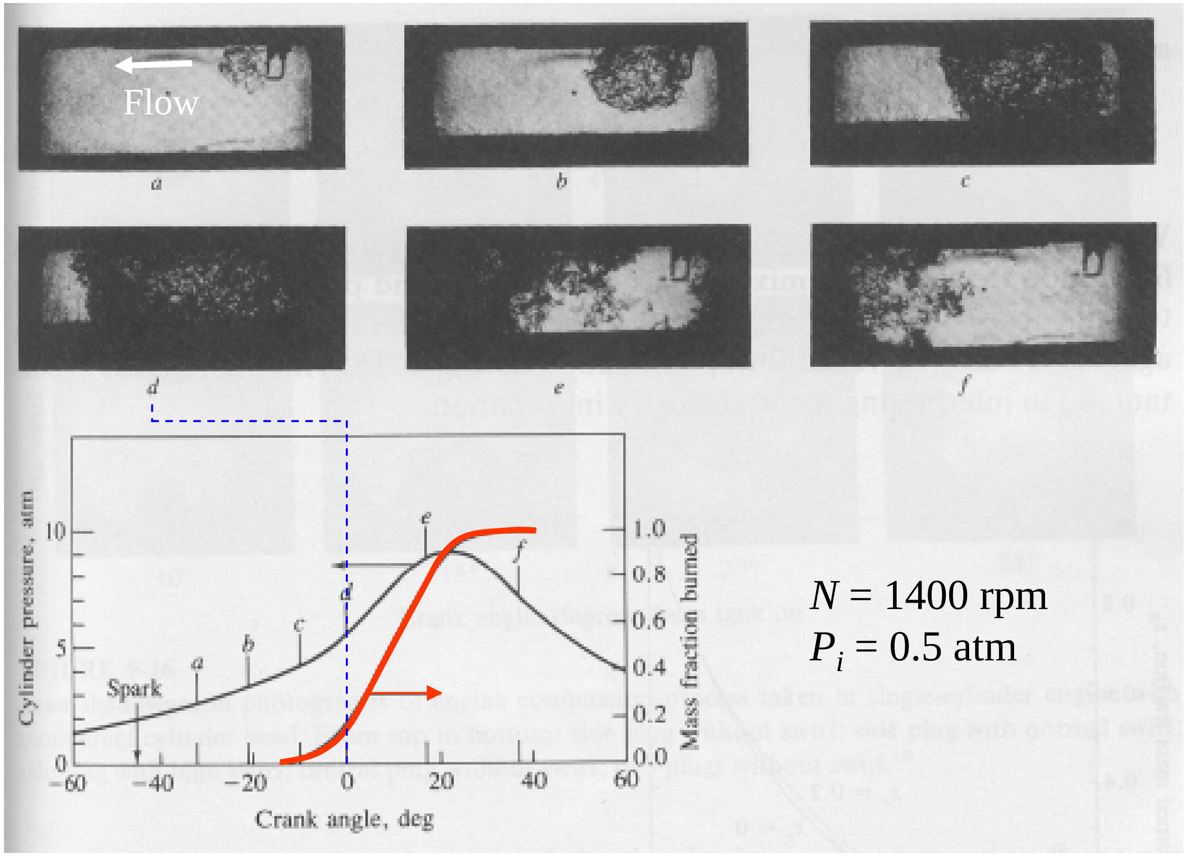
Combustion in IC Engines

Section 6

Flame Propagation in SI Engine

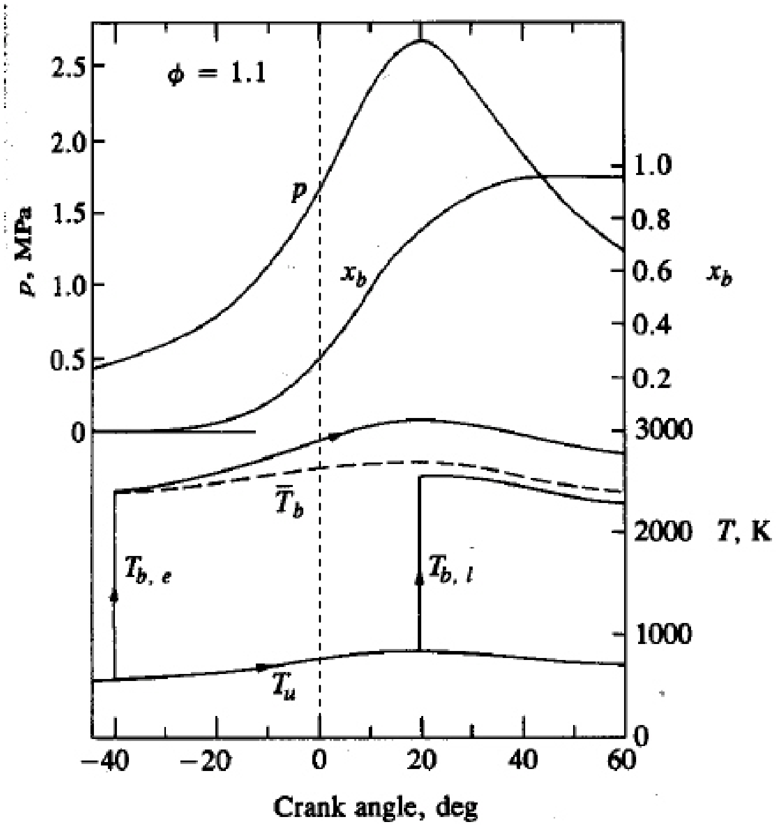
After the intake stroke the fuel-air mixture is compressed and then ignited by a spark plug just before the piston reaches

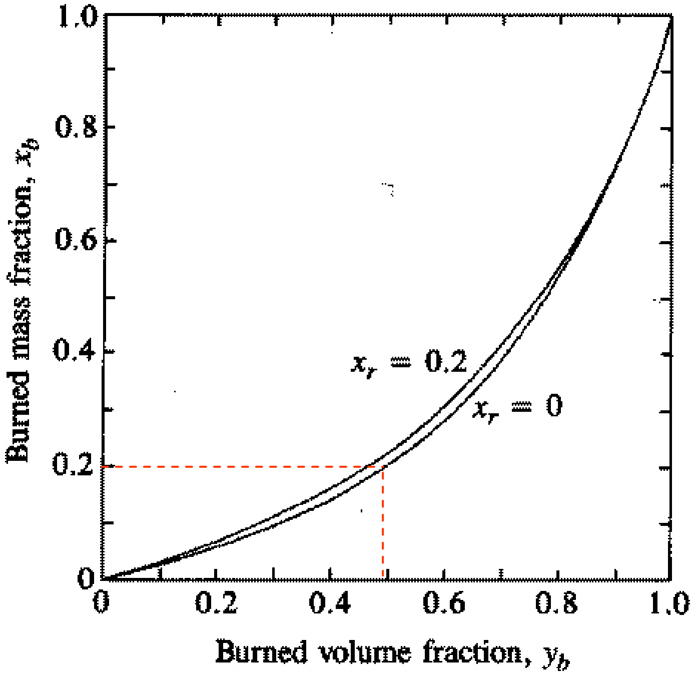
The turbulent flame spreads away from the spark discharge location.



$N = 1400$ rpm
$P_i = 0.5$ atm

In-cylinder Parameters





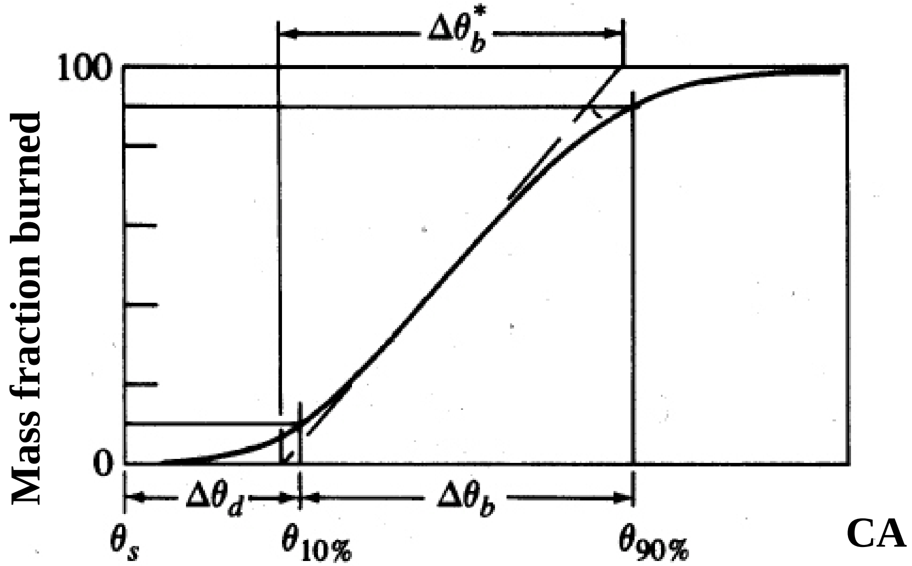
T_u – unburned gas temperature
$T_{b,e}$ – early burning gas elements
$T_{b,l}$ – late burning gas elements

Flame Development

$\Delta\theta_d$ – crank angle interval during which flame kernal develops after spark ignition.

$\Delta\theta_b$ – crank angle required to burn most of mixture

- sum of flame development and rapid burning angles



Mixture Burn Time vs Engine Speed

The time for an is:

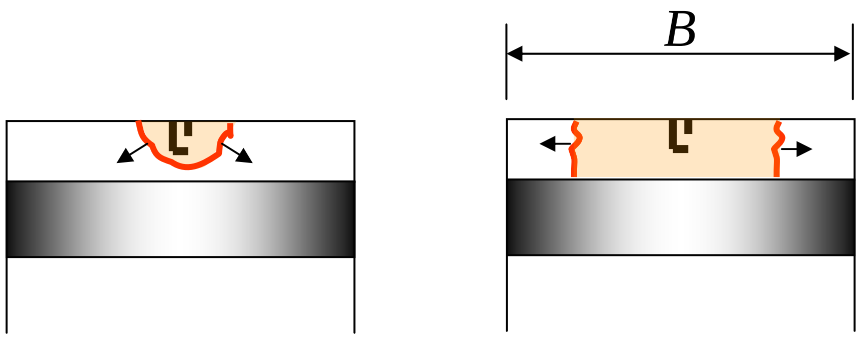
$$t_{90\%} = \frac{\Delta\theta_{90\%}}{N \cdot \left(\frac{\min}{60s}\right) \cdot \left(\frac{360^o}{rev}\right)}$$

If we take a typical value of 50 crank angles for the overall burn

	N (rpm)	$t_{90\%}$(ms)
Standard car at idle	500	16.7
Standard car at max power	4,000	2.1
Formula car at max N	19,000	0.4

Note: To achieve such high engine speeds a formula car engine has a very short stroke and large bore.

