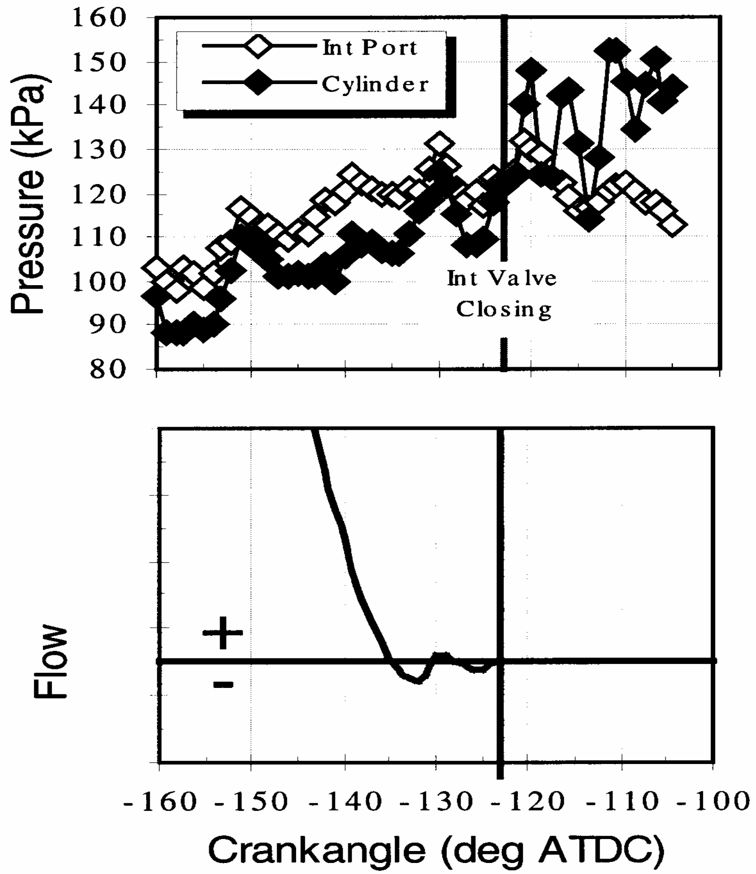
Torque curve optimisation causes the torque curve to become 'peaky',exhibiting significantly increased torque over specific speed ranges



Power Optimisation

Power Optimization

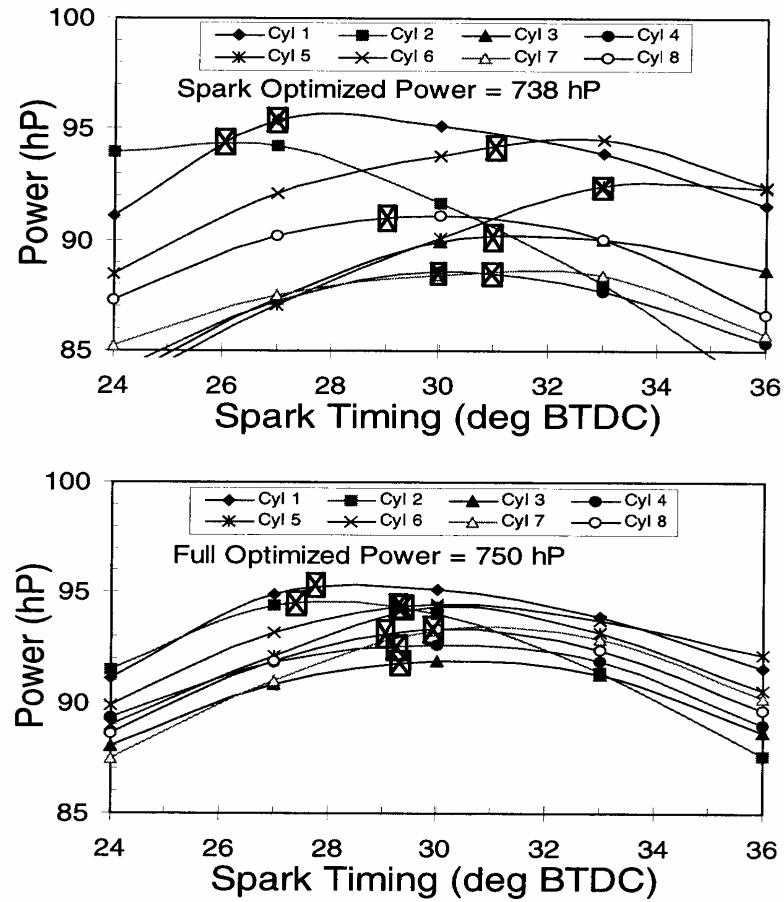
Trapped mass imbalance can be compensated for by timing inlet valve closing to coincide with the arrival of the tuning pulse. This promotes earlier intake valve closing in the center cylinders compared to the corner cylinders.



Power Optimisation

Power Optimization

Reducing maldistribution in trapped mass reduces maldistribution in other parameters such as air-fuel ratio and spark timing, leading to more uniformity across the engine and increased peak power.



Tuning for Power Summary

- Power and torque from a multi-cylinder engine are dictated by the total contributions of the individual cylinders
- Some design features,such as single point air throttling and or single point fuel injection,lead to inherent mal-distribution
- Mal-distribution causes the torque curve to be broad and low. All cylinders suffer compromised performance
- Trapped mass mal-distribution is the single largest source of mal-distribution in other parameters

Tuning for Power Summary cont…

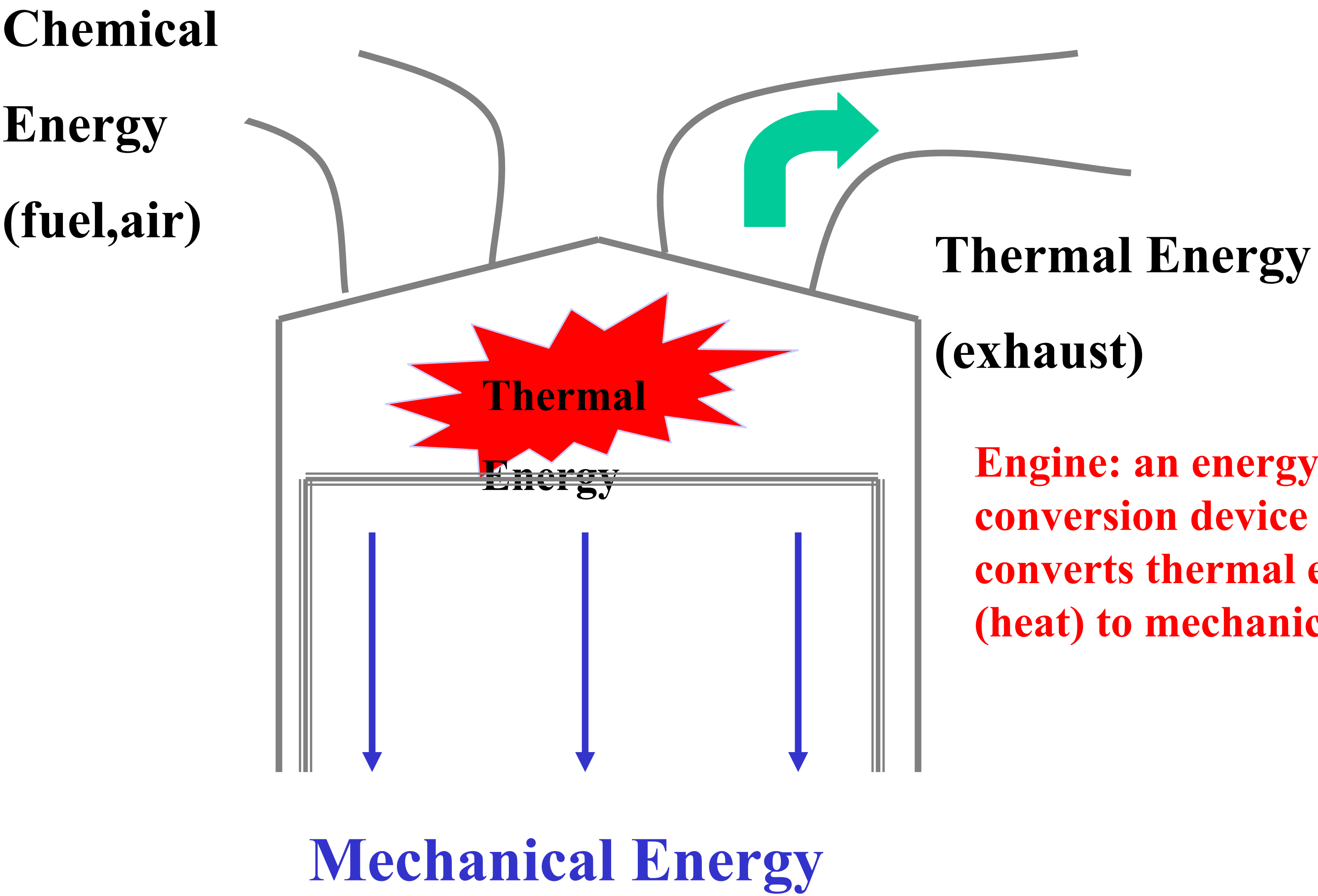
- Compensating for mal-distribution in trapped mass by optimising inlet valve closing reduces the amount of compensation required for other parameters such as ignition timing
- Achieving maximum individual cylinder performance by reducing mal-distribution substantially increases overall engine output

Automatic mapping

- **The trend toward automatic mapping is a ongoing cause for concern.**
- **There are many and disparate variables to be considered, for example**
  - Fuel and ignition timing and duration
  - Variable valve timing
  - Variable Induction length
  - Variable EGR
  - Variable boost

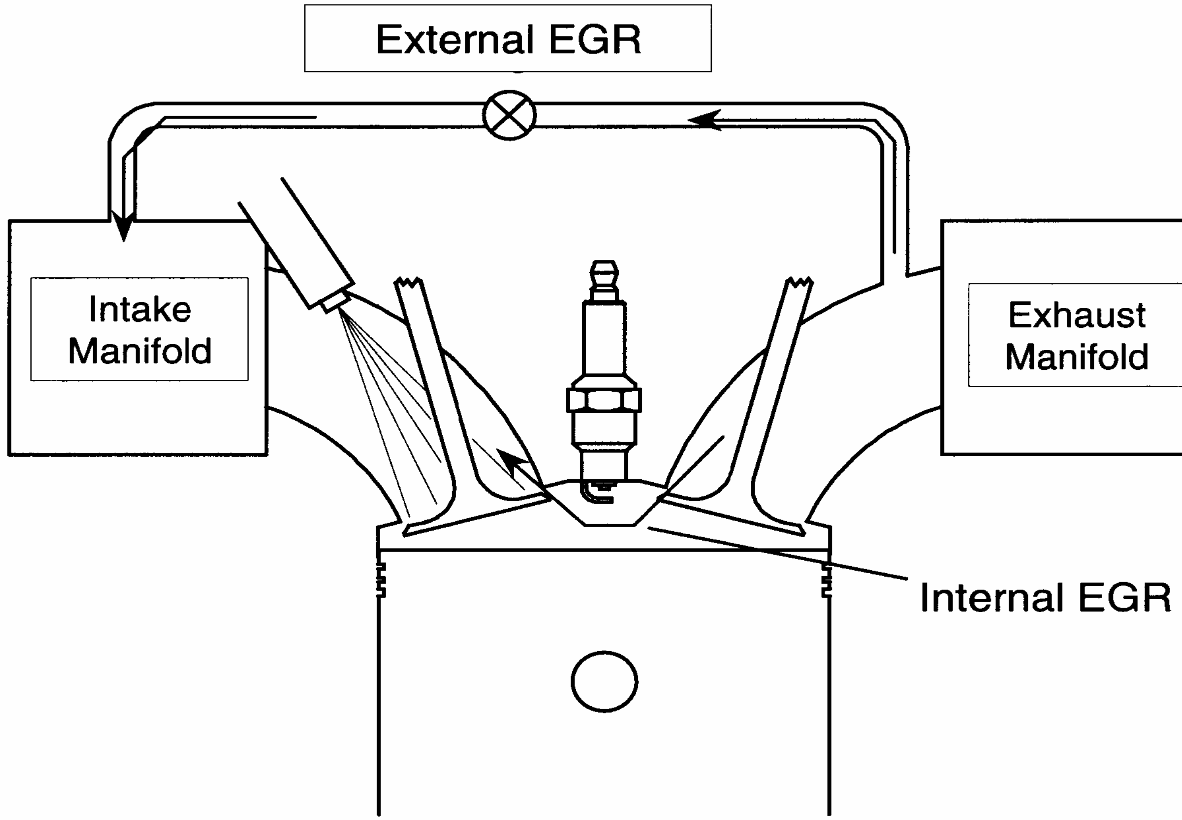
Automatic mapping

- Changing many parameters simultaneously runs contrary to the engineers training , the mantra was change one thing at a time.
- Times have changed, and we must use the available tools effectively
- In order to be able to identify major errors in Automatic mapping data, it is essential that the engineer has a deep understanding of the effect of individual parameter changes on all the associated outputs.
- Steady state loop studies in the running envelope are still required, and again when running the tests, warning bells should ring if the results are too good