Mixture Burn Time



$$t_{comb} = \frac{B/2}{S_l} = \frac{5\,cm}{25\,cm/s} = 0.2\,s = 200\,ms$$

How does the flame burn all the mixture in the cylinder in the time available, especially at $\boxed{}$ engine speeds?

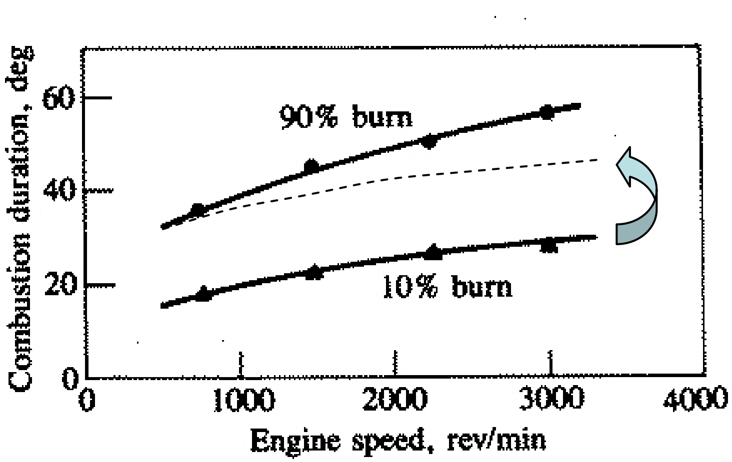
Mixture Burn Time vs Engine Speed

Recall the turbulent burning velocity is proportional to the turbulent intensity $S_t \sim u_t$, which increases with the piston speed,

The piston speed is directly proportional to the engine speed, $u_p \sim N$

Therefore, at higher engine speeds the turbulent flame velocity is also higher and as a result need less time to burn the entire mixture

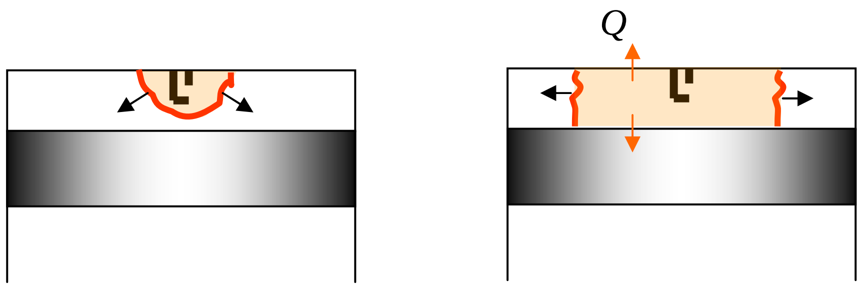
Combustion duration in crank angles (40-60 degrees) only increases a small amount with increasing engine speed.



$\phi = 1.0$
P_i =0.54 atm
Spark 30^o BTC

Heat Losses During Burn

During combustion the cylinder volume is very narrow.



Heat loss to the piston and cylinder head is very important

In order to reduce the heat loss want burn time to be small (high flame velocity) accomplished by either increasing the

- laminar burning velocity, or
- turbulence intensity.

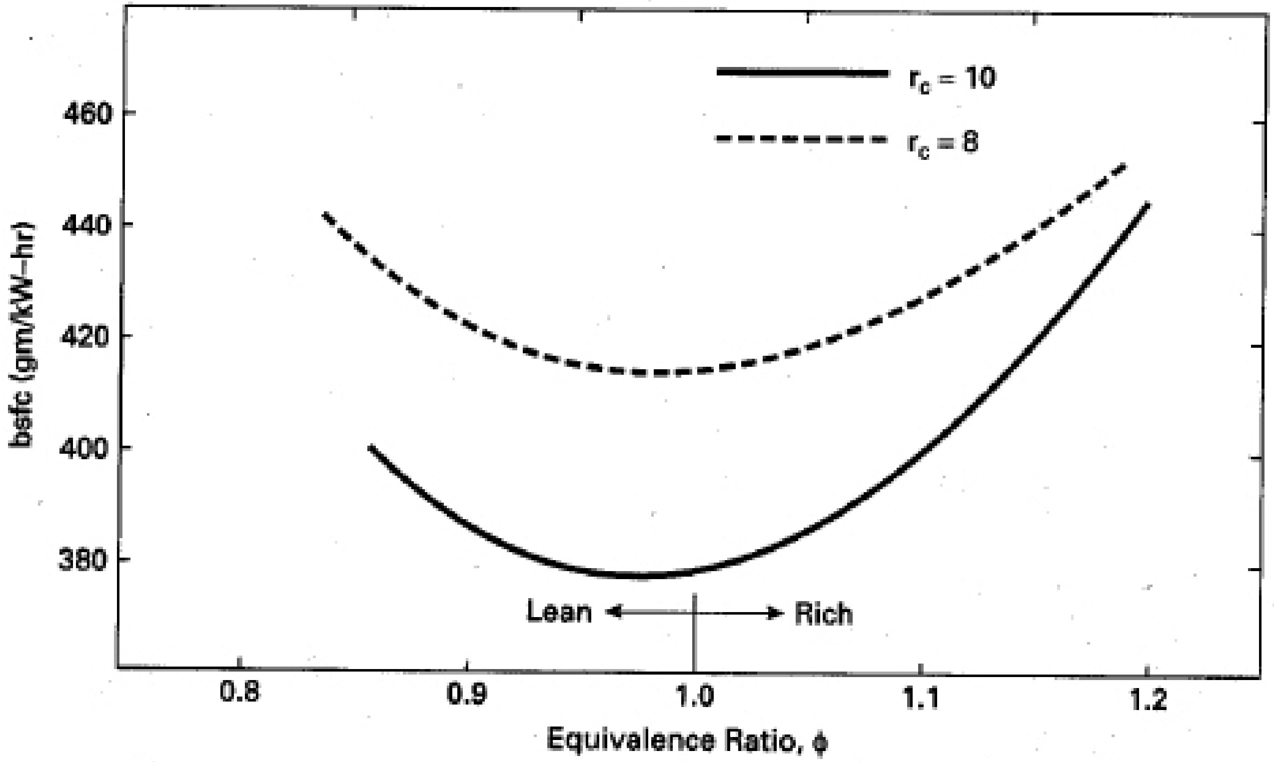
Highest laminar burning velocity is achieved for slightly rich mixtures (for isooctane maximum S_l = 26.3 cm/s at $\phi = 1.13$)

promotes in-cylinder turbulence

Optimum F/A Composition

Maximum power is obtained for a $\boxed{}$ that gives the highest burning velocity (minimum heat loss) and flame temperature (maximum P_{CV})

Best fuel economy is obtained for a F/A that is less than 1.0

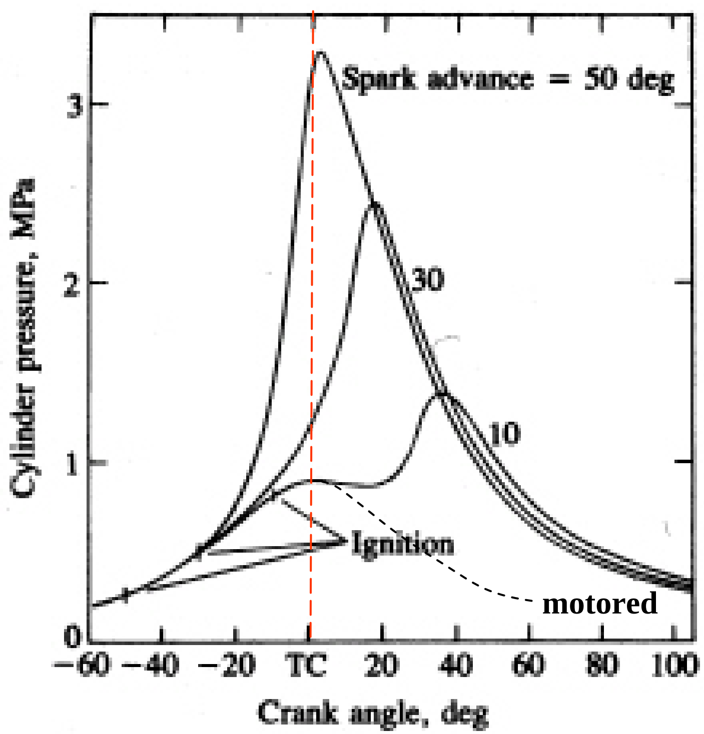


Spark Timing

Spark timing relative to TC affects the pressure development and thus the engine *imep* and power.

Ignite the gas $\boxed{}$ TC in order to centre the pressure pulse around TC.

The overall burning angle is typically between 40 to 60°, depending on engine speed.



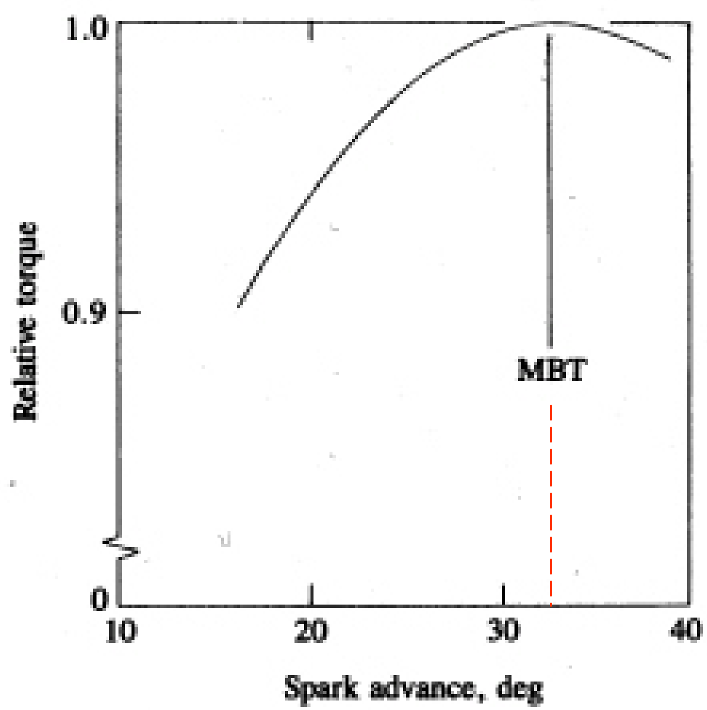
Engine at WOT, constant engine speed and A/F

Maximum Brake Torque Timing

If start of combustion is too early work is done against piston and if too late then peak pressure is reduced.

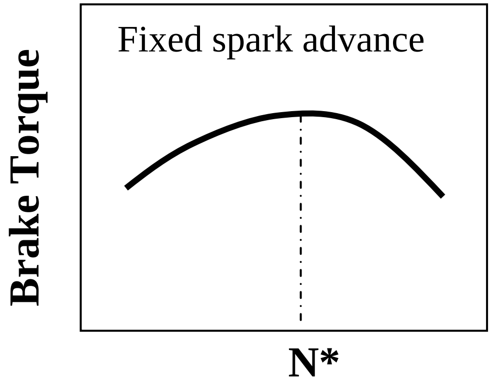
The optimum spark timing that gives the maximum brake torque (MBT) is called

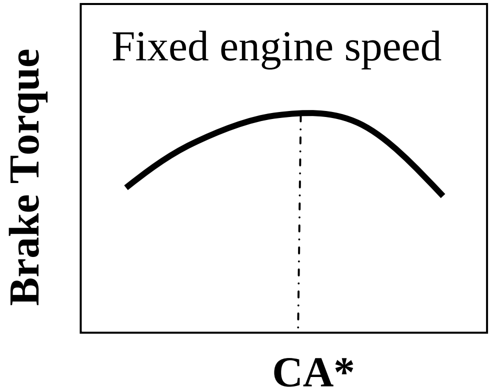
Engine at WOT, constant engine speed and A/F

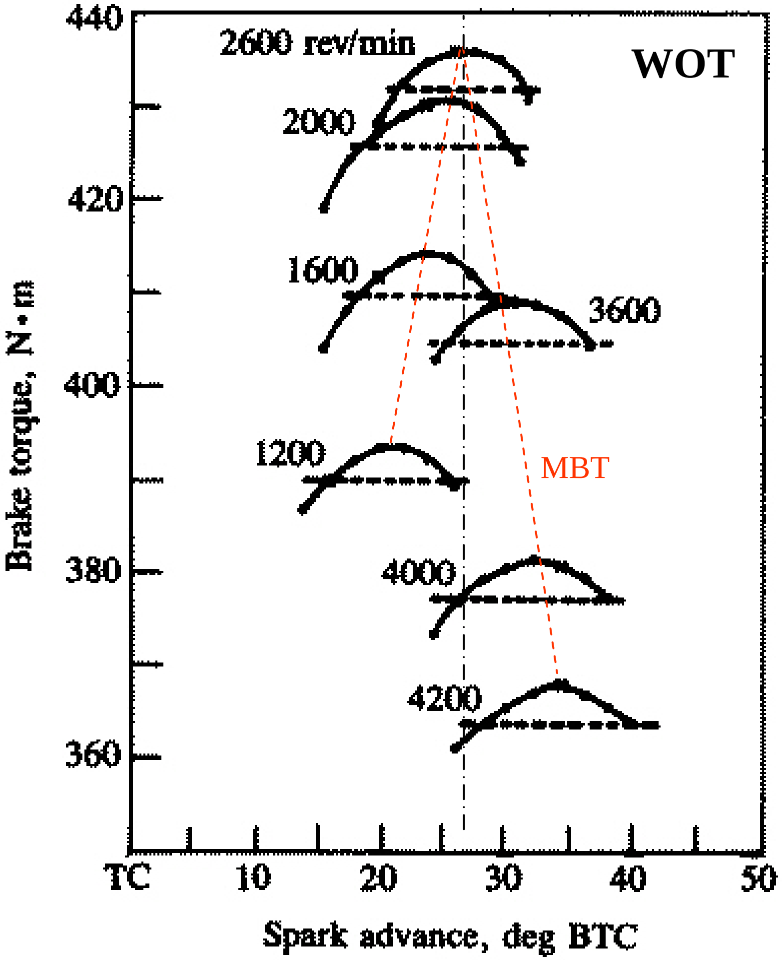


Effect of Engine Speed on Spark Timing

Recall the overall burn angle (90% burn) with engine speed, to accommodated this you need a larger spark advance.



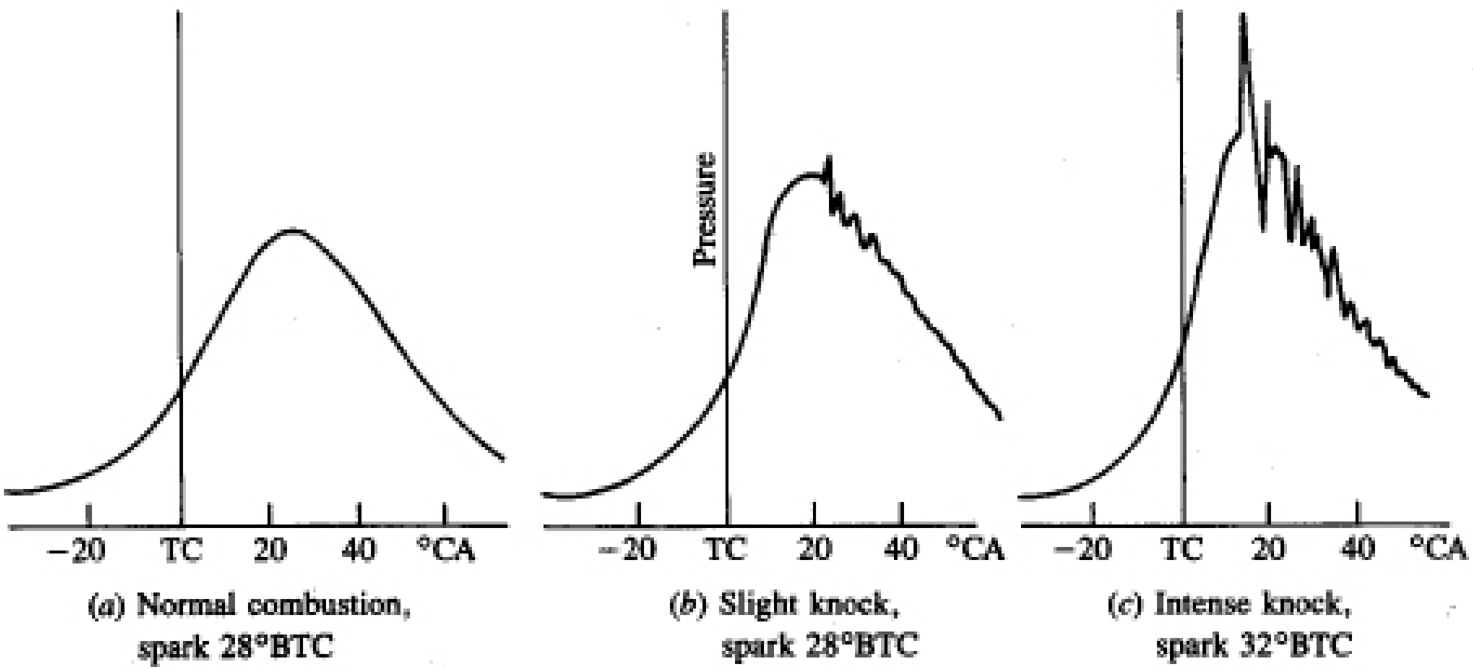




Abnormal Combustion in SI Engine

is the term used to describe a pinging noise emitted from a SI engine undergoing abnormal combustion.

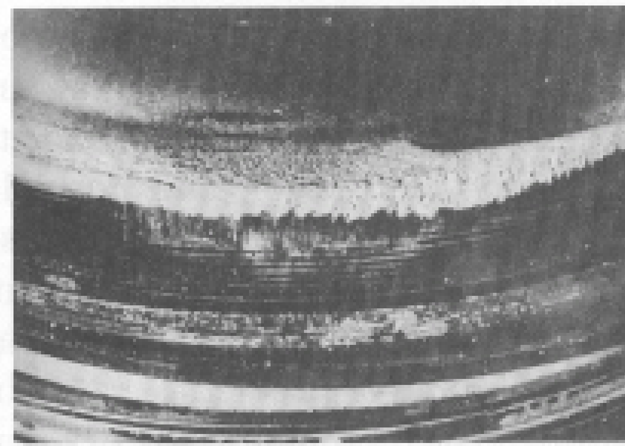
The noise is generated by shock waves produced in the cylinder when unburned gas autoignites.



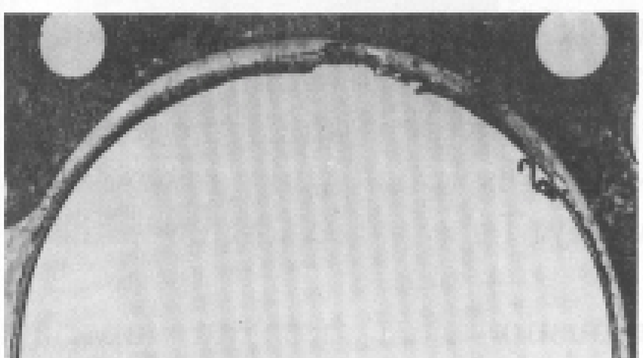
Engine Damage From Severe Knock

Damage to the engine is caused by a combination of high temperature and high pressure.