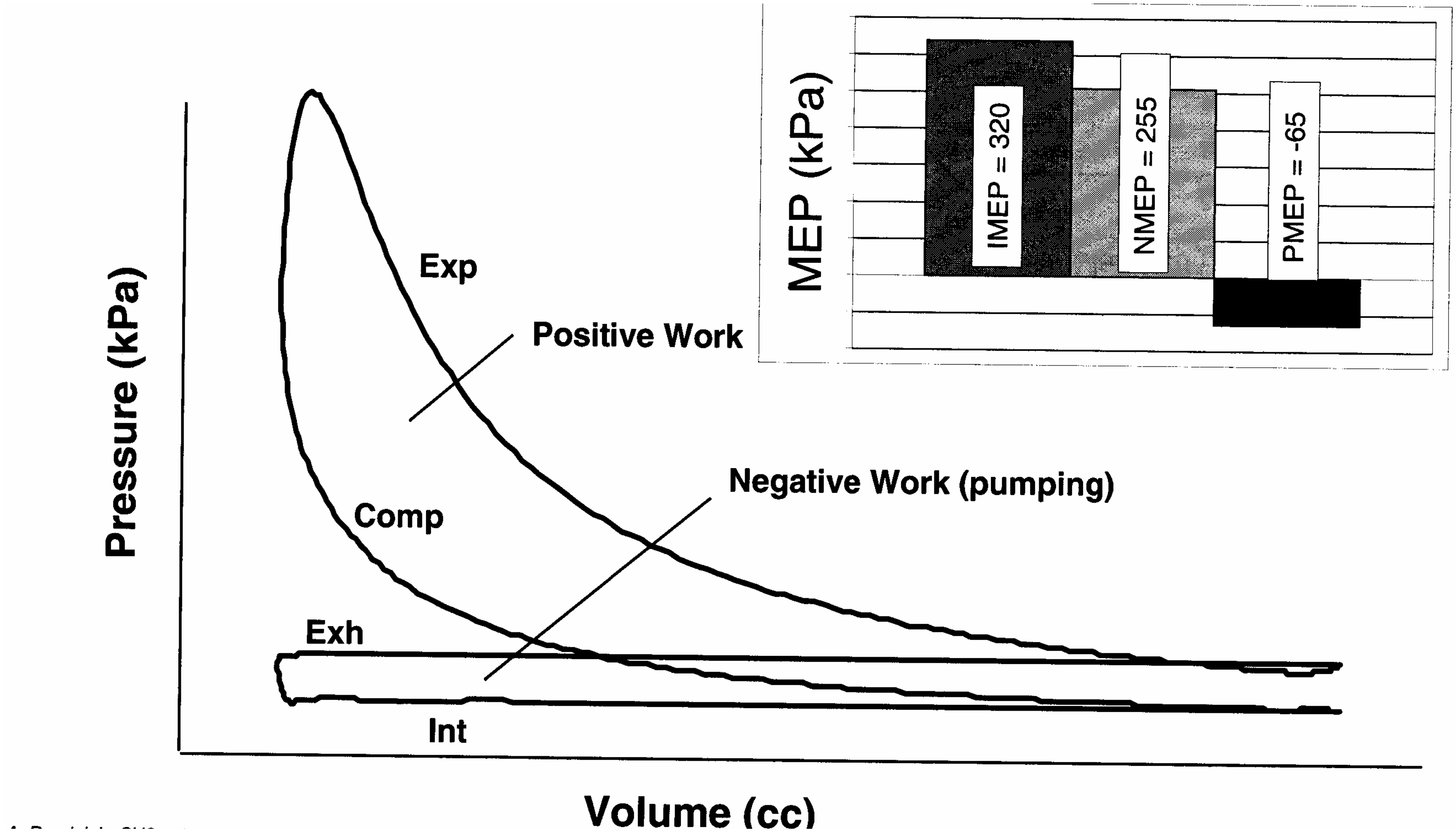


Engine: an energy conversion device that converts thermal energy (heat) to mechanical energy

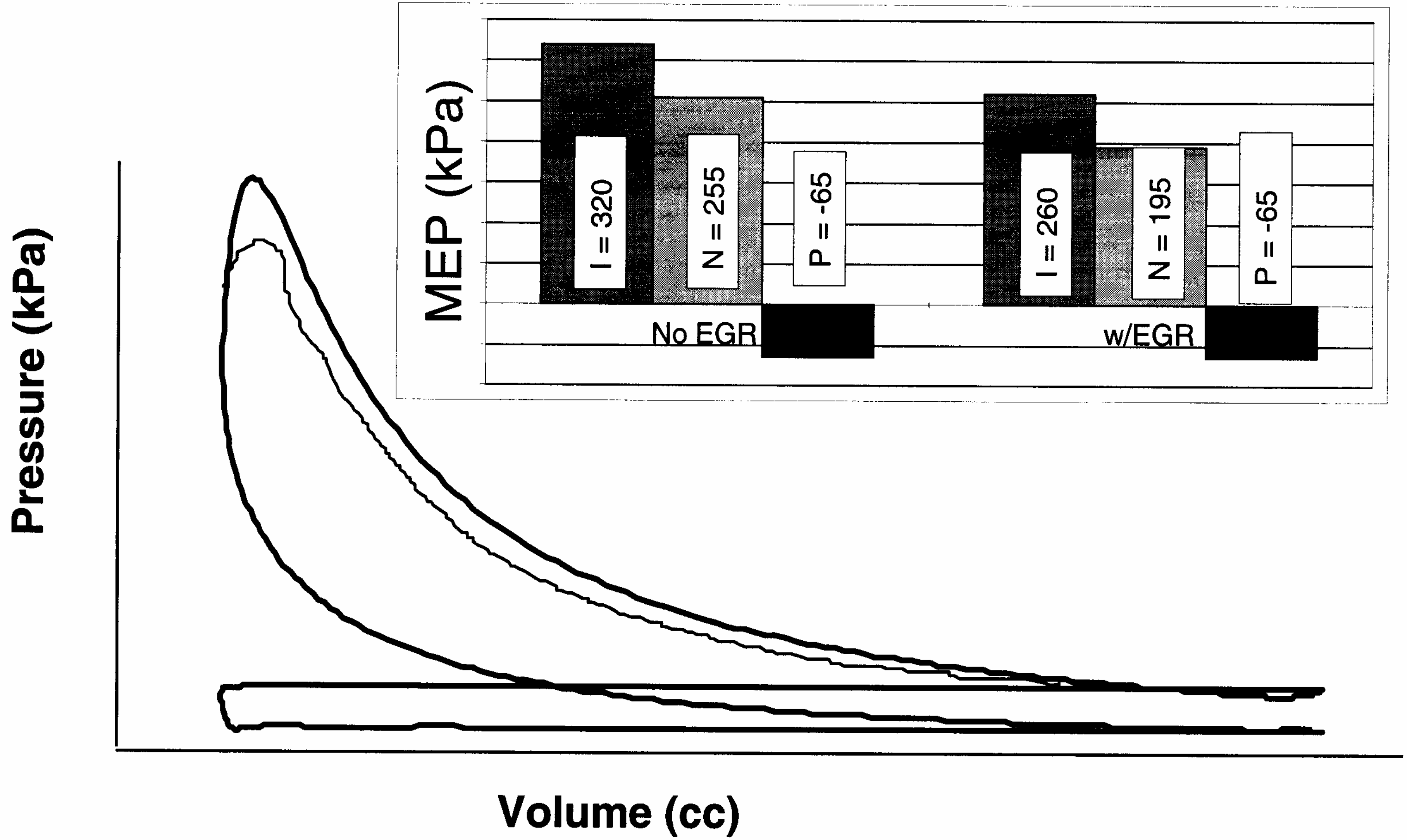
Exhaust Gas Recirculation (EGR)



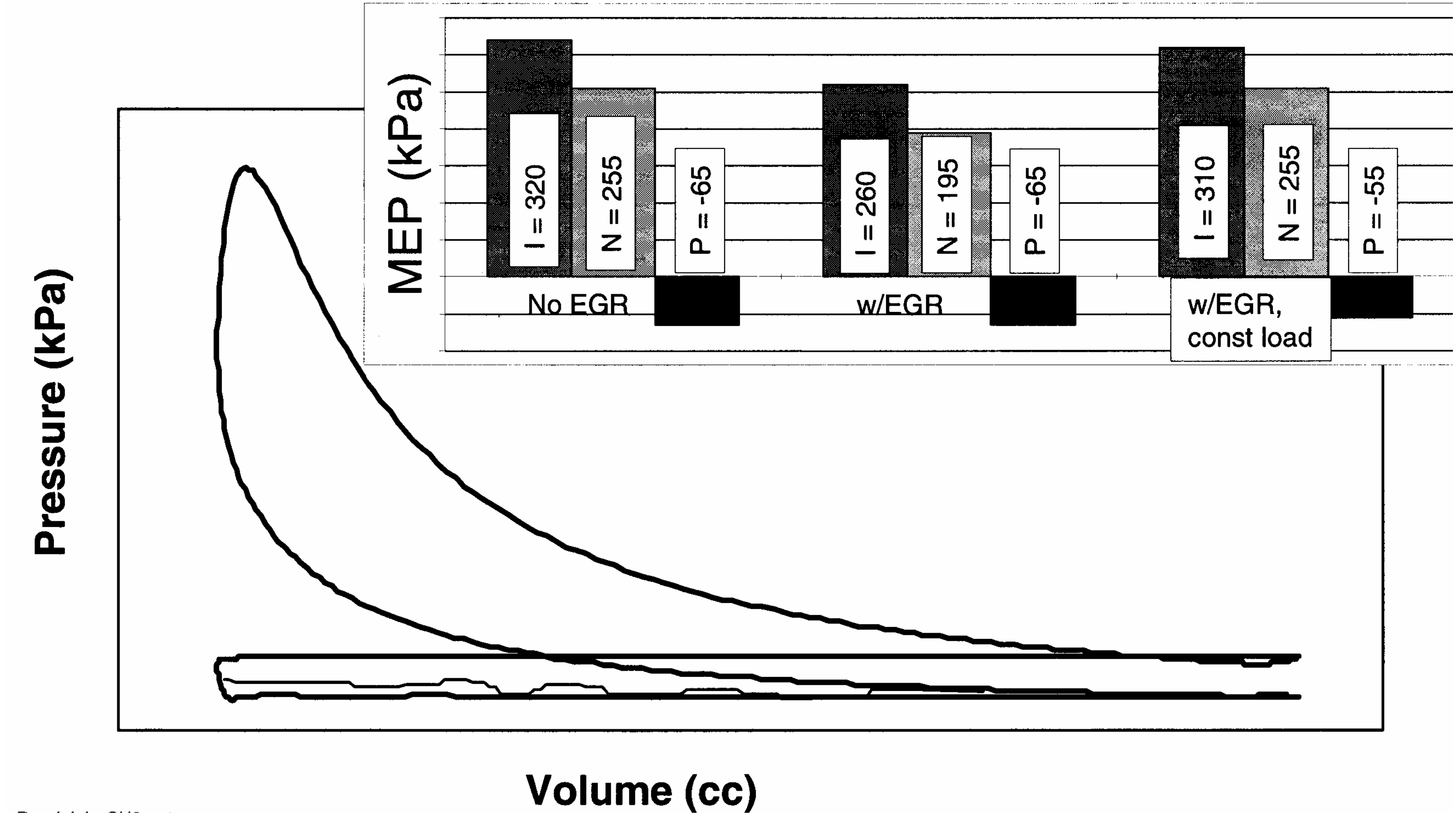
EGR- Increases net thermal efficiency by reducing pumping work



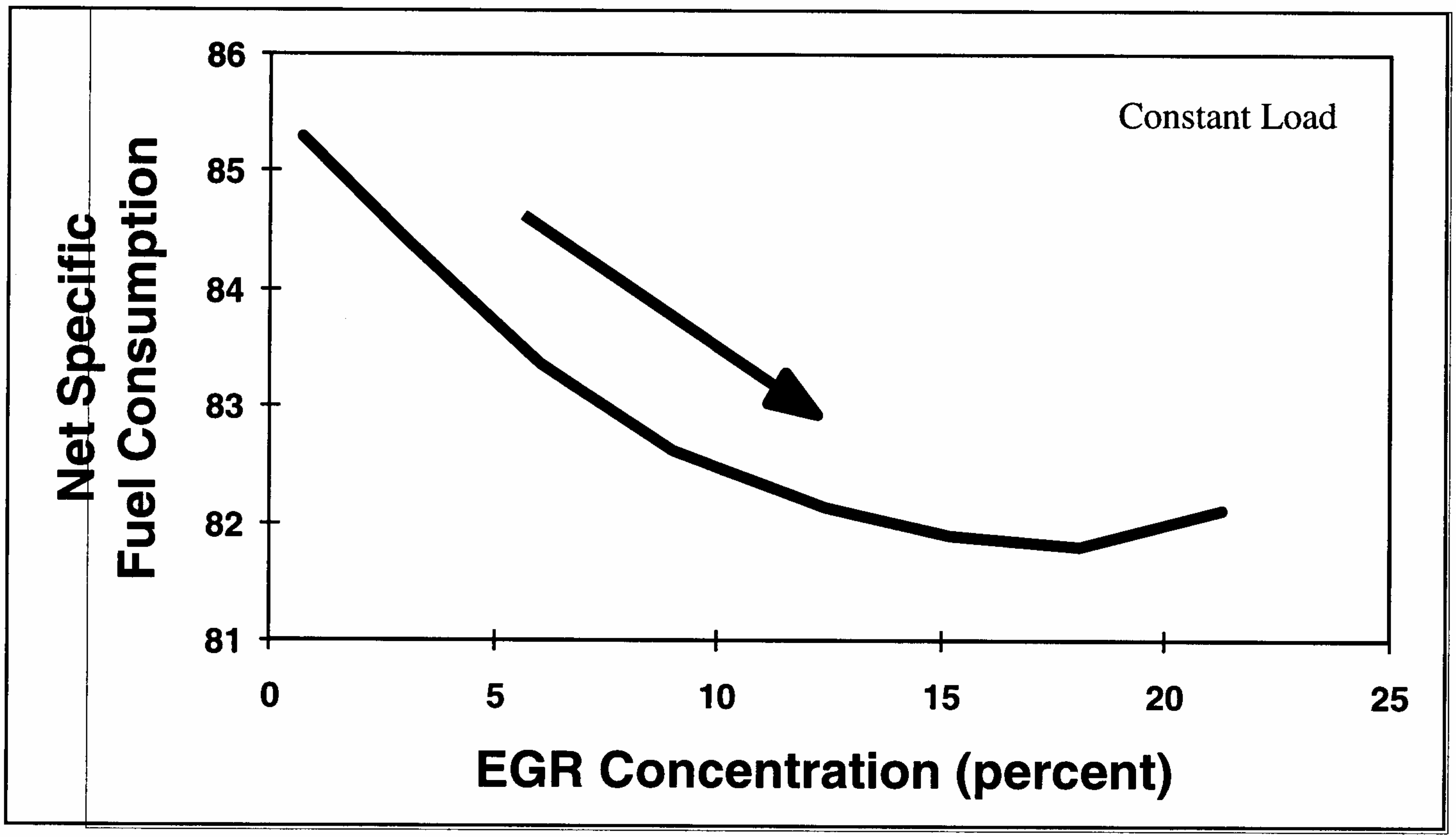
EGR-Output reduced with addition of EGR at constant manifold pressure