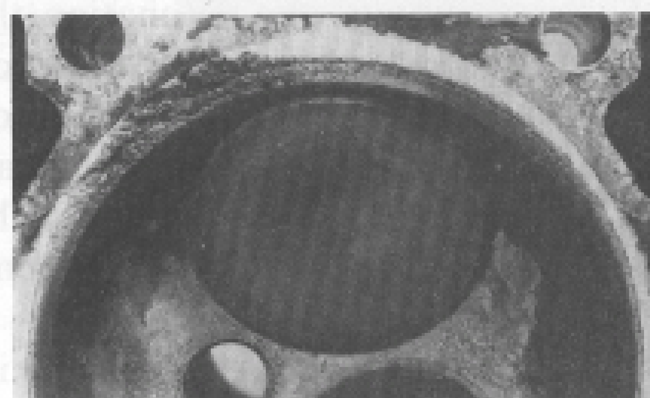
Piston



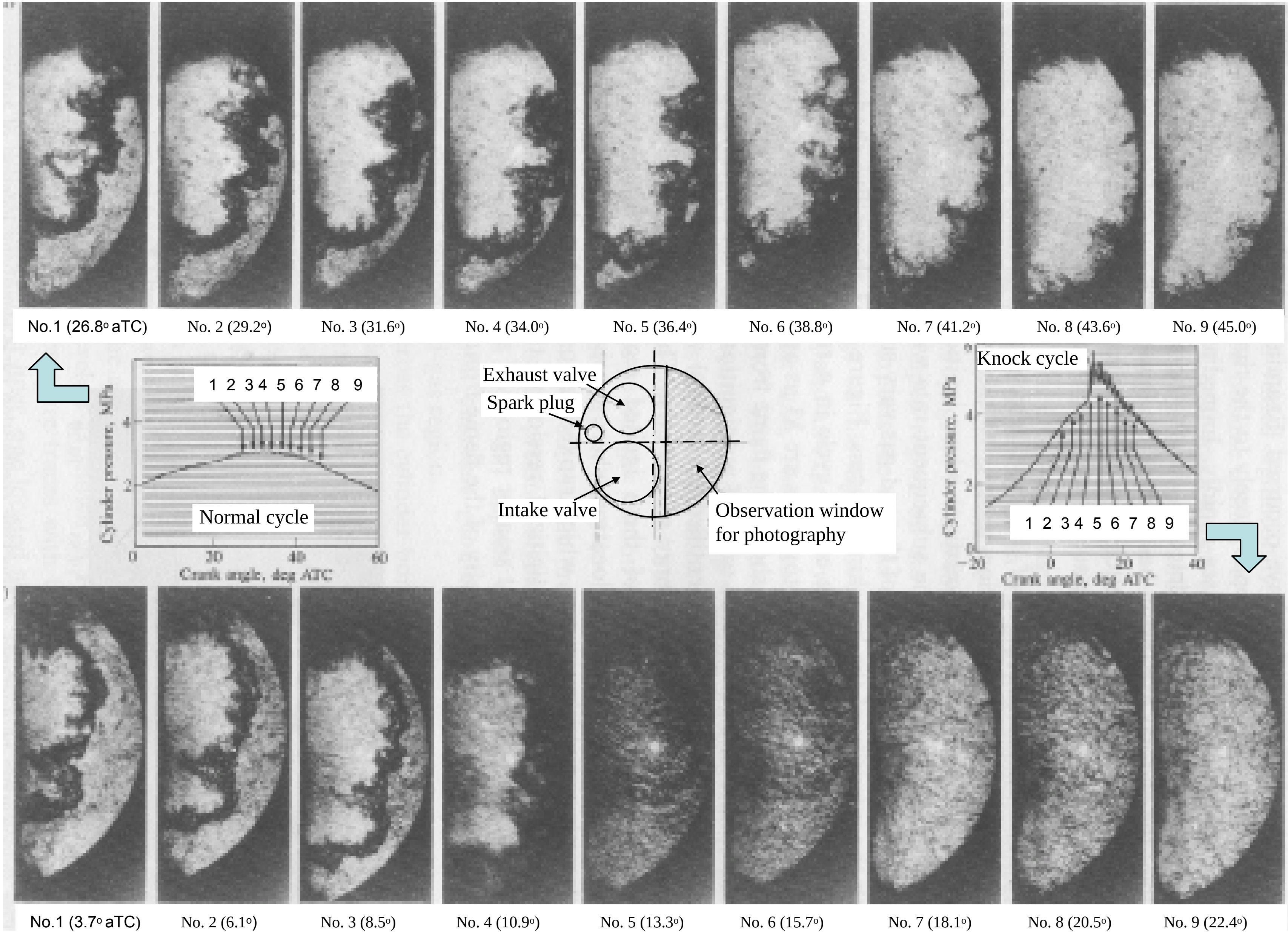
Piston crown



Cylinder head gasket



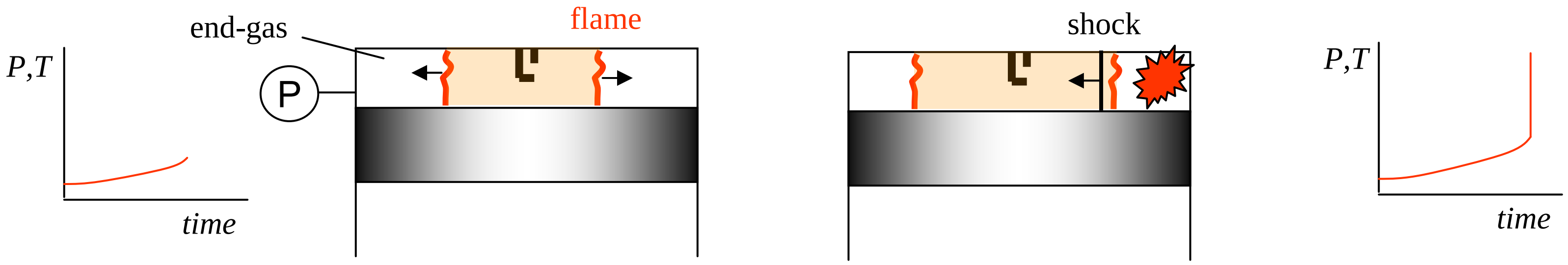
Aluminum cylinder head


No.1 (26.8° aTC)
No. 2 (29.2°)
No. 3 (31.6°)
No. 4 (34.0°)
No. 5 (36.4°)
No. 6 (38.8°)
No. 7 (41.2°)
No. 8 (43.6°)
No. 9 (45.0°)
1 2 3 4 5 6 7 8 9
Normal cycle
Cylinder pressure, MPa
Crank angle, deg ATC
Exhaust valve
Spark plug
Intake valve
Observation window
for photography
Knock cycle
1 2 3 4 5 6 7 8 9
Cylinder pressure, MPa
Crank angle, deg ATC
No.1 (3.7° aTC)
No. 2 (6.1°)
No. 3 (8.5°)
No. 4 (10.9°)
No. 5 (13.3°)
No. 6 (15.7°)
No. 7 (18.1°)
No. 8 (20.5°)
No. 9 (22.4°)

Knock

As the flame propagates away from the spark plug the pressure and temperature of the unburned gas increases.

Under certain conditions the end-gas can and burn very rapidly producing shock waves.



The end-gas autoignites after a certain *induction time* which is dictated by the chemical kinetics of the fuel-air mixture.

If the flame burns all the fresh gas before autoignition of the end-gas can occur then knock is avoided.

Therefore knock is a potential problem when the burn time is long.

Engine Parameters Affecting Knock

i) – at high compression ratios, even before spark ignition, the fuel-air mixture is compressed to a high pressure and temperature which promotes autoignition

ii) – At low engine speeds the flame velocity is slow and thus the burn time is long, this results in more time for autoignition

However at high engine speeds there is less heat loss so the unburned gas temperature is higher which promotes autoignition

These are competing effects, some engines show an increase in propensity to knock at high speeds while others don’t.

Engine Parameters Affecting Knock

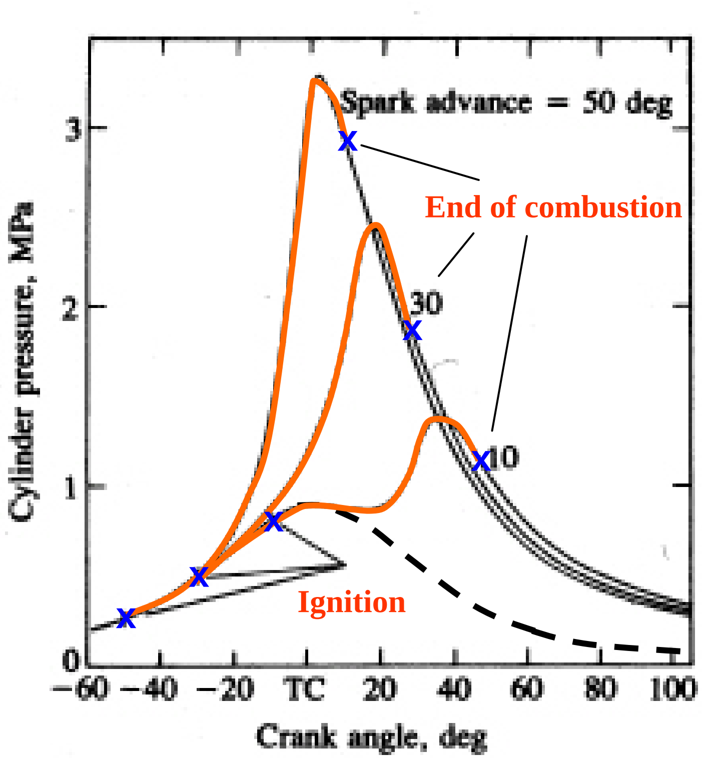
iii) $\boxed{}$ - at part-throttle the residual gas fraction increases due to valve overlap, residual gas is a diluent so it lowers the laminar burning velocity and thus the turbulent burning rate.

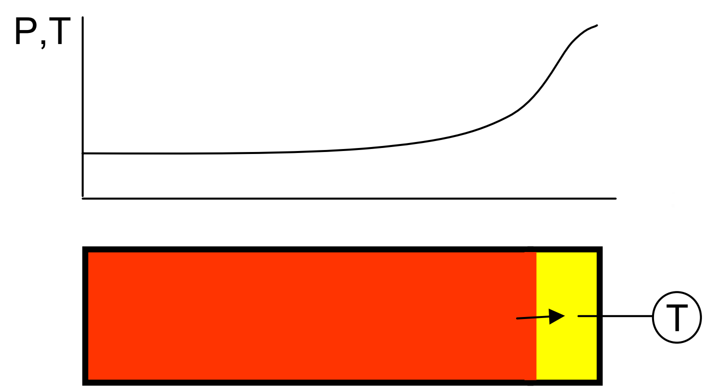
Because of lower burning velocity overall burn angle increases so need to increase spark advance.

At idle, the residual gas fraction is very high → the burn time is very long → long overall burn angle requires more spark advance.

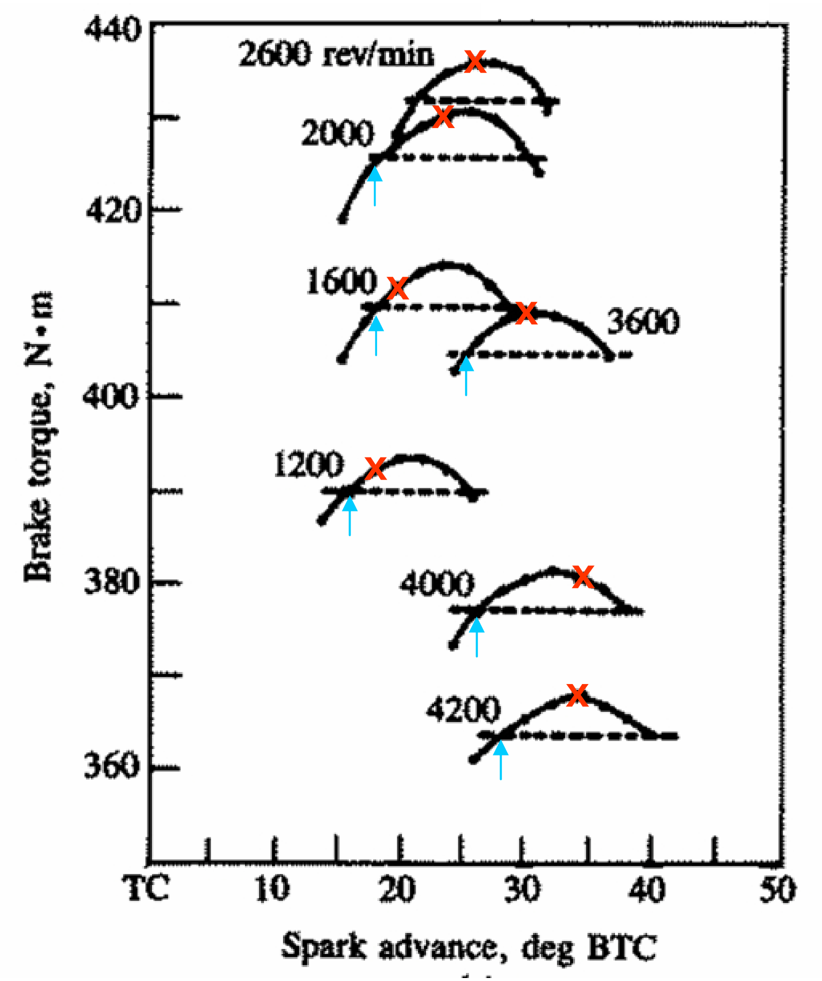
Engine Parameters Affecting Knock

iv) [   ] – increasing the spark advance makes the end of combustion crank angle approach TC and thus get higher pressure and temperature in the unburned gas just before burnout.





Knock Mitigation Using Spark Advance



X crank angle corresponding to borderline knock

.... 1% below MBT

Spark advance set to 1% below MBT to avoid knock

In modern engines the ECU sets the spark advance based on [   ] and throttle position (or air manifold pressure)

Engine Knock Detection

A knock sensor is mounted on the engine block to determine if an engine is knocking. The sensor consists of a piezoelectric accelerometer that produces an analog electrical signal when engine vibration at a specific frequency (6-15 kHz) is measured

In-cylinder pressure transducers are very expensive and are not widely used for knock detection

On receiving a knock signal the ECU temporarily spark timing as a countermeasure to prevent engine damage from knock, and the ECU indicates a “fault”

Some manufacturers have knock sensors for each cylinder

Fuel Knock Scale

To provide a standard measure of a fuel's ability to resist knock, a scale has been devised by which fuels are assigned an ON.

The octane number determines whether or not a fuel will knock for a specified engine at a specified operating condition.

An ON scale is in place where normal heptane (n-C_7H_{16}) has an octane value of zero and iso-octane (i-C_8H_{18}) has a value of 100.

The higher the octane number, the higher the resistance to knock.

Blends of these two hydrocarbons define the knock resistance of intermediate octane numbers: e.g., a blend of 10% n-heptane and 90% iso-octane has an octane number of 90.

Octane Number Measurement

Two methods have been developed to measure ON using a standardized single-cylinder engine developed under the auspices of the Cooperative Fuel Research (CFR) Committee in 1931*.

The CFR engine is 4-stroke with 3.25” bore and 4.5” stroke, compression ratio can be varied from 3 to 30.

Inlet temperature (^{o}C)	52	149
Speed (rpm)	600	900
Spark advance (^{o}BTC)	13	19-26 (varies with r)
Coolant temperature (^{o}C)	100	
Inlet pressure (atm)	1.0	
Humidity (kg water/kg dry air)	0.0036 - 0.0072	

*Note: In 1931 iso-octane was the most knock resistant HC, now there are fuels that are more knock resistant than iso-octane.

Octane Number Measurement

Testing procedure:

- Run the CFR engine on the test fuel at both research and motor conditions.
- Slowly increase the compression ratio until a standard amount of knock occurs as measured by an in-cylinder pressure transducer.
- At that compression ratio run the engines on blends of n-hepatane and isooctane.
- ON is the % by volume of octane in the blend that produces the same knock

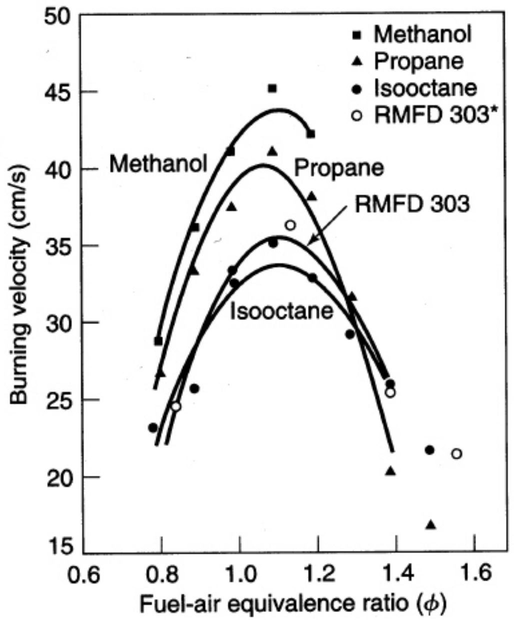
The antiknock index used in N. America is the average of the research and motor octane numbers. Note, Europe uses RON for its antiknock index.

Note the MON is always lower than RON because it uses more severe operating conditions, i.e., higher inlet temperature and more spark advance.

The automobile manufacturer will specify the minimum fuel ON that will resist knock throughout the engine's operating speed and load range.

Knock Characteristics of Various Fuels

Formula	Name	RON	MON
CH_4	Methane	120	120
C_3H_8	Propane	112	97
CH_4O	Methanol	106	92
C_2H_6O	Ethanol	107	89
C_8H_{18}	Isooctane	100	100
Blend of HCs	Regular gasoline	91	83
$n\text{-}C_7H_{16}$	n-heptane	0	0



For fuels with antiknock quality better than octane, the octane number is:

$$ON = 100 + 28.28T / [1.0 + 0.736T+(1.0 + 1.472T - 0.035216T^2)^{1/2}]$$

where T is $\boxed{}$ of tetraethyl lead per U.S. gallon

Fuel Additives

Chemical additives are used to raise the octane number of gasoline.

The most effective antiknock agents are lead alkyls;
(i) Tetraethyl lead (TEL), $(C_2H_5)_4Pb$ was introduced in 1923
(ii) Tetramethyl lead (TML), $(CH_3)_4Pb$ was introduced in 1960
Lead compound reacts with the chain carrier O to reduce its concentration

In 1959 a manganese antiknock compound known as MMT was introduced to supplement TEL (used in Canada since 1978).

About 1970 low-lead and unleaded gasoline were introduced over toxicological concerns with lead alkyls (TEL contains 64% by weight lead).

Alcohols such as ethanol and methanol have knock resistance.

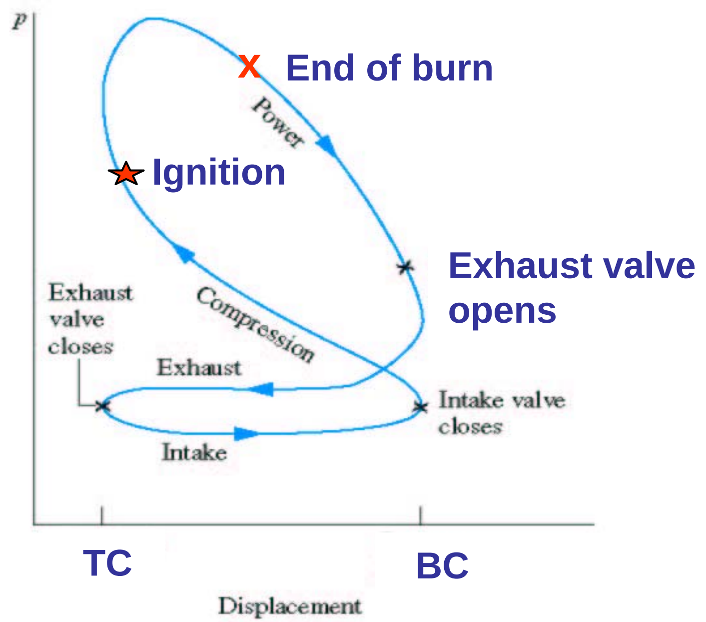
Since 1970 another alcohol, methyl tertiary butyl ether (MTBE), has been added to gasoline to increase octane number. MTBE is formed by reacting methanol and isobutylene (not used in Canada).

Engine Stability

If the fuel-air mixture is leaned out with excess air, or is diluted with increasing amounts of residual gas or $\boxed{}$ → the cycle-by-cycle variations in the combustion process increases.

Eventually a point is reached where engine operation becomes rough and unstable, this point defines the engine's **stable operating limit**.

With little or no dilution combustion occurs prior to the exhaust valve opening consistently cycle after cycle.



Engine Stability cont'd

As the dilution is increased the burn time increases

With increasing dilution, first, in a fraction of the cycles the burns are so slow that combustion is only just completed prior to the exhaust valve opening.

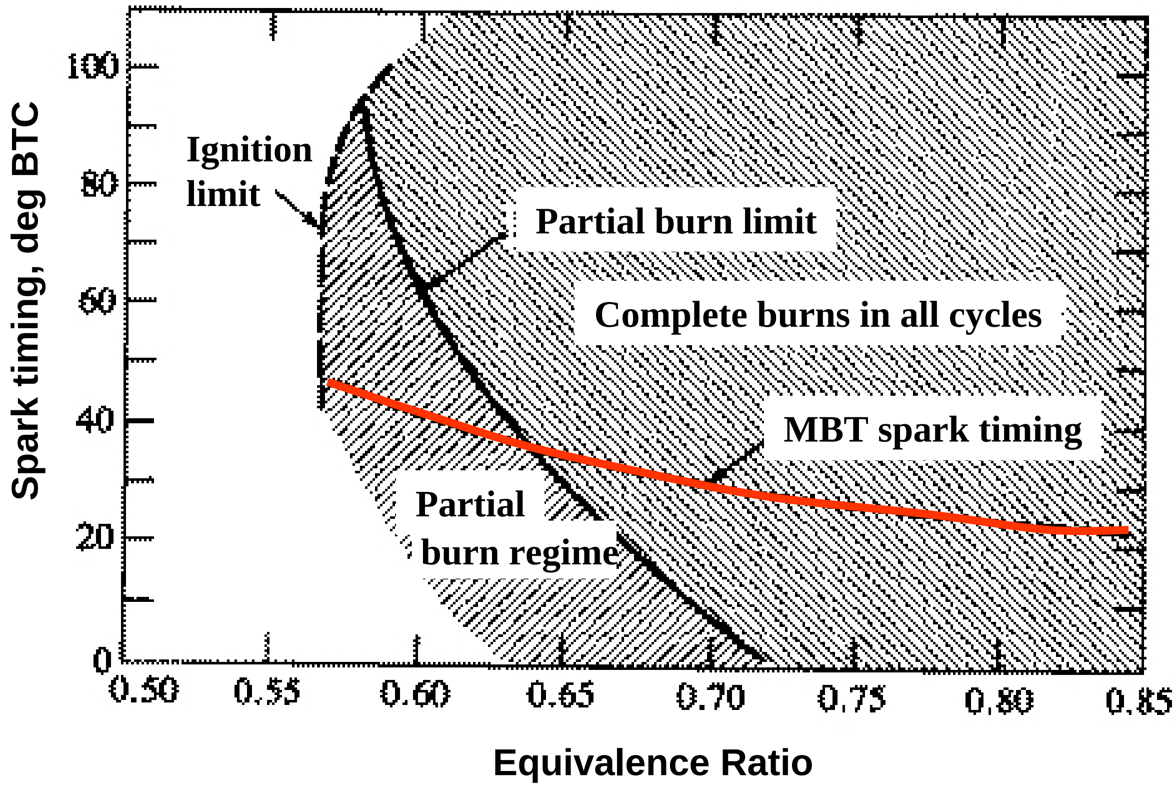
As dilution increases further, in some cycles combustion is not complete prior to the exhaust valve opening and the flame extinguishes before all the fuel is burned.