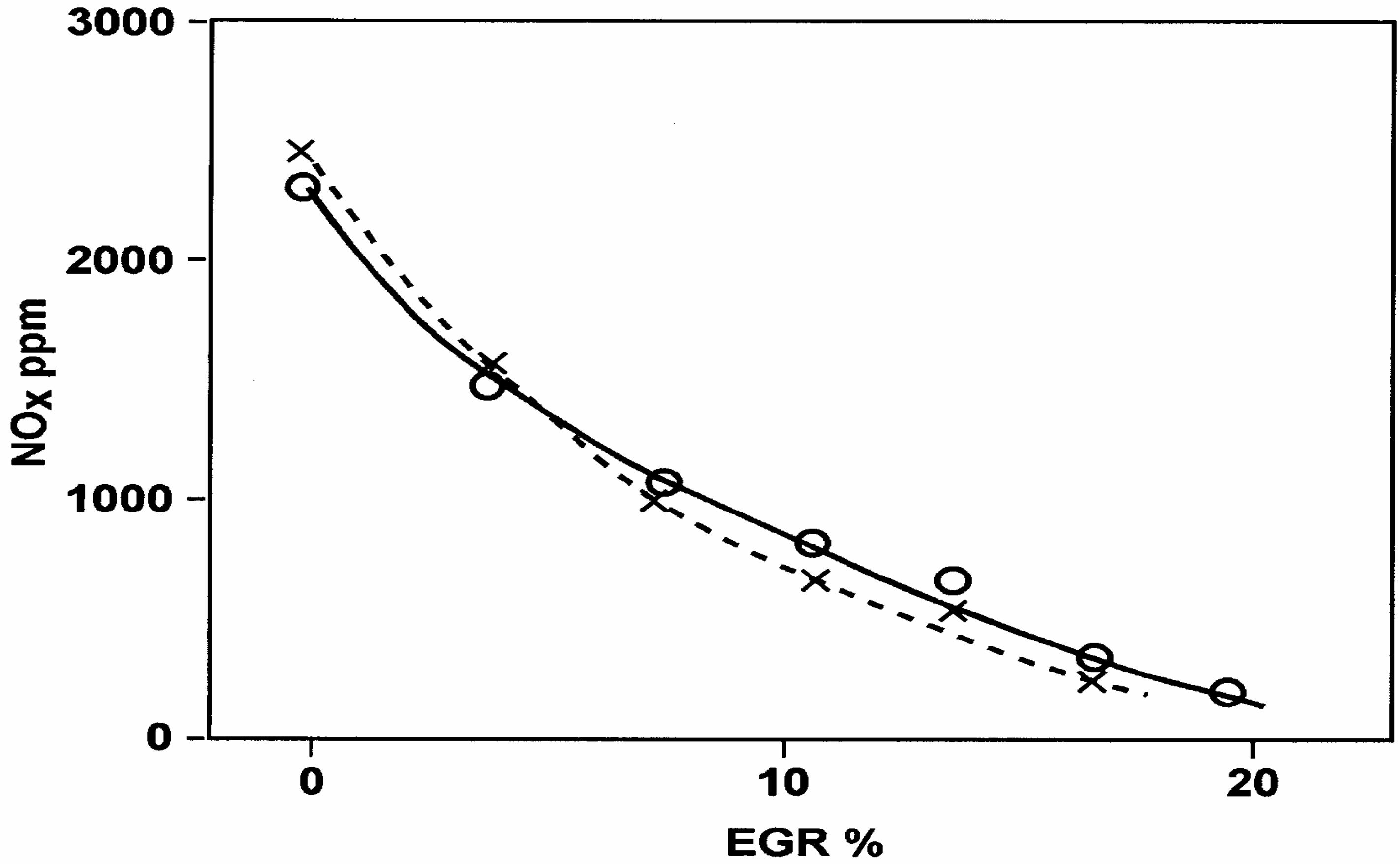
EGR – Must open throttle to recover load, thereby reducing pumping loss (spark ignition only)



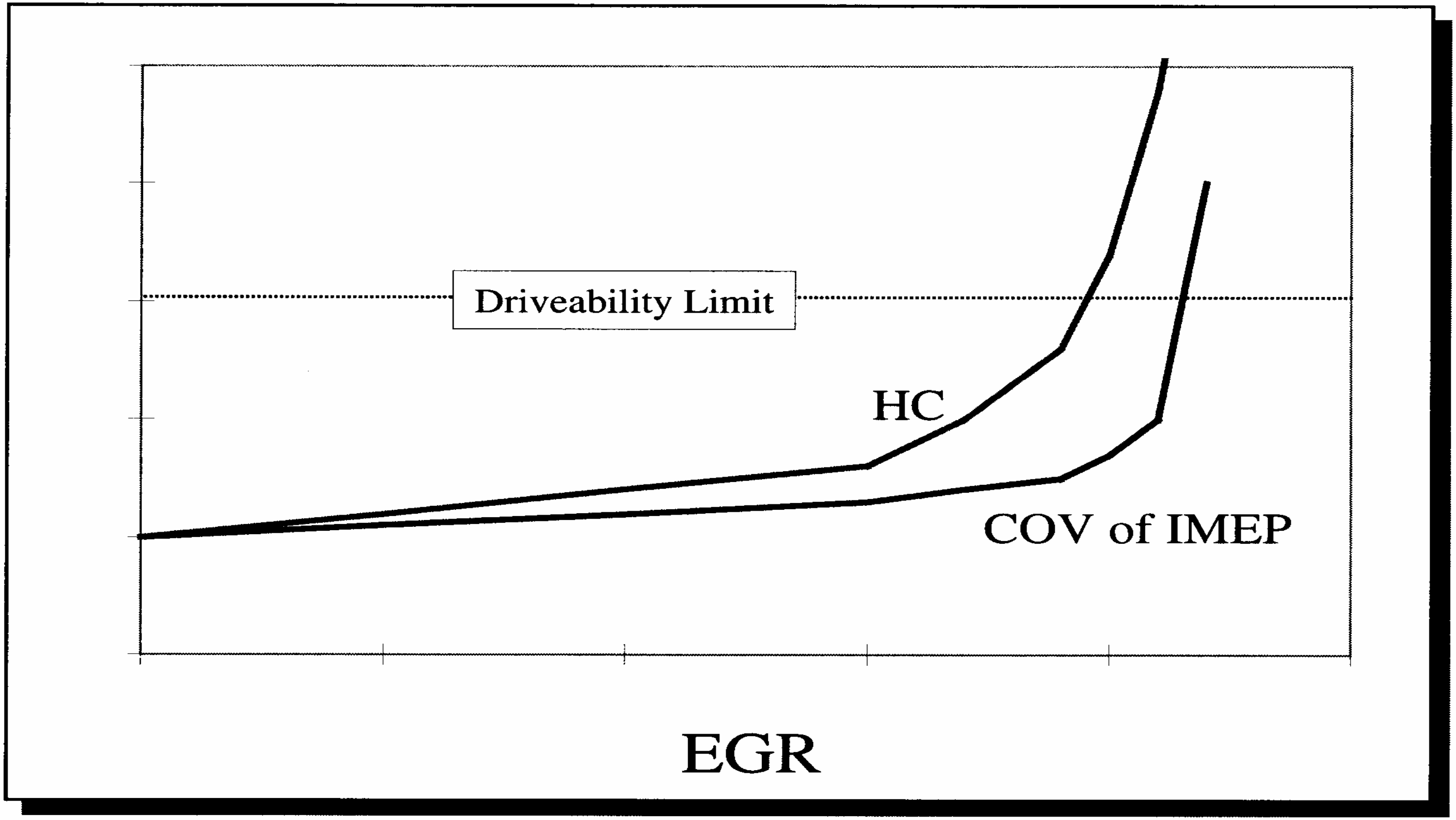
EGR – Performs the same function as the throttle, with out the associated pumping work (Spark ignition only)



EGR – Reduces NOx emissions by reducing the combustion temperatures



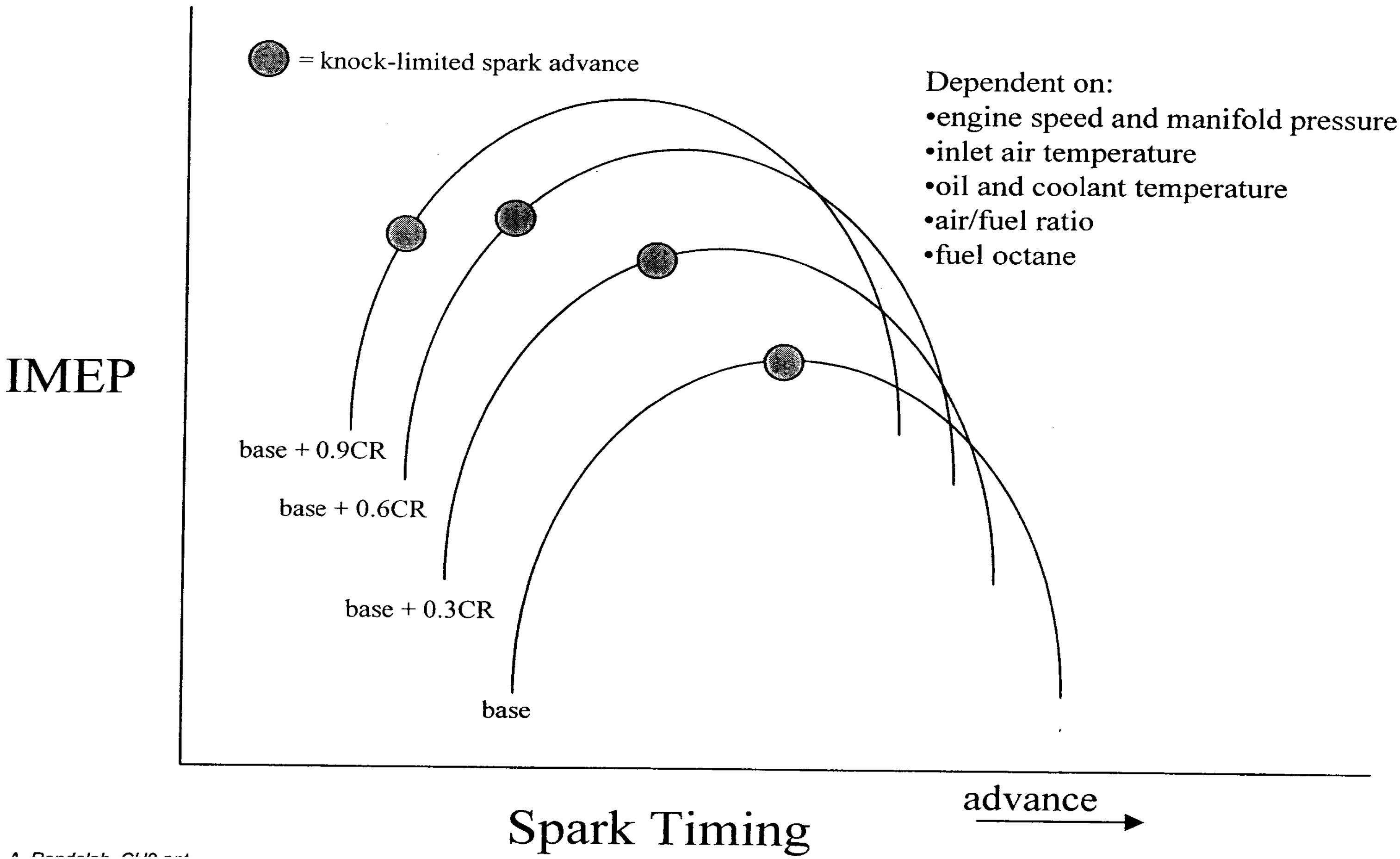
EGR – To much has distinct disadvantages !!!!!