Finally cycles start to occur where the mixture doesn't ignite at all. As the dilution is further increased the proportion of partial burns and misfires increase to a point where the engine no longer runs.

Effect of Fuel-air Dilution

Set spark timing for MBT, leaner mixture needs more spark advance since burn time longer.

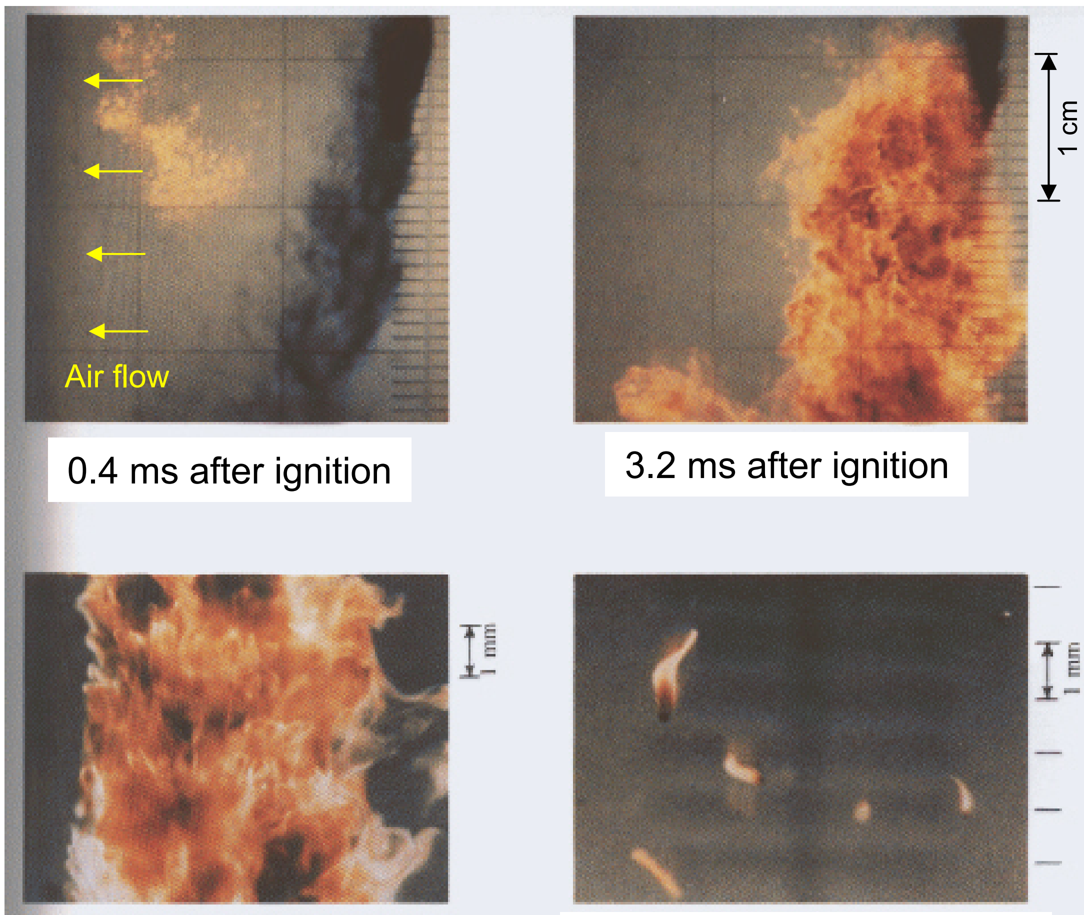
Along MBT curve as you increase excess air reach limit (not all cycles result in complete burn) and then (misfires start to occur).



Combustion in CI Engine

In a CI engine the fuel is sprayed directly into the cylinder and the vaporised part of the fuel mixes with air and ignites

These photos are taken in a RCM under CI engine conditions with swirl



0.4 ms after ignition

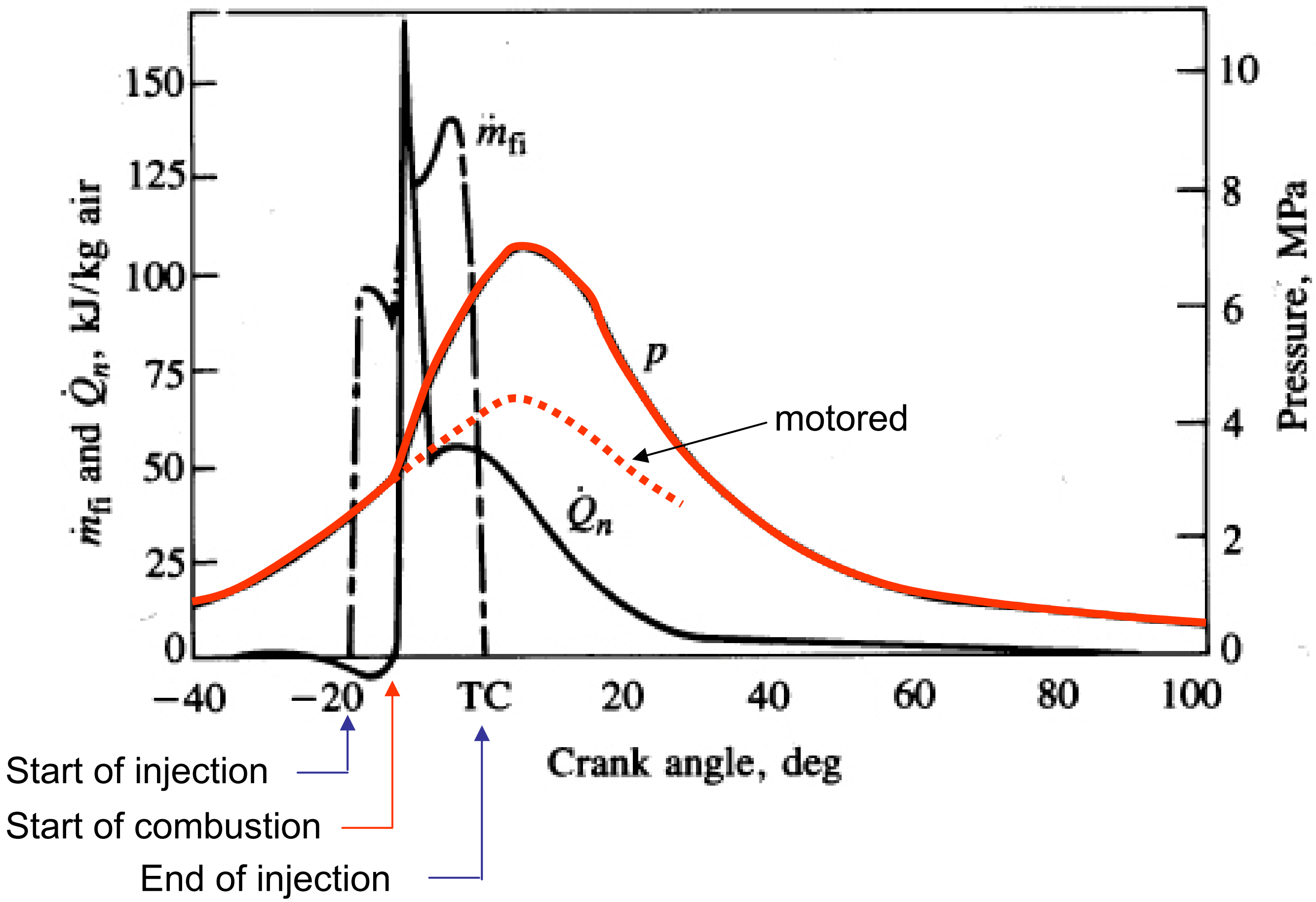
3.2 ms after ignition

3.2 ms after ignition

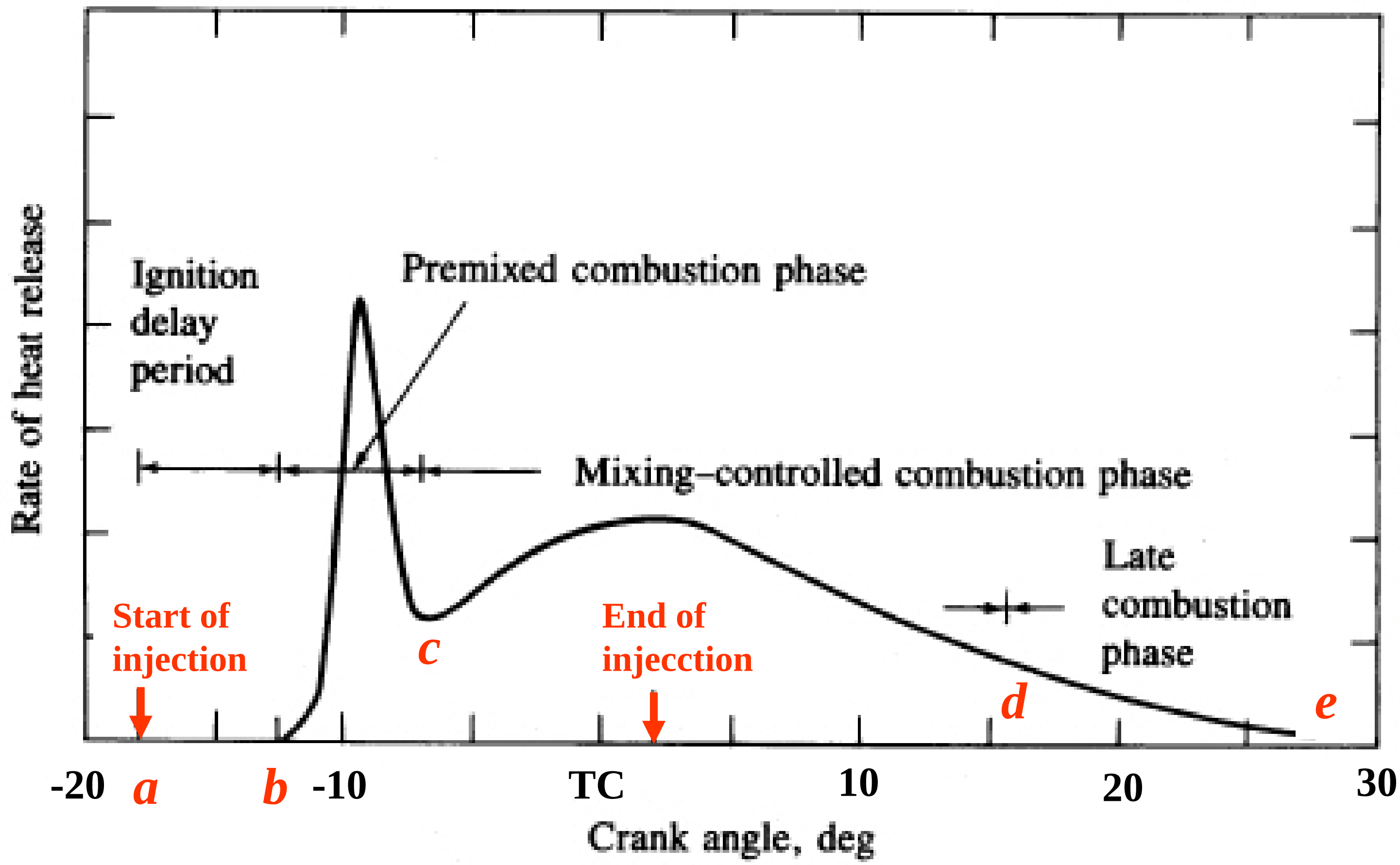
Late in combustion process

In-Cylinder Measurements

This graph shows the fuel injection flow rate, net heat release rate and cylinder pressure for a direct injection CI engine.



Four Stages of Combustion in CI Engines



Combustion in CI Engine

The combustion process proceeds by the following stages:

(ab) - fuel is injected directly into the cylinder towards the end of the compression stroke. The liquid fuel atomizes into small drops and penetrates into the combustion chamber. The fuel vaporizes and mixes with the high-temperature high-pressure air.

(bc) – combustion of the fuel which has mixed with the air to within the flammability limits (air at high-temperature and high-pressure) during the ignition delay period occurs rapidly in a few crank angles.

(cd) – after premixed gas consumed, the burning rate is controlled by the rate at which mixture becomes available for burning. The burning rate is controlled primarily by the fuel-air mixing process.

(de) – heat release may proceed at a lower rate well into the expansion stroke (no additional fuel injected during this phase). Combustion of any unburned liquid fuel and soot is responsible for this.

CI Engine Types

Two basic categories of CI engines:

i) $\boxed{}$ – have a single open combustion chamber into which fuel is injected directly

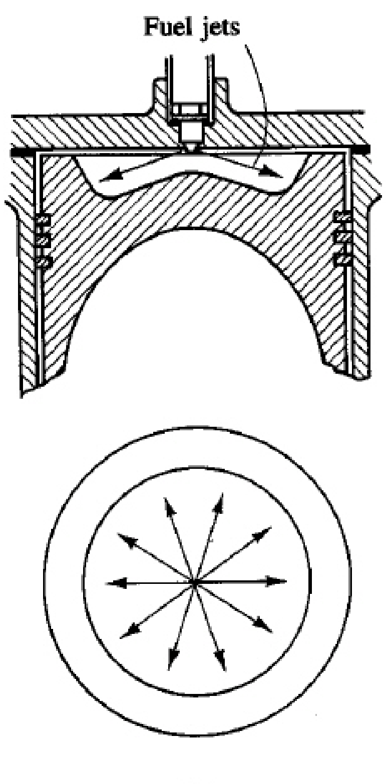
ii) $\boxed{}$ – chamber is divided into two regions and the fuel is injected into the "prechamber" which is connected to the main chamber via a nozzle, or one or more orifices.

- For very-large engines (stationary power generation) which operate at low engine speeds the time available for mixing is long so a direct injection quiescent chamber type is used (open or shallow bowl in piston).

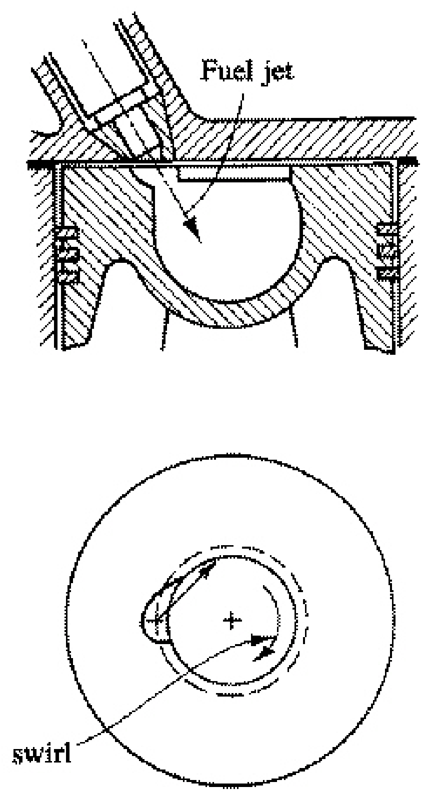
- As engine size decreases and engine speed increases, increasing amounts of swirl are used to achieve fuel-air mixing (deep bowl in piston)

- For small high-speed engines used in automobiles chamber swirl is not sufficient, indirect injection is used where high swirl or turbulence is generated in the pre-chamber during compression and products/fuel blowdown and mix with main chamber air.