EGR trade offs

- High EGR
  - Positive aspects
    - **Increases efficiency (improve fuel economy)**
    - **Reduces NOx emissions**
- High EGR
  - Negative aspects
    - **Increases HC emissions**
    - **Decreases combustion stability**
    - **Complicates transient control**

Compression Ratio Optimisation (S I Application)



Compression Ratio Optimisation

Advantages of Maximising Compression Ratio

- Increased full-load torque through most of the engine speed range
- Reduced full-load combustion-induced engine noise
- Lower peak full-load combustion pressures
- Improved part-load fuel economy(approx 1.5% per 0.5\ratio)
- Increased dilution tolerance through faster burn
- Improved idle stability via lower residuals

Compression Ratio Optimisation

Disadvantages of Maximising Compression Ratio

- Higher part-load hydrocarbon and NOx emissions
- Greater reliance on knock sensing system
- Higher full-load exhaust temperatures
- Increased likelihood of pre-ignition

Compression Ratio Optimisation

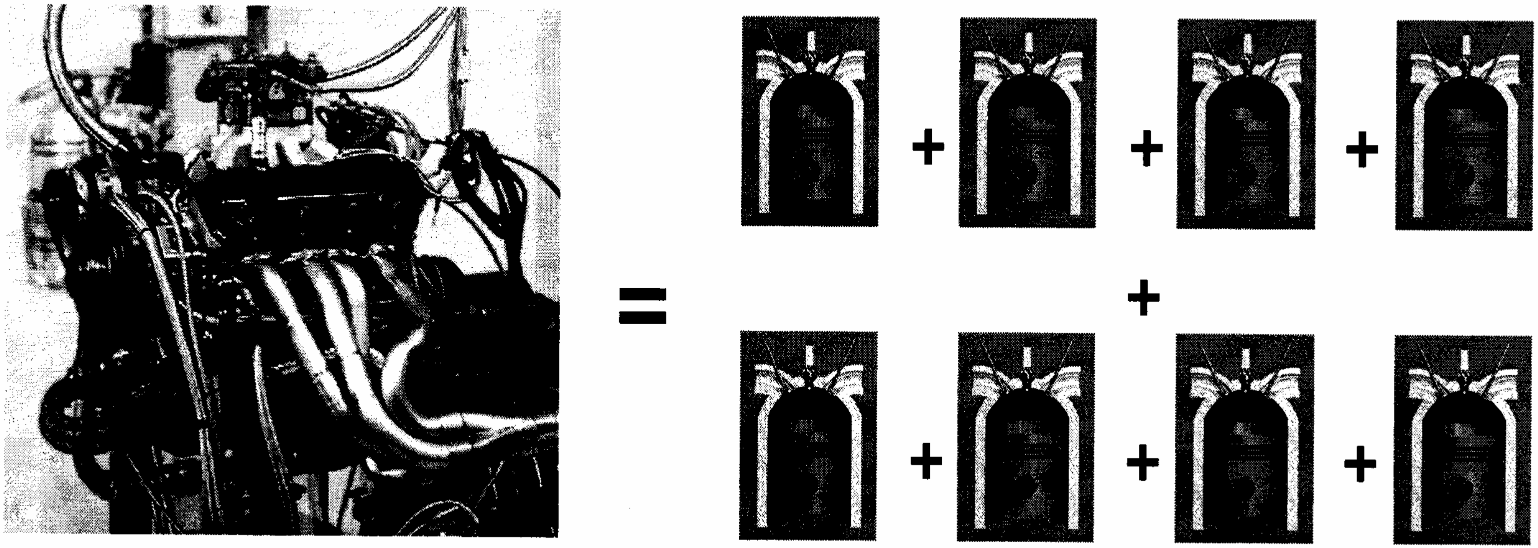
Enablers of High Compression Ratio

- Precise fuel control
- Good cooling of the chamber and combustion chamber
- Reliable knock sensing and control methodology
- Low engine – out emissions

Full Load Performance Optimisation

- Example from a NASCAR Winston Cup race engine development exercise, which demonstrates the clear advantages of utilising combustion analysis techniques to enable accelerated development.

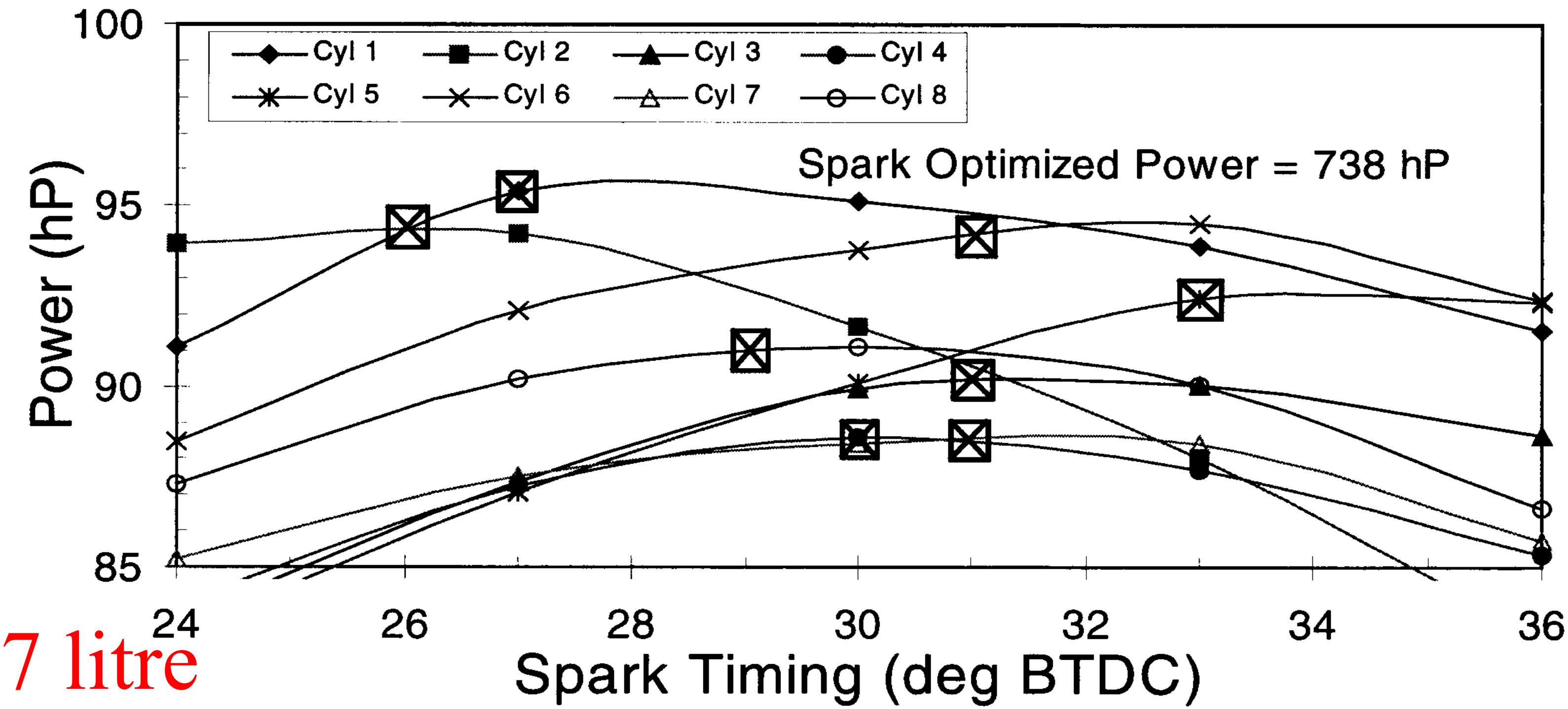
Full Load
Performance Optimisation



⇨ A multicylinder engine is a combination of several single cylinder engines, each of which must be optimized to obtain maximum performance.

Full Load Performance Optimisation

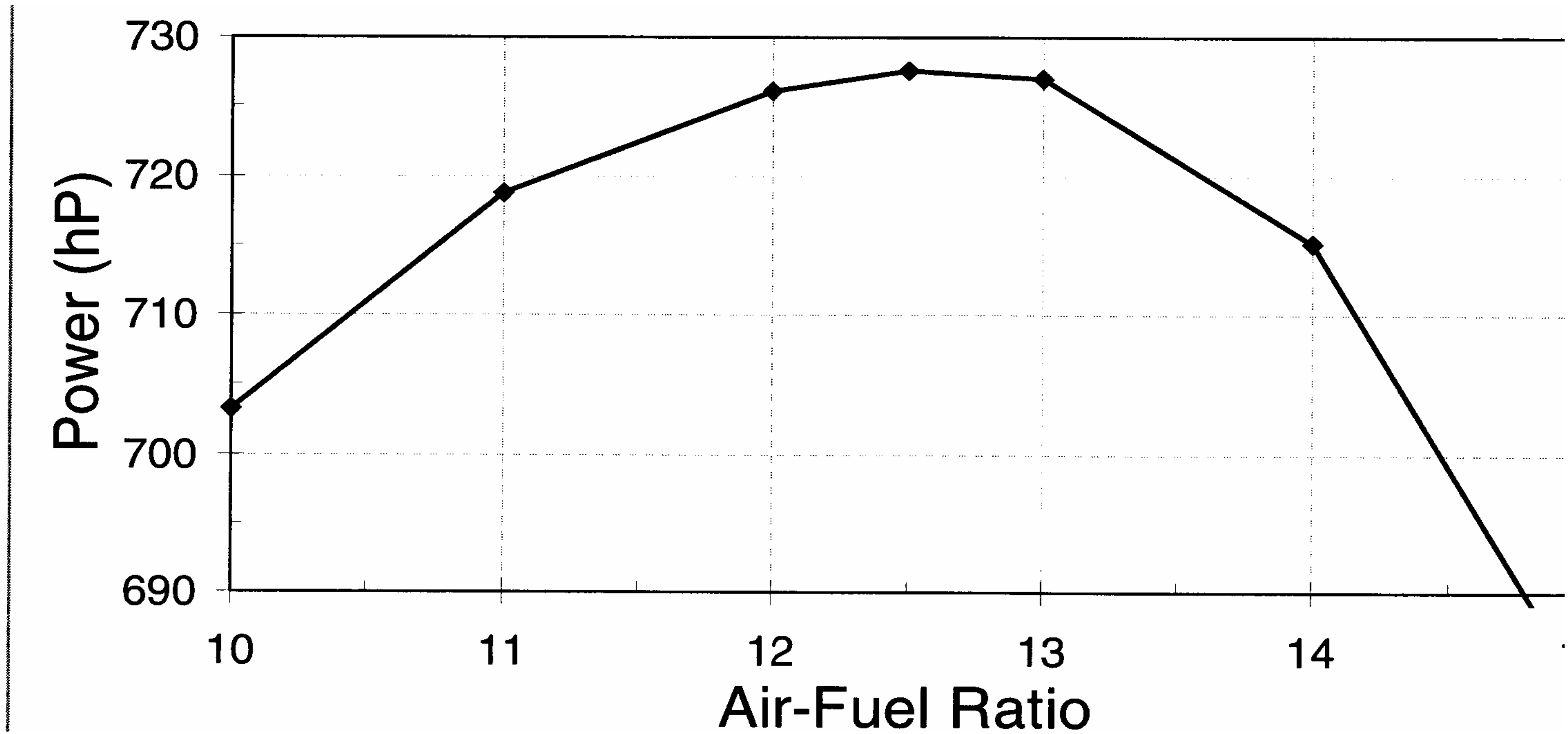
gnition timing is set to the value that maximises output from each ndividual cylinder, leading to a 10 BHP increase in total engine power



5.7 litre push rod

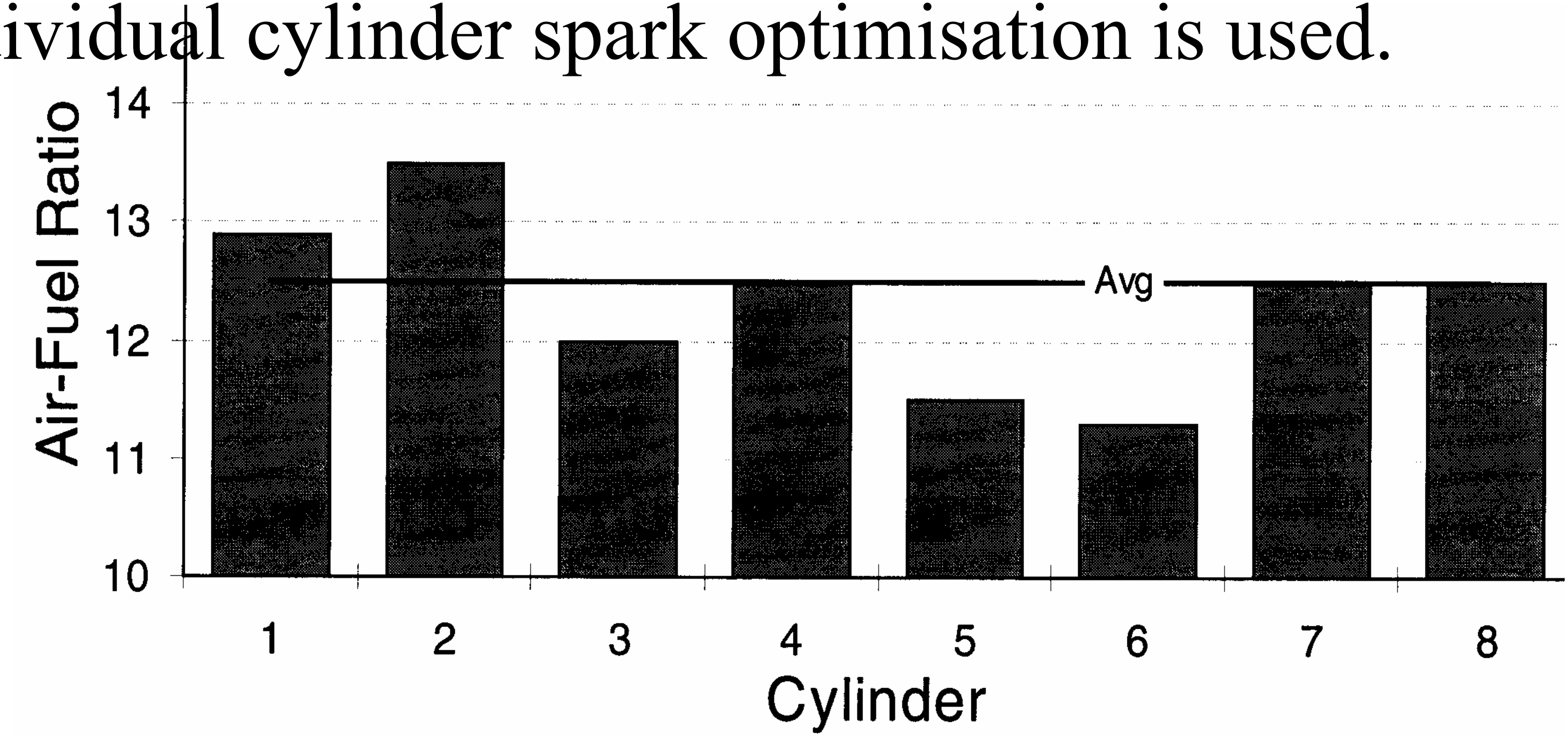
Peak Power: Sensitivity to Air-Fuel Ratio

ndividual cylinder air-fuel ratio mal-distribution also educes total engine peak power



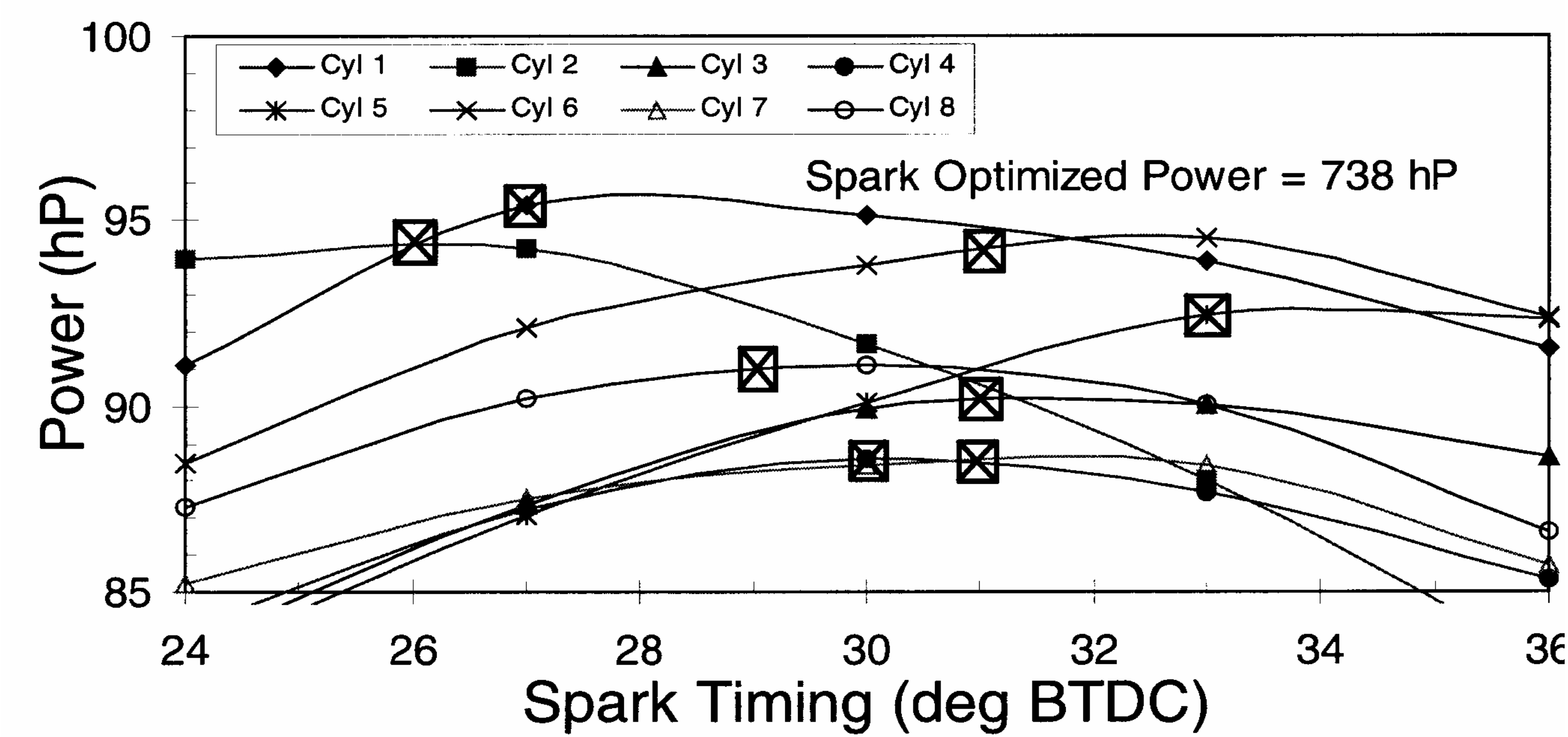
Peak Power: Air-Fuel Ratio Distribution

This amount of mal-distribution costs about 7 BHP when global spark timing is used and 4 BHP when individual cylinder spark optimisation is used.



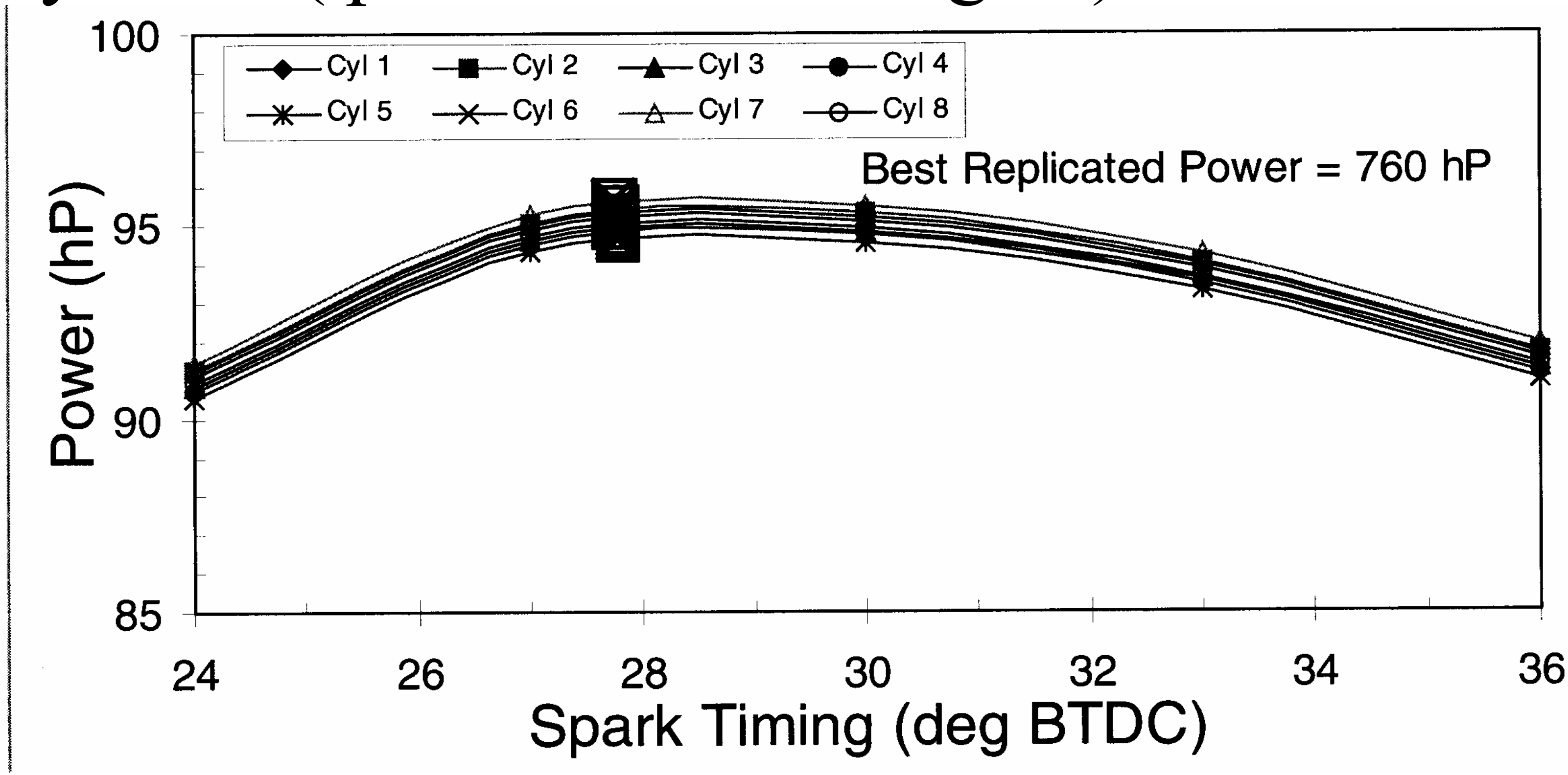
Individual Cylinder Spark Optimisation

Even with individual cylinder spark timing optimisation,power contributions of the individual cylinders differ significantly



Peak Power
Cylinder Replication

Goal is to have each cylinder perform as well as the best cylinder (potential 22 BHP gain)



Replicated Chambers, Ports & Runners

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- Air fuel ratio (air flow / fuel flow)
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  - Tuning lengths
  - Fuel distribution
- Mixture motion
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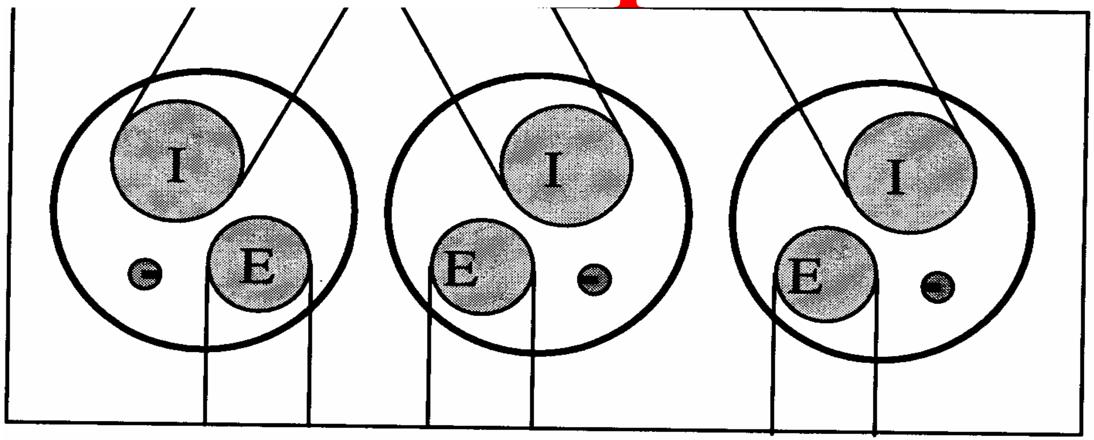
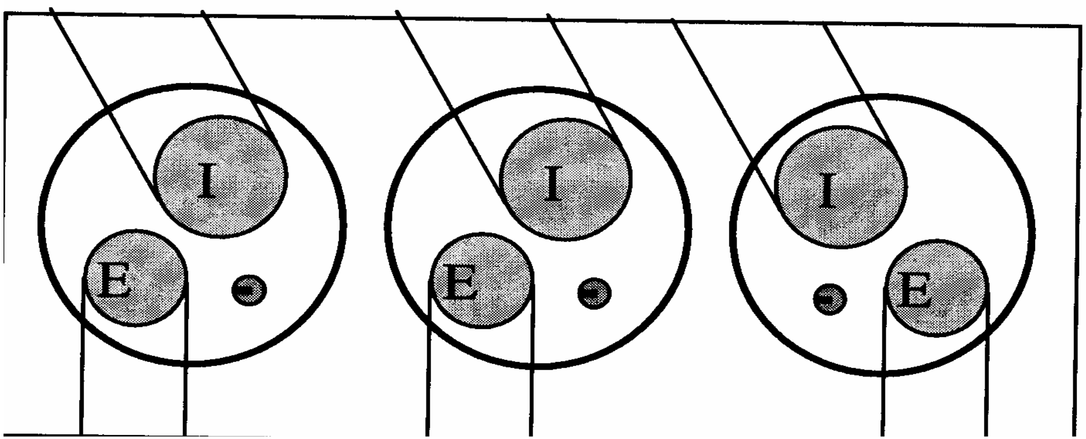
Port/chamber replication ?



NO

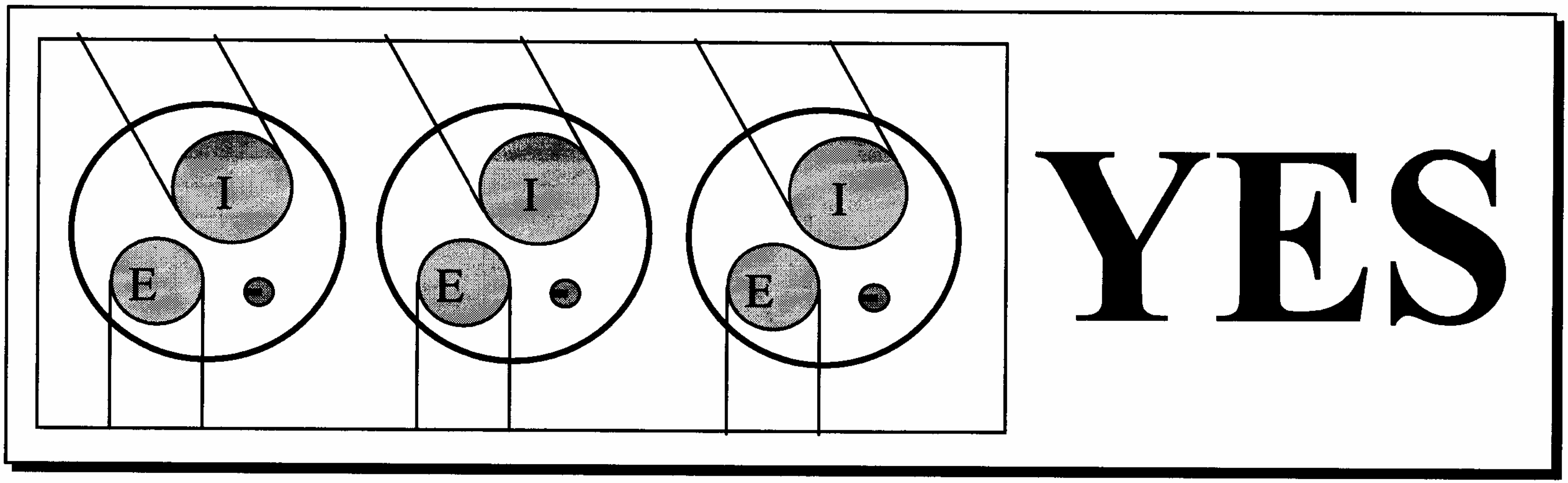
(symmetrical)