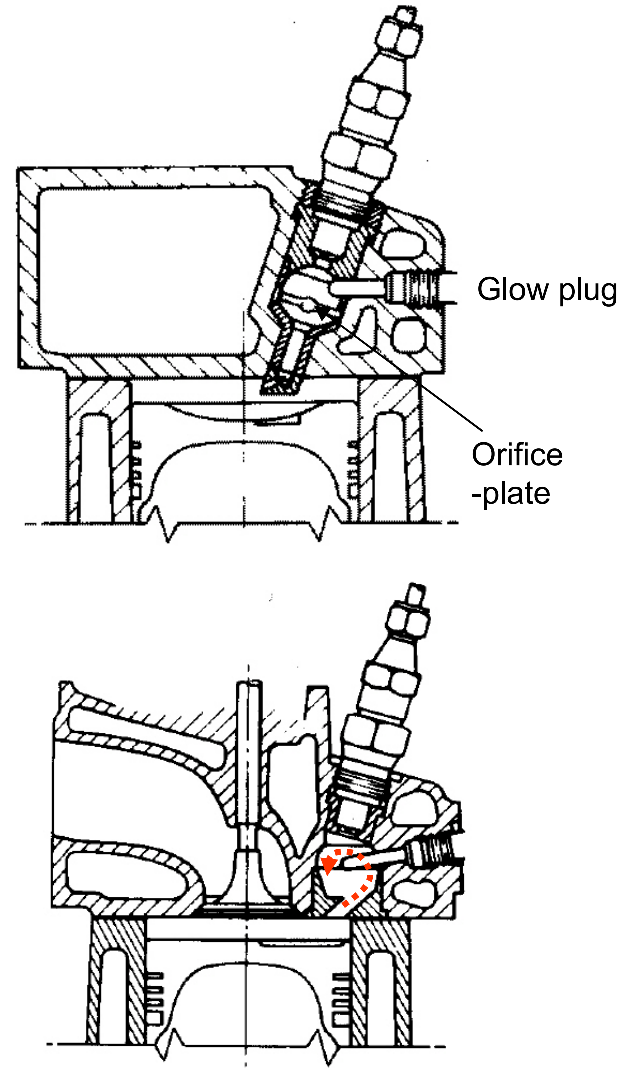
Types of CI Engines



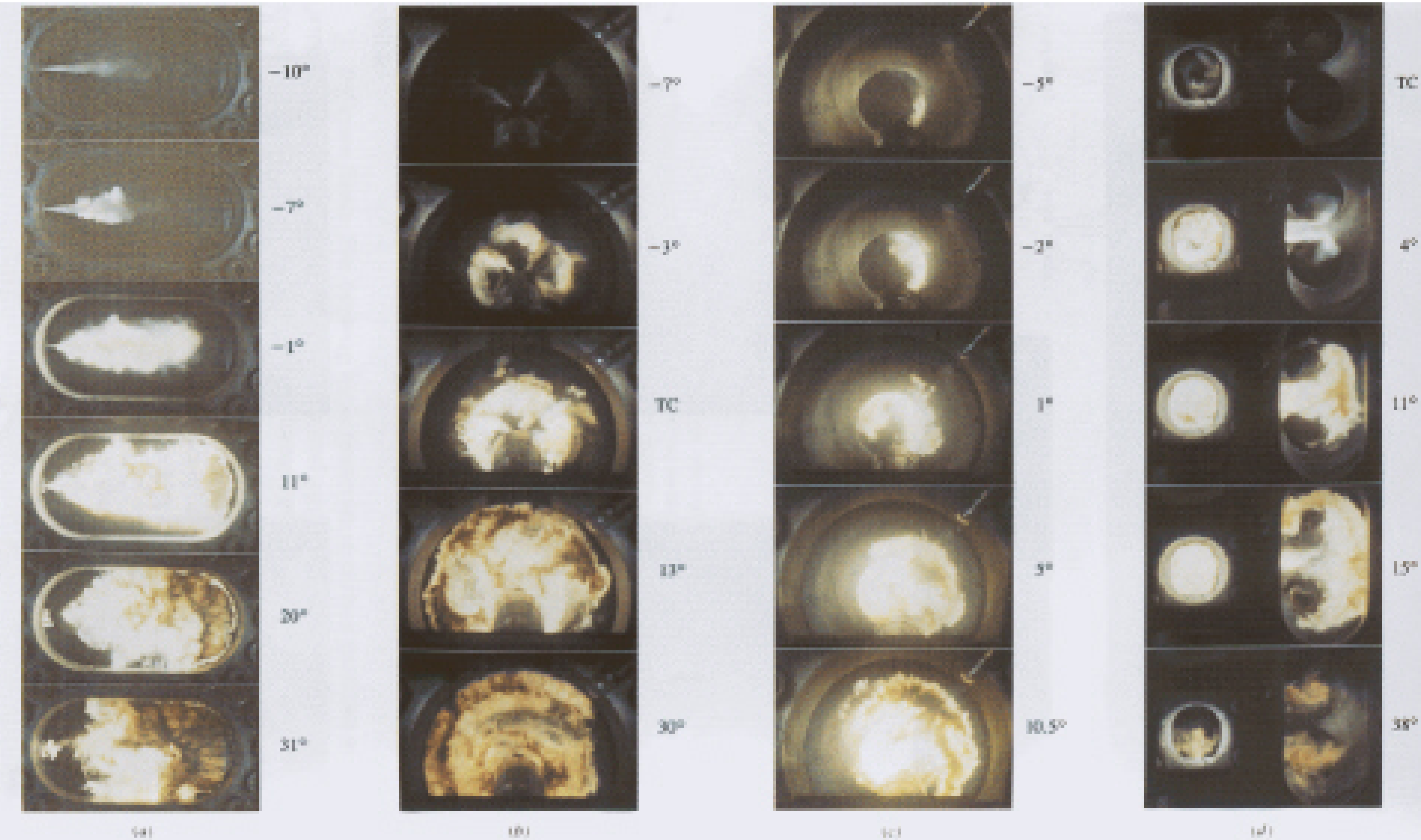
Direct injection:
quiescent chamber



Direct injection:
swirl in chamber



Indirect injection: turbulent and swirl pre-chamber



Direct Injection
quiescent chamber

Direct Injection
multi-hole nozzle
swirl in chamber

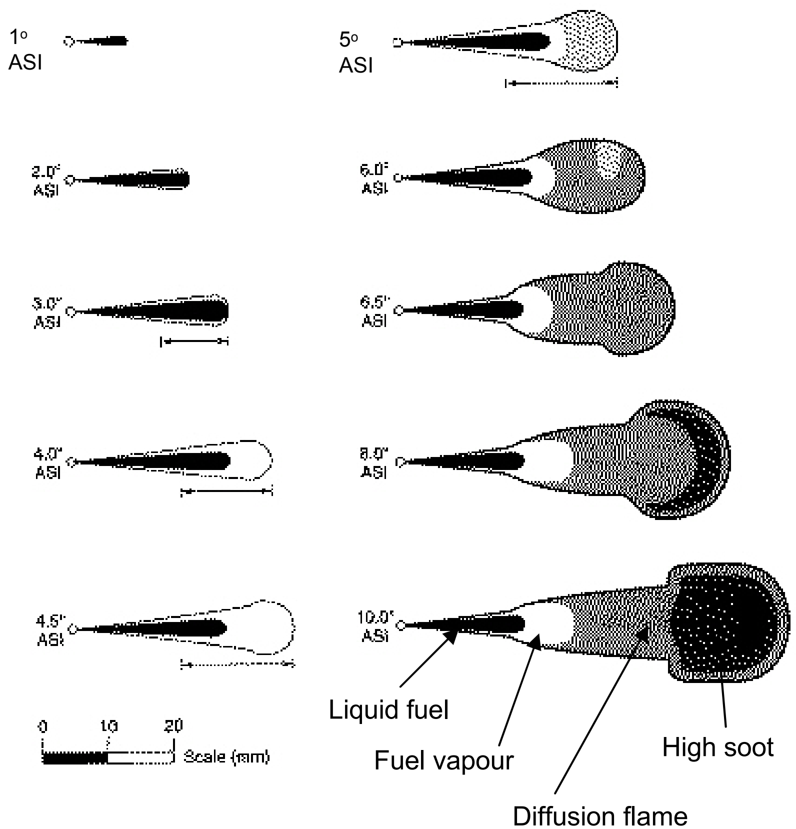
Direct Injection
single-hole nozzle
swirl in chamber

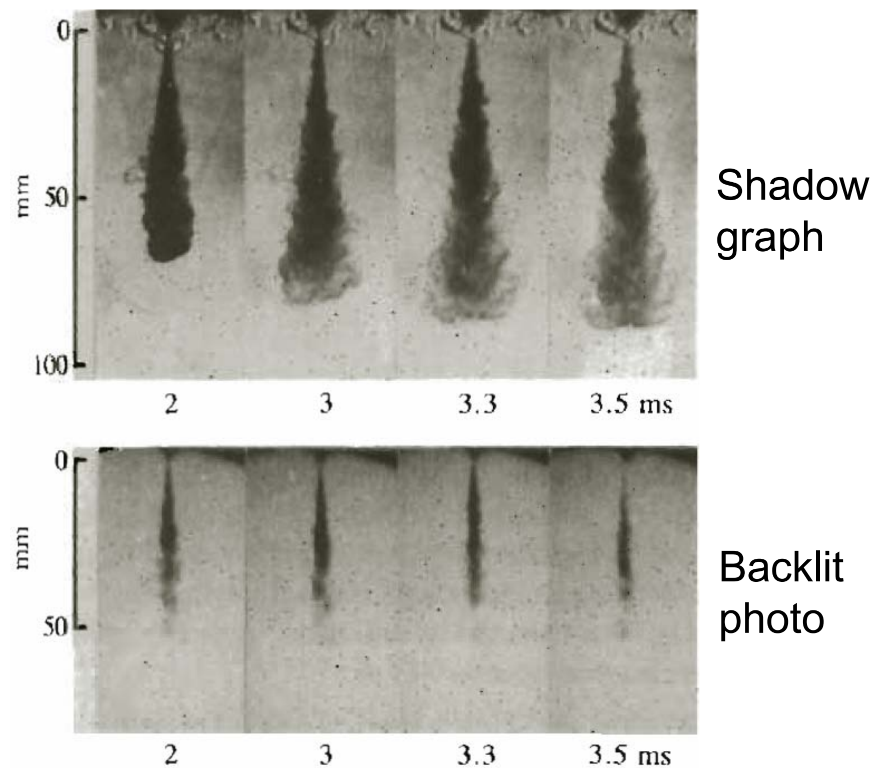
Indirect injection
swirl pre-chamber

Combustion Characteristic

Combustion occurs throughout the chamber over a range of equivalence ratios dictated by the fuel-air mixing before and during the combustion phase.

In general most of the combustion occurs under very ______ conditions within the head of the jet, this produces a considerable amount of solid carbon (soot).





Ignition Delay

Ignition delay is defined as the time (or crank angle interval) from when the fuel injection starts to the onset of combustion.

Both physical and chemical processes must take place before a significant fraction of the fuel chemical energy is released:

include fuel spray atomization, evaporation and mixing of fuel vapour with cylinder air.

• Good atomization requires high fuel pressure, small injector hole diameter, optimum fuel viscosity, high cylinder pressure (large divergence angle).

• Rate of vaporization of the fuel droplets depends on droplet diameter, velocity, fuel volatility, pressure and temperature of the air.

similar to that described for autoignition phenomenon in premixed fuel-air, only more complex since **heterogeneous reactions** (reactions occurring on the liquid fuel drop surface) also occur.

Fuel Ignition Quality

The properties of the fuel affect the ignition delay.

The ignition quality of a fuel is defined by its $\boxed{}$ (CN).

For *low* cetane fuels the ignition delay is *long* and most of the fuel is injected before autoignition and rapid combustion, under extreme cases this produces an audible knocking sound referred to as “diesel knock”.

For *high* cetane fuels the ignition delay is *short* and very little fuel is injected before autoignition, the heat release rate is controlled by the rate of fuel injection and fuel-air mixing – smoother engine operation.

Cetane Number

The method used to determine the ignition quality in terms of CN is similar to that used for determining the antiknock quality of fuels via the ON.

The cetane number scale is defined by blends of two pure hydrocarbon reference fuels.

(heptamethylnonane (HMN), $C_{16}H_{34}$) is assigned a cetane number of 15* and (n-hexadecane, $C_{16}H_{34}$) a value of 100.

The cetane number is given by:

$$CN = (\%\ \textit{cetane}) + 0.15\ (\%\ \text{isocetane})$$

*In the original procedures 1-methylnaphtalene ($C_{11}H_{10}$) with a cetane number of zero represented the bottom of the scale. This has since been replaced by HMN which is a more stable compound.

Cetane Number Measurement

The method employed to measure CN uses a standardized single-cylinder engine with variable compression ratio

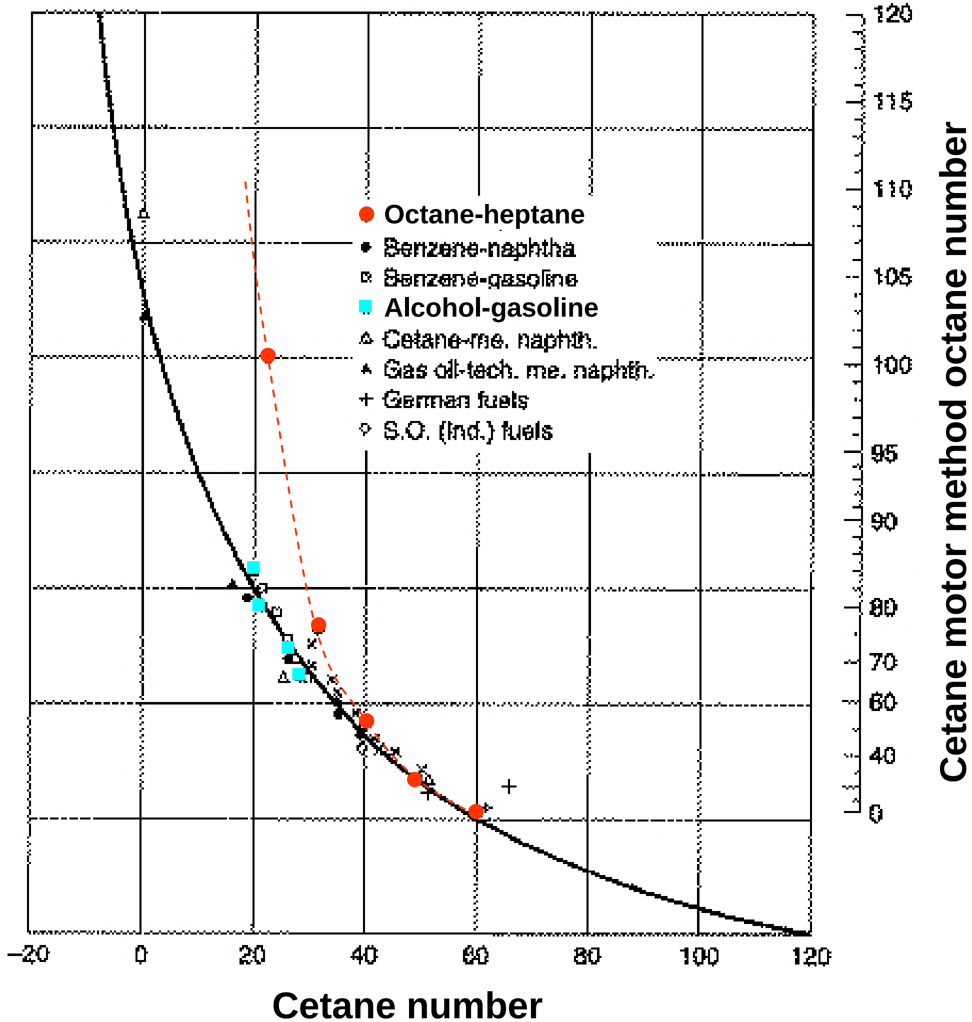
The operating condition is:

Inlet temperature (^oC)	65.6
Speed (rpm)	900
Start of fuel injection (^{o}BTC)	**13**
Coolant temperature (^oC)	100
Injection pressure (MPa)	10.3

With the engine running at these conditions with the test fuel, the compression ratio is varied until combustion starts at $\boxed{}$ → ignition delay period of 13^o.

The above procedure is repeated using blends of isocetane and cetane. The blend that gives a 13^o ignition delay with the same compression ratio is used to calculate the test fuel cetane number.

Cetane Number versus Octane Number



ON and CN are inversely correlated so gasoline makes a poor diesel fuel and vice versa!

Factors Affecting Ignition Delay Time

– At normal engine conditions the minimum delay occurs with the start of injection at about 10-15 BTC.

Earlier or later injection timing results in a lower air temperature and pressure during the delay period → increase in the ignition delay time

– For a CI engine the air is not throttled so the load is varied by changing the amount of fuel injected.

Increasing the load (bmep) increases the residual gas and wall temperature which results in a higher charge temperature at injection → decrease in the ignition delay.

– an increase in either will result in a decrease in the ignition delay, an increase in the compression ratio has the same effect.

Factors Affecting Ignition Delay