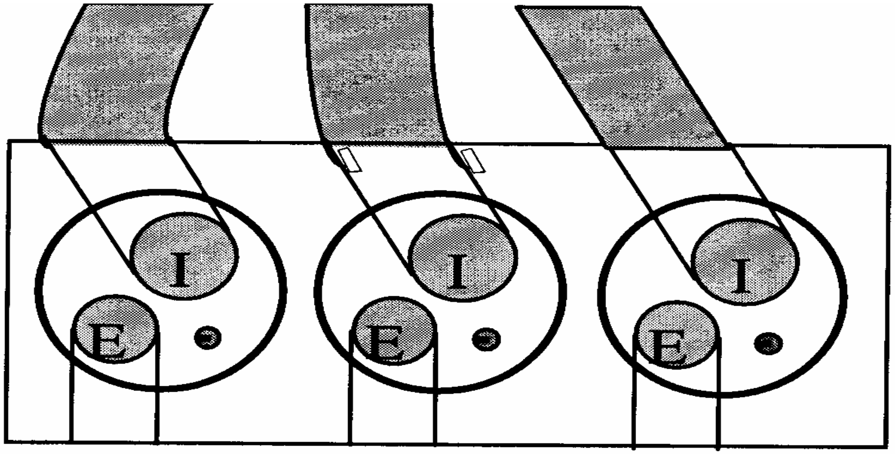
NO

(different)

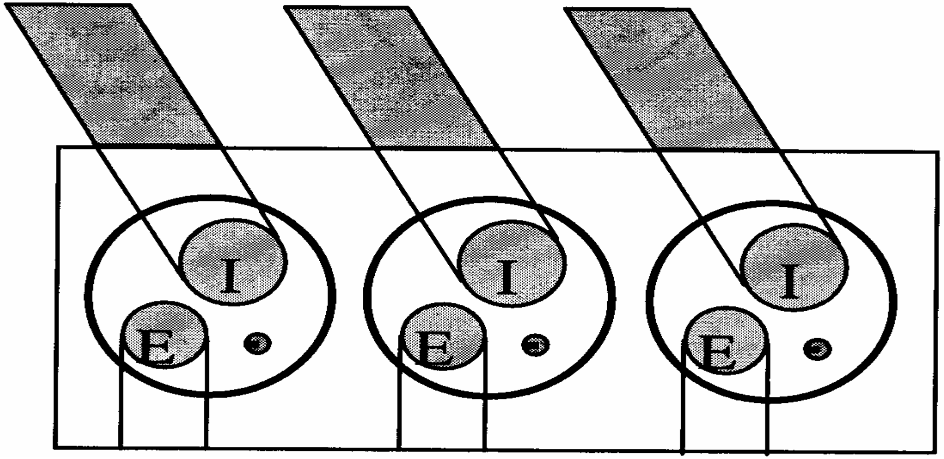
Port/chamber replication ?



Manifold Approach
Replication ?



NO



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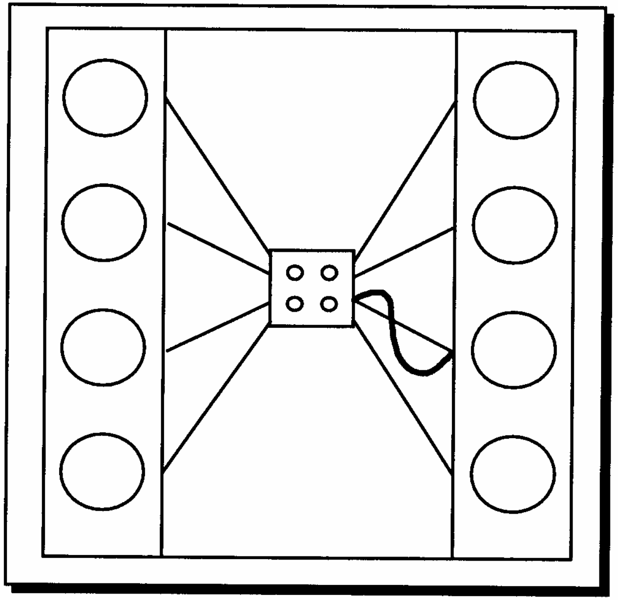

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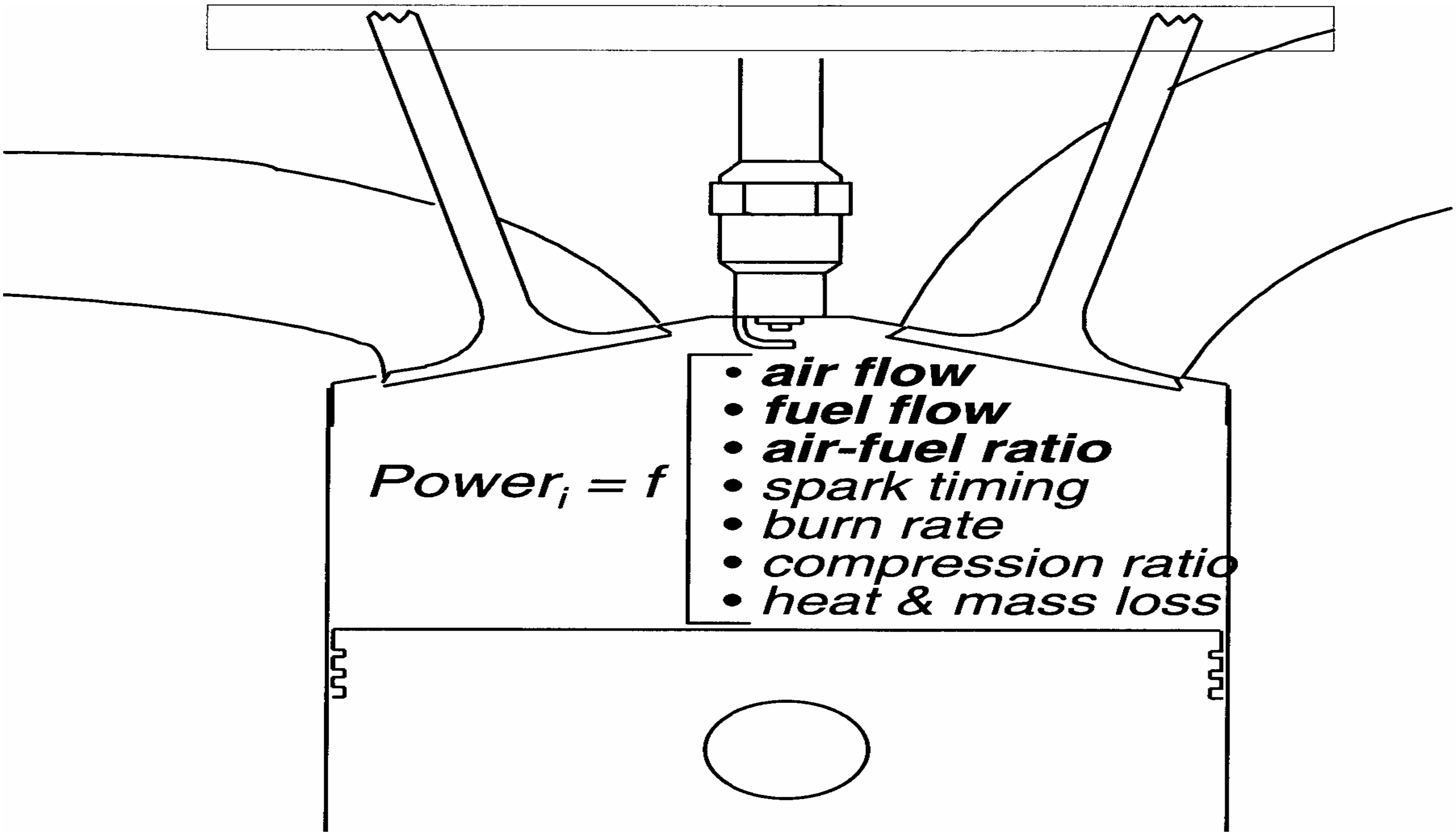

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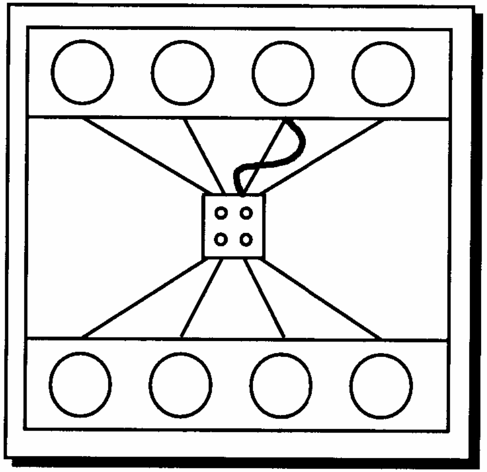

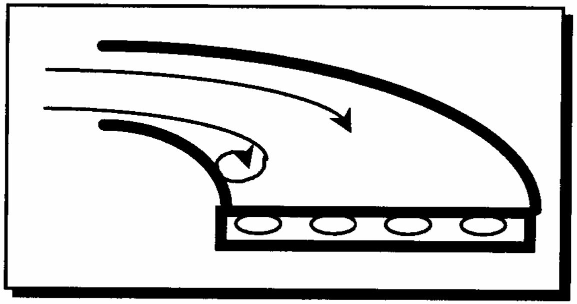

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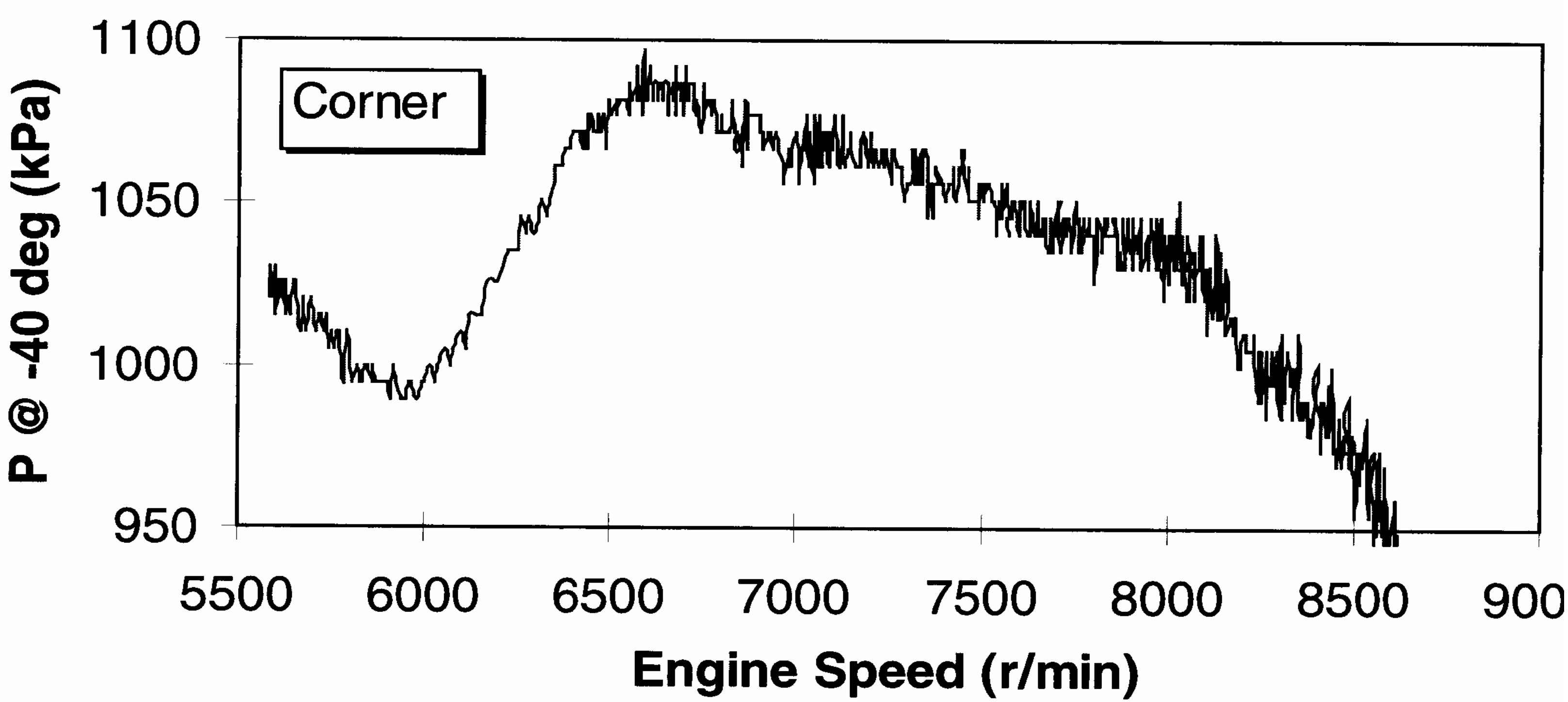

Trapped Mass & IMEP, Single Cylinder

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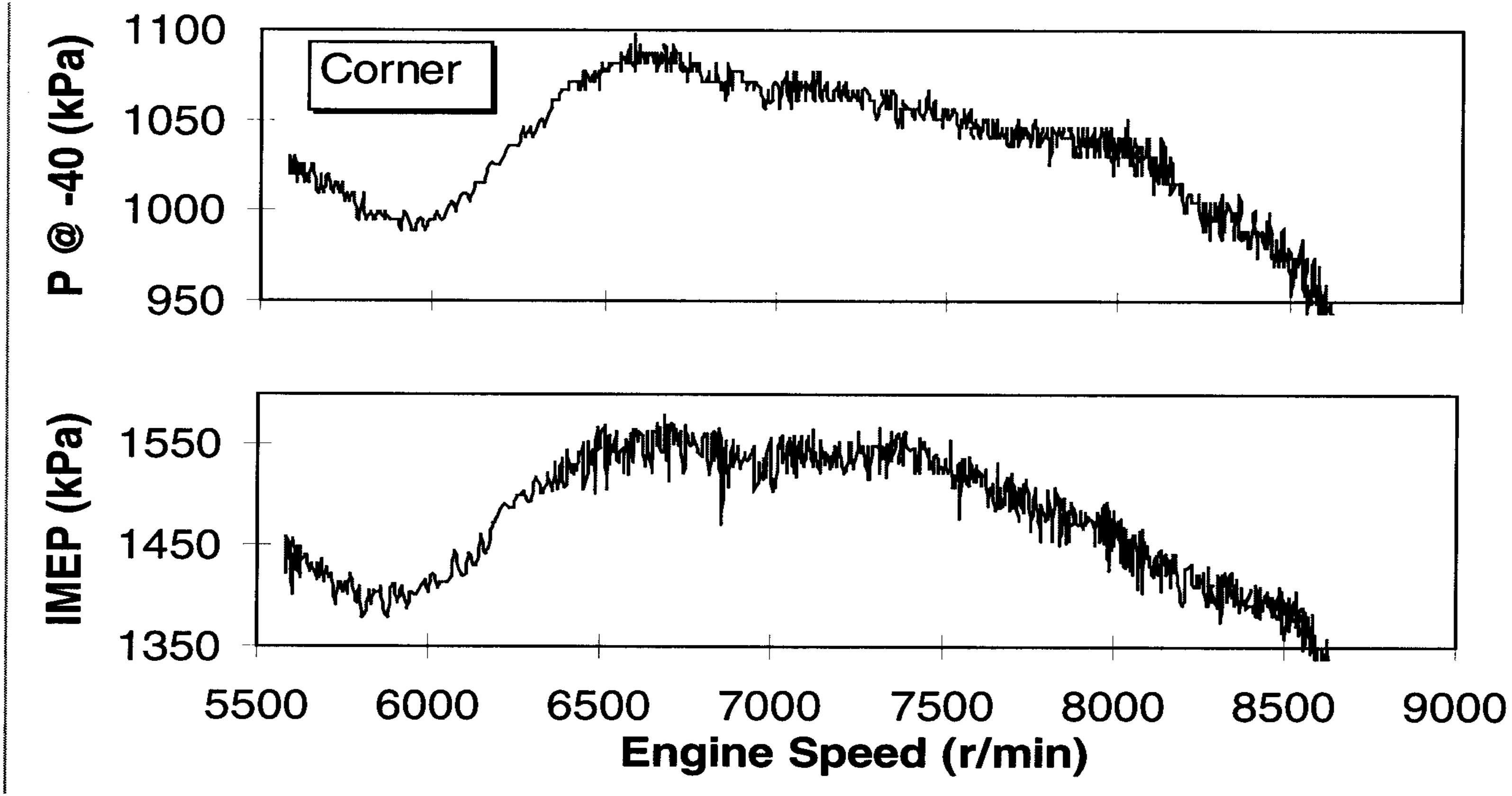

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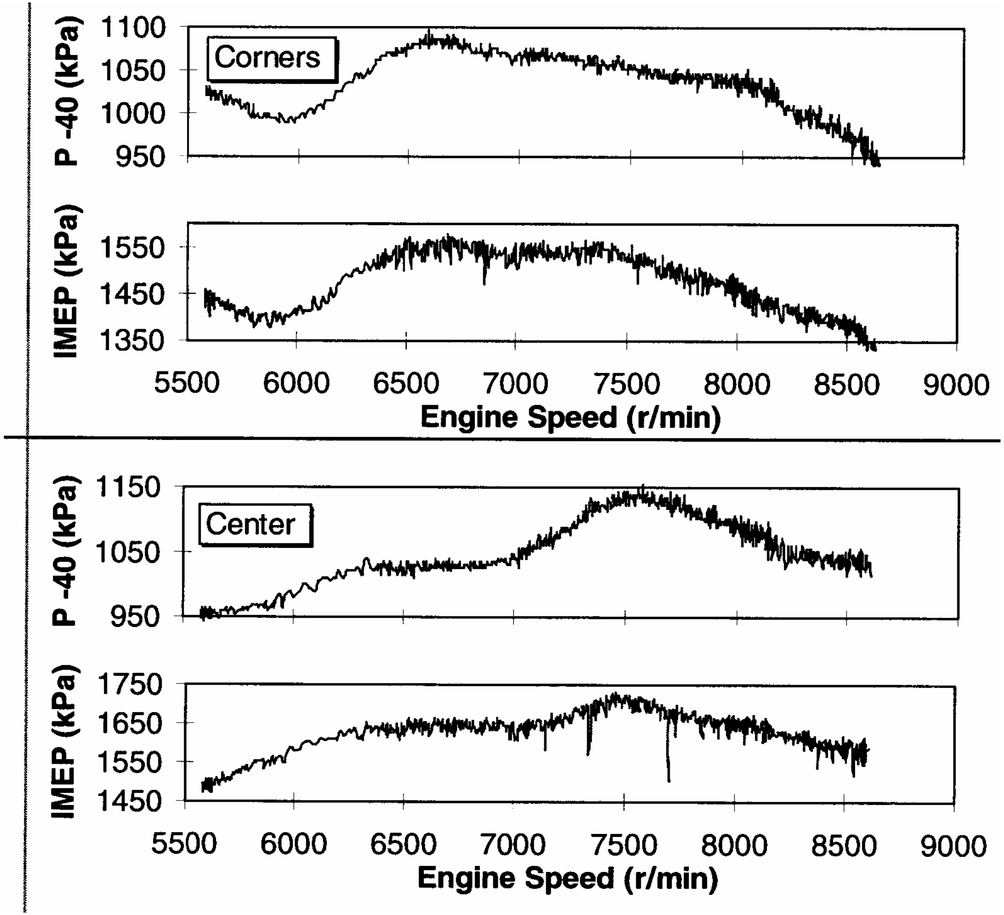

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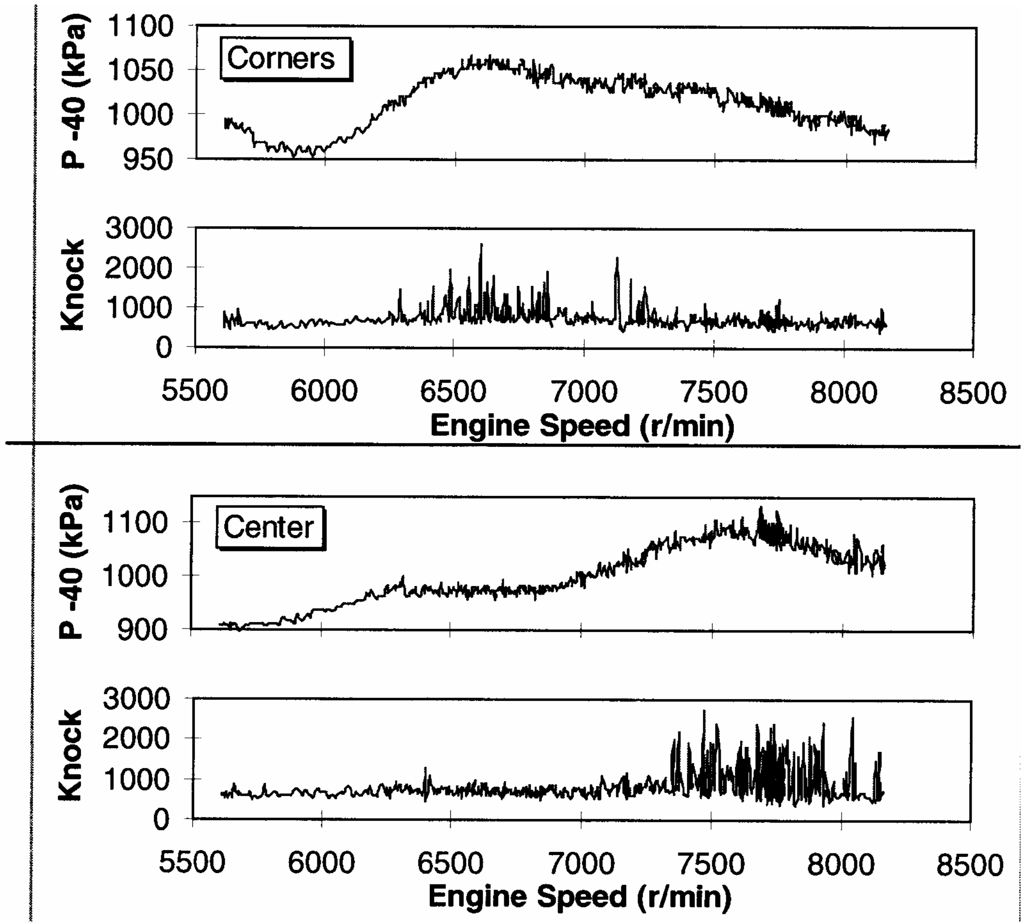

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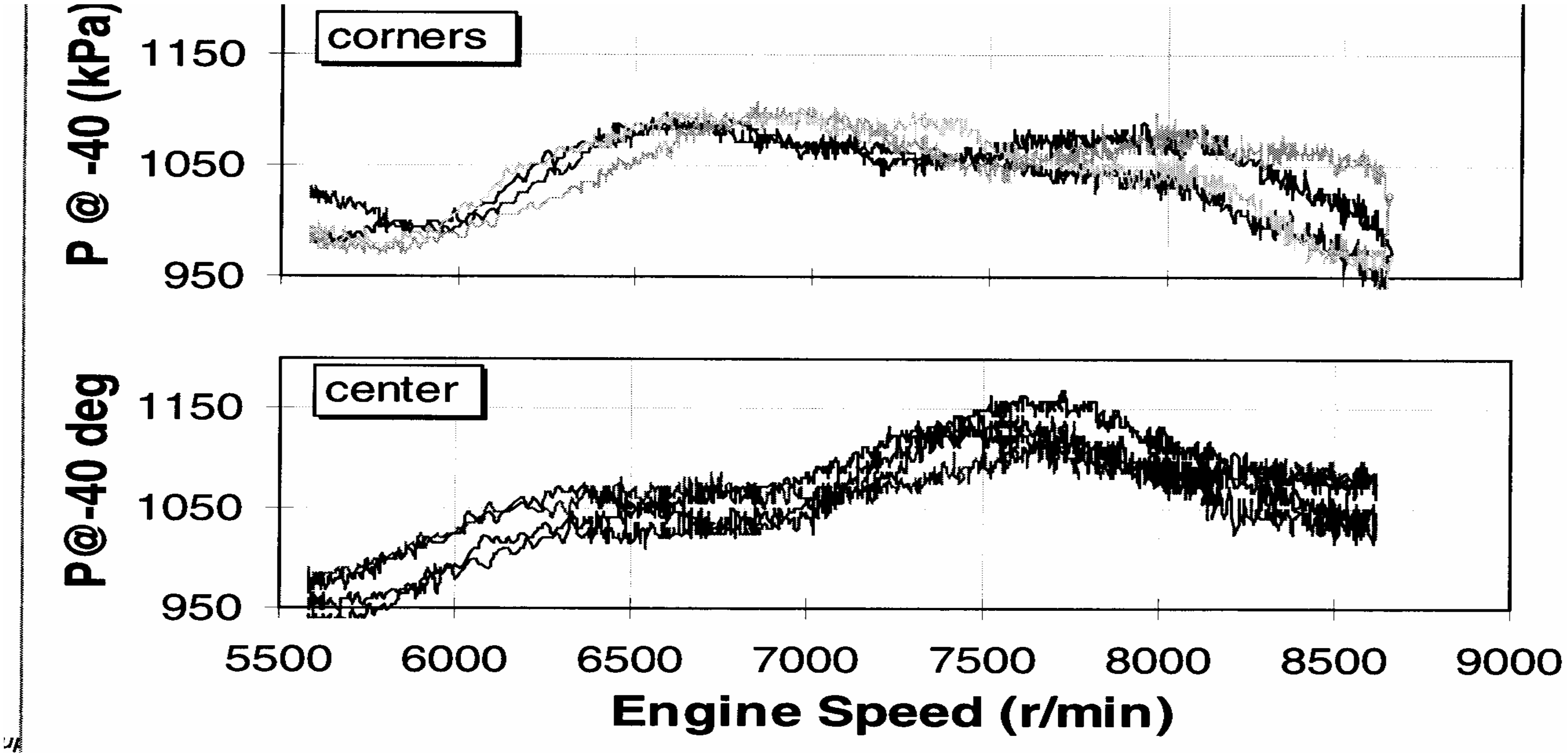

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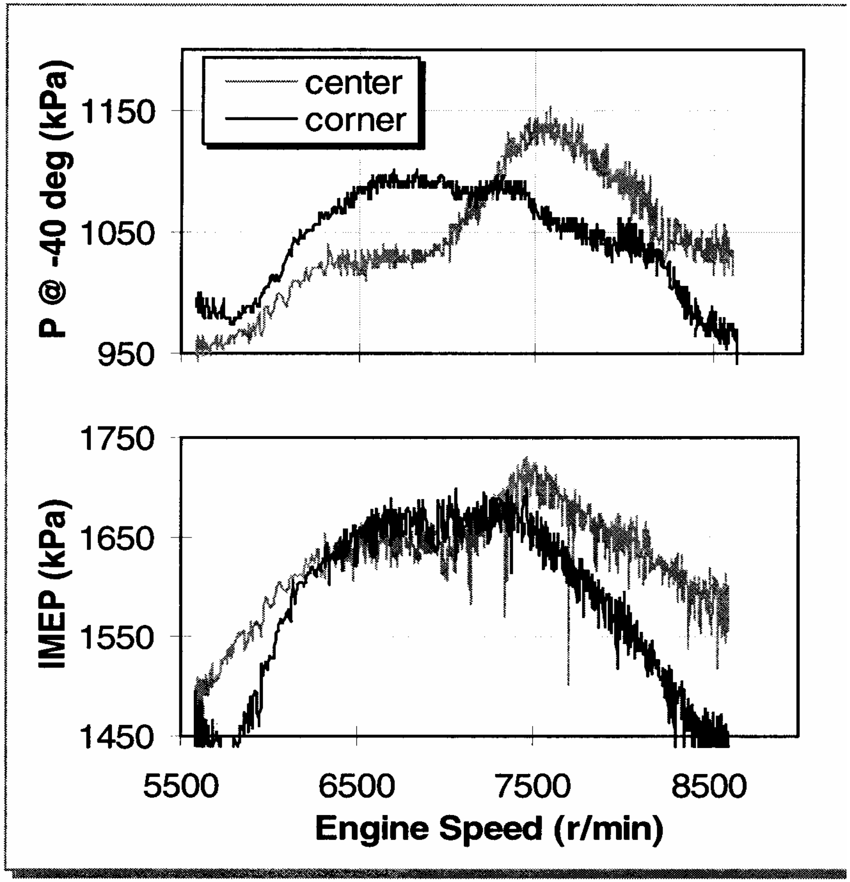

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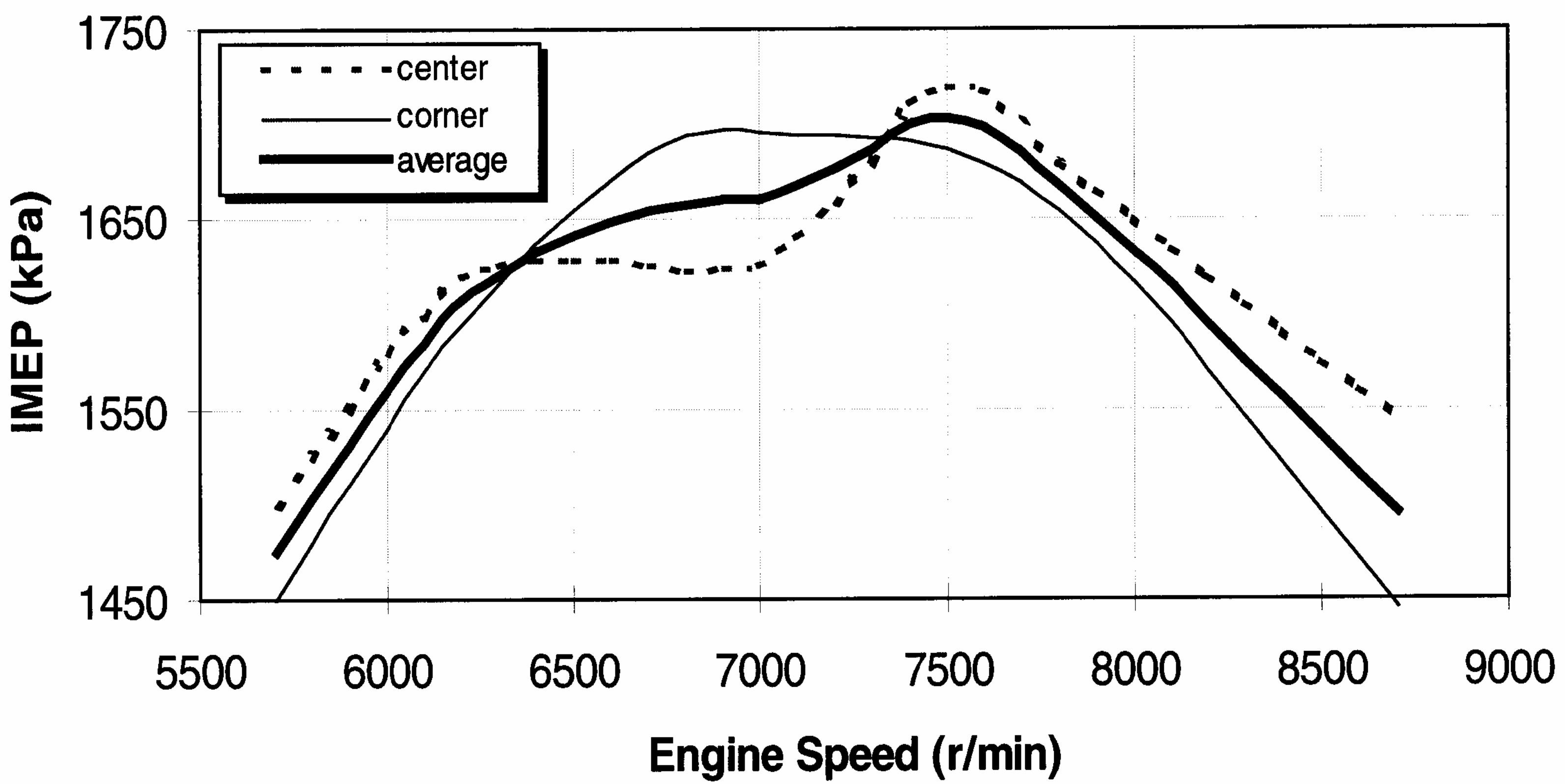

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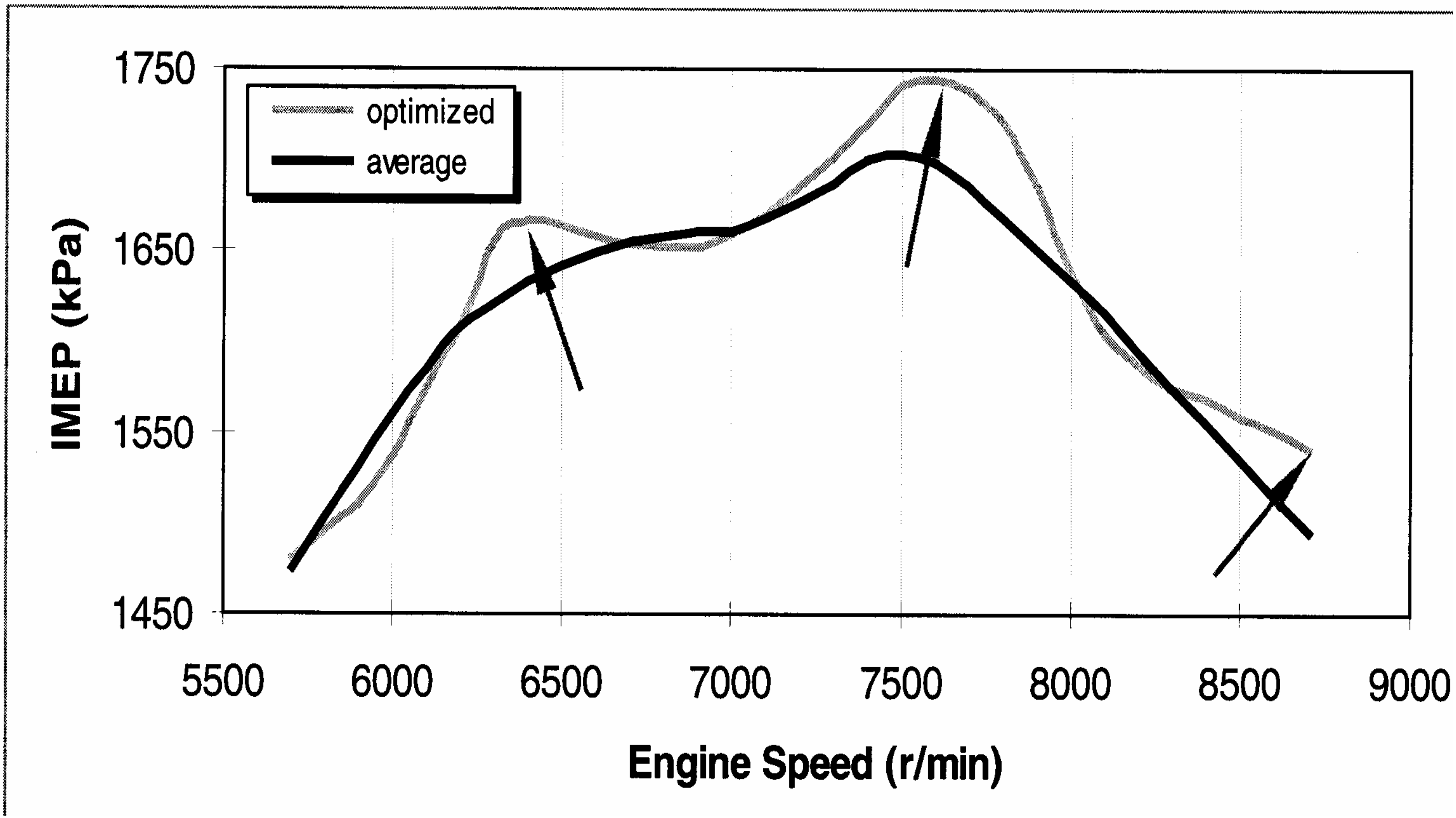

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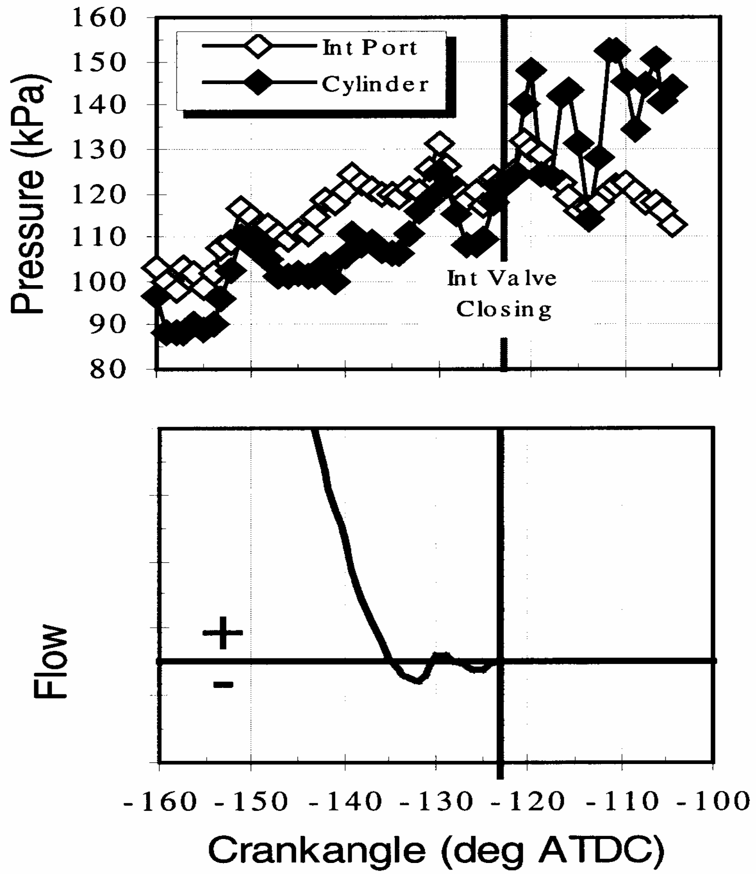

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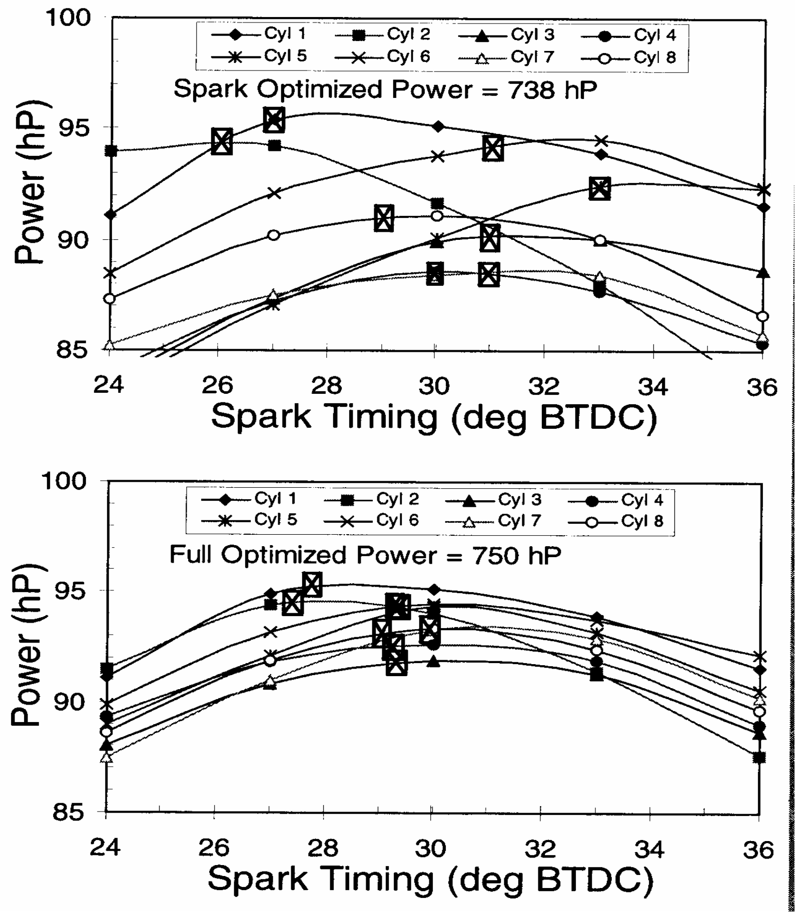

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- Some design features,such as single point air throttling and or single point fuel injection,lead to inherent mal-distribution
- Mal-distribution causes the torque curve to be broad and low. All cylinders suffer compromised performance
- Trapped mass mal-distribution is the single largest source of mal-distribution in other parameters

Tuning for Power Summary cont…

- Compensating for mal-distribution in trapped mass by optimising inlet valve closing reduces the amount of compensation required for other parameters such as ignition timing
- Achieving maximum individual cylinder performance by reducing mal-distribution substantially increases overall engine output